STAR 217-PRE
Progress of Recycling in the Built Environment

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RILEM TC 217-PRE: Use of Recycled Materials

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1. INTRODUCTION AND ACTIVITIES

1.1. OBJECTIVES OF THE BOOK

For centuries, the construction industry has been a voracious consumer of raw materials. The construction industry has become more responsible for the greatest waste stream. According to data published by EUROSTAT, the European Statistical Office, 48% of the waste produced proceeds from the construction and demolition sectors, and third of the prime resources consumed end up transformed into residues and emissions. In other continents, and even within the EU, the proportions can vary according to construction and development activity. In any case, the situation provoked by the amount of waste, can be extrapolated to other countries and even pressing in the future in emerging countries.

Concrete, masonry rubble and stone, stand out as the dominant components of this type of waste. Evidently, such stream of waste can occupy enormous amount of space and ground surface in landfills. As it has been demonstrated for more than half a century, these residues have a great potential for reuse in the same field where they proceed from and taking advantage of this can save raw materials.

From a global point of view, some authors estimate that the replacement percentage of prime resources amounts to 15%. The recycling of this waste was heavily promoted in the 70s, in several countries, on the premise of saving resources and land by slowly reducing the amount o landfills normally available for disposal. Since then recycling of CDW has developed into an ambitious and creative industry that produces recycled aggregate for construction.

Professor Charles F. Hendricks (Hendriks, Nijkerk, & Van Koppen, The Building Cycle, 2000), based material and waste management in the Integral Chain Management concept, which relies on keeping prime resources within a single life cycle for the greatest amount of time possible. This cycle accounts for durability, its derivate products and its return to the cycle with the appropriate treatment once concluded its use, “as long as it is appropriate from an environmental point of view” he added. Thus, the environmental impact of closing the life cycle must then be assessed as well.

This issue has been addressed by the Life Cycle Analysis (LCA) through different methodologies. Although it is not the primary goal of this report to go in depth over the Life Cycle Analysis (LCA), which is subject of increasing publications, we believe we should start by addressing the recycling of construction and demolition waste (CDW) from an environmental perspective.

The last decades have shown beyond doubt that recycled materials can be accepted and have a broad demand. Properly processed construction and demolition waste have enabled the production of quality assured products around which an important market has already begun to develop. Nonetheless, the acceptance of recycled products has clashed in several countries. They still face numerous problems and, even with the recognition of their environmental necessity, they are subject to the imperatives of the free market. Local prices, abundance and demand of natural aggregate, determined by the country's economic situation and development of construction industry, govern the competitiveness of recycled aggregate.
Currently (2011), the economic crisis has hit many countries with distinctive intensity, aggravating in some the challenges of their implementation, which range from the decline in construction activity to lack of CDW due to the near disappearance of demolitions. In other countries, among which are found most of the emerging nations, the waste production and recycling data seems to indicate an opposite tendency. For instance, in 2010, China generated 300 tons of CDW in demolitions related to the Shanghai World Expo alone, while 200 million tons is their annual consolidated figure. The status report included in this publication reveals more than just a takeoff.

In Brazil recycling has started long time ago, but his development has been very slow. The coming international sport events will accelerate the construction activities and the demand of aggregates.

Differences in the proportions of recycled CDW in the EU range from 10% to 90%. The EU Waste Framework Directive, which came into effect in 2010, sets an average quota of a 70% recycling for CDW by 2020. In the Netherlands, Belgium, Switzerland and Austria this figure has already been reached, but there are still many other countries left for which reaching this figure seems a complete utopia.

The objective of this publication is to collect the data of advancements, achievements, problems and solutions most representative of the various situations. Thereby, each country can learn from examples and underpin a pedagogy for the effective implementation of recycling.

Apart from some isolated efforts, systematic research on the use of recycled aggregate in concrete road pavements started in the 70's and appeared in numerous publications. Many suggested their use in structural concrete, promoting what we now call original level and maximum value up-cycling. It was not intended to eliminate the initial practice of using of recycled aggregates in road sub-base (down-cycling), which remains the most widespread and simple application, but to increase the number of applications with greater environmental value.


*The Building Cycle* (2000), and *A New Vision of the Building Cycle* (2004), by Ch. Hendriks et al (Hendriks C., A new vision of the building cycle, 2004), are books that have strongly contributed to under-laying the knowledge base and technological evolution of recycling of CDW.

Following this tradition, the second objective of this publication is to collect and report on the advances in concrete recycling produced since 2005.

Recycled aggregates that are produced in more modern plants, are cheaper than primary aggregates. Cleaning and separation techniques have enabled the removal contaminants, and a
secondary crusher can solve the problem of inadequate forms. The generalized presence of gypsum can be reduced to acceptable levels by jigging or using more sophisticated techniques. Today, there are plenty of new features in recycling plants that enable us to obtain quality aggregates.

**New products** have been developed that extend the field of application of the recycled aggregate. The field of precast concrete products has proven that not only it can absorb its own waste, but that it can produce new successful products based on recycled aggregates. Possibilities have opened up for the application of recycled aggregate in porous concretes, and modular blocks of recycled concrete are being produced.

A complete new approach to the procedure of proportioning concrete mixtures with **recycled aggregate** has been recently presented by A.G. Razaqpur et al (Razaqpur, Fathifazl, Isgor, Abbas, Fournier, & Foo, 2010) which treats the residual mortar as part of the aggregate of the total mortar content. The resulting concrete can satisfy the durability, strength, and other physical and mechanical requirements of structural concrete. This concrete requires less cement, which makes it more economical and environmentally attractive. Other teams like the Materials Section of UPC Barcelona are working in the same direction with some new modifications that extends the field of application.

Recent publications, opinions and discrepancies in relation to the durability of recycled concrete, such as freeze-thaw standards, studies of chloride penetration and diffusion, and sulfate attacks, are examined.

In most countries, the proportion of masonry rubble in CDW is elevated and its use is limited to road base overlays of mixed recycled aggregate. This rather limiting application does not provide a definite solution for future markets.

The recovery of material must always focus on the weakest point of the chain in properties and market. Thus informing on the **advances in masonry recycling** is another objective of this book.

**The use of the fine fraction**, <4mm in Europe and <2mm in Japan, remaining from the production of recycled aggregates appears to pose more problems than solutions as its excessive absorption potential can increase shrinkage and creep in recycled concrete. Since this fraction represents between 20% and 60% of production, significantly influencing the economics of the process, offering a broad vision of possibilities for its use will be our goal. Carefully studying its characteristics, possible applications in the field of prefabricated structures can be found.

Finally the **quality assurance of concrete recycled aggregate** is a general necessity. The physical and mechanical properties are checked in accordance with national and international standards. Aspects related to the incoming wastes, crushing processes, new technologies, and original concrete, among others, are considered.

We hope that this report can give information to recyclers, researchers and consumers about new knowledge. Perhaps it can be a useful tool for countries starting his activities in recycling.
1.2. ABSTRACT OF THE TC'S ACTIVITIES (MEETINGS, METHODOLOGY, SYMPOSIAS)

This report is the result of the work done by the members of the TC and collaborators, discussed in 9 meetings and the rich contributions of the Symposium of Sao Paulo 2008, the Sao Paulo International RILEM Conference Progress of Recycling in the Built Environment 2009 and Shanghai RILEM 2nd International Conference on Waste Engineering and Management 2010. This events were promoted by members of the TC 217 and co sponsored by RILEM.

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2. CONSTRUCTION AND DEMOLITION WASTE RECYCLING IN A BOARDER ENVIRONMENTAL PERSPECTIVE

2.1. Sustainability and recycling construction waste

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2.1.1. Introduction

Recycling of building materials is not a novelty. Romans use construction waste like ceramic in their concrete (Delatte). However, nowadays except from large natural disasters or war (Lauritzen, 1998) and in a few European countries actual recycling of mineral fraction of construction materials is often more an exception than a rule. More than that, most of the recycling implies in downgrading, were aggregates are used in less noble functions than the original ones.

The growing interest in sustainable development and, more specifically in sustainable construction, as a reaction of the society to the growing global environmental and social problems, can be a decisive factor to increase recycling rates in the near future. It has been pointed out that recycling has been frequently presented as sustainable “based on a few strength measurements and a few leaching tests on samples tested in the lab” (Vandecasteele & van der Sloot, 2011) therefore neglecting the complexities of sustainable use of resources. This chapter aim to analyse the prospects for the recycling of the mineral fraction of construction and demolition waste as aggregates within the frame of sustainable construction.

2.1.2. Defining and measuring sustainability

A sustainable solution must seek equilibrium between competing social, economic and environmental demands while fulfilling the technical demands, along its life cycle, cradle to grave. The green movement put emphasis in the environmental aspects of sustainability, which are the more relevant in developing countries. However, in developing countries economic and social aspects are also pressing.

Any production and consumption process has simultaneously multiple environmental impacts. Despite being obvious that it is impossible do judge environmental performance (or even sustainability) of any solution base made based only on a single aspect (e.g. content of recycled materials), many of green building guides or labels adopt this kind of criteria. It has been adopted rather frequently to support the need of recycling construction waste as aggregate. The state-of-the-art tool o judge environmental performance is life cycle assessment (LCA), which is a well-defined, standardized, multi-criteria, cradle-to-gave (or cradle) methodology (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). Traditional LCA methodology aims to be as complete as possible resulting in a rather complex process, which is very intensive on data (Guinee, Gorree, Heijungs, Huppes, Kleijn, & Koning, 2004). Despite being based on a
quantitative inventory of flows of energy and materials for each step of service life, the practical application of the methodology requires subjective decisions which can have enormous influence on the practical results. Examples are the selection of the criteria for allocation of environmental loads, particularly when dealing with generated or recycled waste (Sayagh, Ventura, Hoang, François, & Jullien, 2010) (Ekvall & Finnveden, 2001), defining scope and system boundaries (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). Using LCA in a decision process frequently require weighting the different environmental impacts, which depends on the agenda of the decision-maker. This will be the based for all future environmental product declaration (EPD).

Most of the LCA evaluations and technical decisions are based on data from generic life cycle inventories (LCI) available in the market. In other words, decisions are made based without direct measurements of the actual flows of energy and materials from the particular production process in question. The use of LCI data banks is a necessary simplification given that the number of measurements from a complete LCA is large and many of these measurements require very specialized and expensive equipment and personnel. However, considering that there are significant differences between actual process and raw material and fuel formulation and the changes of any given process overtime, this approach can lead to erroneous decisions even if some adjustment is done. Worst, a significant share of LCI data is based on single measurements and is not even representative of the process that was analysed. An alternative to reduce inference errors is to simplify LCA by concentrating on the more important and/or easy to measure impacts, such as CO₂ emissions (Bala, Raugei, Benveniste, Gazulla, & Fullana-I-Palmer, 2010), energy consumption, use of natural & recycled resources, water consumption, waste generation and toxicity. This approach have de advantage of opening the LCA market to institutions that can’t afford a professional LCI database and even allow smaller organizations to produce relevant environmental products declarations (EPD).

Economic performance assessment is rather standard in the economy. However the whole life economic performance, Life cycle cost (LCC) (Fuller & Petersen, 1996) a cradle to grave tool is not so popular. While traditional economic decision making tools are concerned with direct, indirect and contingency costs and revenues from the production process, to perform a LCC coherent with LCA it is necessary to include external costs – those who are borne by parties other than the company, e.g. the cost that a local authority has to remove illegally dumped construction and demolition wastes (CDW), which also has social impacts since affects public authority investment capability – as well we intangible costs such as costumer loyalty, worker morale and wellness (Norris, 2001).

Assessing social dimension of sustainability still is a rather underdeveloped area. Only in 2009 the UNEP/SETAC released the first guidelines to perform a Social Life Cycle Assessment (S-LCA) (UNEP, SETAC, 2009), which is defined as “is a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle”. It includes all stakeholders during the material service life (Workers/employees; Local community; Society (national and global); Consumers (covering end-consumers as well in the supply chain) and value chain actors It includes aspects like health and safety, transparency, respect to cultural heritage, local employment, fair salary, discrimination (Benoît-Norris, y otros, 2011). The methodology is designed to measure quantitative and qualitative variables trying to evaluate the degree of corporate social responsibility. The methodology implicitly considers that the producers and its supply chain operates accordingly with local regulations.
However that’s not the case in most of the developing countries, particularly regarded to natural aggregate production.

The evaluation of the whole life cycle of a product requires the consideration of future impacts, including construction, use, maintenance, dismantling, eventual recycling and final destination of the materials. Forecasting future impacts implies in developing scenarios of utilization concerning environmental aspects (LCA), economic (LCC) and social. It also requires estimating the service life of the products (Hans & Chevalier, 2005) (John, Sustainable Construction, innovation and durability: trends and research needs, 2011), that might be rather complex especially because it depends on the exact function of the product in the construction (that is not clear for an aggregate.) local environmental variables, integration with other construction parts as well as maintenance profile and local environment. In the case of raw materials, like aggregates and cement, not even the application is clear to the producer. Therefore it is a current practice to perform life-cycle evaluation limited to plant gate (cradle to gate), leaving to the client to complete the life-cycle information and taking a decision. In consequence, even if the cradle-to-gate life cycle analysis demonstrate that the recycled aggregates present better environmental social and economic performance than natural ones it does not implies that they are the more sustainable choice for all uses in all situations.

2.1.1. Environmental drivers for recycling - closing the materials flow cycle

Modern economy depends on a constant flow of materials (Adriaanse & et.al, 1997), which starts with the extraction of natural raw materials and goes to the destination of the post-use waste at the end of service life. The ever-improving industrial technology is making possible the production of a progressively large amount of materials goods. Developed countries demand a direct material input between 17-38t/y.person (Adriaanse & et.al, 1997) (Moll, Bringezu, & Schbütz, 2005). However, the total amount of material extracted from nature is much larger, because it is necessary to consider the hidden flows that do not enter in the economy, which are wasted in the process. In consequence, the total materials requirement in this economics is 45 - 85 t/y per person (Adriaanse & et.al, 1997). Building materials represents a substantial share of the total materials consumption. In 1900, 33% of the total non-energy materials (or non-energy carriers) was construction materials and by 1998, it had grown to 70-73% (Low, 2005).

Materials flow implies in waste generation in every step of its live cycle. A large part of the natural materials extracted become waste: Iron 60%, Copper 99, Gold 99.99% (Gardner, 1998), a significant part of it as a mining tailing. The extraction of commercial wood logs from tropical rain-forest implies selective logging which might destroy 1/3 of the existing biomass (Cederberg, Persson, Neovius, Molander, & Clift, 2011). During the processing the wood, logs in the saw mill that 60% of this logs become wood waste (Pereira, Santos, Vedoveto, & Guimarães, 2010). Considering that all used materials become waste eventually, and all production process and even transport activity generates waste, the amount of waste produced in the economy is to up to five (John, REICLÂGEM DE RESÍDUOSNA CONSTRUÇÃO CIVIL: Contribuição à metodologia de pesquisa e desenvolvimento. Dissertation, 2000) times the amount of commercial materials. Waste generation in mining and short-live materials use is important and in consequence ½ to ¾ of the direct material input are discharged as waste in less than 1 year time (Matthews & et.al, 2000). Construction

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1 Total material requirement includes hidden flows – like deliberate alterations of landscape and quarry cover removal. Direct material input includes only materials that enter in the economy for further processing, like wooden logs, minerals shipped to the mill, etc..
and demolition waste is therefore a small fraction of total waste generated by flow of the building materials in the economy.

Besides of resource consumption and waste generation the extraction, transportation and processing this large amount of materials have all sorts of impacts on the environment. When measured by weight, materials account for 44 per cent of the United States’ resource use, 58 per cent in the case of Japan, and as much as 68 per cent in Germany (Gardner, 1998). The flow of materials is therefore responsible for a significant share of the global ecological footprint being 20% of the ecological footprint in the USA (Gardner, 1998).

Extraction of raw materials always has environmental impact on ecosystems, including endangered ones. Materials contribution to global warming is very important. Cement production is responsible nowadays for something around 5% of anthropogenic CO2 emissions and business as usual this share is expected to grow sharply in the near future (Müller & Harnisch, 2008). In some regions of the Brazilian Amazon rainforest the logging of 20 t of lumber generates in average 85 t of wasted biomass, which will be degraded into 156 t CO2.

Materials flow also generates waste and pollution and, frequently, has important social impacts in neighbourhood communities, affecting their quality of life and traditional economies.

Today only a small fraction of the waste is recycled which is not sustainable since we are using progressively less renewable materials and our system is limited. From materials flow point of view there is a need to progressively move from a open cycled to a close cycle (type III) economy (Brown III, Matos, & Sullivan, 2000), which will require recycling more and more waste.

![Possible materials flow in industrial economies](image-url)

Fig. 2.1: Possible materials flow in industrial economies. The aim is to move to type III close cycle industrial ecosystem (Brown III, Matos, & Sullivan, 2000).

Closing the industrial ecosystem requires recycling to become the most important source of row materials. This challenge includes the building materials industry.

### 2.1.1. The flow of mineral construction materials and construction waste

Materials flow models, which link evolution of social and economic patterns which influences
construction demand with service-life modelling can help to forecast construction materials consumption construction and demolition waste generation as well as the potential impact of recycling strategies (Bergsdal, Bohne, & Brattebo, 2008) (Hu, van der Voet, & Huppes, 2010). To the moment there are no published global studies of future flows of construction and waste materials.

The global demand for construction aggregates was estimated in 2006 to be about 10 t/y.person (Danielsen, 2006), which is a significant part of the direct materials input. Considering that in 2006 the cement consumption was 397kg/y.person (SNIC, 2010), cementitious materials will require something between 2,1 and 3,5t/y.person\(^2\) (13 to 23 Gt/y), value which is coherent with the estimative that in UK approximately 40% of aggregates are used for making concrete (The concrete centre -TCC; Mineral Products Association -MPA, 2010).

Mineral materials wastage rate can be responsible for a significant fraction of this consumption. The reported percentage of waste materials in some developed countries varies from 2-15% in UK, 2-22% in Australia (Formoso, Soibelman, de Cesare, & Isa, 2002), 13-15% in Finland and 1-10% in The Netherlands (Bossink & Brouwers, 1996). A comprehensive study conducted in Brazilian multi-storey residential buildings sites found even higher levels of wastage, around 20% of the materials delivered to the site (Formoso, Soibelman, de Cesare, & Isa, 2002). However, aggregates wastage rate was much higher. Waste rate of coarse aggregate varied between 9 to 294%, with median equal to 38%. Sand waste rate was even higher, between 7 and 311%, with median of 44% (Souza, Andrade, Paliari, & Agopyan, 2003). The factors associated to wastage rates are now all understood, and includes both site management, design decisions, procurement and technical solutions (Formoso, Soibelman, de Cesare, & Isa, 2002) (Bossink & Brouwers, 1996) (Jaillon, Poon, & Chiang, 2009). Preventing aggregate wastage rate is an environmental and economical priority.

The amount of construction materials used in the society has been growing due to the growth of economy and population. Cement production was around 0,7 Gt/yr in 1970, 1,17 Gt/yr in 1990 and 3,1Gt/yr in 2010 in an annual growth rate around in the last 20 years 6% and it is expected to growth to 5Gt by 2030 (Müller & Harnisch, 2008), 1.6 fold grow. This will increase the demand for aggregates to 26-44Gt/y (3 to 5t/y.person, considering a population of 9 billion). This estimative is conservative since it neglects the tendency of decreasing binder intensity of cement based materials due to environmental problems in the near future (Damineli B., Kemeid, Aguiar, & John, 2010).

\(^2\) The average proportion between aggregate and cement varies from country to country and with time – it probably will grow with the tendency of reduction of cement content due to environmental concerns[29,30]. In the literature this proportion has been estimated from 5,4 t/t for the UK[31] to 7,6-8,9 t/t in the USA [17]. The Sustainable Europe Research Institute data accounts for 4,4 t/y.person [32] for total global aggregate consumption, which is inconsistent with data from cement consumption.
Fig. 2.2: Cement production evolution over time and forecast to year 2050 [23]. The forecast assumes that cement use efficiency will not improve in the future.

Thus, the consumption of construction materials, and particularly, mineral aggregates have a relevant environmental impact, mainly due to the production scale.

### 2.1.2. Informal production of aggregates

The informal economy, broadly defined as any economic activity that is not declared to governmental agencies (Schneider & Enste, Shadow Economies Around the World - Size, Causes, and Consequences, 2000), (Schneider & Enste, Shadow Economies Around the World - Size, Causes, and Consequences, 2000), (Danopoulos & Znidaric, 2007) represents a significant stake – more than 70% - of the economy in many developing countries (Schneider & Enste, Shadow Economies Around the World - Size, Causes, and Consequences, 2000), (Gërxhani, 2004). In Brazil about 55% of the total aggregate production was informal in 2006 (FGV PROJETOS-ABRAMAT, 2006), and even large companies can keep part of their operation informal. After extraction and transportation to consumer centres it is difficult to separate legal aggregates from illegal ones, which facilitate the full integration of illegally produced aggregate in the formal economy. (Dada, 2007)

Informal production does not need to respect state regulations, including environmental, social and taxation. This tends to worse environmental impacts and undermines the state capacity to plan and implement policies (Danopoulos & Znidaric, 2007): reduction of informal aggregate production is a precondition to sustainable policies, including recycling.
2.1.3. Economical drivers for recycled aggregates

Natural aggregates are simple and cheaper to process than recycled aggregates, since natural raw material is more homogeneous and have much lower contamination than recycled one. The low cost of natural aggregates has been certainly a limitation factor for a decisive factor for any material, even for sustainable construction. However in many regions the economic factors are changing.

- **Localized scarcity and long transportation distances**
  Even though natural aggregates are available in large quantities in most of the world regions the combination between more strict natural environmental protection laws and concentrated consumption in large cities can cause sharp increase in costs, especially due to long transportation distances. In almost all developing countries most of the cargo transportation is performed by roads, which is significantly more expensive than rail and river.

  In São Paulo metropolitan area, for example, natural sand cost more than USD 39/t (BRL 80) and coarse natural aggregate around USD 25/t (Caixa, 2011), being long distance road transportation a significant fraction of it. In regions were natural rocks are scarce, like the Amazon region in Brazil, prices can be much higher. In Manaus, for example, coarse aggregate cost is USD 66/t (Caixa, 2011). These prices are expected to grow with the increasing demand. These Brazilian prices are much higher than the average price in USA market, respectively USD 7.70 (Bolen, 2011) and 9.91 (Willett, 2011) or in Europe, were the highest prices are about USD 16/t (~12 Euro), observed in Eastern Europe, particularly in Russia, Hungary, Romania and Bulgaria (Neubauer & et.al, 2008).

  This situation can be relevant for a significant fraction of the worldwide aggregate market, since 60% of the urban population of developing countries was leaving in cities with more than 1 million inhabitants and 24% in cities with more than 5 million (Montgomery, 2008). In the year 2050 it is expected that the number of people leaving in cities will be 6.4 billion, twice the number of 2007 (Jiang, Young, & Hardee, 2008).

  The reduction of transportation distance by CDW recycling between the production site to construction site and CDW availability evaluated by population density are the main responsible for the economic feasibility of recycling (Neubauer & et.al, 2008).

- **Increase landfilling costs for waste generator**
  In cities where illegal dumping is viable cost of landfill is an external cost, since the public (local authority) will pay for the cleaning and landfilling. This can be very costly because it requires moving heavy machinery to illegal dumping sites and long distance transportation to landfill. In city of São Paulo, this represent near 13 Euro/t (Schneider D., 2002).

  When a society succeed to control in illegal dumping cost of construction waste management increases. In large metropolitan areas, space for landfilling is normally high which implies in long transportation distances, which is also expensive. Landfill cost in São Paulo is near 100 Euro/t. A deconstruction plan study conducted at city of Sao Paulo has pointed that CDW recyclable sorting and on site recycling of most CDW were the best economical option, which explains why CDW recycling is fast growing at big cities of under development countries.
Landfill and aggregate taxes
The implementation of a landfill tax is also an effective way to promote recycling in regions (or countries). This measures are affected only if illegal dumping and natural aggregate extraction market share is small. In Europe, landfilling is taxed in many countries, at values up to 50 Euro/t (Neubauer & et.al, 2008). In the UK natural aggregate has been subjected a progressive tax (Neubauer & et.al, 2008).

2.1.4. Social drivers
Reduction of local authorities’ costs associated to cleaning illegal dumping is clearly a social benefit from recycling construction demolition waste, especially in developing countries were the rate of illegal dumping is high. Recycling also generates new green jobs (Bibby, 2010) all over the supply chain, from segregation activities, transportation and processing. This can be important especially for countries with high unemployment rates.

2.1.5. Assessing sustainability of recycled aggregates
LCA of recycled aggregates
There are a growing number of LCA assessments of recycled or natural aggregates, and web and Excel data file tools are available. However, this tools are cradle-to-gate (does not account for whole life cycle) and probably are not valid to other regions and applications. Even the technology used to demolish the original building and the transportation distance influence the environmental balance (Coelho & de Brito, 2011).

In many regions of the world, alluvial river virgin quartz sand extraction is still available. and resources depletion can be serious involving aggradations and erosions. On the other hand, CDW recycling avoids illegal dumping; one of the responsible for aggradations in urban areas and, it is scarcely quantified to balance environmental advantages of recycling. Waste generated by CDW recycling is not often considered in spite of fine fraction of aggregates (<4.8 mm) remains without a noble and defined use. Due to major concerning with climate change, partial environmental evaluations have been done and much attention has been directed to CO2 emissions.

Despite abundant crushed rocks are also intensely used in world construction and energy and transportation uses are the main environmental concerning due to fossil combustible use. Countries with hydroelectric power domain, environmental impact by energy use is secondary and transportation has a higher relative importance.

Recycled concrete aggregates (RCA) production demands more intense use of machines and combustibles and, as a consequence, higher CO2 emissions (Marinković, Radonjanin, Malešev, & Ignja, 2010) (Chowdhury, Apul, & Fry, 2010). Other environmental impact categories such as eutrophication, acidification, POC also become worse due to use of combustibles. CDW recycling process generates of large amount of fines (Chen, Lin, & Wu, 2011) that at the present are residues increases the environmental loads of the recycled aggregates, since it reduces the process yield and the effectiveness of the recycling process. Developing practical applications for such fraction is therefore important.

3 http://aggregain.wrap.org.uk/sustainability/sustainability_tools_and_approaches/aggregates_lca.html
4 http://www.ce.berkeley.edu/~horvath/palate.html
Transportation of aggregates accounts 30-40% of total CO₂ emissions of this specific industry for typical distances and road transportation (Fry & Wayman, 2011). The range of CO₂ emissions during transport taking into account consumption of fossil combustibles of different trucks and different emissions factors (GHG, IPCC, etc) can be 12.8-50.6 g of CO₂/t.Km (Bossink & Brouwers, 1996).

The environmental advantage of recycled aggregates use appears in terms of CO₂ emission when road transportation of natural aggregates are significantly higher than recycled ones (Marinković, Radonjanin, Malešev, & Ignja, 2010). Recycled aggregates are generated and commercialized inside cities and significantly reduces transportation distance and it is especially interesting of pavement use. Reduction of 1/6 in transportation distance of aggregates (15 Km of recycled aggregates instead of 100 Km of natural aggregates) can be achieved by recycling near building sites and it reduces CO₂ emissions and becomes environmental feasible the use of recycled aggregates.

However, the sustainability of recycled recycled aggregates cannot be judged without considering the entire life-cycle, which includes application. For example, if aggregates are used in concrete, achieving a positive environmental balance is difficult. For almost all practical situations, cement consumption is the main responsible of CO₂ and other key environmentally important emission of concrete life cycle. Depending on the application, the lower mechanical properties of the typical recycled aggregates in comparison with virgin ones will demand an increase of cement consumption to achieve the same mechanical properties.

Depending on several factors, including concrete strength, recycled aggregate porosity (or oven-dry density in Fig. 2.3a) (Angulo, Carrijo, Figueiredo, Chaves, & John, 2010), as well as degree of natural aggregate replacement, cement content can increase by a factor of two, as shown by Levy & Helene (S.M. & P., 2004). However, in some situations, low porosity recycled aggregate and low strength concrete, the use of recycled aggregate to produce concrete can reduce overall CO₂ emissions, despite the increase of small increase of cement consumption (Marinkovic, Radonjanin, Malešev, & Ignja, 2010). Transportation impacts (or distances), environmental impact of cement production, ecological value of the natural aggregate extraction can also change the conclusions.

Consequently, it is not possible to generalize conclusions on environmental sustainability of the use of recycling aggregates and an LCA is needed to every typical situations.

A simple way to evaluate eco-efficiency of concrete in terms of use of scarce binder materials and for CO₂ emissions is by the binder intensity (bi) (Damineli B., Kemeid, Aguiar, & John, 2010). From a life cycle analysis methodology point of view, this proposition can be understood as changing the functional unit from a unit of concrete volume or weight (1 m³ or kg), which is convenient for measuring the overall environmental impact of any concrete construction, to a unit of functional performance, which in many cases is the compressive strength.

\[ bi = \frac{b}{p} \]

Where \( b \) is the total consumption of binder materials (kg m⁻³), and \( p \) is the performance
requirement (MPa$^{-1}$).

Hence, the CO$_2$ emissions of concretes with porous (low oven-dry density) recycled aggregates can be very high and easily surpass that of concretes with natural aggregates (Fig. 2.3).

![Fig. 2.3: Increase of cement consumption to produce concrete (10-50 MPa) for different oven-dry density aggregates (left) and oven-dry density of aggregates x binder index of concrete (right)](image)

- **Leaching of recycled aggregates: in-use environmental impact**

The use of recycled aggregates in road exposes a high specific surface area material to pure or contaminated water which cause leaching of chemical species, including hazardous ones. Therefore, from theoretical point of view, leaching has to be included on the LCA results (see (Mroueh, Eskola, & Laine-Ylijoki, 2001) for an example).

Hazardous elements may be present in demolition wastes (ENVIRONMENTAL PROTECTION AGENCY, and demolition waste landfills), due to inefficient sorting, incorporation of waste in building materials (Vandecasteele & van der Sloot, 2011) or even exposure to industrial contaminants during use of buildings.

Leaching of metals (Cd, Cu, Mn, Ni, Pb and Zn) of recycled aggregates occurs mainly in acid media (Engelsen, van der Sloot, Wibetoe, Justnes, Lund, & Stoltenberg, 2010). pH media controls the pollutant release due to cement paste solubilisation and it explains most of differences between leaching methods results (Galvin, Ayuso, Jiménez, & Agrela, 2012). Hence, carbonation of cement paste of recycled aggregates will increase leaching (Mulgeta, Engelsen, Wibetoe, & Lund, 2011). Nowadays, leaching can be predicted for use according to different geochemical scenarios (Engelsen, van der Sloot, Wibetoe, Justnes, Lund, & Stoltenberg, 2010).
Gypsum contaminated recycled aggregates implying in higher sulfate concentrations: 890 to 1600 mg/l, especially for fines of CDW (Jang & Townsend, 2001). Such concentration surpass limit for secondary drinking water standard of 250 mg/l and may convert to hydrogen sulfide with organic compounds are presented in soils.

Reduction of leaching can be expected for concrete with recycled aggregates (consolidated material) when compared with base pavement with recycled aggregates (unconsolidated material). In this case, leaching is controlled by diffusion inside pores (Sani, Moriconi, Fava, & Corinaldesi, 2005) (Matthews & et.al, 2000).

Leaching of recycled aggregates as well of materials made with this aggregates are therefore an important step for the life cycle assessment.

### 2.1.1. The need for further developments

There is a need for further development of more comprehensive tools to accesses sustainability of recycled aggregates, including environmental, social and economic dimensions. Materials flow studies can be useful to plan better policies related to recycling construction and demolition waste.

Traditional recycling technologies are very simple, resulting in an rather heterogeneous products. Even when recycling pure concrete, the resulting aggregate does not have the same
performance of the virgin ones. More sophisticated processing technologies aiming to produce better recycled aggregates for every fraction of the mineral construction waste are still needed. In many regions of the world the high cost of natural aggregates and the landfiling costs are increasing the economic viability of such processes. This implies in a significant investment in research and development, since at the moment there are only limited available knowledge in this field.

References

47. Caixa: PREÇOS DE INSUMOS. (2011)


64. ENVIRONMENTAL PROTECTION AGENCY, and demolition waste landfills.


2.2. Global impact assessment of urban renewal based on sustainable recycling strategies for Construction and Demolition Waste

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Ir. Johan A.L. Put, Enviro Challenge, The Netherlands

2.2.1. Why sustainable urban renewal is necessary

Large urban areas worldwide attract more residents, offices and industry. The demand for housing, office blocks, industrial buildings and infrastructure continuously increases. Therefore, the need for building plots rises and so, consequently, do land prices. At the same time, the lifespan of structures without cultural value is only 20 to 30 years for office blocks and industrial buildings, 50 years for housing and 100 years for infrastructure because they no longer comply with current expectations. When applicable, constructions are renovated.

The above-mentioned trends in urban renewal can be perceived around the world in both developed and developing countries. In urban renewal processes, it is obvious that primary raw materials, such as sand and gravel, are utilised.

These high specific gravity materials have to be transported over long distances. On the other hand, however, the regeneration of urban areas results in the production of waste materials, as the original buildings and infrastructure have to be demolished first, in order to create construction space. These developments result in an increase in the long-distance transportation of raw and waste materials with high specific gravity, e.g. lorries from quarry to building site and back (empty), and from demolition site to landfill and back (empty). This traffic eventuates in a considerable increase of CO₂ emission. For urban development purposes, moreover, substantial amounts of primary resources are required, i.e. crude oil as well as minerals.

However, nowadays the decision maker cannot afford to ignore the sustainable approach to urban renewal projects, whereby he is confronted with the impact of his decisions on sustainability issues, such as global warming and the depletion of natural resources. In this context, therefore, strategies for recycling have to be considered. This implies that the waste materials produced during the demolition phase in urban renewal, are recycled into secondary raw materials in substitution for primary raw materials, and subsequently applied in the same urban renewal project.

In the next paragraph is shown how recycling of construction and demolition waste is currently performed in European countries, such as the Netherlands.
2.2.2. How recycling strategies in urban renewal are applied

According to the “Building cycle” model (Ch.F. & G.M.T., 2004) certain waste materials are released which sometimes can be reused as a component. Usually there is no market available and the materials are recycled. Regarding mass, the most relevant waste material in this cycle is the stony fraction. If selective demolition or dismantling is applied, these stony waste materials are free of unwanted matter such as wood, insulation, plastics, textiles, unwanted stony materials (e.g. asbestos and aerated concrete), as well as pollutants (e.g. PAHs).

The recycling of the stony waste materials is carried out by two distinct types of crusher, namely the jaw crusher and the impact crusher. The jaw crusher consists of two plates, one of which is moving (see Fig. 2.5). Because of the force of gravity on the stony waste material and the moving plate, the material is crushed. The impact crusher is composed of a sealed chamber and a fast turning shaft fitted with hammers, which crush the stony waste material. Both crushers are supplied with a pre-sieve and a post-sieve, as well as a magnetic separator, in order to obtain end products, i.e. aggregates, of high technical performance.

Fig. 2.6 visualises the most important links in the chain of construction and demolition waste, from waste disposal to raw material supply. To obtain an efficient recycling process, prevention of undesirable materials in the construction and demolition waste is always better than cleansing. Therefore, selective and environmentally friendly demolition (dismantlement) is necessary. The recycling can take place “off site”, in a plant situated away from the demolition area, or “on site”, on the spot employing mobile machines. The freed up waste materials can, providing an adequate process is used, be transformed into recycled raw materials in substitution for primary raw materials. For recycled building materials different high-grade applications are available, such as in road construction (as sub-base), hydraulic engineering and concrete.
2.2.3. How modelling supports the decision-making process

In this paragraph a web-based logistic computation model is presented, which quantifies the possible savings in CO2 emissions and primary resources as a result of applying the above-explained sustainable urban renewal methods. The model is part of the Expert System “Sustainable Urban Renewal, Demolition and Recycling” and is predominantly based on expert values. Table 2.1 shows the relevant steps to follow.

2.2.4. Why European urban renewal projects are involved

The aforementioned model is illustrated by two case studies, based on actual European renewal projects, which involved one of the authors.

- **NATO Headquarters in Brussels, Belgium (Fig. 2.7)**
  Obliging NATO’s wishes, the government of guest country Belgium, has decided to demolish a Belgian army barracks in close proximity of the old NATO offices, so as to create space for the new NATO Headquarters (further referred to as “NATO Headquarters case”). During demolition, more than 220,000 tonnes of stony waste materials are generated. The Belgian authorities, and moreover the Ministry of Defence, have expressed the explicit wish that traffic movement is monitored so as to minimise the direct and indirect consequences for the surroundings. Therefore, a scenario analysis is executed and recommendations formulated.
Table 2.1: Logistic computation model for global impact of urban renewal

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Demarcation of project area and determination of objects to be demolished</td>
</tr>
<tr>
<td>2</td>
<td>Calculation (per demolition object) of environmental risks, divided into:</td>
</tr>
<tr>
<td></td>
<td>• non acceptable risk, i.e. waste products that need to be dumped or burned</td>
</tr>
<tr>
<td></td>
<td>• acceptable risk, i.e. objects needing to be selectively demolished,</td>
</tr>
<tr>
<td></td>
<td>• no risk, i.e. recycling without further pre-treatment is feasible</td>
</tr>
<tr>
<td>3</td>
<td>Determination (per demolition object and per building object) of materials</td>
</tr>
<tr>
<td></td>
<td>and respective areas, heights, number of storeys and thickness of walls,</td>
</tr>
<tr>
<td></td>
<td>floors and ceilings, resulting in a volume calculation per type of material</td>
</tr>
<tr>
<td>4</td>
<td>Calculation of mass to be demolished and to be built per type of material,</td>
</tr>
<tr>
<td></td>
<td>taking into account the specific gravity of loosely dumped material</td>
</tr>
<tr>
<td>5</td>
<td>Interconnection of environmental risks (red, amber or green light) with mass</td>
</tr>
<tr>
<td></td>
<td>amounts to be demolished per type of material, resulting in an enumeration</td>
</tr>
<tr>
<td></td>
<td>of materials and risk categories</td>
</tr>
<tr>
<td>6</td>
<td>Determination of distance from project to nearest quarry, waste collector,</td>
</tr>
<tr>
<td></td>
<td>concrete supplier, asphalt manufacturer, etc.</td>
</tr>
<tr>
<td>7</td>
<td>Development of logistic scenarios</td>
</tr>
<tr>
<td>8</td>
<td>Choice of rolling stock per scenario (capacity for lorries, type and capacity</td>
</tr>
<tr>
<td></td>
<td>of crusher); definition of assumptions concerning CO₂ emissions, diesel fuel</td>
</tr>
<tr>
<td></td>
<td>consumption for lorries and vans (per 100 kilometres) and share of used</td>
</tr>
<tr>
<td></td>
<td>materials (diesel fuel and primary aggregates) in extraction of raw materials</td>
</tr>
<tr>
<td>9</td>
<td>Calculation of amount of trips for lorries to and fro, and total kilometres</td>
</tr>
<tr>
<td></td>
<td>travelled; calculation of CO₂ emission and equivalent amount of square</td>
</tr>
<tr>
<td></td>
<td>metres of tropical rain forest necessary for the photosynthesis process;</td>
</tr>
<tr>
<td></td>
<td>calculation of total diesel fuel consumption and crude oil extraction;</td>
</tr>
<tr>
<td></td>
<td>calculation of consumption of primary aggregates; calculation of total</td>
</tr>
<tr>
<td></td>
<td>excavation of raw materials (when in the above-mentioned steps new insights</td>
</tr>
<tr>
<td></td>
<td>occur or changes are implemented, recalculation is necessary)</td>
</tr>
</tbody>
</table>

Fig. 2.7: Left- Army barracks in Brussels. Right- New NATO HQ in Brussels (NATO)

- **Rotterdam Harbour, The Netherlands (Fig. 2.8)**
  The second case involves the extension of the residential area at Rotterdam Harbour (Rotterdam City Council & Port of Rotterdam Authority) whilst the harbour is reconstructed further out to sea (further referred to as “Rotterdam Harbour case”). In the Netherlands, where
half the land is below sea level, the awareness of a direct threat to the country, when the sea level is indeed rising, is growing. Because of this social threat, and also thanks to a recent contractual engagement between the City of Rotterdam and the former US-president Bill Clinton to reduce greenhouse gasses, the city developers and politicians wish to put the new city regeneration to tender, taking into account sustainability issues.

![Image](image_url)

**Fig. 2.8:** Left- Fruitport in Rotterdam. Right- New dwellings in Rotterdam

### 2.2.5. How recycling reduces CO₂ emission

Via the Expert System “Sustainable Urban Renewal, Demolition and Recycling” the CO₂ emissions for different scenarios are calculated. In the expert system, the user can define the scenarios for himself. In the context of this paper, identical scenario analyses are performed so as to be able to compare the results of both case studies. The scenarios applied are:

- **scenario 0**: “no” recycling and application of primary raw materials only
- **scenario 1**: “off site” recycling and maximum use of recycled materials on site
- **scenario 2**: “on site” recycling and maximum use of recycled materials on site

For each different scenario the calculation method, as explained in Table 2.1, is applied via the expert system. In appendix 1 and 2, the calculations for the two cases are elaborately presented. Only the relevant sources of emission are taken into account. This implies that for each scenario similar parts are abstracted. Subsequently the relevant absolute CO₂ emission per scenario is calculated. For the two cases this eventuates in:

<table>
<thead>
<tr>
<th>relevant absolute CO₂ emission scenario</th>
<th>NATO Headquarters</th>
<th>Rotterdam Harbour</th>
</tr>
</thead>
<tbody>
<tr>
<td>calculation is based on:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≠ step by step method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≠ CO₂ emissions = 880 g/km for lorries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≠ 260 g/km for vans</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2,420 t</td>
<td>4,170 t</td>
</tr>
<tr>
<td>1</td>
<td>2,068 t</td>
<td>2,281 t</td>
</tr>
<tr>
<td>2</td>
<td>1,725 t</td>
<td>1,027 t</td>
</tr>
</tbody>
</table>

Another approach is to calculate the area of tropical rain forest needed for photosynthesis of the CO₂ emission. This value is called the CO₂ tropical rain forest equivalent and is presented below for the two case studies:
Interesting for the decision maker is the proportion between the scenarios. The result is CO₂ profitability, which is shown below. With the CO₂ profitability ratio it has to be stated that, when a location with relatively few buildings, like an army barracks or a harbour area, is being replaced by a densely built-up area, the profitability ratio is relatively low. This is particularly true in the NATO Headquarters case where a total construction of approximately 220,000 tonnes is replaced by a huge office complex of 850,000 tonnes.

In the Rotterdam Harbour case this phenomenon seems less prevalent, but it needs to be noted that at this stage of the project (strategy building), it is still unclear whether the new residential buildings will consist of two, three or four storeys. Hence the CO₂ profitability ratio is perfectly suitable to compare scenarios within the same project, however not for comparison with other projects.

Another ratio connects the time and area needed to process the CO₂ emission via photosynthesis with the area of the project. Since this ratio shows how quickly the CO₂ emission could be processed, taking into account the area of the project, the ratio is called the CO₂ payback period, analogous to the financial ratios. For both cases this results in:

2.2.6. How recycling signifies savings in primary resources

Based on the same scenarios from the previous paragraph, the total excavation of raw
materials (crude oil and primary resources for aggregates) is calculated and presented below:

Table 2.6: Relevant absolute excavation of primary resources per scenario

<table>
<thead>
<tr>
<th>relevant absolute excavation of primary resources</th>
<th>scenario</th>
<th>NATO Headquarters</th>
<th>Rotterdam Harbour</th>
</tr>
</thead>
<tbody>
<tr>
<td>calculation is based on:</td>
<td>0</td>
<td>538,293 m³</td>
<td>199,635 m³</td>
</tr>
<tr>
<td>- step by step method (see Table 1)</td>
<td>1</td>
<td>412,268 m³</td>
<td>69,137 m³</td>
</tr>
<tr>
<td>- assumptions concerning use of primary resources (see Table 1)</td>
<td>2</td>
<td>411,269 m³</td>
<td>65,489 m³</td>
</tr>
</tbody>
</table>

Recycling strategies followed by use of the recycled materials on site have a beneficial effect on sustainability. This is confirmed in the following overview showing the savings in primary resources for both case studies:

Table 2.7: Relative savings in primary resources per scenario

<table>
<thead>
<tr>
<th>relative savings in primary resources</th>
<th>scenario</th>
<th>NATO Headquarters</th>
<th>Rotterdam Harbour</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{m^3 \text{ excavation primary resources scenario}_x}{m^3 \text{ excavation primary resources scenario}_y}$</td>
<td>1 versus 0</td>
<td>23.41 %</td>
<td>65.37 %</td>
</tr>
<tr>
<td>$\frac{m^3 \text{ excavation primary resources scenario}_x}{m^3 \text{ excavation primary resources scenario}_y}$</td>
<td>2 versus 1</td>
<td>0.24 %</td>
<td>5.28 %</td>
</tr>
<tr>
<td>$\frac{m^3 \text{ excavation primary resources scenario}_x}{m^3 \text{ excavation primary resources scenario}_y}$</td>
<td>2 versus 0</td>
<td>23.60 %</td>
<td>67.20 %</td>
</tr>
</tbody>
</table>

2.2.7. How recycling contributes to diminishing the global impact of urban renewal in both developed and developing countries

The conclusions on both urban renewal case studies indicate that a saving of up to 80 % in CO₂ emissions can be realised by recycling on site, compared to applying only primary raw materials. Moreover, a 70 % decrease in the need for natural resources is feasible. One can add to this other advantages of recycling in respect of the reduction of landfill sites and the creation of employment (FOD Economie & BPF : ‘De aardoliemarkt’, FOD Economie, KMO, Middenstand en Energie, 2007).

In this paper, the model is illustrated by two European case studies. The significance of the advantages greatly depends on a number of factors, e.g.:

- the ratio between the mass of the object to be demolished and the mass of the new object (the higher, the better);
- the application of the recycled product on site (the more, the better);
- the possibility to crush on site (if feasible, better);
- the possibility to produce concrete on site (if feasible, better);
- the ratio between the density of the network of recycling plants and the density of the network of quarries (the higher, the better).

A key premise for the above-described calculations of sustainability advantages is that the recycled products are qualitatively equal to primary raw materials, i.e. that the products are technically, as well as environmentally, equal. This condition can only be fulfilled if the recycling branch in the country concerned utilises an adequate production process such as in Brussels and Rotterdam, with strict acceptance criteria, trained workers, sound machinery,
and a quality system to verify the product quality and adjust the process if necessary.

The European experience has originated from necessity, namely a high population density, a lack of space for waste dumping and the absence of primary raw materials in the surrounding areas. Based on the European knowledge and experience, further case studies will investigate the possibilities of sustainable urban planning and renewal in developing countries, facing similar sustainability issues as referred to in the European case projects. It is expected that, even in developing countries, the utilisation of recycled products in urban renewal is likely to offer significant savings in CO₂ emissions, as well as considerable reductions in the excavation of natural resources, especially as they have the European experience to start from.

2.2.8. Appendix 1 : Calculation NATO Headquarters case

1. Demarcation of project area and determination of objects to be demolished:
carried out by Google Maps and site visit
± 70 ha and ± 70 objects

2 Calculation of environmental risks:
carried out by site visit and checklists
• non acceptable risk (“red light”) : to incinerator
• acceptable risk (“amber light”) : to sorting/washing plant
• no risk (“green light”) : to crusher

3 Determination of materials and calculation of volumen :
 to be demolished
 carried out by Forum S.A, total = 111,690 m³

to be built
 carried out by architects of Asar S.A., total = 354,000 m³

4 Calculation of mass per type of material

5 Interconnection of environmental risks (see Table 2.8):

6 Determination of distance from project to:
• nearest quarry : ± 30 km
• waste collector : ± 10 km
• home base of mobile plants : ± 50 km

7 Development of logistic scenarios :
• scenario 0 : “no” recycling and application of primary raw materials only
• scenario 1 : “off site” recycling and maximum use of recycled materials on site
• scenario 2 : “on site” recycling and maximum use of recycled materials on site
Table 2.8: Interconnection of environmental risks NATO Headquarters case

to be demolished:

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume (m$^3$)</th>
<th>Density (kg/m$^3$)</th>
<th>Weight (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete from road top layers</td>
<td>12,305</td>
<td>2,400</td>
<td>29,532</td>
</tr>
<tr>
<td>Concrete from buildings/roofs, high quality</td>
<td>19,168</td>
<td>2,400</td>
<td>46,003</td>
</tr>
<tr>
<td>Concrete from buildings, normal quality</td>
<td>8,800</td>
<td>2,400</td>
<td>21,120</td>
</tr>
<tr>
<td>Mixed masonry and concrete from buildings</td>
<td>7,179</td>
<td>2,000</td>
<td>14,358</td>
</tr>
<tr>
<td>Mixed masonry and concrete from buildings/chimneys</td>
<td>1,922</td>
<td>2,000</td>
<td>3,844</td>
</tr>
<tr>
<td>Mixed masonry and aerated concrete from buildings</td>
<td>18,000</td>
<td>800</td>
<td>14,400</td>
</tr>
<tr>
<td>Asphalt from roads, tar-free</td>
<td>4,081</td>
<td>2,300</td>
<td>9,386</td>
</tr>
<tr>
<td>Asphalt from roads, tar-containing</td>
<td>435</td>
<td>2,300</td>
<td>1,001</td>
</tr>
<tr>
<td>Original road foundation</td>
<td>39,800</td>
<td>2,000</td>
<td>79,600</td>
</tr>
<tr>
<td>TOTAL</td>
<td>111,690</td>
<td></td>
<td>18,244, 1,001</td>
</tr>
</tbody>
</table>

to be built:

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume (m$^3$)</th>
<th>Density (kg/m$^3$)</th>
<th>Weight (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different kinds of concrete</td>
<td>354,000</td>
<td>2,400</td>
<td>850,000</td>
</tr>
</tbody>
</table>

8 Choice of rolling stock (type and capacity); definition of assumptions concerning CO$_2$ emissions, diesel fuel consumption and share of used materials (diesel fuel and primary aggregates) in extraction of raw materials:
- Capacity lorries: 20 tonnes per load
- Capacity crushers (type: impact crusher): 1,000 tonnes per day per crusher
- CO$_2$ emissions (estimation): 880 g per km for lorries
- Diesel fuel consumption (estimation): 43 litres per 100 kilometres for lorries
- Diesel fuel in crude oil extraction: 16.79%
- Share primary aggregates (sand and gravel) in excavation raw materials: 80%

9 Calculation of total kilometres for lorries and vans; calculation of CO$_2$ emission; calculation of total diesel fuel consumption and crude oil extraction; calculation of consumption of primary aggregates; calculation of total excavation of raw materials:

Scenario 0:
- Transport of waste: $200,000$ t / 20 t/load x 2 (to and fro) x $10$ km/load = $200,000$ km
transport of primary materials = 850,000 t / 20 t/load x 2 (to and fro) x 30 km/load = 2,550,000 km
CO₂ emission = 2,750,000 km x 880 g CO₂/km = **2,420 t** = 242 ha year tropical rain forest

Excavation of primary resources for aggregates = 850,000 t / 80 % = 1,062,500 t or 531,250 m³

**Total excavation of raw materials = 7,043 m³ + 531,250 m³ = 538,293 m³**

**Scenario 1:**
- Transport of waste = 200,000 t / 20 t/load x 2 (to and fro) x 10 km/load = 200,000 km
- Transport of secondary materials = 200,000 t / 20 t/load x 2 (to and fro) x 10 km/load = 200,000 km
- Transport of primary materials = 650,000 t / 20 t/load x 2 (to and fro) x 30 km/load = 1,950,000 km

CO₂ emission = 2,350,000 km x 880 g CO₂/km = **2,068 t** = 207 ha year tropical rain forest

Crude oil extraction = (2,350,000 km x 43 l / 100 km) / 16.79 % = 6,018,463 l or 6,018 m³

Excavation of primary resources for aggregates = 650,000 t / 80 % = 812,500 t or 406,250 m³

**Total excavation of raw materials = 6,018 m³ + 406,250 m³ = 412,268 m³**

**Scenario 2:**
- Transport of mobile crushers = 2 x 2 x 2 loads x 2 (before and after project) x 50 km/load = 800 km
- Transport of mobile concrete plant = 2 x 2 loads x 2 (before and after project) x 50 km/load = 400 km
- Personnel of mobile plants = 3 teams x 100 days x 100 km/day = 30,000 km
- Transport of primary materials = 650,000 t / 20 t/load x 2 (to and fro) x 30 km/load = 1,950,000 km

CO₂ emission = 1,951,200 km x 880 g CO₂/km + 30,000 km x 260 g CO₂/km = 1,725 t = 172 ha year rain forest

Crude oil extraction = (1,951,200 km x 43 l / 100 km + 30,000 km x 12 l / 100 km) / 16.79 % = 5,018,559 l or 5,019 m³

Excavation of primary resources for aggregates = 650,000 t / 80 % = 812,500 t or 406,250 m³

**Total excavation of raw materials = 5,019 m³ + 406,250 m³ = 411,269 m³**
2.2.9. Appendix 2: Calculation City Harbour Rotterdam

1. Demarcation of project area and determination of objects to be demolished:
   carried out by Google Maps and site visit
   ± 70 ha and ± 60 objects

2. Calculation of environmental risks:
   carried out by site visit and checklists (preliminary)
   • non acceptable risk (“red light”): to incinerator
   • acceptable risk (“amber light”): to sorting/washing plant
   • no risk (“green light”): to crusher

3. Determination of materials and calculation of volumes:
   to be demolished: carried out by engineers of GWRO, total = 106,960 m³
   to be built: estimated by Enviro Challenge, total = 166,667 m³
   (assumption: 800 dwellings and 500 tonnes per dwelling)

4. Calculation of mass per type of material

5. Interconnection of environmental risks (see Table 2.9):

6. Determination of distance from project to:
   • nearest quarry: ± 170 km
   • concrete supplier: ± 18 km
   • waste collector: ± 17 km
   • home base of mobile plants: ± 17 km

7. Development of logistic scenarios:
   • scenario 0: “no” recycling and application of primary raw materials only
   • scenario 1: “off site” recycling and maximum use of recycled materials on site
   • scenario 2: “on site” recycling and maximum use of recycled materials on site

8. Choice of rolling stock (type and capacity); definition of assumptions concerning CO₂ emissions, diesel fuel consumption and share of used materials (diesel fuel and primary aggregates) in extraction of raw materials:
   • capacity lorries: 30 tonnes per load
   • capacity concrete mixers: 10 tonnes per load
   • capacity crusher (type: impact crusher): 1,000 tonnes per day
   • CO₂ emissions (estimation): 880 g per km for lorries
     260 g per km for vans
   • diesel fuel consumption (estimation): 43 litres per 100 kilometres for lorries
     12 litres per 100 kilometres for vans
PROGRESS IN RECYCLING IN THE BUILT ENVIRONMENT
RILEM TC 217-PRE. Final report - March 2012

- share diesel fuel in crude oil extraction: 16.79 %
- share primary aggregates (sand and gravel) in excavation raw materials: 80 %

Table 2.9: Interconnection of environmental risks City Harbour Rotterdam case
to be demolished:

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume (m³)</th>
<th>Density (kg/m³)</th>
<th>Weight (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>concrete from buildings (walls), high quality</td>
<td>3,929</td>
<td>2,400</td>
<td>9,430t</td>
</tr>
<tr>
<td>concrete from buildings (floors), high quality</td>
<td>25,528</td>
<td>2,400</td>
<td>61,267t</td>
</tr>
<tr>
<td>concrete from road top layers, normal quality</td>
<td>4,828</td>
<td>2,400</td>
<td>11,587t</td>
</tr>
<tr>
<td>concrete elements from parking lots, normal quality</td>
<td>23,581</td>
<td>2,400</td>
<td>56,834t</td>
</tr>
<tr>
<td>concrete from foundation, low quality</td>
<td>2,427</td>
<td>2,400</td>
<td>5,825t</td>
</tr>
<tr>
<td>lime stone from buildings (walls)</td>
<td>2,599</td>
<td>1,750</td>
<td>4,548t</td>
</tr>
<tr>
<td>asphalt from roads (tar-free/containing = uncertain)</td>
<td>3,020</td>
<td>2,000</td>
<td>6,040t</td>
</tr>
<tr>
<td>masonry from buildings (walls)</td>
<td>17,741</td>
<td>1,800</td>
<td>31,934t</td>
</tr>
<tr>
<td>copper slag pavement</td>
<td>14</td>
<td>2,400</td>
<td>34t</td>
</tr>
<tr>
<td>original road foundation</td>
<td>23,193</td>
<td>2,000</td>
<td>46,386t</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>106,960</strong></td>
<td></td>
<td>± 227,811</td>
</tr>
</tbody>
</table>

to be built:

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume (m³)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>different kinds of concrete</td>
<td>166,667</td>
<td>2,400</td>
</tr>
</tbody>
</table>

9 Calculation of total kilometres for lorries and vans; calculation of CO₂ emission; calculation of total diesel fuel consumption and crude oil extraction; calculation of consumption of primary aggregates; calculation of total excavation of raw materials:

scenario 0:

- transport of waste = 227,811 t / 30 t/load x 2 (to and fro) x 17 km/load = 258,186 km
- transport of primary materials = 100,000 t / 30 t/load x 2 (to and fro) x 170 km/load = 1,133,333 km
- transport of concrete = 300,000 t / 10 t/load x 2 (to and fro) x 18 km/load = 1,080,000 km
- transport of primary materials (concrete) = 200,000 t / 30 t/load x 2 (to and fro) x 170 km/load = 2,266,667 km
- CO₂ emission = 4,738,186 km x 880 g CO₂/km = 4,170 t = 417 ha year tropical rain forest
- crude oil extraction = (4,738,186 km x 43 l / 100 km) / 16.79 % = 12,134,723 l or
12,135 m³
excavation of primary resources for aggregates = 300,000 t / 80 % = 375,000 t or 187,500 m³
**total excavation of raw materials = 12,135 m³ + 187,500 m³ = 199,635 m³**

**scenario 1:**
transport of waste = 227,811 t / 30 t/load x 2 (to and fro) x 17 km/load = 258,186 km
transport of secondary materials = 100,000 t / 30 t/load x 2 (to and fro) x 17 km/load = 113,333 km
transport of concrete = 300,000 t / 10 t/load x 2 (to and fro) x 18 km/load = 1,080,000 km
transport of secondary materials (concrete) = 100,000 t / 30 t/load x 2 (to and fro) x 1 km/load = 6,667 km
transport of primary materials (concrete) = 100,000 t / 30 t/load x 2 (to and fro) x 170 km/load = 1,133,333 km

**CO₂ emission** = 2,591,519 km x 880 g CO₂/km = **2,281 t** = 228 ha year tropical rain forest

**Crude oil extraction** = (2,591,519 km x 43 l / 100 km) / 16.79 % = 6,637,005 l or 6,637 m³

excavation of primary resources for aggregates = 100,000 t / 80 % = 125,000 t or 62,500 m³
**total excavation of raw materials = 6,637 m³ + 62,500 m³ = 69,137 m³**

**scenario 2:**
transport of mobile crusher = 2 x 2 loads x 2 (before and after project) x 17 km/load = 136 km
transport of mobile concrete plant = 2 x 2 loads x 2 (before and after project) x 17 km/load = 136 km
personnel of mobile plants = 2 teams x 228 days x 17 km/day = 7,752 km
transport of secondary materials = 27,811 t / 30 t/load x 2 (to and fro) x 17 km/load = 31,519 km
transport of primary materials (concrete) = 100,000 t / 30 t/load x 2 (to and fro) x 170 km/load = 1,133,333 km

**CO₂ emission** = 1,165,124 km x 880 g CO₂/km + 7,752 km x 260 g CO₂/km = 1,027 t = 103 ha year tropical rain forest

**Crude oil extraction** = (1,165,124 km x 43 l / 100 km + 7,752 km x 12 l / 100 km) / 16.79 % = 2,989,479 l or 2,989 m³

excavation of primary resources for aggregates = 100,000 t / 80 % = 125,000 t or 62,500 m³
**total excavation of raw materials = 2,989 m³ + 62,500 m³ = 65,489 m³**
References


71. In: NATO. Available at: http://www.nato.int

72. In: Rotterdam City Council & Port of Rotterdam Authority. Available at: http://www.cityportsrotterdam.com


3. OVERVIEW REGARDING CONSTRUCTION AND DEMOLITION WASTE IN SEVERAL COUNTRIES

3.1. Recycling in Belgium: An overview of the present situation in Belgium from the recycling industry and research about CDW

Mr. Jeroen Vrijders, Belgian Building Research Institute, Brussels, Belgium

Mr. Jan Desmyter, Belgian Building Research Institute, Brussels, Belgium

3.1.1. Current market situation

Anno 2011, the Belgian recycling sector can be considered ‘grown up’, with well developed and certified installations. It comprises over 150 fixed recycling locations (crusher plants, sorting plants, etc) and 50 mobile crushers in Flanders and about 40 recycling centers active in the Walloon region. Several of the companies also operate a mixing installation for lean concrete or structural concrete.

On annual basis, about 11 million tons of recycled aggregates are produced in Flanders, and about 3.5 million ton in the Walloon region, resulting in about 14.5 million tons a year (including Brussels).

It can be estimated that 90% of the recycled aggregates are used as sub base and base layers in road construction. The other 10% is used in road-like applications on construction sites and about 100,000 to 200,000 tons is nowadays used as aggregate for structural concrete in the private market. This means that less than 1% of the recycled aggregate is used in high-grade applications.

Two certification bodies are active in the market, COPRO and CERTIPRO. In order to be recognised as a secondary raw material, specific environmental hygiene legislation has been established in the nineties by the regional authorities. In the Flemish region, before a recycled aggregate is allowed to the market, it has to be certified on its environmental qualities for specific technical applications.

3.1.2. Standards and recommendations for application

- **Aggregates – Standards**
  The European set of standards for aggregates is used.
  NBN EN 13242 - Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction
  NBN EN 13043 - Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas
  NBN EN 13285 – Unbound mixtures
  NBN EN 14227 series – Hydraulically bound mixtures
  PTV 406 – Codification of recycled aggregates, based on the EN standards for aggregates, is also used as national reference. No other Belgian addenda to the EN standards exist.
• **Road construction**

General technical prescriptions exist in Flanders, Brussels and the Walloon region, and can be considered the main reason for the uptake of recycled aggregates in practice: RW99-2004 (version 2009 in preparation) for the Walloon Region and SB250 v2.2 (Standaardbestek 250 voor de wegenbouw) in Flanders (newest version 2010) form the basis for defining specific requirements for road construction or renovation sites.

For illustration, the applications for recycled aggregates in SB250 are mentioned in Table 3.1.

• **Concrete**

The European standards are used, with EN 206-1 as basis. This standard is completed by the Belgian standard NBN B15-001. At the moment (august 2011), there is a pre-standard prNBN B15-001:2011 that contains specifications for the use of recycled aggregates:

- On aggregate level (§5.1.3)
  The general suitability is demonstrated for recycled aggregates fullfilling EN 12620, with additional requirements:
  - $D \geq 10\text{mm}$, $d \geq 4\text{mm}$
  - $Re_{90}/Rcu_{95}/Ra_{1-}/XRg_{0.5-}/FL_{2-}$ (EN 12620)
  - $FI_{20}$, $f_{1.5}$, $LA_{40}$, $SS_{0.2}$, $A10$ van (EN 12620)
  - $\rho_{rd} \geq 2200 \text{kg/m}^3$
  - water absorption is max. 10%, with a variance of max. 2% on declared value

Remark: for the requirements of (internally produced) aggregates for concrete for prefabricated products, reference is made to NBN EN 13369 and NBN B21-600

- Use of the recycled aggregate (§5.2.3.5)
  The recycled concrete aggregate can be used in exposure classes X0 and XC1 and (Belgian) environmental classes E0 and EI. The strength class is limited to C25/30. For use in other environments and strength classes, the suitability has to be demonstrated.

  Recycled aggregate can be added to a max. of 20%v/v to the total of coarse aggregates.

No other recommendations, certification schemes, technical prescriptions, etc, exist at the moment in Belgium.

• **Hydraulically bound applications**

Based upon the NBN EN 14227-x series of standards, recycled aggregates are also used in hydraulically bound applications. A specific certification document, known as TRA21, has been established by COPRO, one of the 2 certification bodies active in the area of recycled aggregates. Current application of this document is still limited, although the importance may grow in the near future due to the uptake in technical specification documents of the regional authorities.
Table 3.1: Applications for recycled aggregates in SB250-Recycled sand

<table>
<thead>
<tr>
<th>a. RECYCLED SAND</th>
<th>Technical Prescriptions</th>
<th>Sieving sand</th>
<th>Crusher sand</th>
<th>Concrete</th>
<th>crusher sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backfilling &amp; embankments</td>
<td>Environmental quality (for all applications)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sand for draining</td>
<td>Grading, MB_r, glauconite</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand for subbases</td>
<td>Grading, f_{16}, MB_F</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand for lean concrete for road bases and bases for buildings and structures</td>
<td>SC (calcereous materials), CC (Cl-ions), Grading, f_{10}, MB_F</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand for sand-cement mixes</td>
<td>f_{22}</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand for bituminous mixtures</td>
<td>Grading, fines (f &amp; MB), PSV</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand for draining foundations in sand-cement-mixtures</td>
<td>Filler &lt;3%, fineness modulus CF</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand for concrete for roads</td>
<td>CA (Cl-ions), Grading, f_{r}, sand equivalent a, PSV</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand to fill aggregate bases</td>
<td>Grading, methylene blue</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand for pavement layers</td>
<td>Grading, methylene blue</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand for joint filling</td>
<td>Grading, fines</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sand for concrete for buildings and structures</td>
<td>Grading, fines, ...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2: Applications for recycled aggregates in SB250-Coarse aggregates

<table>
<thead>
<tr>
<th>Requirements:</th>
<th>Backfill &amp; embankments</th>
<th>Sub base</th>
<th>Not-continuous base</th>
<th>Continuous base</th>
<th>Lean concrete for foundations</th>
<th>Bituminous mixtures</th>
<th>Concrete for road layers and concrete elements</th>
<th>Concrete for buildings and structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading, $f_4$, $F_{I35}$, $C_{50/10}$, $L_{A35}$</td>
<td>$f_4$, $F_{I35}$, $C_{50/10}$, $L_{A40}$ of $L_{A50}$</td>
<td>$f_2$, $L_{A40}$</td>
<td>Natural aggregates, $G_{c85/20}$, $f_4$ (2/4 &amp; 4/6,3) and $f_{1.5}$ (other), $F_{I20}$, $L_{A15}$ or $L_{A35}$ (small roads), $P_{S_{V50}}$</td>
<td>Natural aggregates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Masonry aggregate | X | X | |
| Mixed aggregate | X | X | X (bound) | X |
| Concrete aggregate | X | X | X | X | |
| Asphalt-concrete mixed aggregate | X | X | |
| Asphalt aggregate without tar | X (max 30%) | X<sup>(1)</sup> | X<sup>(2)</sup> |
| Asphalt aggregate with tar | X<sup>(3)</sup> | |

(1) treated with cement and addition of 15-20% sand for grading improvement.
(2) max. 50% of total mass of binder (old+new) comes from recycled aggregate
(3) Asphalt aggregate cement foundation

3.1.3. Principal problems related to standards and applications

- **Aggregate level**
  Lack of experience with EN 933-11 – Classification test for the constituents of coarse recycled aggregate + overlap/interference in requirements set by (environmental) authorities and administrations.

- **Road construction**
  Use of recycled aggregates in the road construction is mainly based upon the normative documents and the usual technical specifications of the regional authorities. These specifications are informative, but serve as a basis for defining the specific requirements for most road construction sites.
Concrete
Some of the requirements on aggregate level require testing methods that are not familiar to the executing laboratories. This also implies the lack of comparable and reliable threshold values.
- Determination of water-soluble sulphates - EN 1744-1
- Determination of the influence of recycled aggregate extract on the initial setting time of cement - EN 1744-6

The draft standard prNBN B15-001 is the first standard in Belgium allowing for recycled aggregates.
- The domain of application of recycled aggregate in concrete is limited (first – careful- step). It is possible to go further, when suitability is demonstrated. However, no real manual to demonstrate this suitability exists.
- There is little experience or documentation on quality certification of this type of concrete, while quality certification of concrete is required a lot in the Belgian market.

3.1.4. New applications and research

VALRECON20 is a research project, operated by KHBO, Lessius Mechelen and the BBRI to investigate the possibilities to use 100% recycled coarse aggregate in ‘normal concrete’ (C20/25, C25/30; EE2). Strength evaluation shows good results, durability analysis is underway.

The University of Ghent is working on a new type of concrete, that can be recycled as resource for cement production.
3.2. Recycling in Brazil: An overview of the present situation of CDW in managing and recycling

Prof. Dr. Vanderley John, Lab. Microestrutura e Ecoeficiencia de Materiais Escola Politecnica da USP, Sao Paulo, Brazil

Dr. Sergio Angulo, Instituto de Pesquisas Tecnologicas do Estado de Sao Paulo, Sao Paulo, Brazil

3.2.1. CDW generation and composition

After 1970, Brazil experienced an intense urbanization process, especially concentrated and the surrounding of southern megacities like city of Sao Paulo and Rio de Janeiro. This scenario has changed in the last years with urbanizations of middle-size cities in other Brazilian states (Minas Gerais, Goias, etc). In terms of construction and demolition Waste (CDW) generation, construction sector increases its relative importance for middle and large-size cities Table 3.3.

<table>
<thead>
<tr>
<th>Cities</th>
<th>Population (10^3 inhab)</th>
<th>Origin of CDW (%)</th>
<th>CDW per capita generation (kg/hab.ano)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novo Horizonte (SP)</td>
<td>36</td>
<td>27</td>
<td>33</td>
</tr>
<tr>
<td>Vitoria da Conquista (Bahia state)</td>
<td>262</td>
<td>18</td>
<td>81</td>
</tr>
<tr>
<td>Piracicaba (SP)</td>
<td>329</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Uberlandia (MG)</td>
<td>501</td>
<td>38</td>
<td>62</td>
</tr>
<tr>
<td>Santo Andre (SP)</td>
<td>649</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td>Guarulhos (SP)</td>
<td>1,073</td>
<td>44</td>
<td>56</td>
</tr>
</tbody>
</table>

Construction sector mostly acts like an economic formal sector in small-size and middle-size cities, therefore, official database of constructed area from building companies has been successfully applied to indirect prediction of CDW generation at building sites (kg/m^2 constructed). Only in large-size cities and megacities, self-construction practices become more common (Fig. 3.1), increasing legalization requests of informal constructed areas in surrounding large-distance urban areas and slums in geological risk areas where environmental accidents are not rare in daily magazines.

A quite different scenario has been found from renovation and demolition sector. Renovation is mostly done informally by population and especially important for small-size cities. Small-size cities represent around 90% of municipalities in Brazil. In all cities, the formal demolition companies are more dedicated for industrial than residential areas and do not exist in small-size cities. Official database of demolished area is very low and all indirect estimations using waste generation indicator (kg/m^2 demolished) are imprecise.
CDW generation predictions for each state or all states are quite difficult. Available data are most concentrated in Sao Paulo state yet. For this state, some predictions of CDW per capita generations have been done by use of Human Development Index (Fig. 3.2), somehow independently of the population density (Muech, Closed loop of concrete rubble?, 2007).

Analyses of CDW composition of coarse fractions (25.4-4.8 mm) of arriving containers in CDW sorting or recycling sites have shown that **heterogeneity is the major problem for implementing recycling practices**. First, even in municipalities where CDW managing is implemented, **decontamination is the most important activity**, especially because higher contents of glazed tiles (from renovation sites), of gypsum (from commercial offices), cement asbestos (from self-construction and industrial sites) and intermixed soils.
25% of arriving containers has intermixed soil in CDW, probably due to the fact that this material is classified in the same group of concrete and masonry wastes in accordance with proposed Brazilian management for CDW (CONSELHO NACIONAL DO MEIO AMBIENTE (CONAMA), 2002)

The absence of high efficiency sorting practices and technologies will certain affect CDW recycling potential in Brazil. This characterization study and other two studies conducted at IPT demonstrated that, when no sorting practices are implemented, the average contents of gypsum (1.9%) and glazed tiles (2.8%) are higher than the value recommended by Brazilian standard for CDW recycled aggregates (NBR 15.116 (ABNT), 2004a) becoming impossible recycling practices.

Second, CDW in Brazil is essentially mixed. Arriving containers of pure concrete waste is scarce (18-44% of loads), since concrete pavements are not common and most of reinforced concrete buildings have masonry as wall partitioning, which are not currently sorted by dismantling procedures. Further, the red ceramic contents are variable for each arriving container in CDW sorting or recycling site increasing porosity becoming recycled aggregates more friable and weaken and, then, downcycling the use (subbase with restricted transportation load, leveling mortar or scrid floor).

### 3.2.2. CDW management and recycling

The first directive to CDW management was approved by National Council for the Environment in 2002 to be totally implemented at 2004 (CONSELHO NACIONAL DO MEIO AMBIENTE (CONAMA), 2002): resolution 307 and 348. The main points are:

**Segregation of CDW in four classes:** a.1 Class A, composed of concrete and masonry waste; a.2 Class B, mainly steel reinforcement, wood, plastics, glass, and bitumen; a.3 Class C, gypsum and a.4, hazardous wastes (cement lamps and paints with heavy metals and cement asbestos).
Implementation and management of small CDW public collection areas (Fig. 3.4): to receive waste from generators of informal renovations and self-constructions with intention of avoiding illegal dumping at streets.

Obligation of CDW sorting at construction building sites or CDW private recycling network use: to force legal construction sector in reuse and recycling practices at local or municipality level (legal framework of transportation companies, private CDW sorting and/or recycling areas) by use of a public controlled document.

Disposal of reuse or recyclable CDW is prohibited at sanitary landfills: CDW recycled aggregates uses in pavement (Table 3.4: Technical criteria applied to CDW recycled aggregates for pavement (NBR 15.113 (ABNT), 2004b) Table 3.4) and concrete became technically supported by National standards (NBR 15.116 (ABNT), 2004a), as well as CDW earthwork fillings (Table 3.5) (NBR 15.113 (ABNT), 2004b).

![Fig. 3.4: Small CDW public collection area in city of Sao Paulo – www.itaimpaulista.com.br](a) and wood materials sorted in city of Guarulhos (b). Both are in state of Sao Paulo.

Recently, a national policy for solid waste management (Brazil 2010) was approved that will probably help in: a) implementation of legal framework to oblige gypsum and paint waste collection at building and renovation sites by producers; and b) implementation of regional CD waste management scenarios involving a group of small-size municipalities.

Table 3.4: Technical criteria applied to CDW recycled aggregates for pavement (NBR 15.113 (ABNT), 2004b)

<table>
<thead>
<tr>
<th>Properties</th>
<th>CDW recycled aggregates</th>
<th>Brazilian standards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coarse</td>
<td>Fine</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>Coefficient of uniformity Cu &gt; 10</td>
<td>NBR 7181</td>
</tr>
<tr>
<td>D max</td>
<td>≤ 63mm</td>
<td>NBR NM 248</td>
</tr>
<tr>
<td>Shape index</td>
<td>≤ 3</td>
<td>-</td>
</tr>
<tr>
<td>Mass passing at sieve 0.42mm</td>
<td>10%-40%</td>
<td>NBR 7181</td>
</tr>
</tbody>
</table>
Table 3.5: Some technical and environmental criteria applied to CDW inert landfills (NBR 15.113 (ABNT), 2004b)

<table>
<thead>
<tr>
<th>Phase of Criteria</th>
<th>Project</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area must be located in order to minimize geological and hydrological impacts and has drainage system.</td>
<td>The filling must be done in layers (never at the top) and landfill stability must be monitored.</td>
</tr>
<tr>
<td></td>
<td>Leaching monitoring in the surroundings are not necessary if volume of CDW landfill is lower than 10,000 m³.</td>
<td>Trackability of sorted CD waste, intermixed with soils or not, classified as Class A (only concrete and masonry waste) and dumped at inert CDW landfill by official documents.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CDW waste inert landfill leaching monitoring.</td>
</tr>
</tbody>
</table>

(*), Traffic conditions: N ≤ 106 repetitions with standard axis of 8,2tf (80kN).

In fact, only medium-size and large-size cities (around 50 of 5,565 municipalities) has implemented national CDW management directives (Pinto & Rodrigo, 2005), especially the highest DHI municipalities.

Since renovation or self-construction sites done by informal generators are an important
source of CDW, society did not respond in bringing waste for public areas as well as municipalities in the last years could not offer so many public areas to collect the amount of waste generated.

Fig. 3.6 shows that the public area offer significantly increased in the last four years in city of Sao Paulo, but the amount of collected waste had slowly grown. Projections to 2020 indicates that city of Sao Paulo will be able to collect in small public areas only 30% of CDW generated today. **Dematerization waste practices have to be implemented in future.**

Besides, **CDW sorting at building sites have also achieved partial benefits** (Pinto T. P., 2005). Sorted wood and steel can be recycled, but it represents not more than 10% of CDW generated. Almost 90% of concrete and masonry waste are taking out of building sites without recycling strategies inside, showing clearly the difficult in sustainability comprehension. **Wastage reduction is the most important strategies; however, yet neglected in most cases.** (Marques, 2009) has pointed that the main barrier to implement CD waste management and recycling in around 5,000 small-size Brazilian municipalities is financial resource and trained human resources to deal with the topic.

An USP, CETEM and Macae municipality cooperation research project was conducted in 2005 about CDW recycling technology. Analyses of Brazilian CDW characteristics have demonstrated that crusher may not necessary in order to recycle for ground reinforcement and subbase of pavements.

A simple mobile sieving system combined with large conveyor belts for hand sorting (Fig. 3.7) implemented by IPT is able to produce 60% (kg/kg) of high purity CDW recycled aggregates (< 50 mm) for pavement use and 40% (kg/kg) of geotechnical stabilization materials (> 50 mm). A mixture with such aggregates and local soils seem to be a good solution for local soil stabilized roads in the countryside of state of Sao Paulo (IPT, 2011), drastically affected by rain during spring. This low cost technological solution may help to disseminate CDW recycling plants to small-size municipalities in Brazil.
CDW recycling started on 1990’s operated by stationary and very simple public owned CDW recycling plants (Fig. 3.8). In the last years CDW recycling is becoming more and more a private business. Evidence is also the foundation of National Association of CDW recycling companies (www.abrecon.org.br).

Despite there are public or private efforts to manage and recycle CDW in Brazil, plants until 2007 can recycle lower than 5% of CDW generated. Crusher mobile plants and modern demolition tools (pulverizer and crusher buckets) are being currently offered by international producers and private demolition sector start to offer recycling integrated solutions for demolition/construction building sites focus on CD recycled aggregates in pavements.

This dissemination will certainly improve national CDW recycling rates. The pressure for CDW recycled aggregates use for many geotechnical applications, mortar and concrete will increase, bringing technology approach to produce high quality CDW recycled aggregates in future.

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5 www.mbcrusher.com
The large use of CDW recycled aggregates in structural concrete requires technological improvement. It is not sustainable use 100% of low quality recycled aggregates due to high cement demand to achieve a similar mechanical performance of concrete made with natural aggregates (Angulo & al, On the classification of mixed construction and demolition waste aggregate by porosity and its impact on the mechanical performance of concrete., 2010). Substitution of natural aggregates by 10-20% low quality recycled aggregates seems to be not interesting for recycling market despite technically feasible.
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3.3. Recycling in North America: State-of-the art of RCA-concrete in North America

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Mr. Gholamreza Fathifazl, Adjeleian Allen Rubeli Consulting Structural Engineers, Ottawa, ON, Canada

3.3.1. Introduction

In North America recycled concrete aggregate (RCA) is primarily used in non-structural applications, such as backfill material, base or fill for drainage systems, pavement base and sub-base, lean-concrete bases, concrete blocks, highway sound barrier walls, partition walls, embankments, etc. The concrete industry perceives a number of fundamental barriers to the use of recycled concrete aggregates in structural grade concrete, including lack of technical data, insufficient specifications with respect to quality control in the processing of RCA and in the production of concrete mixes made with RCA, and the belief that concrete made with RCA is inferior to conventional concrete.

From the regulatory point of view, there is no impediment to the use of RCA in structural concrete. Recycling and reusing demolished concrete as substitute for virgin aggregate has been recognized in North America for nearly 30 years. Since 1982, ASTM C33 (ASTM C 33-82, 1982) has included crushed hydraulic cement concrete in its definition of coarse aggregate while ASTM 125 (ASTM 125-79a, 1979) has permitted crushed hydraulic-cement concrete as manufactured sand; therefore, in principle there is no regulatory barrier to the use of recycled concrete in the United States.

The Federal Highway Administration reported (FHWA-Federal Highway administration, 2004) that 41 of the 50 states in the US recycle old concrete into aggregate. In 38 of these states RCA is used primarily for road base/sub-base while in the remaining states it is also used in new concrete. Based on a report of the US Geological Survey, Li et al (Li, Nantung, & Jiang, 2005) reported that 100 million tons of RCA was produced in the US in 2000, 68% of which was used as road base material, 14% as rip rap and other fill, 9% as aggregate in asphalt concrete, 6% in Portland cement concrete, and 7% in other applications.

In Canada, the C-2000 Green Building Standards have set the goal of making recyclable materials up to 75% of the materials used in the construction of new buildings and structures (Mishulovitch, 2003), but other than stating that concrete be separated from other demolition waste (Taschereau, 2001), they do not provide specific guidance about either the processing or the proper use of these materials. According to the Cement Association of Canada, the use of recycled concrete was included in the Ontario Provincial Standard Specification (OPSS) in 1993, which specifies that recycled aggregates may be used as road or parking lot base and sub-base as well as sewer bedding and backfill (Wilson, 2003). According to a report by the
Ministry of Natural Resources of Ontario (Ontario Ministry of Natural Resources, 2010), 184 million tons of aggregate was consumed in Ontario in 2007, which included 13 million tons of recycled aggregate, with practically all the recycled aggregate used in non-structural applications. It was also reported that municipalities in Ontario have no specific polices about either recycling concrete or using RCA, but they avoid using recycled materials in general due to either unfavorable past experience, or lack of any experience, or due to the tendency to use high-performance materials, which prohibit use of recycled materials.

In our opinion, the reasons for minimal use of RCA in structural concrete in North America are its already extensive use as base, sub-base and backfill material, lack of evidence to show its economic benefits when used in structural concrete versus the existing applications, the lack of technical specifications and guidelines for quality control and production of RCA and RCA-concrete, the findings of many research works which have consistently reported that RCA-concrete has higher creep and shrinkage, and lower elastic modulus than conventional concrete with similar composition. To overcome the perceived problem of the inferiority of RCA-concrete and to promote its use as structural concrete, more recently more research has been undertaken in various institutions in North America as described in the following section.

### 3.3.2. Development of a New Mixture Proportioning Method for RCA-concrete

One of the difficulties with achieving consistent properties for RCA-concrete is lack of a suitable mix design method. Although ACI-555R (Lamond, y otros, 2002) provides some guidelines for proportioning of concrete mixes containing RCA, neither it nor any other standard/guideline gives a mix design method specifically for RCA-concrete with specified fresh and hardened properties. According to Fathifazl et al. (Fathifazl, Abbas, Razaqpur, Isgor, Fournier, & Foo, 2009), RCA-concrete is traditionally proportioned by applying conventional natural aggregate concrete (NAC) mix proportioning methods, treating RCA akin to natural aggregate (NA). In these methods, RCA is treated as a homogeneous single phase aggregate that can be used to partially or totally replace the NA in a reference mix. In reality, they state, at macro level RCA consists of at least two phases, viz. NA and residual mortar; therefore, a simple replacement of NA by RCA increases the proportion of overall mortar (residual plus fresh mortar) and decreases the proportion of natural aggregate in the RCA-concrete mix compared to the reference mix. They postulated that this difference in the composition of the two types of mixes is generally responsible for the inferior properties of RCA-concrete.

To address the problem, Fathifazl et al. proposed, and experimentally validated, a new mix proportioning method for RCA-concrete mixes and named the method EMV (Equivalent Mortar Volume). In the development of the EMV method, they examined the fundamental principles that govern the mechanical and physical properties of composite materials. In this method RCA is treated as a two-phase material comprising mortar and NA; and the residual mortar in RCA is considered as part of the total mortar (fresh plus residual mortar) in the mix. The method requires less fresh mortar in a RCA-concrete mix compared to the reference mix; therefore, it also requires proportionally less cement. The smaller cement requirement makes RCA-concrete environmentally friendly and possibly more economical.

In order to proportion RCA-concrete by the EMV method, the residual mortar content (RMC) of RCA needs to be quantified. This is crucial to the application of the EMV method. An
experimental method was proposed by Abbas et al. (Abbas, Fathifazl, Isgor, Razaqpur, Fournier, & Foo, Proposed method for determining the residual mortar content of recycled concrete aggregates, 2008) to conveniently determine RMC. The quick laboratory method utilizes a combination of mechanical and chemical stresses that disintegrate the residual mortar and breaks up the bond between the mortar and the coarse natural aggregate in RCA. The RMC obtained by this procedure was validated by image analysis techniques (Abbas, y otros, 2009). The EMV method allows partial or total replacement of coarse virgin aggregate by RCA, but depending on the RMC content, it may not permit total replacement. In the study by Fathifazl et al. the two types of RCA used had RMC of 41% and 23%, which resulted in mixes with RCA content, as percentage of the total coarse aggregate volume, equal to 63.5% and 74.3%, respectively.

Their investigation into the hardened concrete properties, including, elastic modulus, compressive strength, creep and shrinkage (Fathifazl, Razaqpur, Isgor, Abbas, Fournier, & Foo, Creep and Drying Shrinkage Characteristics of Concrete produced with Coarse Recycled Concrete Aggregate (RCA),) revealed that RCA-concrete mixes proportioned by the EMV method had comparable properties to conventional concrete made with virgin aggregate, but the companion mixes proportioned by the conventional method had inferior properties. Also, in general, the mixes proportioned by the EMV method were found to be more ductile compared to the mixes, with or without RCA, proportioned by the conventional method.

A study by Banthia and Chen (Banthia & Chan, 2000) involved the use of RCA in shotcrete and involving both the wet and dry processes. The mixes produced by the wet process also contained short steel fibres. The major conclusion of the study was that RCA can be used in shotcrete produced by the wet process, but it will have lower compressive and tensile strength than companion shotcrete made with virgin aggregate. It was also reported that shotcrete made with RCA is tougher and less brittle than that made with natural aggregate, but the addition of steel fibres to the shotcrete made with RCA lowered its toughness and ductility compared to the one made with virgin aggregate.

3.3.3. Structural Behaviour and Strength of RCA-concrete Members

The flexural performance of reinforced RCA-concrete beams was investigated by Fathifazl et al. (Fathifazl, Razáapur, Isgor, Abbas, Fournier, & Foo, Flexural Performance of Steel Reinforced Recycled Concrete (RRC) Beams, 2009) and included the study of the following parameters: tensile reinforcement ratios, compression steel ratio, RCA source, and concrete type (with/without RCA). The minimum and maximum reinforcement ratios were calculated according to the Canadian CSA A23.3-04 (CSA A23.3-04, 2004) provisions for conventional concrete, and the reinforcement ratio varied from 0.493% to 3.310%. Based on the results of their investigation, the authors found for beams under flexure no major difference between the failure modes of reinforced RCA-concrete and the control beams made of NAC. For all the test beams, irrespective of the type of concrete, the maximum deflection corresponding to service load level was found to be within the permissible limits specified by ACI 318M-05 (ACI 318-05, 2005). However, reinforced RCA-concrete beams displayed slightly smaller crack spacing but there was no major difference between the cracking patterns of the reinforced RCA-concrete beams and the NAC beams. The cracking moments of the reinforced RCA-concrete beams with/without compression reinforcement were also found to be lower than those of the NAC beams. For the same reinforcement ratio, the ultimate flexural strengths of the reinforced RCA-concrete beams were higher than those of the NAC beams,
regardless of the RCA source and the actual tension and compression steel content. The authors concluded based on their test results that provided the RCA-concrete mix is proportioned by the EMV method, existing flexural analysis and design procedures can be applied to RCA-concrete beams without any modification.

To investigate the shear behaviour of reinforced concrete beams made with RCA-concrete, Fathifazl et al. (Fathifazl, Razaqpur, Isgor, Abbas, Fournier, & Foo, Shear Strength of Steel Reinforced Recycled Concrete Beams with Stirrups, 2010) (Fathifazl, Razaqpur, Isgor, Abbas, Fournier, & Foo, Shear Strength of Steel Reinforced Recycled Concrete Beams without Stirrups, 2009) investigated the effect of the following parameters: shear span-to-depth ratio (1.5, 2.0, 2.7 and 4.0), beam size (depth of 250 to 550 mm), flexural reinforcement ratio (1.0% to 2.5%), shear reinforcement ratio (no reinforcement, 3 times the minimum shear reinforcement and six times the minimum shear reinforcement), RCA source and concrete type (with/without RCA). The minimum shear reinforcement was determined in accordance with CSA-A23.3-04 (CSA A23.3-04, 2004) requirements for NAC. As in the case of flexure, the authors did not observe any major difference between the failure modes, crack spacing, cracking moment, ultimate shear strength, load-deflection response, and load-shear deformation response of reinforced RCA-concrete and NAC beams. Contrary to previous findings reported in the literature, the concrete contribution to shear resistance in RCA-concrete beams was found to be higher than that in the NAC beams and the former beams more ductile than the latter.

The applicability of some major concrete design standards and other pertinent methods for calculating the concrete contribution to the shear resistance of reinforced RCA-concrete beams without stirrups was investigated by Fathifazl et al. (Fathifazl, Razaqpur, Isgor, Abbas, Fournier, & Foo, Shear Capacity Evaluation of Steel Reinforced Recycled Concrete (RRC) Beams, 2011). Results of a relatively comprehensive experimental program were used to compare the actual shear strength of test beams with their corresponding predicted values. The concrete mixes for these beams were proportioned by the EMV method. The results showed that the shear capacity of a reinforced RCA-concrete beam is comparable, or sometimes superior, to that of a companion beam made of NAC. Based on these analyses, they concluded that provided the RCA-concrete mixture is proportioned by the EMV method, existing shear design methods, such as those specified by ACI, CSA and Eurocode, can be applied to reinforced RCA-concrete beams without modification.

3.3.4. Bond and Development Length

In accordance with ASTM A944.99 procedure (ASTM A 944-99, 1999 (Reapproved 2004)), Fathifazl et al. (Fathifazl, Structural performance of steel reinforced recycled concrete members. Dissertation., 2008) carried out beam end bond tests on 600 x 230 x 500 mm reinforced concrete blocks. The test variables comprised two RCA source, three concrete types (RCA-concrete using EMV and conventional mix design methods and NAC), and two bar sizes with nominal diameters of 15 mm and 30 mm. Generally, the bond strength of all RCA-concrete mixes proportioned by the conventional method was found to be lower than that of the companion NAC for both bar sizes and RCA sources, while those proportioned by the EMV method showed comparable or higher bond strength than the NAC specimens. Despite the lower bond strength of specimens made of RCA-concrete proportioned by the conventional method and/or specimens containing the larger bar size, the overall bond behaviour was found to be independent of the mix proportioning method and aggregate type.
Butler and Tighe (Butler, West, & Tighe) also investigated the influence of RCA on the bond strength of RCA-concrete using the ASTM A944.99 (ASTM A 944-99, 1999 (Reapproved 2004)) procedures. Two sources of RCA were used and all the mixes were proportioned by the conventional method of ACI. Two types of RCA-concrete mixtures were produced and in both 100% of the coarse aggregate was RCA. The first type of mixtures was designed with constant w/c ratio and the second with constant target compressive strength. On average, NAC specimens were found to have 9 to 19% higher bond strengths than the equivalent RCA-concrete specimens.

3.3.5. Durability and Long-term Performance

Abbas et al. (Abbas, Fathifazl, Isgor, Razaqpur, Fournier, & Foo, Durability of Recycled Aggregate Concrete Designed with Equivalent Mortar Volume Method. Special Issue of the Journal of Cement and Concrete Composites on Sustainability of Civil Engineering Structures - Durability of Concrete, 2009) studied the freeze-thaw, chloride penetration and carbonation resistances of RCA-concrete mixes proportioned by the EMV method, RCA-concrete mixes proportioned by the conventional method and companion NAC. In compliance with ASTM C666-97 requirements, for each mix three 75x100x400 mm prisms were prepared for freeze-and-thaw tests. Using the durability factor as a performance indicator, RCA-concrete produced with either conventional mix design method or with the EMV method exhibited strong resistance against freeze-and-thaw action, similar to NAC. The RCA-concrete proportioned by the EMV method was found to have higher resistance against freeze-thaw action than RCA-concrete proportioned by conventional mix design method, likely due to the lower RCA content, and therefore, lower total mortar content of the former mix.

For the chloride penetration, Abbas et al. (Abbas, Fathifazl, Isgor, Razaqpur, Fournier, & Foo, Durability of Recycled Aggregate Concrete Designed with Equivalent Mortar Volume Method. Special Issue of the Journal of Cement and Concrete Composites on Sustainability of Civil Engineering Structures - Durability of Concrete, 2009) tested three 100x200 mm cylindrical specimens for each of the three types of mixture as per ASTM C 1556-06 (ASTM, 2003). According to their results, the maximum acid soluble chloride concentration (as % of mass) for all specimens was found to be below the limit of 0.2% by mass of cement as specified by ACI 222 (ACI 222R-96, 1996). Also, the apparent chloride diffusion coefficients for the three mixtures were reported as being of the same order of magnitude.

Abbas et al. (Abbas, Fathifazl, Isgor, Razaqpur, Fournier, & Foo, Durability of Recycled Aggregate Concrete Designed with Equivalent Mortar Volume Method. Special Issue of the Journal of Cement and Concrete Composites on Sustainability of Civil Engineering Structures - Durability of Concrete, 2009) also carried out carbonation tests using a setup recommended by RILEM (RILEM Recommendations CPC-18, 1988) and using concrete specimens made with the same three mixtures as used for chloride penetration tests. Three 100x100x406 mm prisms were prepared for each mixture for the accelerated carbonation tests. RCA-concrete specimens showed comparable and lower level of carbonation than NAC specimens. The authors noted that the carbonation coefficient of specimens made of RCA-concrete proportioned by conventional mix design method was lower than that of RCA-concrete prepared based on the EMV method, likely due to the lower cement content, and therefore lower reserve alkalinity, in the concrete proportioned by the EMV method.
Salem et al (Salem, Burdette, & Jackson, Resistance to Freeze and Tawing of Recycled Aggregate Concrete, 2003) studied the freeze-thaw durability of RCA-concrete mixes proportioned by conventional methods. They studied mixes with w/c ratio of 0.47, with or without air entrainment, and another mix with w/c ratio of 0.29 without air entrainment. They concluded that without air entrainment the RCA concrete mixes had inferior durability compared to NAC while air entrainment rendered RCA-concrete as durable as NAC. Salem and Burdette (Salem & Burdette, Role of Chemical and Mineral Admixtures on Physical Properties and Frost Resistance of Recycled Aggregate Concrete, 1998) also investigated the freeze-thaw durability of RCA-concrete mixes containing Class F fly ash and 1.5 to 5% air content. The water/cementitious materials ratio was kept at 0.47 while the cement/fly ash ratio was maintained at 4.8 or 6.0. They concluded that high fly ash content in both RCA-concrete and NAC significantly improved their freeze-thaw resistance and had no negative effect on their physical properties. They observed that air entrainment also increased the freeze-thaw resistance of both types of concrete, but it also negatively affects their physical properties.

Shehata et al. (Shehata, Christidis, Mikhaiel, Rogers, & Lachemi, 2010) (Shehata, Mikhaiel, Lachemi, & Rogers, June 14-18, 2011) reported the findings of a comprehensive research project that investigated the reactivity of RCA produced from concrete affected by alkali-silica reactivity (ASR). The research was conducted on concrete containing RCA retrieved from a 12-year old concrete block made with reactive aggregate. Reactivity was evaluated using the Concrete Prism Test as the main method. Based on their results, the coarse RCA was found to produce the same level of expansion as that produced by the original virgin aggregate. Fine RCA (materials passing 5 mm sieve) was also found reactive but to a lesser extent. The results demonstrate that not all the reactive silica in the virgin aggregate was consumed during the service life of the old concrete. In addition, processing the demolished concrete to produce RCA exposes fresh surfaces of the virgin aggregate (parts that did not react during the service life of the old structure); these surfaces react with alkalis and form new reaction products that cause expansion in the RCA-concrete. Moreover, fractures formed within the original stones during crushing of RCA serve as channels for transport of alkalis to fresh reaction sites.

Due to the high reactivity of the tested RCA, Shehata et al. (Shehata, Christidis, Mikhaiel, Rogers, & Lachemi, June 14-18, 2011) (Shehata, Christidis, Mikhaiel, Rogers, & Lachemi, 2010) found that higher levels of preventive measures were needed to mitigate the expansion in concrete containing reactive RCA, compared to the levels required for concrete containing virgin reactive aggregate. In other words, the level of preventive measures that can suppress expansion in concrete containing virgin aggregate was not sufficient to suppress the expansion in RCA-concrete. One of the reasons for this observation was stated to be the alkalis contributed by the residual mortar in RCA to the pore solution of the new concrete. The elevated alkali content sustained ASR and called for higher levels of supplementary cementitious materials (SCM) to suppress the expansion. The SCM blends that were found effective in suppressing the expansion were ternary blends of 5% silica fume and 20% fly ash with CaO and Na₂O contents of less than 20% and 2.0%, respectively. Binary blends containing either 30% fly ash or 50% granulated blast furnace slag, were not effective in suppressing the ASR expansion.

Another practical approach to mitigate expansion in concrete containing reactive coarse RCA was proposed by Shehata et al. (Shehata, Mikhaiel, Lachemi, & Rogers, June 14-18, 2011). In this method, it was suggested that the reactive RCA be blended with non-reactive natural
aggregates. At a blending ratio of 30% non-reactive aggregate to 70% reactive RCA, the level of expansion was found to decrease and the level of SCM required to suppress the expansion was reduced to moderate levels. Indeed, 25% fly ash with CaO < 20% or 50% slag were enough to maintain the expansion of the concrete prisms below the specified limit (0.04% at 2 years). Blending reactive RCA with non-reactive natural aggregate is also beneficial for other concrete properties, including creep, shrinkage, strength and workability.

A joint research program was undertaken by Laval University, the University of Wyoming, Ryerson University and Oregon State University to identify the best approach for reliably evaluating the potential for ASR in RCA. RCA was produced by crushing concrete blocks incorporating a number of reactive aggregates. The blocks had been subjected to natural environmental conditions for more than 10 years. Other blocks were retrieved from the different structural elements (massive base, columns and bridge deck) of a large bridge that was demolished in 2010 in Québec City, Canada. The 45 year old bridge was severely damaged by ASR involving local reactive siliceous limestone aggregate. The potential expansion due to ASR for the resulting RCA-concretes was evaluated using the Accelerated Mortar Bar Test (AMBT) (ASTM, 2003) and the Concrete Prism Test (ASTM, 2003). A multi-laboratory study was performed to observe the repeatability of the AMBT test between the partner laboratories, to evaluate the effect of different replacement percentages of RCA on the non-reactive aggregate, and to observe the reactivity difference between two types of RCA materials: (1) fine material recovered from the large scale crushing operations used to produce coarse RCA from the concrete blocks (called «crusher’s fines») and (2) fine material produced from crushing of coarse RCA (5 to 20 mm in size) (called «re-crushed RCA»). Specimens with 100% RCA, 50% RCA and 25% RCA content were cast for both the crusher’s fines and re-crushed material. Non-reactive natural sand was used for the balance of the fine aggregate in the mixture. The results showed that higher replacement levels of reactive RCA results in higher expansion, but similar to Shehata’s (Shehata, Christidis, Mikhaiel, Rogers, & Lachemi, 2010) observation, lower expansion occurred in the mix containing the crusher’s fines than the one containing re-crushed material (Adams, y otros, 2012). Petrographic examination performed on the different fractions used in mortar bars showed that the difference in the behaviour of the above materials is related to the composition of the particles, especially the residual mortar content in the different fractions of aggregate material (Beauchemin & Fournier, 2011). The multi-laboratory test results showed that the precision statement in ASTM C 1260 (ASTM, 2003) for multi-laboratory testing is applicable to RCA.

3.3.6. Research on RCA in Pavement Concrete

Smith & Tighe (Smith & Tighe, Moving Towards an Environmental Sustainable Concrete Pavement Using Recycled Concrete Aggregate., 2008) (Smith & Tighe, Recycled Concrete Aggregate Coefficient of Thermal Expansion: Characterization, Variability, and Impacts on Pavement Performance. National Academy of Sciences., 2009) investigated the effect of RCA on the coefficient of thermal expansion (CTE) and its impact on pavement performance. CTE is a key property of concrete and relates to the amount of expansion and contraction caused by changes in temperature. CTE testing was conducted on 16 cores containing various amounts of coarse RCA using a simplified methodology. Testing showed that concrete performance improved as the amount of RCA increased.

Pervious concrete with minimal fine aggregate and a high void content is a green alternative
to conventional pavements. Pervious concrete allows water to infiltrate through the pavement and thereby reduces the requirement for storm water management systems. This research incorporated RCA into pervious concrete to create a very sustainable concrete product for paving. Cylinders were cast in the laboratory for each percentage of RCA together with a control mix containing only virgin aggregate. The cylinders were tested for compressive strength, permeability, and void content. The results showed that pervious concrete mix containing 15% RCA had strength, permeability, and void content comparable to the control mix (Rizvi, Henderson, Tighe, & Norris, 2010).

Chan and Tighe (Chan & Tighe, 2010) utilized some sustainability tools such as the Ministry of Transportation of Ontario GreenPave, and examined the life cycle benefits of using RCA in concrete pavement. In general, GreenPave credits consist of three types: design credits, construction credits, and innovation credits. Design credits are awarded based on pavement design assessment. Each design alternative proposed in a project will be assessed for design credits in GreenPave. Construction credits are awarded at the end of construction. Innovation credits are awarded for sustainable practices that are not identified in GreenPave. RCA provides credits and it appears that it will be incorporated into Ontario practices.

Based on this overview, in North America a reasonable amount of research has been conducted on various aspects of RCA, but despite the many favourable research findings regarding the good short- and long-term performance of RCA-concrete, RCA is still predominantly used as backfill, base and sub-base material rather than substitute for virgin aggregate in structural quality concrete. At this juncture, there does not seem to be any short- or long-term strategy for increasing the use of RCA in structural concrete. However, the finding that the existing design codes analysis and design provisions for the different limit states can be directly applied to RCA-concrete members made of mixes proportioned by the EMV method may remove one of the major hurdles to the use of RCA-concrete in structural applications.

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3.4. Recycling in China: An overview of study on recycled aggregate concrete

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3.4.1. Introduction.

China is a large resource consumer with shortage of resources and extensive management, its economic growth is increasingly constrained by resources and the environment. According to statistics, China's consumption of cement is 820 million tons and accounts for 55% of the world. It is estimated that approximately 200 million tons of waste concrete are currently produced annually in the mainland of China (Xiao J., 2008, in press). Moreover, some natural disasters such as Wenchuan earthquake (2008) and Yushu earthquake (2010) in China have resulted in a great quantity production of waste concrete. Additionally, in the construction process of Shanghai Expo 2010, nearly 300 million tons of construction and demolition wastes were generated by the demolition work.

Consequently, it is becoming a special problem of human environment pollution. The environmental and economic implications of this are no longer considered sustainable. Therefore, a possible solution to these problems is to recycle demolished concrete and produce an alternative aggregate for structural concrete. And Recycled concrete technology is one of the main measures in the development of green concrete and realizing the sustainable development of construction, resources and environment.

To deal with this problem, in recent years, many Chinese researchers have been studied on recycled aggregate concrete and nearly all aspect of mechanical properties and structural performances have been covered. And until now, two national symposiums on recycled concrete and one international Conference on Waste Engineering and Management were held in China. To summarize all of those achievements, this paper is not only written primarily as a state-of-the-art report on the recycled concrete but to provide the theoretical basis of the preliminary for the further study on recycled concrete.

3.4.2. Mechanical properties of recycled concrete: Strength.

The strength of concrete is the property most valued by designers and quality control engineers. The water/cement ratio is important in determining the porosity of both the matrix and the transition zone and hence the strength of recycled concrete, factors such as aggregate size and mineralogy as well as replacement rate of recycled aggregate, admixtures, type of stress, and the rate of loading can also have an important effect on strength. In this section the influence of various factors on recycled concrete strength is examined in detail. Since the uniaxial strength in compression is commonly accepted as a general index of concrete strength, the relationship between the uniaxial compressive strength and other strength type such as tensile, flexural, shear, and biaxial strength are discussed.

- Compressive strength and factors effect on it.
  - Influence of water/cement ratio
    Deng (Deng X., 2005) studied the influence of the water/cement ratio on the compressive strength of concrete with 100% RCA. It was found that the compressive strength of RAC relies heavily on the water/cement ratio. If the water/cement ratio is higher than 0.57, the compressive strength of RAC decreases with the increase of water/cement ratio. However, if water/cement ratio is below 0.57, the compressive strength of RAC increases with the improvement of water/cement ratio.
A more comprehensive experimental work has been performed by Li (Li J., 2004), who investigated the relationship between the 28 days compressive strength and the water-cement ratio for concrete with different RCA percentages. The test results are illustrated in Fig. 3.10. It can be seen that the compressive strength is higher with lower water/cement ratio for concretes with RCA percentages of 30%, 70% and 100%. However, in case of concrete with 50% RCA, the compressive strength first increases and then decreases as the water/cement ratio increases. It can be seen that there exists a linear relationship between compressive strength and the water/cement ratio for RAC with 30%, 70% and 100% RCA; but for concrete with 50% RCA, the relationship is a nonlinear one, which needs further study.

Liu and Chen (Liu & Chen, 2009) also reported excellent straight-linear relations for the compressive strength and water/cement ratios for RAC with RCA replacement percentage of 30%, 70% and 100%, and a nonlinear relation for RAC with 50% RCA. This phenomenon might be explained from a further investigation on the meso- and micro-level properties of the RAC.

### 2.1.1.2 Influence of RAC

Numerous experiments on the influence of RCA on the compressive strength of concrete have been conducted e.g., Li (Li J., 2004), Xiao and Li et al. (Xiao, Li, & Huang, Influence of recycled coarse aggregate replacement percentage on compressive strength of concrete. (only available in Chinese), 2006), Tang (Tang J., 2007), Jin and Wang et al. (Jin, Wang, Akinkurolere, & Jiang, 2008). The results indicate that the amount of RCA has remarkable influences on the compressive strength of concrete. Some typical findings are shown in Fig.2, which illustrates the relationship between the RCA replacement percentage (% in mass) and the relative compressive strength, defined as the ratio of the compressive strength of RAC to that of the conventional concrete, i.e., with no RCA.

It can be seen from Fig. 3.11 that, in general, the concrete compressive decreases with the increase of the RCA content. With a RCA replacement percentage of 100%, the reduction is between 10% and 30%. However, if the RCA content is less than 30%, the influence on compressive strength is not very remarkable. Several reasons could be responsible for the reduction of the compressive strength for RAC, including an increased concrete porosity and a weak aggregate-matrix interface bond. These observations have been recently explained by Xiao and Liu et al. (Xiao J., Liu, Li, & Tam, 2009) on the basis of photomicrographs of the fracture patterns of RAC. Furthermore, it was found by Xiao et al. (Xiao J., Li, Sun, & Hao, 2004) that it is quite possible to achieve a desirable compressive strength by adjusting the waster/cement ratio. This confirmed the earlier results by Buck (Buck, 1977) which also showed that it is possible to make RAC stronger than the parent concretes from which the RCA are derived.
2.1.1.3 Influence of density

Xiao et al. (Xiao, Li, & Zhang, On relationships between the mechanical properties of recycled aggregate concrete: An overview., 2006) found that there exists approximately a linear relationship between the compressive strength ($f_{cu}$) and the mass density ($\rho$), as can be seen in Fig. 3.12. Through a statistical regression analysis, the following equation was developed. Similar results were obtained by Li and Zhang et al. (Li, Zhang, & Liu, 2009):

$$f_{cu} = 0.069 \rho - 116.1$$

(1)
Due to the high absorption characteristic of RCA, some adjustments have to be made for the mix design of RAC. A comprehensive experimental work has been carried out by Xiao et al. (Xiao J., Li, Sun, & Hao, 2004) and Li et al. (Li, Xiao, & Sun, 2004). It is found that, in general, the mix design procedure for RAC does not differ much from that for conventional concrete. However, more water is required to attain a similar workability owing to the high absorption of RCA. It is thus recommended by Xiao et al. (Xiao J., Li, Sun, & Hao, 2004) and Zhang et al. (Zhang, Qin, Sun, Hao, & Ning, 2002) to divide the water for RAC into two groups: the first part is determined according to the mix procedure for conventional concrete (with similar strength); while the second part is determined according to the water absorption capacity (usually the 10 minute one) of the RCA, which is used to compensate the loss of slump of RAC. In practical mixing, the two parts of water are added together. This method has been generally accepted and utilized by many other researchers in China.

Effect of Micro- and Meso-structure on strength

Poon and Shui et al. (Poon, Shu, & Lam, Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates., 2004) investigated the effect of microstructure of ITZ on compressive strength of RAC. SEM observations revealed that the aggregate-cement matrix interfacial zone of RAC consists mainly of loose and porous hydrates whereas the aggregate–cement matrix interfacial zone of conventional concrete consisted mainly of dense hydrates (see Fig. 3.13). It was found that the hydrates in the vicinity of the interface mainly consist of loose granular compounds, and the porosity near the interfacial zone was similar to those observed in the natural aggregate–cement matrix ITZ. A small amount of fine flake-like and whisker-like crystals formed an inter-penetrating mat in the voids.
Du (Du, 2006) reported that some voids, micro cracks and loose hydrates of Ca(OH)$_2$ crystal exist in the RCA-cement matrix ITZ, and the micro hardness values in the ITZ are lower than those of the cement matrix, but the disadvantageous feature in ITZ is gradually weakened and the ITZ becomes much stronger from the RCA to the cement matrix.

Shui and Pan et al. (Shui, Pan, Zhu, & Zhan, 2003) found that the micro-structural properties of the ITZ is related to the density of the RCA, i.e., excessively dense or loose RCA surface leads to a porous interfacial zone or well-crystallized hydrates, whereas a moderately dense RCA surface results in a relatively dense ITZ.

Xiao and Liu et al. (Xiao J., Liu, Du, & Zhang, 2007) studied the interactions between the old and new interfaces in RAC. The results implied that the qualitative and quantitative changes of the old and new interfaces during the loading process induce a notable fluctuation of the mechanical and the physical properties of RAC.

Xiao, Liu and Li et al. (Xiao J., Liu, Li, & Tam, 2009) founded that the RCA can be regarded as a composite system consisting of four components: new mortar, old mortar attached to the RCA, mortar-aggregate bond and natural aggregate of RCA (see Fig. 3.14). It was shown that the mortar attached to RCA has influence on the mechanical properties of RAC, and the mortar-aggregate bond strength plays a vital role in the failure mec.

![Fig. 3.13: Microstructure of concrete prepared with RCA (Poon, Shu, & Lam, Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates., 2004)](image)

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![Fig. 3.14: The micro-and meso-structure of RAC (Xiao J., Liu, Li, & Tam, 2009)](image)
3.4.3. Behaviour of concrete under various stress stages

- **Uniaxial tensile strength**
Xiao and Lan (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese) , 2006) investigated the behavior of RAC with different amounts of RCA under uniaxial tension. The test results, given in Fig. 3.15, indicate that an increase of the RCA content leads to a reduction in uniaxial tensile strength. When the RCA replacement percentage is 100%, the strength reduced by 31% compared to that of conventional concrete with similar composition. Based on a regression analysis, the following equation was proposed for predicting the uniaxial tensile strength from the compressive strength:

$$f_t = (0.24 - ar) f_{cu}^{2/3}$$  \hspace{1cm} (2)

Where \( f_t \) and \( f_{cu} \) are the uniaxial tensile strength and cube compressive strength of RAC, respectively. Parameter \( r \) is the RCA replacement percentage, and parameter \( a = 0.06 \).

Fig. 3.15: Uniaxial tensile strength as a function of RCA replacement percentage for RAC (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese) , 2006)

- **Splitting tensile strength**
Owing to the difficulties in carrying out uniaxial tensile test, the splitting tensile strength is usually used to evaluate the behavior of concrete in tension. Yang and Wu et al. (Yang, Wu, & Liang, 2009), Cheng (Cheng, 2005) as well as Ge and Zeng (Ge & Zeng, 2004) investigated the influence of RCA on the splitting tensile strength of concrete. In their tests, cube specimens of 150×150×150 mm were used. Their test results are presented in Fig. 3.16. From the figure, it is evident that the splitting tensile strength reduces as the RCA content increases. For RAC with 100% RCA, the reduction in the splitting tensile strength is approximately 30% to 40%.

Xiao et al. (Xiao, Li, & Zhang, On relationships between the mechanical properties of
recycled aggregate concrete: An overview. (2006) proposed the following equation to describe the relationship between splitting tensile strength ($f_{sp}$) and cube compressive strength ($f_{cu}$). This equation was adopted in the Technical Code for “Application of Recycled Concrete” (DG/TJ08-07):

$$f_{sp} = 0.24 f_{cu}^{0.65}$$

(3)

Xiao and Lei et al. (Xiao, Lei, & Yuan, Splitting tensile strength distribution of concrete with different recycled coarse aggregates. (only available in Chinese), 2008) investigated the splitting failure and splitting tensile strength distribution and the relationship between splitting tensile strength and compressive strength of RAC with different RCA. It was found that the splitting failure of RAC initiates not only from the interfaces between RCA and new cement paste, but also from some of the RCA itself. With the same water/cement ratio, the splitting tensile strength of RAC with different kinds of RCAs was smaller than that of concrete with only one uniform RCA, while the difference of the standard deviations as well as the coefficients of variation was not distinct. It was confirmed that normal model can be used to describe the distributions for the splitting tensile strength of concrete with different RCAs (see Fig. 3.17).

Fig. 3.16: Splitting tensile strength as a function of RCA replacement percentage for RAC (Cheng, 2005), (Ge & Zeng, 2004)

Fig. 3.17: Histograms for the distribution of splitting tensile strength of RAC (Xiao, Lei, & Yuan, Splitting tensile strength distribution of concrete with different recycled coarse
aggregates. (only available in Chinese), 2008)

- **Flexural tensile strength**

Flexural tensile test is another approach for evaluating the behavior of concrete subjected to tension. Xiao and Li (Xiao & Li, Study on relationships between strength indexes of recycled concrete. (only available in Chinese), 2005), Zhou and Liu et al. (Zhou, Liu, & Lu, 2008) found that the RCA replacement percentage has only marginal influence on the flexural strength of the RAC, see Fig. 3.18. Similar results were also obtained by Hu (Hu M., 2007).

![Fig. 3.18: Flexural tensile strength as a function of RCA replacement percentage for RAC (Xiao & Li, Study on relationships between strength indexes of recycled concrete. (only available in Chinese), 2005)](image)

Based on the regression analysis of test data, the equation below is suggested for describing the relationship between the flexural tensile strength ($f_f$) and the compressive strength ($f_{cu}$) of the RCA. This equation was firstly developed by Li (Li J., 2004) and later adopted in the Technical Code for “Application of Recycled Concrete” (DG/TJ08-07).

$$f_f = 0.75 f_{cu}$$ (4)

- **Shear strength**

Huang, Deng and Luo et al. (Huang Y., Deng, Luo, & Yang, 2010) investigated the shear behavior of RAC with different amounts of RCA. The shear test was performed on four-point-load beam with the same height and different width, e.g. 650×120×150 mm (Guo & Shi, 2003). It is found that the shear failure mode of RAC is similar to that of conventional concrete. However, the shear strength decreases with the increase of the RCA content (see Fig. 3.19). For concrete with 100% RCA, the shear strength is approximately 30% lower than that of conventional concrete.
Based on a regression analysis of the test data, the relation below was set up for the shear strength $f_s$ and the cube compressive strength $f_{cu}$ of RAC:

$$f_s = 0.18f_{cu}^{0.75}$$  \hspace{1cm} (5)

- **Multiaxial compressive strength**

So far, no sufficient experimental data are available in China for evaluating the strength of RAC in biaxial and triaxial compression directly at the material level, e.g. on plate, cube or cylinder specimens. However, the behavior of RAC in triaxial compression has been investigated through RAC filled steel tube and GFRP (glass fiber reinforced plastics) confined RAC specimens.

Based on the related axial tests on conventional concrete and RAC-filled steel tube columns, Wu and Yang (Wu & Yang, 2005) as well as Yang (Yang Y., Theoretical research on load-deformation of recycled aggregate-filled steel tubular members. (only available in Chinese), 2007) reported that the loading capacity of the RAC column is lower than that of conventional concrete column. When the RCA replacement percentage increases, a distinct reduction of the loading capacity is found. However, the load-deformation relationship for RAC columns is similar to that of conventional concrete columns.

Xiao and Yang (Xiao & Yang, On recycled concrete confined by GFRP tube under axial compression. (only available in Chinese), 2009) investigated the property of RAC confined GFRP (glass fiber reinforced plastics) under axial compression. It was found that the confinement offered by the GFRP greatly improves the ultimate and deformation capacity as well as the post-peak ductility. The ultimate strength of $(f_{cu})$ GFRP confined RAC is approximately 30% higher compared to that of unconfined RAC. The test data also indicates that with the increase of the RCA content, the loading capacity of the columns decreases (see Fig. 3.20).
Fig. 3.20: The stress-strain relationships as a function of RCA replacement percentage (Xiao & Yang, On recycled concrete confined by GFRP tube under axial compression. (only available in Chinese). , (2009))

- **Bond strength between recycled concrete and steel rebar.**

Xiao and Li et al. (Xiao, Li, & Qin, Study on bond-slip between recycled concrete and rebars. (only available in Chinese), 2006) studied the bond behavior between RAC and steel rebar through pull-out tests according to RILEM standard. In their tests, three RCA replacement percentages (0, 50% and 100%) and two kinds of steel rebar, i.e., plain and deformed with a diameter of 10 mm, were used. It was found that, the bond strength decreases 12% and 6% with RCA replacement percentage of 50% and 100% when plain rebar is used. Whereas the amount of RCA has only a minor influence on the bond strength when deformed rebar is used. This is because the bond strength between RAC and deformed rebar depends mainly on the mechanical anchorage and friction resistance, while the bond between RAC and plain rebar depends mainly on the adhesion between rebar and concrete. The latter is strongly influence by the RCA content. It is also observed that the bond strength between deformed rebar and RAC is approximately 100% higher than that between plain rebar and RAC, see Fig. 3.21.

Fig. 3.21: Comparison for the normalized bond-slip curves of RAC with 100% replacement percentage. (Xiao, Li, & Qin, Study on bond-slip between recycled concrete and rebars. (only available in Chinese), 2006)
The following mathematical model was proposed by Xiao and Li et al. (Xiao, Li, & Qin, Study on bond-slip between recycled concrete and rebars. (only available in Chinese) , 2006) for the bond-slip relationship of RAC:

\[
\frac{\tau}{\tau_u} = \begin{cases} \left(\frac{s}{s_u}\right)^a & (s/s_u) \leq 1 \\ \frac{b(s/s_u - 1)^2 + s/s_u}{s/s_u} & (s/s_u) > 1 \end{cases}
\]

(6)

Where parameters \( \tau, s \) are the bond stress (MPa) and slip (mm), respectively; \( \tau_u, s_u \) are the bond strength (MPa) and corresponding slip (mm); parameter \( a \) is 0.3 for all tests. The parameter \( b \) depends on the type of the steel rebar and the RCA amount. It is 0.038 for plain rebar with all RCA replacement percentages; while for deformed rebar, \( b \) is 0.10 for RAC with 0 and 50% RCA, while for RAC with 100% RCA, \( b \) is 0.18.

- **Strength after high temperatures**
  - **Residual compressive strength**

Xiao and Huang (Xiao & Huang, Residual compressive strength of recycled concrete after high temperature. (only available in Chinese) , 2006) studied the behavior of RAC exposed to high temperatures. In their tests, five RCA replacement percentages, i.e., 0, 30%, 50%, 70% and 100%, were used and the concretes were heated from 20 °C to 800 °C. A total of 160 cube specimens with 150×150×150 mm sizes were tested.

Fig. 3.22 presents the influence of RCA replacement percentage on the relative residual compressive strength of RAC with different RCA replacement percentages. It can be seen that, when the temperature is lower than 300 °C, the residual compressive strength for all the concrete follow the similar trend; however, after 300 °C, the influence of RCA begins to be remarkable. For RAC with 30% RCA replacement, the residual compressive strength decreases sharply, which is similar to conventional concrete; while for RACs with 50%, 70% and 100% RCA, the residual compressive strengths tend to increase until 500 °C. After that the residual compressive strength begins to decrease.

![Fig. 3.22: Relative of residual compressive strength of RAC with different RCA replacement percentage (GB50010, 2002)](image-url)
The following equations were proposed to describe the relationship between the residual compressive strength ($f'_{cm}$) of RAC and elevated temperature.

For RAC with RCA replacement percentage of 30%:

$$
\frac{f'_{cm}}{f'_{cm0}} = \begin{cases} 
1.018 - 0.088(T/100) & (T \leq 300^\circ C) \\
0.93 - 0.059(T/100) & (300^\circ C < T < 600^\circ C) \\
1.62 - 0.174(T/100) & (600^\circ C < T \leq 800^\circ C)
\end{cases}
$$

For RAC with RCA replacement percentage more than 50%:

$$
\frac{f'_{cm}}{f'_{cm0}} = \begin{cases} 
1.015 - 0.075(T/100) & (T \leq 300^\circ C) \\
0.489 - 0.096(T/100) & (300^\circ C < T < 600^\circ C) \\
2.086 - 0.224(T/100) & (600^\circ C < T \leq 800^\circ C)
\end{cases}
$$

Where $f'_{cm}$ is the residual cube compressive strength of RAC after elevated temperature $T$ (MPa), $f'_{cm0}$ is cube compressive strength of RAC at room temperature (MPa), and $T$ is the temperature ($T_{\circ}$ C).

**Residual flexural strength**

Xiao and Huang et al. (Xiao, Huang, & Zheng, Residual flexural strength of recycled concrete after elevated-temperatures. (only available in Chinese), 2009) further investigated the residual flexural strength of RAC with different replacement percentages of RCA (i.e. 0, 30%, 50%, 70% and 100%) after fire. The specimens were prism with 100×100×400 mm and 150×150×550 mm and they were exposed to temperatures from 20°C to 800°C. The test data are illustrated in Fig. 3.23. The results reveal that the residual flexural strength of RAC decreases with the exposed temperatures; however, the effect of the RCA replacement percentage on the residual flexural strength is less remarkable in comparison with the residual compressive strength.

![Fig. 3.23: Relative of residual flexure strength of RAC with different replacement percentage](image)

The following equations were suggested to describe the variation of the residual flexural strength ($f'_{f}$) for RAC with the elevated temperatures:
Where  is the residual flexural strength of RAC after elevated temperature (MPa),  is flexural strength of RAC at room temperature (MPa) and  is the temperature (°C).

3.4.4. Deformation characteristics

- **Modulus of elasticity**

  The modulus of elasticity for RAC is always lower than that of corresponding conventional concrete. This is mainly due to the fact that a large amount of old mortar is often attached to original aggregate particles in RCA and these mortars usually have relatively smaller elastic modulus. Many tests on the modulus of elasticity for RAC have been carried out.

  Xiao (Xiao J., Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading. (only available in Chinese), 2007) found up to 45% lower modulus of elasticity for RAC made with the 100% RCA in comparison with that of conventional concrete. Fig. 3.24 illustrates the relationship between the modulus of elasticity and the RCA content. Hu et al. (Hu, Song, & Zou, Experimental research on the mechanical properties of recycled concrete. (only available in Chinese), 2009) reported the elastic modulus of RAC is 15% to 25% lower than that of conventional concrete, depending on the qualities of the parent concrete and the properties of the RCA as well. Moreover, Xiao and Du (Xiao & Du, Complete stress-strain curve of concrete with different recycled coarse aggregates under uniaxial compression. (only available in Chinese), 2008) stated that the elastic modulus of RAC is mainly controlled by the RCA with lower parent concrete strength grade.

  Different equations have been suggested for describing the relationship between the elastic modulus  and the compressive strength  of RAC. To accurately predict the modulus of elasticity for RAC, it is believed that the influence of RCA content should be taken into account. For instance, Xiao and Li et al. (Xiao, Li, & Zhang, On relationships between the mechanical properties of recycled aggregate concrete: An overview., 2006) proposed an equation as given in Eq. (10). A former equation was firstly recommended for determining the modulus of elasticity for RAC by Ravindrarajah and Tam (Ravindrarajah & Tam, 1985), see Eq. (11). Fig. 3.25 illustrates that the elastic modulus decrease with the increase of the replacement percentage of RCA. It should be noted that Eq. (10) is very close to the results given in Eq. (11).

\[
E_e = \frac{10^4}{2.8 + \left(40.1/f_{cm}\right)}
\]  

(10)

\[
E_e = 7770f_{cm}^{0.33}
\]  

(11)
Fig. 3.24: Elastic modulus as a function of RCA replacement percentage (Xiao J., Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading. (only available in Chinese), 2007)

- Poisson’s ratio

The Poisson’s ratio of RAC reflects the ratio of the lateral to axial deformation. Hu et al. (Hu, Song, & Zou, Experimental research on the mechanical properties of recycled concrete. (only available in Chinese), 2009) found that the initial Poisson’s ratio of RAC varies between 0.15 and 0.23, which is in fact similar as that of conventional concrete. The change of the Poisson’s ratio with the stress level was also investigated by Hu et al. (Hu, Song, & Zou, Experimental research on the mechanical properties of recycled concrete. (only available in Chinese), 2009) and Song (Song, 2003). The influence of types of RCA on the Poisson’s ratio is shown in Fig. 3.25.

Fig. 3.25: Poisson’s ratio of RAC with different types of RCA (Hu, Song, & Zou, Experimental research on the mechanical properties of recycled concrete. (only available in Chinese), 2009)

In the Technical Code for “Application of Recycled Aggregate Concrete” (DG/TJ08-07), a value of 0.2 is recommended for the initial Poisson’s ratio of RAC, irrespective of the RCA replacement percentage.
• **Strain at peak stress**

Xiao and Li et al. (Xiao, Li, & Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, 2005) studied the peak strain $\varepsilon_1$ of RAC under uniaxial compression with different RCA contents. The peak strains of RAC with different RCA contents are shown in Fig. 3.26. It can be seen that the value of the peak strain increases as the RCA content increases. For the RCA replacement percentage of 100%, the peak strain is increased by 20%. The main reason for the increase of the peak strain of RAC is due to the reduced elasticity modulus of RCA, which leads to a larger deformation. Xiao (Xiao J., Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading, 2007) also found the peak strain is approximately 20% higher for the RAC with 100% replacement percentage than for the corresponding conventional concrete.

![Fig. 3.26: Peak strain as a function of RCA replacement percentage (Xiao, Li, & Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, 2005)](image)

• **Ultimate Strain**

The ultimate strain $\varepsilon_u$ is taken as the longitudinal strain in the stress-strain curve at a stress level equals to 85% of the peak stress. Xiao (Xiao J., Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading, only available in Chinese, 2007) and Li (Li J., 2004) reported the ultimate strain on different RCA replacement percentages, i.e., 0, 30%, 50%, 70% and 100%. It can be seen from Fig. 3.27 that the ultimate strain may decrease or increase with the increasing RCA replacement percentage, depending on the value of replacement percentage. For a low value, the ultimate strain decreases with increasing of replacement percentage, while the opposite may be the case for a high value of replacement percentage.
Xiao (Xiao J., Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading. (only available in Chinese), 2007) also studied the influence of the RCA replacement percentage on the $\varepsilon_\mu / \varepsilon_0$-value of RAC. It can be concluded that the $\varepsilon_\mu / \varepsilon_0$-value of RAC is smaller than that of the conventional concrete, as shown in Fig. 3.28. This means that under the same loading and deformation conditions, the energy absorption capacity of RAC is reduced. Compared to the conventional concrete, the RAC is more brittle with a poor ductility.

3.4.5. Stress – Strain relationship

- **Uniaxial compression**
  The stress-strain curve of RAC in uniaxial compression is very important for nonlinear analysis of this kind of concrete structure. Several studies have been carried out to investigate the influence of RCA content on the complete stress-strain curves, e.g. Xiao and Li et al. (Xiao J., Experimental investigation on complete stress-strain curve of recycled concrete
under uniaxial loading. (only available in Chinese), 2007), (Xiao, Li, & Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, 2005), Xu (Xu W., 2006), Hu and Song et al. (Hu, Song, & Zou, Experimental research on the mechanical properties of recycled concrete. (only available in Chinese), 2009) and Song (Song, 2003). Prism specimens of 100×100×300 mm were usually used in these tests. The typical test results obtained by Xiao and Li et al. (Xiao J., Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading. (only available in Chinese), 2007), (Xiao, Li, & Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, 2005) for concrete with various replacement percentages of RCA, namely 0, 30%, 50%, 70% and 100%, are illustrated in Fig. 3.29.

![Fig. 3.29: Complete stress-strain curves of RAC under uniaxial compression (Xiao, Li, & Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, 2005)](image)

The following important characteristics for the complete stress-strain curves of RAC under uniaxial compression were found:

1. The RCA content has a remarkable influence on the stress-strain curves of concrete. Nevertheless, the shape of the stress-strain curves for all the RAC was similar to that of the control concrete, irrespective of the RCA contents;

2. The complete stress-strain curve of RAC with various RCA content can be divided into three characteristic parts. The first part represents the linear portion, the second represents the nonlinear portion of the ascending branch, and the third part is the descending branch;

3. The curvature of each ascending branch of the stress-strain curve increase with the increasing of the RCA content, while the slope of the descending branch of the complete stress-strain curves decrease as the RCA content increases.

The above findings are based on tests on concrete made of RCA with relatively uniform quality. If the RCA has a non-uniform quality, the diversity of stress-strain curves might become greater. This has been confirmed by Xiao and Du (Xiao & Du, Complete stress-strain curve of concrete with different recycled coarse aggregates under uniaxial compression. (only available in Chinese), 2008). In their tests, the RCA used was a mixture of three RCAs produced from six different kinds of parent concrete (see Fig. 3.30).
Various mathematic models for the stress-strain relationships of RAC under uniaxial compression have been proposed, e.g. Xiao and Li (Xiao J., Experimental investigation on complete stress-strain curve of recycled concrete under uniaxial loading. (only available in Chinese), 2007), (Xiao, Li, & Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, 2005), Hu and Song et al. (Hu, Song, & Zou, Experimental research on the mechanical properties of recycled concrete, (only available in Chinese), 2009), Deng and Yang et al. (Deng, Yang, Lin, & Wen, 2008). In the Technical Code for “Application of Recycled Concrete” (DG/TJ08-07), the following analytical model was recommended:

$$y = \begin{cases} \frac{a x + (3 - 2 a) x^2 + (a - 2) x^3}{b (x - 1)^2 + x} & 0 \leq x < 1 \\ \frac{a x + (3 - 2 a) x^2 + (a - 2) x^3}{b (x - 1)^2 + x} & x \geq 1 \end{cases}$$

(12)

where $x = \varepsilon / \varepsilon_t$, $y = \sigma / f_t$, $\varepsilon_t$ is the peak strain and $f_t$ is the prism compressive strength. The parameters $a$ and $b$ are determined, depending on the RCA replacement percentage ($f_r$).

$$a = 2.2(0.75 - 1.23 f_r + 0.975)$$

$$b = 0.8(7.64 f_r - 1.142)$$

(13)

Eq. (12) is in fact from Chinese Code for “Design of concrete structures” (GB5001-2002) for conventional concrete under uniaxial compression (GB50010, 2002). The above model has been used to by some researches in their nonlinear finite element analysis of RAC structures, e.g. Yang (Yang Y., Theoretical research on load-deformation of recycled aggregate-filled steel tubular members. (only available in Chinese), 2007). Fairy good results have been achieved.

**Uniaxial Tension**

Xiao and Lan (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese), 2006) evaluated the stress-strain curve of RAC through an intensive test by five group of prism specimens with dimension of 100×100×400 mm. The experimental investigation on the uniaxial tensile behavior of RAC were carried out with the
same effective water-cement ratio but different RCA contents.

The uniaxial tensile stress-strain relationship curves of RAC with different replacement percentage are shown in Fig. 3.31. With an increase of the RCA replacement percentage the peak tensile strain of the RAC is slightly increased whereas the tensile strength and the tangent modulus of the RAC are decreased.

Fig. 3.31: Uniaxial tensile stress-strain curves of RAC with different replacement percentage (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese) , 2006)

The analytical model which was firstly proposed by Guo et al. (Guo & Shi, 2003) for the uniaxial tension stress-strain relationship of conventional concrete was extended by Xiao and Lan (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese) , 2006) for RAC under uniaxial tension, as shown below:

\[
y = ax - (a-1)x^6
\]  
(14)

Where \( x = \frac{e}{e_0} \), \( y = \frac{\sigma}{f} \), the parameter \( a \) is related to the RCA replacement percentage \( f \) and can be determined by statistical regression analysis, given as:

\[
a = 0.07f + 1.15
\]  
(15)

• **Pure shear**

The behavior of RAC subjected to pure shear was investigated based on the shear test of four-point loading beam with the same height and different width by Huang, Deng and Luo et al. (Huang Y., Deng, Luo, & Yang, 2010). The result shows that the failure mode of the sheared RAC specimens is similar to that of conventional concrete, but shear strength and deformability of the girders are lower than those of conventional concrete.

The following analytical formulation was used to describe the stress-strain curve of RAC under pure shear:

\[
y = ax^4 - 2ax^3 + (a+1)x
\]  
(16)

Where \( x = \gamma / \gamma_i \), \( y = \tau / f_i \), \( \gamma \) is shear strain, \( \gamma_i \) is peak shear strain, \( \gamma \) is shear stress (MPa), \( f_i \) is shear strength (MPa). The parameter describes the influence of the RCA replacement percentage and can be determined by regression analysis, as given in Table 3.6.
Table 3.6: Relationship between RCA replacement percentage and parameter a (Huang Y., Deng, Luo, & Yang, 2010)

<table>
<thead>
<tr>
<th>Replacement percentage (%)</th>
<th>0</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>The parameter $a$</td>
<td>0.8</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

3.4.6. Durability

The durability of recycled concrete is a very important area in the research of recycled concrete. It is defined as its ability to resist weather action, chemical attack, abrasion, or any other process of deterioration. Chinese researchers had carried out a lot of investigations with various effects of environment on durability of recycled concrete. However, the results show that the low density, high absorption, high crushing index and poor durability of recycled aggregate have led to the recycled concrete have poor carbonation resistance, freezing and thawing resistance, permeation resistance, abrasion resistance, and so on. The promotion and application of recycled aggregate concrete is greatly limited by the defects of recycled aggregates. Based on the Analysis of literature, this paper introduce the development status of durability of recycled concrete in China from carbonation resistance, Chloride penetration, freezing and thawing resistance, drying shrinkage, creep and abrasion resistance, and give some suggestions for the further research on the durability of recycled concrete.

3.4.7. Carbonization

The carbonization of concrete is a phenomenon that CO$_2$ in the air and water interact with hydration product (mainly Ca(OH)$_2$) of set cement in concrete, producing carbonate or some others, thus lowering the concrete alkalinity (neutralization, in other words). The density of recycled aggregate concrete is lower than the natural concrete for the porosity of recycled aggregate is higher than natural aggregate, which will undoubtedly reduce the carbonation resistance. On the other hand, the old mortar on the surface of recycled aggregate increase the total amount of may be carbonized material, which is a beneficial effect to the carbonation resistance of recycled concrete.

The experiment by Yuan (2010), Zhuang (2009), Sun (2006) and Lei (2008) show that the depth of recycled concrete carbonation Increase with replacement rate of recycled aggregate. Yuan (2010) has carried out experimental investigations on the durability of recycled concrete. The results showed that the anti-carbonizing capability of recycled aggregate is worse than that of normal concrete. Fly ash have adverse effects on the carbonation resistance of recycled concrete, the influence of fly ash should be considered when its content more than 10%. The Experiment of Zhang (2009) concluded that the carbonation resistance of recycled concrete decrease with the increase of replacement rate of recycled aggregate, but the carbonation depth of recycled concrete will reduce when the replacement rate of recycled aggregate is more than 70%. Increasing water-cement ratio will reduce the carbonation resistance of recycled concrete, but the carbonation resistance of recycled concrete can be improved when the water-cement ratio is constant. What’s more, the recycled concrete will have better carbonation resistance by some technical measures, such as reduce the maximum size of recycled aggregate, the second mixing process, using recycled aggregate with state of semi-saturated surface dry, Adding mineral admixture(Fly ash or slag), etc. Through experiment, Lei (2008) concluded that carbonation depth of recycled concrete is proportional...
to the square root of carbonization time; the carbonation rate slow with the increase of age; the carbonation depth of recycled concrete is inversely proportional to the strength of original concrete; and the carbonation depth of recycled concrete will increase when the recycled coarse aggregates mixed with brick aggregate. Liu (2009) studied the influence of cement content, the type and replacement rate of recycled fine aggregate to the carbonation of recycled concrete. The result show that the same replacement rate of high-quality recycled fine aggregate concrete is superior to simple crushed recycled fine aggregate concrete in carbonation resistance, but inferior to the natural fine aggregate concrete carbonation.

3.4.8. Chloride Penetration

Chloride ingress is one of important reasons causing steal rust, therefore the durability of concrete structure is effected and even the structure will be destroy. As recycled concrete, chloride resistance capability is also an important factor for the durability of structure. As the existence of old cement mortar in the recycled aggregate and cracks of recycled aggregate produced in the broken process, which makes the chloride penetration resistance decreased some extent. What’s more, the old interface in the recycled aggregate have an impact on the chloride resistance of recycled concrete also.

Zhang (2009) has studied the effect of some factors (such as the replacement rate of recycled coarse and fine aggregate, mineral admixture and so on) on chloride permeability of RC. The results showed that the permeability of concrete with recycled fine aggregate of high quality surpassed that of natural aggregate concrete, whereas there is little difference between the permeability of concrete with recycled coarse aggregate of high quality and that of natural aggregate concrete. It is also concluded that blending in superfine mineral powder and silica fume would remarkably improved the permeability of RC, nevertheless, the fly ash had adverse impact on the permeability of RC. After experimental study, Wu (2010) found that fly ash can improve the chloride resistance of recycled concrete, and the best quantity of fly ash is from 10% to 15%. Ye (2009) studied the influence of high-quality recycled aggregate (using the production technology of Wang (2007)) to the chloride resistance of recycled concrete. The results show that the chloride resistance of high-quality recycled concrete is better than normal recycled aggregate concrete, but worse than normal concrete. The experiment operated by Sun (2009) showed that the chloride resistance of recycled concrete reduced with the increase of replacement rate of recycled aggregate. This is because the porosity and interface of recycled concrete will increase with the replacement rate of recycled aggregate for the porosity of recycled aggregate is higher than normal aggregate and the old interface existence in the recycled aggregate. The experiment performed by Du (2006) showed that recycled concrete has good resistance to chloride penetration, but its resistance to chloride penetration is somewhat less than normal concrete. The chloride penetration resistance of recycled concrete will be enhanced with the increase of strength of recycled concrete; it can be improved when the Mineral admixture (Slag, fly ash, silica fume, etc) was mixed also, the composite mixing of mineral admixture is better than separately and the effect of silica fume best. Through experiment, Wu (2009) concluded that the chloride penetration resistance of recycled concrete will be improved with the increase of strength of recycled concrete. The chloride penetration resistance of recycled concrete and normal concrete only has little difference under same strength grade.
3.4.9. Freeze and Thaw.

The frost resistance of concrete is the property of concrete (with saturation condition) which could withstand freeze-thaw cycle several times with no failure occurred, and the decrease in concrete strength is limited. Recycled aggregate in recycled concrete always Freeze-thaw damage before the new cement matrix for the old mortar have a higher absorption and it absorb water very fast, which makes the frost resistance of recycled concrete very poor. In the other hand, the larger porosity of recycled aggregate can also play a role in micro-conservation to improve the frost resistance of recycled concrete.

At present, the research of Chinese scholars on the frost resistance of recycled concrete is still in the initial stage. The study result on the frost resistance of recycled concrete is quite different, there are not a unified conclusion until now. Wang (2009) has researched on the frost resistance of RC with 100% recycled aggregate. The results showed that, along with the increasing of freeze-thaw cycle times, the declining rate of quality and relative dynamic elastic modulus of RC is less than that of NC, while the declining rate of strength of RC is greater than that of NC. Cheng (2008) have studied the effect of RA, which is strengthened by water glass solution with different concentration, on the frost resistance of RC. The results showed that higher concentration of water glass was of benefit to improving the frost resistance of RC if the concentration of water glass is less than 7% (by mass). Dai (2007) taking advantage of waste concrete recycled aggregate studied the freezing-thawing resistance of recycled concrete by using recycled aggregate from 50 age period of waste concrete, and the replacement ratio of recycled aggregate respectively by 25%, 50%, 75% and 100%. The result show that the recycled concrete incorporated different percentages of recycled aggregate and normal concrete have little difference in mass loss after some freezing and thawing cycles. The reason is due to the large water absorption of recycled aggregate and freeze-thaw cycle experiment was carried out mainly in the water, so recycled concrete absorb more water than normal concrete. The large water absorption of recycled aggregate has a harmful influence for itself Frost heave, which lead to the strength loss of recycled concrete higher than normal concrete. The experiments of Cui (2006) and Zou (2010) concluded that the loss rate of relative dynamic elastic modulus of recycled concrete is higher than normal concrete, and loss rate of relative dynamic elastic modulus increase with the replacement rate of recycled aggregate. Through using ordinary method, pre-wet slurry method and increasing cement method three mix proportion design method, Zhang (2005) studied the frost durability of recycled concrete. The result show that recycled concrete can achieve even surpass normal concrete in frost durability after air-entraining agent Incorporated, and the effect is best when adopt increasing cement method. In addition, reducing water-cement ratio can improve the frost resistance of recycled concrete. Li (2003) studied the influence of fly ash to the frost resistance of recycled concrete, and found the effect is not obvious when 12% cement replaced by fly ash. Qin (2005) studied the performance of recycled concrete after one-time freeze in the early hardening. The result show that the pre-curing time (curing period before cold) and freezing day has a greater influence to the later stage strength of recycled concrete; difference freezing temperature has a smaller influence to later stage strength of recycled concrete but a large influence to the strength when one-time freeze was thawed; recycled is not suitable for winter construction for it need a longer time to make the late strength was not damaged.

3.4.10. Abrasion.

Abrasion resistance is an important indicator in judging the performance of concrete
pavement. The abrasion resistance of concrete in pavement is determined by its strength and hardness, especially in the surface layer. Coarse aggregate play a important role in the abrasion resistance of concrete. Recycled aggregate has an adverse effect to the abrasion resistance of recycled concrete for its strength is lower than nature aggregate.

As shown in the work by the authors Li (2010) and Peng (2009) stated that the abrasion resistance of recycled concrete is lower than normal concrete when their s same. Peng (2009) studied the influence of blending fly ash and slag into cement and its content to the abrasion resistance of recycled concrete. The result show that the influence of blending fly ash and slag into cement to the abrasion resistance of recycled concrete is not obvious in early stage, but it has significant influence to abrasion resistance in the late stage; the best ratio of fly ash and slag is 4to 1; the abrasion resistance of recycled concrete decrease with the increase of replacement rate of fly ash and slag in the early stage, and the best replacement rate in improving the abrasion resistance of recycled concrete in late stage is 20%. After the study the influence of recycled coarse aggregate, polypropylene fibers and air entraining and water reducing admixture to the abrasion resistance of recycled concrete. Chen (2010) conclude that the replacement rate of recycled aggregate has the greatest impact on the abrasion resistance of recycled concrete and the replacement rate of recycled aggregate is not suitable more than 40%.

3.4.11. Structural performance of recycled concrete

To make RAC as a widely accepted structural material, a comprehensive experimental study has been carried out in recent years in China. The study covers not only the monotonic behaviour of the common reinforced RAC members (including beams, columns and slabs) but also the seismic performance of reinforced RAC elements and structures, such as beam-column joints, shear walls and frame structures. These investigations provide valuable information on the structural performance of RAC.

Based on the test results, some recommendations for the design of reinforced RAC members are given in the first specifications and standard for RAC in China—Technical Code for Application of Recycled Aggregate Concrete (DG/TJ08-2018-2007) (Xing & Zhou, 1998). This paper gives a summary and discussion on the related findings and also a brief introduction on the design provisions in the technical code (DG/TJ08-2018-2007).

3.4.12. Reinforced RAC elements under monotonic loadings

- **Flexural behaviour of RAC beams**
  The flexural behaviour of reinforced concrete beams is the basic and very important property. A large number of experiments on the cracking behaviour, the failure mode, the flexural capacity as well as the deflection of RAC beams, have been undertaken in China. Simply-supported RAC beams were incorporated in most of the tests. Fig. 3.32 shows the test setup of Xiao and Lan (Xiao & Lan, Experimental Study on Flexural Performance of Recycled Concrete Beams. (only available in Chinese), 2006).
Fig. 3.32: Bend test and results of RAC beams (Xiao & Lan, Experimental Study on Flexural Performance of Recycled Concrete Beams. (only available in Chinese), 2006)

The most important mechanical parameters and the corresponding test conditions collected are briefly described and given in Table 3.7.

Table 3.7: Collected test results on the flexural behaviour of RAC beams

<table>
<thead>
<tr>
<th>Investigator</th>
<th>RCA content(%)</th>
<th>28 Day compressive strength (MPa)</th>
<th>Size(mm)</th>
<th>reinforcement ratio</th>
<th>Ultimate load(kN)/moment (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiao and Lan</td>
<td>0 (BF0)</td>
<td>31</td>
<td>2300×150×300</td>
<td>0.77%</td>
<td>133/33.3</td>
</tr>
<tr>
<td>(Xiao, Li, &amp; Lan, Research on recycled aggregate concrete - A review. (only available in Chinese), 2003)</td>
<td>50(BF50)</td>
<td>35</td>
<td>34</td>
<td>131/32.8</td>
<td></td>
</tr>
<tr>
<td>(Xiao, Li, &amp; Lan, Research on recycled aggregate concrete - A review. (only available in Chinese), 2003)</td>
<td>100(BF100)</td>
<td>34</td>
<td></td>
<td>128/32.0</td>
<td></td>
</tr>
<tr>
<td>Li and Song et al. (Xu &amp; Shi, 2006)</td>
<td>0</td>
<td>41.9</td>
<td>2000×150×300</td>
<td>0.82%</td>
<td>155/46.5</td>
</tr>
<tr>
<td>Li and Song et al. (Xu &amp; Shi, 2006)</td>
<td>30</td>
<td>45.6</td>
<td>300</td>
<td>0.82%</td>
<td>153/45.9</td>
</tr>
<tr>
<td>Li and Song et al. (Xu &amp; Shi, 2006)</td>
<td>70</td>
<td>43.7</td>
<td>39.1-50.5</td>
<td>0.55%~</td>
<td>114-</td>
</tr>
<tr>
<td>Li and Song et al. (Xu &amp; Shi, 2006)</td>
<td>100</td>
<td></td>
<td></td>
<td>2.43%</td>
<td>317/47.1-95.1</td>
</tr>
</tbody>
</table>
The following variables were involved:
- The influence of recycled coarse aggregates (RCA) replacement ratio, which is defined as the weight percentage of RCA within the gross coarse aggregates. (Xiao and Lan (Xiao & Lan, Experimental Study on Flexural Performance of Recycled Concrete Beams. (only available in Chinese), 2006), Ding et al. (Ding, Sun, Guo, Dai, Ni, & Shen, 2009) and Li et al. (Li PX, 2008).
- The influence of longitudinal reinforcement ratio (Li et al. (Li PX, 2008), Hu et al. (Hu, Huang, & Zou, Experimental study on partial recycled concrete beams. (only available in Chinese), 2009))

Based on the experiments noted above, the following conclusions can be drawn:
- The reinforced RAC beams show very similar crack patterns and failure feature, irrespective of the recycled aggregate percentage (Fig. 3.33).
- The assumption of “plane sections remain plane” in the classic flexure theory, that is, sections perpendicular to the axis of bending which are plane before bending remain plane after bending, is also valid for reinforced RAC beams with various recycled aggregate percentages (Fig. 3.34). That means the procedure developed for reinforced conventional concrete beams could be suitable for the analysis of RAC beams subjected to flexure.
- Under same conditions, the cracking and ultimate moment of the RAC beam are similar to the natural aggregate concrete (NAC) beam, nevertheless, the stiffness of the RAC beam reduces to a certain extent.
- Comparing the RAC beam to NAC ones, the research results show that under the action of the same load, the maximum width of cracks of the former, are slightly larger.

Fig. 3.33: Crack patterns and failure mode of RAC beams (Xiao, Li, & Lan, Research on recycled aggregate concrete-A review. (only available in Chinese), 2003)
To estimate the flexural capacity of reinforced RAC beams, the predictions from the design equations recommended in EC 2 (EN 1992-1-1, 2004) and Chinese Code for Design of Concrete Structures (GB 50010-2002) (GB50010, 2002), and the test data are compared.

In the Technical Code for Application of RAC (DG/TJ08-2018-2007), the following formula is recommended to calculate the flexural bearing capacity of RAC beams.

\[
M_u = \alpha_m f_y b (h_0 - \frac{x}{2})
\]

\[
\alpha_m f_y b x = f'_c A_s
\]  \hspace{1cm} (17)  \hspace{1cm} (18)

Where \( M_u \) is the ultimate moment (kNm); \( b \) is the width and the effective height of the section (mm); \( f_y \) are the yield strength (MPa) and the area (mm\(^2\)) of the longitudinal reinforcement; \( f'_c \) are the cylinder compressive yield strength (MPa) of the RAC; \( \alpha_m \), the modified parameter for \( f'_c \), can be taken as 0.95.

In addition, Xiao et al. (Xiao J., Li, Sun, & Hao, 2004) carried out the reliability analysis of the recycled concrete beams bending capacity by the Montcalo method. The main findings of the reliability analysis can be summarized as the following:

- The reliability index of recycled concrete beams is proved to meet with the requirement of the Unified Standard for Reliability Design of Building Structures (GB 50068-2001) (GB50068, 2001).
- The effect of uncertainty coefficient associated with resistance is obvious, while the partial safety factor of recycled concrete compressive strength on the reliability index of ideally reinforced recycled concrete beams bending capacity is neglectable.

- **Shear behaviour of reinforced RAC beams**

Unlike in reinforced concrete beams under flexure, where the longitudinal reinforcement governs the structural response, concrete plays a more significant role in beams subjected to shear loadings. Taking into account the difference between RAC and conventional concrete, the study on the shear performance of reinforced RAC beams is of more importance.

To investigate the influence of the recycled aggregates on the shear behaviour of the reinforced concrete beams, experimental work has been carried out, both on beams with and without web reinforcements. The details of the experiments are presented in Table 3.8.
Table 3.8: Collected test results on the shear behaviour of RAC beams

<table>
<thead>
<tr>
<th>Investigator</th>
<th>RCA content (%)</th>
<th>28 Day compressive strength (cube) (MPa)</th>
<th>Size (mm) L×B×H</th>
<th>the percentages of stirrups</th>
<th>The shear-span ratio</th>
<th>Ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiao and Lan (Zhang, Qin, Sun, Hao, &amp; Ning, 2002)</td>
<td>0</td>
<td>31 (BS0)</td>
<td>2300×150×300</td>
<td>0.25%</td>
<td>1.5</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>35 (BS50)</td>
<td></td>
<td></td>
<td></td>
<td>298</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>34 (BS100)</td>
<td></td>
<td></td>
<td></td>
<td>274</td>
</tr>
<tr>
<td>Zhou et al. (Xiao, Li, &amp; Huang, Influence of recycled coarse aggregate replacement percentage on compressive strength of concrete. (only available in Chinese), 2006)</td>
<td>0</td>
<td>42.2</td>
<td>2250×150×300</td>
<td>0.16%</td>
<td>1.5</td>
<td>190.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>188.0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>37.8</td>
<td></td>
<td></td>
<td></td>
<td>185.4</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>34.9</td>
<td></td>
<td></td>
<td></td>
<td>181.4</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>34.2</td>
<td></td>
<td></td>
<td></td>
<td>174.0</td>
</tr>
<tr>
<td>Zhang et al. (Tang J., 2007)</td>
<td>0</td>
<td>28.7-38.7</td>
<td>2400 (2000)×150×300</td>
<td>0</td>
<td>1.0-3.0</td>
<td>114-530</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>32.4</td>
<td>(2000)×150×300</td>
<td></td>
<td>3.0</td>
<td>336</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>33.3</td>
<td></td>
<td></td>
<td>1.5</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>30.4</td>
<td></td>
<td></td>
<td>1.5</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>29.6-34.1</td>
<td></td>
<td></td>
<td>1.5</td>
<td>119-509</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0-3.0</td>
<td>114-530</td>
</tr>
</tbody>
</table>

As shown in Fig. 3.35, Xiao and Lan (Xiao & Lan, 2004), Zhou and Jiang (Zhou & Jiang, Shear behaviour of recycled coarse aggregate concrete beam. (only available in Chinese) , 2009) tested the shear behaviour of RAC beams with web stirrups. On the basis of the test results, the characteristics of shear behaviour of RAC beams were discussed. By using a general finite element method, the influences of recycled aggregates’ replacement percentage, the shear span to depth ratio and the percentage of stirrups on the shear behaviour of RAC beams were theoretically analyzed (Xiao & Lan, 2004). These studies show that the shear capacity of recycled concrete beam reduces with the increase of recycled coarse aggregates content, whereas, the deflection and diagonal crack width is similar to that of the conventional concrete beam. The shear failure pattern of RAC beam is typical shear-compression failure when the beam is properly designed. The diagonal section cracking load of RAC beams is slightly lower than that of NAC beams, and average diagonal crack width of RAC beams is slightly larger than that of NAC beams.
Fig. 3.35: Shear test and results of RAC beams (Xiao & Lan, 2004)

It is evident that the influence of RAC can be better reflected using reinforced beams without web reinforcements. To investigate the shearing capacity of RAC beams without stirrups, Zhang et al. (Zhang, Zhang, & Yan, 2006) conducted an experiment using 13 RAC beams and a natural aggregate concrete (NAC) beam. The effects of replacement percentages of recycled coarse aggregates and shear-span ratio on the characteristics of shear capacity and deformation of RAC beams were studied. The test result shows the deflection and diagonal crack of RAC concrete beams are bigger than NAC beams, the shear capacity of RAC beams reduces with the increase of recycled coarse aggregates’ content, the shear capacity reduces with the increase of shear-span ratio.

In the Technical Code for Application of Recycled Aggregate Concrete (DG/TJ08-2018-2007) (DG/TJ08-2018-2007, 2007), the following formula is used to calculate the shear capacity of RAC beams,

\[
V_u = \alpha \left( 0.7 f_{th} h + 1.25 f_{ty} \frac{A_{sy}}{s} h_b \right)
\]

In which, \( \alpha \) is the reduction coefficient considering the RCA content influence; \( f_{th} \) is the tensile strength of RAC (MPa); \( f_{ty} \), \( A_{sy} \), \( s \) are the yield strength (MPa), the area (mm\(^2\)) and the spacing of the stirrups (mm). The other signs share the same meanings as in Eq. (17) and (18).

### Reinforced RAC columns under axial and eccentric compression

The compressive behaviour of RAC columns under axial loading was studied by Zhou et al. (Zhou, Yang, & Jiao, Experimental study on axial pressure bearing capacity of recycled concrete column. (only available in Chinese) , 2008). The compressive behaviour of reinforced RAC columns under axial and eccentric compression was studied by Xiao et al. (Xiao, Shen, & Huang, Test on compression performance of recycled concrete columns. (only available in Chinese) , 2006). A summary of the specimens tested is presented in Table 3.9.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>RCA content (%)</th>
<th>28 Day compressive strength (MPa)</th>
<th>Slenderness ratio</th>
<th>Eccentricity (mm)</th>
<th>Section size (mm)</th>
<th>Ultimate load (kN)</th>
</tr>
</thead>
</table>

Table 3.9: Collected test results on the compressive performance of unconfined RAC column
Based on the experimental results from Table 3.9, as well as from Fig. 3.36, it was proved that, in comparison with the NAC columns, the failure modes of RAC columns still have compression failure, tensile failure and a balance failure under compressive loading with different eccentricities. The assumption “plane sections remain plane” is also suitable for RAC columns. The load capacity calculation of RAC columns can be estimated by the equation for NAC columns used in the current Chinese Code GB50010 (2002) (GB50010, 2002). In the technical code for RAC (Zhou & Jiang, Shear behaviour of recycled coarse aggregate concrete beam. (only available in Chinese), 2009), the following equation is used to predict the compression bearing capacity of RAC column under axial loading.

\[ N \leq 0.9\alpha_n \Phi (f_{c'd} A + f_{y'd} A_t) \]  

(20)

Where \( \alpha_n \) is adjustable coefficient of RAC column; \( \Phi \) is the stability coefficient. The other signs share the same meanings as in Eq. (17) and (18).
Compressive performance of RAC filled steel tube columns

For concrete filled steel tube columns, numerous experiments have verified the benefits due to the confinement of the steel tube on the core concrete. To investigate the possible confinement of RAC, Yang and Han (Yang & Han, Experimental behaviour of recycled aggregate concrete filled steel tubular columns., 2006) tested the compressive performance of RAC filled steel tube (RACFST) columns. In their tests, 56 RACFST members under short-term loadings, including 24 stub columns, 8 beams and 24 eccentrically loaded columns, were tested. The corresponding normal CFST members, including 6 stub columns, 2 beams and 6 eccentrically loaded columns, were also tested to evaluate the differences between them. The specimens were designed to investigate the effects of the following parameters: (1) cross-section type, circular and square; (2) RCA replacement ratio, from 0 to 50%; (3) load eccentricity ratio, from 0 to 0.53 (Yang Y., Performance of recycled aggregate concrete-filled steel tubular members under various loadings., 2010).

Table 3.10: Collected test results on the compressive performance of confined RAC columns

<table>
<thead>
<tr>
<th>Investigator</th>
<th>28 Day compressive strength (cube) (MPa)</th>
<th>Dimension of section D × t (mm)</th>
<th>L (mm)</th>
<th>e (mm)</th>
<th>e/r₀</th>
<th>Nₑₑ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yang and Han (Xiao J., Liu, Li, &amp; Tam, 2009)</td>
<td>42.7 (0% RCA)</td>
<td>○- 165×2.57</td>
<td>1650</td>
<td>0</td>
<td>0</td>
<td>1090-1158</td>
</tr>
<tr>
<td></td>
<td>41.8 (25% RCA)</td>
<td>□- 150×2.94</td>
<td>1732</td>
<td>0</td>
<td>0</td>
<td>1245-1273</td>
</tr>
<tr>
<td></td>
<td>36.6 (50% RCA)</td>
<td></td>
<td></td>
<td>20</td>
<td>0.27</td>
<td>825-875</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40</td>
<td>0.53</td>
<td>625-686</td>
</tr>
</tbody>
</table>

The test results (Table 3.10) show that all the columns failed due to overall buckling of steel tube. Comparisons were made with predicted ultimate bearing capacity of RACFST columns using the existing codes, such as ACI Committee 318 (ACI Committee 318, 1999), AIJ-1997 (AIJ, 1997). Fig. 3.37 shows the effects of RCA replacement ratio (r) on bearing capacity of stub columns (Nₑₑ,s) and columns under eccentric loading (Nₑₑ,e), where D and B are the outside diameter and width of circular and square members respectively, e is the load eccentricity, and r₀ is D/2 or B/2 for circular or square specimens respectively. It can be seen that, with increase of RCA replacement ratio, the bearing capacity of the tested specimens gradually decreases.
A theoretical model for normal concrete filled steel tube (CFST) columns is adopted for RACFST columns. Similar to normal CFST, confinement factor ($\xi$) is suggested to model the interaction between outer steel tube and core RAC of RACFST columns, and it is defined as:

$$\xi = \frac{A_s \cdot f_y}{A_c \cdot f_c}$$

(21)

Where $A_s$ and $A_c$ are the cross-sectional area of the steel tube and core concrete (mm$^2$); $f_y$ and $f_c$ are the yield strength of steel and the characteristic compressive strength of RAC, respectively (MPa).

**Flexural performance of RAC slabs**

Zhou et al. (Zhou, Wang, & Yu, Mechanic behaviour test on recycled concrete simply-supported rectangular slabs. (only available in Chinese), 2008) studied the performance of RAC slab which are simply supported on four sides. In their tests, 12 slabs divided into four groups were tested. All the slabs shared the same cross-section and reinforcement ratio but with different recycled aggregates’ replacement percentage, i.e. 0%, 5%, 10%, 15%, respectively. A summary of the specimens tested is listed in Table 3.11.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>RCA content (%)</th>
<th>cracking load (kN)</th>
<th>Ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhou et al (Xiao, Li, &amp; Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, 2005)</td>
<td>0 (RC0)</td>
<td>17.4-18</td>
<td>69.8-72.1</td>
</tr>
<tr>
<td></td>
<td>5 (RC5)</td>
<td>15.9-16.9</td>
<td>63.5-67.5</td>
</tr>
<tr>
<td></td>
<td>10 (RC10)</td>
<td>14.5-15.6</td>
<td>58.0-62.4</td>
</tr>
<tr>
<td></td>
<td>15 (RC15)</td>
<td>13.2-14.2</td>
<td>13.2-14.2</td>
</tr>
</tbody>
</table>
The specimens were designed to be subjected to concentrated load. The test results indicate that the recycled aggregates replacement percentage influences the load mid-span deflection behaviour, as shown in Fig. 3.38.

Fig. 3.38: Load mid-span deflection curve of RAC slabs (Zhou, Wang, & Yu, Mechanic behaviour test on recycled concrete simply-supported rectangular slabs. (only available in Chinese), 2008)

It is also found that with the increase of recycled aggregates’ replacement percentage, the cracking load and the ultimate load of the slab decrease while the deformation of the slab increase; however, the decreasing tendency of the ultimate load is greater than that of the cracking load.

By studying the deflection of the RAC slabs, the general method (equation 22) used for determining the deflection of conventional concrete slab is not suitable for estimating the deflection of the RAC slabs.

\[ \Delta = \alpha \frac{M}{B \Delta} \]  

(22)

Where \( \Delta \) is the deflection value of the slab (mm); \( \alpha \) is deflection coefficient; \( B \Delta \) is the stiffness of the slab (N/m); \( l \) is the effective length of the section (mm); \( M \) is the ultimate moment (kNm). Nevertheless, the test results show that the deflection of the RAC slabs can be also obtained by multiplying the value of \( \Delta \) with an amplification factor which can be taken as 1.4.

- **Steel deck RAC composite slabs**

In order to investigate the promotion of RAC in the steel deck concrete composite slabs, 6 cold formed steel deck-RAC composite slabs without stud were tested under static loading by Xiao et al. (Xiao J.-Z., Li, Jin, & Li, 2010). The test specimens and various stages load of the composite slabs are shown in Table 3.11. Where \( P_{cr} \) is the critical value of the slab; \( P_{u} \) is the ultimate load; \( P_{dc} \) is the load value when the deflection value of the slab is \( L/200 \).

Based on the test results, the effects of shear-span to depth ratio to the failure model as well as the relationship between the longitudinal slide and load were investigated. The test setup and the main test result are given in Fig. 3.39.
It was found that the slip between RAC and steel deck was relatively large. The failure mode was a longitudinal splitting failure. By analyzing the measured load-slip curves, the influence of recycled aggregate content on the bearing capacity of steel deck RAC composite slabs was investigated. With increasing RCA content, the bearing capacity of the slabs first increased and then decreased. Nevertheless, the RCA content had nearly no influence on the ultimate shear bearing capacity of the slabs. Longitudinal shear capacity became lower as the shear span ratio increased. A formula related to the shear capacity of the slabs was proposed and recommended as expressed in Equation 23.

\[ V_u = \alpha_{sh} \cdot \left( 175 \cdot 0.406 \cdot \frac{\rho h_0}{L} \cdot 0.0391 \sqrt{f_c} \right) \]

(23)

Where \( \alpha_{sh} \) is the shear capacity coefficient; \( \rho \) is the steel reinforcement ratio; \( h_0 \) is the shear span (mm); \( L, h_0 \) is the effective height of the section (mm); \( f_c \) is the cylinder compressive yield strength of the RAC (MPa).

### 3.4.13. Reinforced RAC structures under cyclic loadings

- **RAC beam-column joints**
  
  Xiao and Zhu (Xiao & Zhu, Study on seismic behaviour of recycled concrete frame joints. (only available in Chinese) , 2005) investigated the behaviour of reinforced beam-column joints under low frequency reversed lateral loads. In their study, 3 half-scaled specimens were tested. The objective of the test was to investigate the influence of the recycled aggregate on the seismic performance of the reinforced concrete frame joints. The used recycled aggregates’ replacement percentages were 0%, 50% and 100% respectively. Fig. 3.40(a) shows the typical test specimens. Based on the test observations, the failure features, the hysteresis loops, the ductility and the degeneration of strength and stiffness under seismic loads were comparatively investigated.

Table 3.12: Summary of specimens for seismic behaviour of RAC column-beam joints

<table>
<thead>
<tr>
<th>Investigator</th>
<th>RCA content (%)</th>
<th>28 Day compressive strength (cube) (MPa)</th>
<th>Ductility coefficient</th>
<th>Ring stiffness</th>
</tr>
</thead>
</table>

Fig. 3.39: Test setup and main load-relative slip curve of composite slabs (Xiao, Li, & Zhang, On relationships between the mechanical properties of recycled aggregate concrete: An overview. , 2006)
The test results in Table 3.12 indicate that the seismic behaviour of the reinforced beam-column joints made of RAC is slightly weaker than that with conventional concrete, as can be seen from the skeleton curves of the specimens illustrated in Fig. 3.40 (b). However, it is found that the ductility coefficient and the stiffness of the RAC joints are able to meet the related requirements for the current earthquake-resistance design provisions.

\[ V_s = 0.1 \left(1 + \frac{N}{f_c' b_c h_c}\right) f_y b_j h_j \int_{s} A_p \left(h_o - a_s \right) \]  

(24)

Where \( f_c' \) is the cylinder compressive yield strength (MPa); \( b_c, h_c \) is the width and the effective height of the column section (mm); \( b_j, h_j \) is the effective width and the effective height of the joint core section (mm); \( N \) is the axial compression of the column (kN); \( a_s \) is the cover thickness (mm). The other signs share the same meanings as in Eq. (19).

- **Pre-cast RAC beam-column joint**

To explore the potential of RAC in precast concrete structures, Xiao et al (Xiao, Tawana, & Wang, Test on the seismic performance of frame joints with pre-cast recycled concrete beams and columns., 2010) investigated the behaviour of RAC frame joints with precast beams and columns. The testing variables were the types of steel reinforcement connections, i.e., welded reinforcement, beam reinforcement connector and column reinforcement connector. Four specimens were tested under lateral reverse loadings with simulated practical boundary conditions. The test setup and steel reinforcement connection are displayed in Fig. 3.41.
The test results (Table 3.13) indicate that the behaviour of the pre-cast RAC joints is similar to that of joints with conventional concrete. The failure process can be divided into five stages: crack primarily, crack entirely, beam yielding, and limit state and ultimate failure. The type of the steel reinforcement connections has a significant effect on the bearing capacity, ductility and energy consumption of the joints. However, the ductility, energy consumption of the RAC joints is found to be able to meet the design requirements for precast concrete structures. This study gives a positive result towards the use of RAC in precast concrete structures.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Name of specimens</th>
<th>Types of steel reinforcement connections</th>
<th>28 Day compressive strength (cube) (MPa)</th>
<th>Ductility coefficient</th>
<th>Stiffness deterioration coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiao et al (J.B., Xiao, &amp; Huang, 2006)</td>
<td>PJ-0</td>
<td>welding</td>
<td>42.0</td>
<td>7.54</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>PJ-1</td>
<td>welding</td>
<td>36.8</td>
<td>9.34</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>PJ-3</td>
<td>Beam connector</td>
<td>38.1</td>
<td>2.13</td>
<td>1.89</td>
</tr>
<tr>
<td></td>
<td>PJ-4</td>
<td>column connector</td>
<td>37.3</td>
<td>8.59</td>
<td>0.88</td>
</tr>
</tbody>
</table>

- **RAC high rise shear walls**

CAO et al. (Cao, Xu, Liu, Zhang, & Zhang, 2009), (Cao, Dong, & Zhang, Study on seismic performance of RAC shear wall with different shear-span ratio. , 2010) evaluated cyclic behaviour of high rise shear walls made of RAC (Table 3.14). The aims of their study were to investigate the influence of the recycled aggregates on the structural performance of the concrete shear walls and the role of concealed bracing in enhancing the cyclic behaviour of the RAC shear walls. To this objective, 6 high-rise shear wall specimens with shear-span ratio 2.0 were designed. The percent of coarse and fine recycled aggregates’ replacement of the specimens were changed from 0% to 100%. The reinforcement percentage in the lower half part of the walls was 0.25 while that in the upper half part was 0.25 or 0.15. The axial-force ratio was 0.2 or 0.4. Specimen RCSW2.0-6 was designed the same as RCSW2.0-4 except that the extra inclined steel bracings were embedded in the walls. The size of the specimen, as can
be seen in Fig. 3.42, was 160×1000×2000 mm. The properties of all the specimens are listed in Table 3.14.

![Steel details of RCSW2.0-2](image1)

![Schematic view of test arrangements](image2)

**Fig. 3.42: Steel details and test setup of RAC high rise shear wall (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese), 2006)**

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Percentage of recycled aggregate replacement (%)</th>
<th>Reinforcement percentage in the walls (%)</th>
<th>Axial-force ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-rise shear wall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCSW1.0-1</td>
<td>0</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW1.0-2</td>
<td>100</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW1.0-3</td>
<td>100</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW1.0-4</td>
<td>100</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW1.0-5</td>
<td>100</td>
<td>0.25</td>
<td>0.4</td>
</tr>
<tr>
<td>RCSW1.0-6</td>
<td>0</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW1.0-7</td>
<td>100</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>High-rise shear wall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCSW2.0-1</td>
<td>0</td>
<td>0.25(0.25)</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW2.0-2</td>
<td>0</td>
<td>0.25(0.15)</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW2.0-3</td>
<td>50</td>
<td>0.25(0.15)</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW2.0-4</td>
<td>100</td>
<td>0.25(0.15)</td>
<td>0.2</td>
</tr>
<tr>
<td>RCSW2.0-5</td>
<td>100</td>
<td>0.25(0.15)</td>
<td>0.4</td>
</tr>
<tr>
<td>RCSW2.0-6</td>
<td>100</td>
<td>0.25(0.15)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Based on the test findings, the load-carrying capacity, the stiffness and its degradation, ductility, hysteretic behaviour, energy dissipation and failure phenomena of each shear wall
were analyzed. The results indicate that compared to the high-rise NAC wall, RAC shear wall show poorer performance, and the more of the coarse aggregates replacement, the poorer the performance of the recycled aggregate concrete shear wall, but it is still able to satisfy seismic requirements through rational design.

- **RAC low rise shear walls**

Cao et al. (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese) , 2006), (Yang, Wu, & Liang, 2009) further examined the cyclic behaviour of low rise shear walls made of RAC with a size of 160×1000×1000 mm. 7 specimens (Table 3.14) were tested. The influence of the recycled aggregates’ replacement percentage, the axial load ratio, as well as the presence of the concealed bracing was investigated. The failure mode of some specimens is shown in Fig. 3.43.

![Fig. 3.43: Failure mode of some RAC low rise shear walls (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese) , 2006)](image)

The main findings of the tests (Table 3.15) are:
- Compared to the low-rise NAC wall, the RAC shear walls with recycled coarse aggregates show almost the same performance on load-carrying capacity, stiffness, ductility and energy dissipation (Fig. 3.44). It is feasible to use recycled coarse aggregates as a replacement to natural coarse aggregates in the shear wall.
- Compared to the low-rise NAC wall, the seismic performance of RAC shear walls with recycled fine aggregates shows a little decline. Compared to the recycled coarse aggregates, the recycled fine aggregates have slightly larger influence on the seismic performance of the shear wall. The replacement ratio of recycled fine aggregates should be strictly controlled.
- The recycled concrete shear wall with concealed bracing shows good performance on load-carrying capacity, stiffness, ductility, energy dissipation. With setting of concealed bracing in the low-rise shear wall with recycled concrete, seismic performance was improved obviously.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>specimens</th>
<th>Research parameters</th>
<th>Ductility coefficient</th>
<th>Stiffness deterioration coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cao et al. (Cao, Xu, Liu, Zhang, &amp; Zhang, 2009)</td>
<td>high-rise RAC shear walls</td>
<td>RA content, replacement ratio, concealed bracing</td>
<td>7.359-8.789</td>
<td>0.188-0.197</td>
</tr>
</tbody>
</table>
Cao et al. (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese), 2006) investigated the tensile behavior of recycled aggregate concrete. The axial compression ratio, RA content, replacement ratio, and concealed bracing were considered. The axial compression ratio ranged from 5.108-7.817, the RA content from 0.088-0.153.

**Fig. 3.44:** The measured load-displacement hysteretic loops of some specimens (Xiao & Lan, Investigation on the tensile behavior of recycled aggregate concrete. (only available in Chinese), 2006)

- **RAC block walls**
  Xiao et al. (Xiao, Huang, & Yao, Experimental study on seismic behaviour of recycled concrete small-sized block walls. (only available in Chinese), 2010) reported the seismic behaviour of small-sized RAC hollow block walls. The test, including four specimens confined by tie column-beam systems, was carried out under low cyclic horizontal loadings, as shown in Fig. 3.45.
The testing variables were axial-load ratio and the different ratios of reinforcement at tie column. Corresponding test results are listed in Table 3.16, where $P_\text{cr}$, $P_{\text{max}}$, $P_u$ are the critical value, maximum value, and ultimate value of the load, respectively; $\Delta_\text{cr}$, $\Delta_{\text{max}}$, $\Delta_u$ are the corresponding displacements.

Based on the experiment observations, the damage process, the failure mode, the ultimate load and the deformation capacity as well as the energy dissipation of each specimen were studied. In addition, the interaction mechanism between the RAC block masonry wall and the tie column-beam confined system was investigated.

It can be seen that, generally, the small-sized RAC block wall has good seismic behaviour; the increase of the reinforcement ratio in the columns does not improve the seismic performance of the walls. The inflection point was found to occur in the descending stage of skeleton curves, which means the tie column-beam confined system affects the resistance mechanism of the small-sized RAC block wall specimens.

- **RAC Plane Frame**

Xiao, Sun and Falkner (Xiao, Sun, & Falkner, Seismic performance of frame structures with recycled aggregate concrete, 2006) investigated the seismic behaviour of plane frames. The
important parameters and objective of the test are presented in Table 3.16. Based on the tests of 4 large scaled frame specimens under low frequency cyclic lateral load with constant vertical actions, as shown in Fig. 3.45, the failure pattern, the hysteresis curved, the skeleton curves, the energy dissipation capacity, and the stiffness degradation laws of the frame structures made with recycled coarse aggregates were investigated. The effects of different recycled aggregates’ replacement percentages (i.e., 0%, 30%, 50% and 100%) on the performance of the reinforced RAC frames were examined. It is concluded that the general seismic performance of the frame structure made of RAC declines with an increase of the recycled aggregates’ replacement percentage. Nevertheless, a frame structure with a higher content of recycled aggregates still behaves well enough to resist an earthquake attack.

The interesting test results indicated that:
- All the investigated frames behaved similarly in the aspects of the failure pattern under low frequency lateral loading regardless of the recycled aggregates’ replacement percentage.
- The presence of recycled aggregates reduced the yield, the maximum and the ultimate loads of the frames; however this reduction was less than that of the mechanical properties of the concrete material.
- The characteristic displacements among the test specimens proved that there are no obvious differences between the frames with RAC and conventional concrete, particularly in the aspects of the ductility coefficients and lateral rotations.
- From the hysteresis loops, the energy dissipation and the rigidity degradation points of view, the seismic performance of the frames made with RAC is comparable to that with conventional concrete. And the frames with a properly designed RAC according to Chinese Code GB50011 (2001) (GB50011, 2001) is able to resist an earthquake.

In addition, Sun and Xiao et al. (Sun, Xiao, & Zhou, 2005) further examined the influence of the filling of RAC blocks on the performance of the RAC frames subjected to cyclic lateral loading (Fig. 3.46). The main finding can be summarized as the following: The infilled wall can work together well with the frame, stiffness and capacity of resistive horizontal loads of frame are improved obviously, but deformation and energy dissipation performance are weaker than frames without the filling of RAC blocks. The influences of infilled wall of frame on main frame structure should arouse attention of designers.

![Test specimen filled with recycled concrete blocks](image)

**Fig. 3.46: Test specimen filled with recycled concrete blocks (Xiao & Li, Study on relationships between strength indexes of recycled concrete. (only available in Chinese), 2005)**
3.4.14. Shaking table tests on RAC structures

To more realistically check the seismic behaviour of RAC, the much expensive and complex shaking table tests were also carried out in China on RAC structures. This work was performed towards the reconstruction of the damaged areas during the Wenchuan Earthquake.

- **Small-sized RAC hollow block structure**

Xiao et al. (Zhou, Liu, & Lu, 2008) investigated the behaviour of a RAC masonry structure with the shaking table test. In the study, the Wenchuan Wolong seismic wave parameters were used to study the behaviour of RAC masonry structure of ‘tie column + ring beam + cast-in-place slab’ under seismic conditions. The test, as shown in Fig. 3.47, included not only the dynamic characteristics of structure, but the damping ratio, the frequency changes and the top floor displacement of the structure under different levels of seismic activity. Fig. 3.48 shows the displacement time history of the top floor under three occurrences.

![RAC block masonry model](image)

(a) Maximum storey displacement in the X-direction under different test phases

(b) Maximum storey displacement in the Y-direction under different test phases

![Displacement time history](image)
On the basis of the test results, it is found that maximum drift of the model structure is less than the allowable value of earthquake resistant structure in the Code for Seismic Design of Buildings (GB50011, 2001). Although tiny cracks were found on the walls, the test results prove that RAC masonry structure confined by a ‘tie column + ring beam’ system exhibits fairly good seismic behaviour.

- **RAC frame structure**

Xiao et al. (Xiao, Wang, Li, & Tawana, 2010) also investigated the seismic performance of RAC frame structures using the shaking table test, see Fig. 3.49.

![General view of the RAC frame model](image)

**Fig. 3.49: General view of the RAC frame model (Xiao, Wang, Li, & Tawana, 2010)**

The structure has six stories, and non-symmetrical lay out. The seismic fortification intensity is 8 degree, the design group is the second group of earthquake, according to the related Chinese Code (Xiao, Lei, & Yuan, Splitting tensile strength distribution of concrete with different recycled coarse aggregates. (only available in Chinese), 2008). After the shaking table test, the failure mechanism of the model structure was analyzed. The natural frequency and damping ratio of the model structure were calculated. In addition, the acceleration response and displacement response of the model for each loading case were also obtained. The maximum storey displacements obtained from WCW during earthquake simulation tests with PGA of 0.130g, 0.185g, 0.370g, 0.415g, 0.550g and 0.750g were compared and shown in Fig. 3.50. The maximum inter-storey displacements obtained from WCW were demonstrated in Fig. 3.48. The capacity curve of the RAC frame model structure was obtained through fitting of the form of exponential function for the maximum reaction values as shown in Fig. 3.51. Each data point as demonstrated in Fig. 3.52 represents an earthquake simulation test case, and the label beside the data point is the actual input peak acceleration.
Based on the intensive analysis of test results, the following conclusions and corresponding suggestions are derived:
- In the shaking table model tests, the RAC frame structure with 100% RCA replacement, failure first occurred at the end of the beams, and then at the bottom of columns, which is characterized in a manner of “strongest joints, stronger columns and weaker beams”.
- The structural displacement response is considerably influenced by the lower order vibration modes, and the distribution of the maximum storey displacement assume inverted triangular form basically along the height of the RAC frame model structure throughout the shaking table model tests.
- The structural system in the RAC frame model demonstrates good performance in resisting earthquakes. The test result indicates that the RAC frame model structure has good ultimate deformation capacity and enough ductility.
- The RAC frame structure with proper design and construction has good load-bearing capacity, deformation capacity and other seismic performances. It is feasible to apply and popularize the recycled concrete frame buildings in the Sichuan Wenchuan post-earthquake reconstruction area.

3.4.15. Conclusions and recommendations.

This paper gives a state-of-the-art report on the relevant researches and findings on the mechanical properties and structural performance of RAC in the mainland China. The main conclusions can be summarized as the follows:

- The compressive strength of RAC relies heavily on the water/cement ratio.
- The quality of RCA has a considerable effect on the probability distribution for the strength of RAC.
- The compressive, tensile and shear strength of RAC are generally lower than that of conventional concrete.
- The modulus of elasticity for RAC generally reduces as RCA increases; however the strain at peak stress is larger than that of conventional concrete.
- The RCA replacement percentage has nearly no influence on the bond strength between RAC and deformed rebar.
- The RCA has a remarkable influence on the residual strength of RAC after high temperatures.
- The carbonation resistance of recycled concrete decrease with the increase of replacement rate of recycled aggregate and that the anti-carbonizing capability of recycled aggregate is worse than that of normal concrete.
- The chloride resistance of recycled concrete reduced with the increase of replacement rate of recycled aggregate and fly ash can improve the chloride resistance of recycled concrete, and the best quantity of fly ash is from 10% to 15%. Recycled concrete has good resistance to chloride penetration, but its resistance to chloride penetration is somewhat less than normal concrete.
- Recycled concrete absorbs more water than normal concrete and harmfully influence frost resistance.
- The replacement rate of recycled aggregate has the greatest impact on the abrasion resistance of recycled concrete and the abrasion resistance of recycled concrete is lower than normal concrete.
- The structural behaviour of RAC elements/members is generally weaker in comparison to that of structures made of NAC;
- Through proper design, RAC can be used as a structural material from the view point of the
loading capacity behaviour.
- More tests on the serviceability properties of RAC elements and structures need to be carried in the future.
- The reliability index of recycled concrete beams is proved to meet the requirements of the Unified Standard for Reliability Design of Building Structures (GB 50068-2001).

Acknowledgements
The present work was sponsored by the New Century Excellent Talents in Ministry of Education Project (NCET-06-0383), the Key Projects in the National Science & Technology Pillar Program (2008BAK48B03), as well as the support by the the National Science Foundation (50738005) and the Shanghai Science and Technique Committee (No. 10231202000).

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3.5. Recycling in Germany: Overview regarding CDW in Germany

Anette Mueller, Bauhaus Universität Weimar, Weimar, Germany

3.5.1. Amounts of Construction and Demolition Waste and fields of utilization

The volume of Construction and Demolition Waste can be taken together with informations on raw material consumption of the construction industry from the regular monitoring reports submitted by the Kreislaufwirtschaftsträgers Bau, a working group of the German trade and industry associations involved in the construction sector (Arbeitsgemeinschaft Kreislaufwirtschaftsträger Bau (KWTB), 2000, 2001, 2003, 2005, 2007), (Arbeitsgemeinschaft Kreislaufwirtschaftsträger Bau (KWTB), 2008). The 2007 report (Arbeitsgemeinschaft Kreislaufwirtschaftsträger Bau (KWTB), 2008) shows that in Germany in 2004 72.4 million tons of building waste were generated divided in the different groups mineral debris from buildings (50.5 million tons), concrete and asphalt debris from road
construction (19.7 million tons) and construction site waste, including gypsum-based construction waste (2.2 million tons). The recycling rate as the ratio of the recycled quantity and the generated quantity was over 70%. A total of 548.5 million tons of raw materials were consumed in the construction sector, which were taken at about 85% of natural resource deposits. So Construction and Demolition Waste represents the largest waste stream in Germany, at the same time the construction industry has a considerable demand of resources.

Looking at the data available since 1996 for the amount of Construction and Demolition Waste and its use (Table 3.17) it is clear that at the figures for the volume of construction waste some fluctuations occur, which can be cyclical. The recycling rates are relatively constant, however. The reasons for this may be that large amounts are generated under intense construction activity. At the same time an intensive building activity attracts a high demand for raw materials and building materials which is sometimes covered with recycled materials.


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</tr>
</thead>
<tbody>
<tr>
<td>Construction rubble (mostly from buildings)</td>
<td>58,1</td>
<td>58,5</td>
<td>54,5</td>
<td>52,1</td>
<td>50,5</td>
<td>57,1</td>
</tr>
<tr>
<td>Rubble from road construction</td>
<td>17,6</td>
<td>14,6</td>
<td>22,3</td>
<td>16,6</td>
<td>19,7</td>
<td>14,3</td>
</tr>
<tr>
<td>Mixed rubble (from 2004 inclusive rubble of gypsum)</td>
<td>7,5</td>
<td>4,0</td>
<td>11,8</td>
<td>4,3</td>
<td>2,2</td>
<td>11,3</td>
</tr>
<tr>
<td>Total</td>
<td>83,2</td>
<td>77,1</td>
<td>88,6</td>
<td>73,0</td>
<td>72,4</td>
<td>82,7</td>
</tr>
</tbody>
</table>

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Road construction</td>
<td>38,2</td>
<td>40,4</td>
<td>42,5</td>
<td>35,5</td>
<td>32,9</td>
<td></td>
</tr>
<tr>
<td>Earth works</td>
<td>13,4</td>
<td>11,8</td>
<td>11,9</td>
<td>9,9</td>
<td>12,3</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>1,6</td>
<td>0</td>
<td>1,9</td>
<td>0,8</td>
<td>2,4</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>5,3</td>
<td>3</td>
<td>5,1</td>
<td>4,9</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>58,5</td>
<td>55,2</td>
<td>61,4</td>
<td>51,1</td>
<td>49,6</td>
<td>56,2</td>
</tr>
</tbody>
</table>

| Rate of recycling [%] | 70,3 | 71,6 | 69,3 | 70,0 | 68,6 | 68,0 |

The treatment of CDW to recycling building materials can be made in mobile or in stationary plants. The task of the processing is to generate a usable product with defined characteristics from the rubble delivered. Already during the delivery distinction is made between masonry material and concrete Fig. 3.53.

![(a) masonry](image1)

![(b) concrete](image2)

Fig. 3.53: Rubble from demolished masonry material and concrete before processing
In mobile processing plants, the material from the demolition, which must be pre-\textit{comminuted}, if necessary, is separated first by pre-screening into two factions. The coarse material is fed to the crusher and crushed. An overhead magnet, which is located after the crusher, removed the steel and iron parts. The products created with this treatment technology are the so called pre-screen material and the actual recycling building material. With this variant, essentially only the grain size is influenced. A direct influence on the material composition is not possible.

More sophisticated technologies for the treatment of CDW can be achieved in stationary facilities. Here, these additional processing steps can be carried out:

- Two-stage crusher: Impact crusher, following a jaw crusher
- Sorting of contaminants and impairing substances on a sorting belt and using air-separation or washing in water
- Production of grain fractions by vibration screens.

In connection with the emission control of stationary and mobile recycling facilities schemes of treatment plants and an overview about the state of the art of the used equipment are given (VDI-Richtlinie 2095, 2011).

As shown in the diagram in Fig. 3.54, the number of mobile units in Germany is much higher than the number of stationary or semi-mobile plants. The number of stationary plants has changed over the period from 1996 to 2008 only little, while the number of mobile plants has larger fluctuations. The processed amount of Construction and Demolition Waste in mobile units is 30 million tons/year on average (Fig. 3.54). The amount that is processed in stationary and semi-mobile plants is 64 million tons/year. From these values and the number of plants an average capacity of 25,700 ton/year for mobile units and 43,500 ton/year for stationary and semi-mobile plants can be calculated.
Fig. 3.54: Number of recycling plants for CDW in Germany (data taken from (Umweltstatistische Erhebungen, Abfallwirtschaft, 2011))

Fig. 3.55: Amount of CDW treated in recycling plants in Germany (data taken from (Umweltstatistische Erhebungen, Abfallwirtschaft, 2011))

In the areas of application for recycled building materials, made from Construction and Demolition Waste, the road construction dominates, followed by earthworks. Only a small percentage of the material is currently used as aggregate for concrete production (Fig. 3.56). In 2004 2.4 million tons were used for the concrete production. In relation to the production of ready-mixed concrete and concrete products this corresponds to a share of about 4%.

Fig. 3.56: Percentages of the different fields of application of recycling materials from processed CDW (Arbeitsgemeinschaft Kreislaufwirtschaftsträger Bau (KWTB), 2000, 2001,
3.5.2. Standards and recommendations

Rules exist for the required structural properties of recycled building materials, if the material is used in road construction as well as in concrete production. For both applications the requirements on the physical characteristics of recycled building materials such as particle size and particle size distribution, particle density, water absorption, grain strength, frost resistance, etc. are in the center. In addition there are specifications for the building material composition, to remove components with unfavorable physical properties like non-mineral materials, and bituminous materials, glass, ceramic, gypsum grains. With regard to ingredients harmful to the concrete and / or the reinforcement chemical analyses it is important to determine the levels of chloride, sulfate, sulfur compounds and organic matter. Because the possibility of damaging alkali-silica reaction must be considered tests on alkali-sensitive components, which may originate from the primary aggregate, and analyses of the alkali content must be carry out (TL Gestein-StB 04, 2007) (DIN EN 13043:2002-12, 2002) (DIN EN 206-1:2001:07/A1:2004-10/A2:2005-09, 2007) (DIN 1045-2:2008-08, 2008) (DIN EN 12620:2008-07, 2008) (DIN EN 13055-1:2002-08 Berichtigung1:2004-12, 2002) (DIN 4226-100:2002-02, 2002) (Deutscher Ausschuss für Stahlbeton: DAFStb-Richtlinie, 2004) (Deutscher Ausschuss für Stahlbeton: DAFStb-Richtlinie, 2007).

Furthermore, the recycled materials have to meet strict requirements for environmental compatibility. The environmental demands concern both the use of recycled materials in road construction, earthworks and landscaping as well as the use of recycled building materials for the manufacture of construction products (LAGA-Mitteilung 20, 2003) (Deutsches Institut für Bautechnik (DIBt), 2009) (Pawel, 2007). Just as primary building materials recycled construction materials should not include components that can be leached by water and result in negative effects of the ground water or the soil. In addition, the contaminant content of the solid matter must be below certain limits. On concrete, the release of substances is evaluated to be mobilized from the building product. The obligatory establishment of procedures for the preparation of aqueous eluates of the recycling materials and the leaching of the concrete as well as the limits of the concentration of the pollutants are still under discussion (Susset & Leuchs, 2008) (Gäth & Luckner, 2008).

The requirements on recycled aggregates that shall be used in concrete are summarized in the standard DIN EN 4226-100. This specification uses the content of certain building materials as index additionally to the density and the water absorption (Table 3.18). The further requirements on properties of recycled aggregates are similar to the requirements on natural aggregates.

Table 3.18: Quantities of CDW in Germany, fields of application and rates of recycling (Deutscher Ausschuss für Stahlbeton: DAFStb-Richtlinie, 2004)

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Type 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany DIN 4226-100: Recycled aggregates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Only the chippings of recycled aggregates according type 1 and 2 can be used for the production of concrete according to DIN EN 206-1 and DIN 1045-2. The crusher sand is excluded from the reuse as aggregate. Further rules and limitations are given in the final draft of a guideline of the German Committee for Reinforced Concrete (DIN EN 13043:2002-12, 2002):

- Maximum strength class C30/37
- No lightweight concrete, no prestressed concrete
- Application in dry environments or in environments with low humidity
- Limited portions acc. Table 3.19.

Table 3.19: Permissible portions of recycled aggregates > 2 mm related to the total amount of aggregate (Deutscher Ausschuss für Stahlbeton: DAfStb-Richtlinie, 2004)
WF (humid) Exposure class X 0 Exposure class XC 1 to XC 4 Exposure class XF 1 and XF 3 Exposure class XA 1
≤ 45 ≤ 35 ≤ 35 ≤ 25 ≤ 25

If the portions of recycled aggregates are equal or lower than the required limits the RC-concrete can be designed like concrete made from gravel.

Recycled aggregates from concrete rubble that meet the quality requirements of DIN 4226-100 and that can be used in accordance with the directive of the German Committee for Reinforced Concrete for concrete production can be produced with a minimum technology as well as an advanced technology of processing depending on the quality of the input material:

- Only when an unmixed input material "concrete rubble" is available recycled aggregates according to the requirement can be generated by a treatment that consists only of a comminution in an impact crusher and a subsequent classification.

- If applied an advanced technology, consisting of a two-stage crushing, a sieve classification for setting a defined particle size distribution and a wet scrubber, which can remove light impurities the requirements for the input material can be reduced somewhat.

As part of several projects recycled aggregates from both treatment options were examined and used for the production of concrete (Ifeu-Institut Heidelberg, 2010). As an example of the achieved quality parameters the properties of the recycled aggregates generated in a stationary system can be named. They showed a high purity (content of concrete and natural aggregates ≥ 98.6%) and a low water absorption (fraction 2/8 mm: ≤ 3.8%; fraction 8/16 mm: ≤ 3.2%). At levels of the recycled aggregates of 25-35 Vol-% of the total aggregates the qualities of the RC concrete were well (Mettke, RC-Beton - Qualität und Qualitätssicherung. Aufbereitung von Baustoffen und Wiederverwertung, 2010)to very good. The results underscore the importance of a qualified treatment and / or a high purity of the input materials for the manufacture of high quality recycled aggregates

3.5.3. New realizations and projects

Periodically increased efforts can be observed to establish closed circuits in the building sector. Here reuse of recycled aggregates for the concrete production are in the focus.

The first demonstration activity was the use of recycled aggregates for the construction of an office building of the Deutsche Bundesstiftung Umwelt DBU in Osnabrueck in 1994. Then a number of buildings follow in connection with the research project “Baufindkreislauf im Massivbau BiM”. Recently, concrete was made of RC aggregate acc. to the current standards. It was used in the context of several flagship projects in residential and administrative buildings. In Table 3.20 some examples of the composition of the concrete with recycled aggregates and the buildings in which it was used are summarized.

<table>
<thead>
<tr>
<th>Building</th>
<th>Characteristics / mixing design of the concrete</th>
</tr>
</thead>
</table>
| Administration building Osnabrueck | Built in 1994/95 Components: Interior walls  
Strength class: C 30/37  
Amount of RC-concrete: 120 m³ |
|                                 | Natural sand 0/4 mm 669 kg/m³  
RC-aggregates 4/16 mm 669 kg/m³  
RC-aggregates 16/32 mm 294 kg/m³  
Portland cement 45 F 290 kg/m³  
Fly ash 70 kg/m³  
Water-cement-ratio 0.69  
Plasticizer 1.8 kg/m³  
Fresh concrete: Slump after 10 min 410 mm  
Hardened concrete: Compressive strength after 28 days 41 N/mm² |
| Residential- and administration building Itzehoe | Built in 1996/1997 Components: Interior and external walls at moderate moisture |
|                                 | Natural sand 0/2 mm 36 %  
RC-aggregates 2/8 mm 14 %  
RC-aggregates 8/16 mm 20 %  
RC-aggregates 16/32 mm 30 %  
Cement CEM II/A-L 32,5 R 350 kg/m³  
Fly ash No information  
Water-cement-ratio  
Plasticizer FM 72  
Fresh concrete: Slump after 10 min 570 mm  
Hardened concrete: Compressive strength after 28 days 45 N/mm² |
|                                 | Natural sand 0/2a mm 585 kg/m³  
RC-aggregates 2/8 mm 545 kg/m³  
RC-aggregates 8/16 mm 568 kg/m³  
Cement CEM I 42,5 R 310 kg/m³  
Fly ash 40 kg/m³  
Water-cement-ratio 0.55  
Plasticizer FM 26 5-18 ml/kg  
Fresh concrete: Slump after 10 min 550 mm  
Hardened concrete: Compressive strength after 28 days 45 N/mm² |
### Residential building “Waldspirale” Darmstadt
**Built in 1999/2000**
**Components:** Interior walls and floor plate
**Strength classes:** C 20/25, C 30/37
**Amount of RC-concrete:** 12000 m³

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural sand 0/2a mm</td>
<td>616</td>
</tr>
<tr>
<td>RC-aggregates 2/8 mm</td>
<td>530</td>
</tr>
<tr>
<td>RC-aggregates 8/16 mm</td>
<td>569</td>
</tr>
<tr>
<td>Portland cement CEM I 42,5 R</td>
<td>300</td>
</tr>
<tr>
<td>Fly ash</td>
<td>50</td>
</tr>
<tr>
<td>Effective water-cement-ratio</td>
<td>0.59</td>
</tr>
<tr>
<td>Plasticizer BV</td>
<td>1.5</td>
</tr>
<tr>
<td>Consistence of fresh concrete</td>
<td>Regular</td>
</tr>
<tr>
<td>Hardened concrete:</td>
<td></td>
</tr>
<tr>
<td>Compressive strength after 28 days</td>
<td>42.9 N/mm²</td>
</tr>
</tbody>
</table>

### Guest house in the residential area on the Rhine Avenue in Ludwigs-hafen
**Built in 2009**
**Components:** ceilings, walls and elevator shaft
**Quality of RC-concrete:** C 30/37, XC 1, F3
**Amount of RC-concrete:** 600 m³

<table>
<thead>
<tr>
<th>Characteristics of the RC-aggregates 2/8 mm and 8/16 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content of concrete and natural rock in the used fractions</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Bulk density</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Water adsorption</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

### Residential buildings Stuttgart-Ost
**Built in 2010**
**Production of concrete of different strength and exposure**

<table>
<thead>
<tr>
<th>Characteristics of the RC-aggregates 2/16 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content of concrete and natural rock in the used fraction 2/16 mm</td>
</tr>
<tr>
<td>Bulk density</td>
</tr>
</tbody>
</table>
classes with recycled aggregates | Water adsorption | 3.3 %
--- | --- | ---
Fresh concrete: Slump after 10 min
C 8/10; X 0 | 480 mm |
C 12/15, X 0 | 490 mm |
C 20/25, XC 3 | 480 mm |
C 25/30; XC 4 | 490 mm |
C 30/37; XC 1 | 490 mm |
Hardened concrete: Compressive strength after 28 days
C 8/10, X 0 | 17 N/mm² |
C 12/15, X 0 | 21 N/mm² |
C 20/25; XC 3 | 32 N/mm² |
C 25/30, XC 4 | 38 N/mm² |
C 30/37, XC 1 | 44 N/mm² |

Residential buildings Stuttgart Rotenbergstraße / Raitelsbergstraße
Built in 2010
Components: lean concrete, ceilings, walls
Quality of RC-concrete:
from C 8/10 to C 30/37
Amount of RC-concrete:
1500 m³, i.e. 68 % of the whole concrete quantity

All of the flagship projects were carried out in Stuttgart or in the surroundings of Stuttgart. The processing took place in a stationary plant which was equipped with two crushers and a wet scrubber as well as in a mobile plant. In the case of the mobile plant the operator was also responsible for the demolition, thus it was guaranteed that the input material consists of very clean concrete rubble. An additional advantage were the short transport distances between demolition site, processing plant, ready mix concrete plant and location of the construction project. On base of the positive experience more and more commercial projects using RC-concrete in buildings are in progress.

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### 3.6. Recycling in Italy: Overview regarding construction and demolition waste

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Mr. Marco Quattrone, Politecnico di Milano, Milano, Italy
3.6.1. Preliminary remarks about the method

On the eve of the new European Directive’s absorption concerning wastes (2008/98 EC), it is essential to know, in a reliable way, data about construction and demolition waste production, about the number and the location of plants. Without this kind of information, it is very difficult to start new politics about inert wastes’ management and recycling.

The European Commission has set the goal, for construction and demolition wastes’ recycling, at 70% by 2020. Considering that the actual Italian recycling rate is about 10%, it is clear the necessity of new politics to reach that goal. Regarding C&DW production data, the last “Official Italian Waste Report” indicates a total production of C&D wastes equal to 52’083 million tons (last official available data are dated 2006).

To achieve a correct evaluation of special waste quantities, ISPRA (Environmental Protection and Research Institute) has combined data coming from the waste quantities’ declarations through estimate’s procedures. In particular, the CDW quantity has been estimated from management operations data, coming from Environmental Declaration Form (MUD) removing the MUD’s declarations regarding the midway phases of the management process. The used methodology sets the total production of CDW equal to the recovered/landfilled quantities. Regarding the recycling material’s quantification, the Italian Waste Report presents data concerning not dangerous special wastes; in that Report, there are not specific information about construction and demolition wastes. That depends on the complexity of the waste management and authorization system and, today, a sectorial data collection is impossible.

The data presented in this paper come from the annual report by National Association of Recycled Aggregates Producers (ANPAR). However, this year, cause of the economic situation, the number of plants involved in the study has been lesser than that of the past. It has been chosen to considerer data come from all the plants involved in this analysis during the last 4 years.

It has been asked, to the plants’ manager, to fill a questionnaire with the wastes’ quantities relating to the following codes:

- EWC 17 01 01 Concrete
- EWC 17 01 02 Bricks
- EWC 17 01 03 Tiles and ceramics
- EWC 17 01 07 Mixture of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06
- EWC 17 03 02 Bituminous mixtures containing other than those mentioned in 17 03 01
- EWC 17 04 05 Iron and steel
- EWC 17 05 04 Soil and stones other than those mentioned in 17 05 03
- EWC 17 05 06 Dredging spoil other than those mentioned 17 05 05
- EWC 17 08 02 Gypsum-based construction materials other than those mentioned in 17 08 01
- EWC 17 09 04 Mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03
Fig. 3.57 shows the geographic location of the plants; they are above all located in northern Italy.

Fig. 3.57: Location of plants involved in the study [source: ANPAR]

The difficulties to conduct a complete CDW recycling plants census and the consequent lack of data, does not allow to determine clearly how much the analyzed sample can be representative.

A first step in this direction could be the report on the waste treatment plants published by Environmental Services Companies Association (FISE) (AA. VV, 2009). The mentioned study has the purpose to arrange a frame concerning the waste treatment plants to understand the actual situation and to arrange corrective measures (AA. VV., 2010).

### 3.6.2. The production of recycled aggregates in Italy: Qualitative aspects

The composition of inert waste is very variable; this is linked to the different wastes’ source that depends on local typology and construction technique, climate conditions, economic activities and technologic development of a specific area, furthermore the availability of raw materials.

The analysis of provided data, coming from recycling plants involved in this study, shows that the most of plants receives construction and demolition wastes, including contaminated soil (EWC 17.XX.XX). The ratio between the EWC 17.XX.XX wastes and total waste’s quantity is more than 85% except for three cases. The reasons of that difference can be found in the particular conditions of those places. The first two plants have decided to dedicate their activity on industrial waste while the third one is located near some travertine quarries that send their scraps to the plant. However, the mentioned data are not sufficient to modify the general trend.
Considering the plants in function of their geographic location (North, Centre, South), the percentage of wastes belonged to EWC 17.XX.XX is always higher than 90% of the overall; this confirms that the most CDW comes from construction sector. Concerning the average composition of treated wastes, Fig. 3.58, Fig. 3.59, Fig. 3.60 and Fig. 3.61 show that, in different proportions, the wastes sent to the plants with important percentages, compared with total, are those belonged to the EWC code shown in Table 3.21.

Table 3.21: Significant percentages of wastes sent to the plants [source: ANPAR]

<table>
<thead>
<tr>
<th>EW Code</th>
<th>Definition</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 09 04</td>
<td>mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03</td>
<td>32</td>
</tr>
<tr>
<td>17 05 04</td>
<td>iron and steel</td>
<td>14</td>
</tr>
<tr>
<td>17 01 07</td>
<td>mixture of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06</td>
<td>27</td>
</tr>
<tr>
<td>17 03 02</td>
<td>bituminous mixtures containing other than those mentioned in 17 03 01</td>
<td>11</td>
</tr>
</tbody>
</table>

The “geographic” analysis of these data allows us to notice some significant differences. Below the subdivision of main waste’s typology has reported:

- The code 17 09 04 has a national average equal to 32% that is 17% in the North, 4% in the Centre and 22% in the South.
- The code 17 05 04 has a national average equal to 14% that is 20% in the North, 61% in the Centre and 56% in the South.
- The code 17 01 07 has a national average equal to 27% that is 8% in the North, 15% in the Centre and 1% in the South.

These differences are not very significant and can be justified considering that in the northern plants other kinds of wastes, not only the construction and demolition ones, are sent. Those wastes, after a separation treatment, to eliminate undesirable fractions, and a granulometry sorting became recycled aggregates.

Fig. 3.58: Average composition of wastes treated inside the involved recycling plants
PROGRESS IN RECYCLING IN THE BUILT ENVIRONMENT
RILEM TC 217-PRE. Final report - March 2012

Fig. 3.59: Average composition of wastes treated in the North Italy’s recycling plants

Fig. 3.60: Average composition of wastes treated in Centre Italy’s recycling plants

Fig. 3.61: Average composition of wastes treated in South Italy’s recycling plants
3.6.3. Quantitative aspects

Official data, regarding the inert wastes’ recycling, even if poorly reliable, indicate that the yearly produced quantity of Italian construction and demolition wastes is about 52 million tons.

Despite during the last years the attention on this kind of waste has considerably risen, nowadays it is possible to state that the C&DW recycling sector is strongly underdeveloped and uncoordinated.

About that:
- An official census of the plants located on the Italian Territory does not exist;
- The construction and demolition waste flow’s size is unknown so as its split in the different final destinations (landfill site, recycling plants, volumetric reduction plants, etc.);
- A considerable inert waste’s quantity is not recycled/disposed of in a suitable way;
- A homogeneous material’s flow, that can be treated and reused inside a construction site, exists but this one has never taken in account from a quantitative point of view.

In 2009, just 49 plants have been involved in this study, 3 plants less of the 2008. However, only data coming from 14 plants have been taken into account. These plants were involved in the study even during the past 4 years as Fig. 3.62 shows.

From the analysis, it is possible to state that after an increase during the 2006, the quantities of C&D wastes sent to the plants have remained constant during the 2007 and have slowly decreased in 2008, according with the trend of the construction activity.

Fig. 3.62: Inert wastes sent to the plants during the period 2005-2008
If we consider that the official provided data show a positive trend in production of construction and demolition wastes, while, concerning the delivered C&DW quantities, the plants involved in this study recorded an estimated negative trend of about 10%.

3.6.4. Normative aspects

From 2005 to date, major developments in the use of recycled aggregates have been made. The main reasons can be found in the enacting of two laws: the “Environmental Code” (Decree 152/2006) and the “Construction Regulations”.

Regarding the “Environmental Code”, which absorbs eight European Directives, the main innovation consists in putting national regulations in line with European standards, especially those concerning the definition of C&D waste, their classification and the test methods adopted to quantify the pollutants.

Previous environmental regulations already promoted the recycling and the use of recycled aggregates for non-structural applications (road sub-layer, embankment etc.). However, these uses are subject to the leaching test performance. In the past, Italian pollutant limits were more restrictive than those of other European Countries; i.e., the outdated Italian test method produced high values of pollutants so the use of recycled aggregates was almost impossible. Regarding the “Construction Regulations”, it is necessary to precise that in 2005 the promulgation of the law’s first version allowed the use of recycled aggregates for structural applications. However, this one has been ignored because of a series of mistakes and adverse opinions by some advisory bodies.

Its review has led to the enacting of the aforementioned construction regulations, which are in force since March 2008. Regarding the use of recycled aggregates, the new standard introduces some limit values. These values, expressed in function of concrete’s strength class (after 28 days), are listed in Table 3.22.

Table 3.22: Percentage of use of recycled aggregates in concrete

<table>
<thead>
<tr>
<th>Origin of the recycling material</th>
<th>Class of Concrete</th>
<th>Rate of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demolition of buildings (debris)</td>
<td>C 8/10</td>
<td>Up to 100%</td>
</tr>
<tr>
<td>Demolition of concrete or reinforced concrete</td>
<td>≤ C30/37</td>
<td>Up to 30%</td>
</tr>
<tr>
<td></td>
<td>≤ C20/25</td>
<td>Up to 60%</td>
</tr>
<tr>
<td>Reuse in certified precast concrete industries - any class of concrete</td>
<td>≤ C45/55</td>
<td>Up to 15%</td>
</tr>
<tr>
<td>Reuse in certified precast concrete industries - class of concrete &gt; C45/55</td>
<td>Same class of original concrete</td>
<td>Up to 5%</td>
</tr>
</tbody>
</table>

It is important to highlight that the new regulations do not provide information about the different values of mechanical properties that recycled aggregate concrete could show compared to traditional concrete.

Regarding the technical standards, the new regulations absorb the EN standards, in particular the EN 12620 “Aggregates for concrete”. This standard defines the properties that aggregates need to have in order to comply with the requirements of EN 206-1 “Concrete - Specification, performance, production and conformity”.

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The Italian standards UNI 8520-1 and UNI 8520-2 provide the complementary instruction necessary to apply the UNI EN 12620. The former gives prescriptions about designation method and conformity criteria, while the latter specifies requirements of the aggregates for concrete.

Applications of recycled aggregates for civil engineering work and for road construction are provided in the UNI EN 13242 “Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction”.

3.6.5. A comparison with European data

Every year, in Europe, about 850 million tons of construction and demolition wastes are produced. They represent the 31% of the total European wastes’ production [source: EUROSTAT and ETC/RWM, 2008]. Table 3.23 shows the production’s development of C&DW per capita, concerning the old Member Countries and Norway, since 2001. The average for the European Union (27 Countries and Norway) is of 1.74 tons/year per capita.

Table 3.23: Construction and demolition waste production in Europe (tons per capita) [source: EUROSTAT and ETC/RWM, 2008]

<table>
<thead>
<tr>
<th>Country</th>
<th>Year</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.81</td>
<td>-</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Belgium</td>
<td>0.81</td>
<td>0.80</td>
<td>1.11</td>
<td>1.06</td>
<td>1.22</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>0.63</td>
<td>0.75</td>
<td>0.70</td>
<td>0.83</td>
<td>0.97</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>Finland</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.99</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.5</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>3.05</td>
<td>2.92</td>
<td>2.71</td>
<td>2.33</td>
<td>2.24</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Greece</td>
<td>0.41</td>
<td>0.38</td>
<td>0.37</td>
<td>0.37</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Ireland</td>
<td>1.70</td>
<td>-</td>
<td>-</td>
<td>2.74</td>
<td>3.60</td>
<td>3.95</td>
<td></td>
</tr>
<tr>
<td>Italy*</td>
<td>0.54</td>
<td>0.65</td>
<td>0.74</td>
<td>0.80</td>
<td>0.78</td>
<td>0.88*</td>
<td></td>
</tr>
<tr>
<td>Luxemburg</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.9</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Netherland</td>
<td>1.48</td>
<td>1.47</td>
<td>1.46</td>
<td>1.47</td>
<td>1.58</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Norway</td>
<td>0.27</td>
<td>0.28</td>
<td>0.27</td>
<td>0.70</td>
<td>0.32</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Portugal</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.09</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>0.59</td>
<td>0.58</td>
<td>0.66</td>
<td>0.74</td>
<td>0.80</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.14</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>1.74</td>
<td>1.74</td>
<td>1.75</td>
<td>1.66</td>
<td>1.90</td>
<td>1.89</td>
<td></td>
</tr>
</tbody>
</table>

*The datum has been updated and aligned to the last “Italian Waste Report”

Analyzing the data it is possible to notice as there are many differences among the old EU configuration’s Countries. France and Luxembourg produce 5.5 and 5.9 tons/year per capita respectively. Germany and Ireland produce between 2 and 4 tons/year per capita, while for other Countries the range fluctuates between 0.2 of the Norway and the 2 of the United Kingdom; Italy produce 0.88 tons/year per capita. Even concerning new Member Countries, Table 3.24 shows many differences, however all data are below 1 ton/year per capita except for Malta that produces almost 2 tons/year.
Table 3.24: Construction and demolition waste production in Europe (tons per capita) [source: EUROSTAT and ETC/RWM, 2008]

<table>
<thead>
<tr>
<th>Country</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulgaria</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cyprus</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.58</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>0.85</td>
<td>0.85</td>
<td>1.00</td>
<td>1.44</td>
<td>1.20</td>
<td>1.15</td>
</tr>
<tr>
<td>Estonia</td>
<td>0.64</td>
<td>0.94</td>
<td>0.93</td>
<td>1.12</td>
<td>1.61</td>
<td>1.78</td>
</tr>
<tr>
<td>Hungary</td>
<td>0.49</td>
<td>0.59</td>
<td>0.51</td>
<td>0.43</td>
<td>0.49</td>
<td>0.54</td>
</tr>
<tr>
<td>Latvia</td>
<td>-</td>
<td>0.06</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>Lithuania</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.10</td>
<td>-</td>
<td>0.18</td>
</tr>
<tr>
<td>Malta</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.95</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Poland</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.11</td>
<td>0.14</td>
<td>0.44</td>
</tr>
<tr>
<td>Romania</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>Slovakia</td>
<td>-</td>
<td>-</td>
<td>0.07</td>
<td>0.26</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Slovenia</td>
<td>0.83</td>
<td>0.82</td>
<td>1.00</td>
<td>1.41</td>
<td>0.42</td>
<td>1.18</td>
</tr>
<tr>
<td>EU 27+ Norway</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.74</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The pro capita production C&D waste index is certainly a data linked to the industrialization level of a Country however, the sensible noticed data difference can be justified because a different data collection’s methodology has been used in the different Countries.

To present a clear picture of the problem, it is also important to consider the annual production of aggregates. In 2006, 3.6 billion tons of aggregates have been produced in 21 European Countries. Table 3.25 summarizes these data.

Table 3.25: Best Estimates of Aggregates Production Data for 2009 [source: UEPG 2010-2011]

<table>
<thead>
<tr>
<th>Country</th>
<th>Total number of Producers (Companies)</th>
<th>Total number of extraction sites (Mt)</th>
<th>Sand &amp; Gravel (Mt)</th>
<th>Crushed Rock (Mt)</th>
<th>Marine Aggregates (Mt)</th>
<th>Recycled Aggregates (Mt)</th>
<th>Manufactured Aggregates (Mt)</th>
<th>Total Production (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>1062</td>
<td>1362</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>97</td>
</tr>
<tr>
<td>Belgium</td>
<td>78</td>
<td>104</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>15</td>
<td>1</td>
<td>78</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>190</td>
<td>280</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Croatia</td>
<td>260</td>
<td>338</td>
<td>7</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>Cyprus</td>
<td>23</td>
<td>23</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Czech Rep</td>
<td>198</td>
<td>384</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>65</td>
</tr>
<tr>
<td>Denmark</td>
<td>350</td>
<td>500</td>
<td>3</td>
<td>0</td>
<td>9</td>
<td>5</td>
<td>0</td>
<td>44</td>
</tr>
<tr>
<td>Finland</td>
<td>400</td>
<td>2091</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>65</td>
</tr>
<tr>
<td>France</td>
<td>1428</td>
<td>2481</td>
<td>14</td>
<td>20</td>
<td>6</td>
<td>15</td>
<td>6</td>
<td>376</td>
</tr>
<tr>
<td>Germany</td>
<td>1280</td>
<td>2265</td>
<td>23</td>
<td>21</td>
<td>5*</td>
<td>61</td>
<td>36</td>
<td>555</td>
</tr>
<tr>
<td>Greece</td>
<td>192</td>
<td>213</td>
<td>1</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>71</td>
</tr>
<tr>
<td>Hungary</td>
<td>100</td>
<td>100</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>57</td>
</tr>
</tbody>
</table>
3.6.6. Characteristics of plants - Technology

The plants’ technology, actually popular in Italy, can be grouped in two categories: the stationary and the mobile ones.

Recycling process of C&D waste consists of these stages:
- Coarse separation
- Crushing
- Separation of ferrous elements
- Screening
- Removal of impurity (if necessary)

The coarse separation, made by grab or shears, is the first operation made on the rubble. The purpose of it is to reduce the dimensions of the debris to feed the crusher easily. During the crushing stage, made by the crusher, the dimensions of rubble are reduced to obtain a product of suitable size. This characteristic is obtained by mechanical action as:
- Squeezing
- Impacting
- Grinding

Generally, the crushing cycle is distinguished in primary crushing, secondary crushing and milling to obtain a product with decreasing size.

The classification in different granulometry classes is made by the screening operation. If it is necessary to eliminate impurity like wood, plastic and paper, air separation is the best process to do this: it does not produce washing mud that are hard and expensive to dispose of.

The process ends with the storage of the products.

The main components of a recycling plant are:
- The crusher
- The magnetic separator
- The screen
- The air classifier (if necessary)

Actually the recycled aggregate washing is rare because washing mud disposal is very expensive, and the administrative procedure is complex.

The flowchart in Fig. 3.63 highlights represents the different stages of the material during the recycling process in a typical stationary Italian plant. The productive cycle is organized in order to avoid that unsuitable material is recycled.

Qualitative and quantitative controls are carried out in order to match the information about loaded and truck drivers. The plant is managed by only three operators who use a system for video surveillance. The computerization of the data allows identifying the truck driver if the input material is not conforming to the admittance criterion. The material to process, stored in heaps of same kind, is transferred to the feeding by one mechanical digger thus reducing the probability to introduce unsuitable material. A video camera, videoing the exit mouth of the feeding, holds under control the rubble before it begins the treatment cycle.

In this stage, the operator can stop the feeding and check or put aside the material. To avoid the milling of the fine fraction, a vibrating screen performs the first selection. The coarse material is then sent to the crusher.

After the crusher, an atomized water system allows to eliminate dusts and to pick up them. The output material goes under a magnetic separator and iron elements are stored in a metallic box. Then, a vibrating screen classifies ceramic materials in different granulometry classes (0÷30 mm, 0÷70 mm, >70 mm this one can be crushed once again).

The vibrating screen also separates plastic, wood and paper elements and puts them into a special box. The 30÷70mm fraction can be stored or sent to another cycle of crushing. At the end of the process the different fractions are stored in heaps by a revolving device which minimizes the dust of fall. Another conveyor belt can feed a further screening station which produces 0÷6mm, 6÷15mm and 15÷30mm fractions.
These granulometry classes are further purified from impurities that are put in special boxes. Mobile plants, compared to the fixed ones described above, are constitutes by mobile or semi-mobile machines of suitable sizes for road transport. It is less expensive to buy and to manage these machines than the fixed ones, but they are less productive. Their advantage is the possibility to use them inside the demolition site thus avoiding excessive handling of the debris and reducing the high transport costs.

In the field of the recycling of C&DW, mobile plants consist of a crusher, with magnetic separator on the exit mouth, and of a vibrating screen for the granulometry classification. These machines are positioned in series to achieve a recycling station (see Fig. 3.64(a)). Crusher and screen are usually separated.

Nowadays, it is possible to find a single machine with crusher, magnetic separator and screen (see Fig. 3.64(b)).
3.6.7. The administrative procedure to install a recycling plant and the complementary activities

For realizing and managing a new recovered/recycling plants, an authorization is needed; local authorities give that one. Two kinds of authorization are necessary. To achieve the first one it is necessary to present the plant’s project and the technical documentation concerning the territorial planning, public welfare/health and the environment one.

The business concerning the recovering of wastes can be done following two procedures: the former follows a simplified administrative procedure while the latter follows the ordinary one. The difference between the two ones concerns the times to achieve the authorizations and the size of the business (for example with the simplified procedure, times are of about 90 days).

The Legislative Decree 4/08, however, has introduced some news; plants’ managers that decide to follow the simplified procedure, if the business regards the treatment of not dangerous wastes and the production is higher than 10 tons/day, must necessarily submit the Environmental Impact Evaluation. At this point, there is not a substantial difference between the simplified and the ordinary administrative procedures, concerning the documents to produce for, the only difference (this is the real problem) are the times, always too long.

Often, the construction and demolition waste recycling has carried out parallel to other activities (Fig. 3.65) so that it is possible to optimize the management of wastes and the selling of the products.

In Europe, during the last years, a significant collaboration quarry and recycling activity has developed. On February 2008, the European Aggregates Association and the International Recycling Federation have launched the European Platform for Recycled Aggregates (EPRA). The mission of EPRA is to achieve the best use of recycled aggregates in the most of applications.

The match of quarry and recycling activities, although can generate some problems, concerning the administrative procedures, cause many advantages:
possibility to have in the same production place aggregates from different source; raw material can be used just for high performance applications while the recycled ones for the others;
- reducing the environmental impact linked to the quarry activity on the territory;
- solving the problem of the quarry waste production, they can be recycled inside the plant;
- providing to a third party a recovering service for construction and demolition wastes.

3.6.8. Work modalities

It is possible to state that every stationary plant, independently if it makes up by stationary or mobile machines, has a quality control production system. This kind of tools allows to the producers to warranty homogeneous materials’ stocks. The knowledge of the own materials’ characteristics is an unavoidable requirement. The presence of internal laboratories is a proof of that and is the only way to test and know, quickly, the produced recycled material’s characteristics.

However, the EC marking on the aggregates, even if mandatory especially for recycled aggregates, is not frequently required from the market when those are used in low performance applications. The enforcement of EU rules, as happen in the structural concrete sector, is producing a significant impulse.

Fig. 3.65: Percentage distribution of integrative activities carried out inside the recycling plants member of National Association of Recycled Aggregates Producers

3.6.9. The recycled aggregates’ market

Different factors influence the recycled aggregates’ market. Among these it is possible to cite the following:

- mining activity taxation;
- landfill cost;
- availability and cost of natural aggregates;
- bias against recycled materials.
Different policies on wastes’ management and the availability of natural aggregate are the main cause about this problem. Countries where landfill costs are higher have generally an high recycling rate, on the contrary the availability of raw materials and the low landfill costs, e.g. Italian situation, impede the knowledge’s development about recycled aggregates performances and possible applications’ fields. For example, concerning landfill cost, prices can be in a range from 5 € per ton in Italy to 50 € per ton in Denmark. Regarding the availability and the natural aggregate’s cost, these factors depend on the Country, by the mines’ availability in a specific area and by the transport’s cost. Actually in Europe the price per ton fluctuates between a minimum of 2.5 €/t and a maximum of 12 €/t. Countries like Italy that have a big availability of natural aggregates tend to sell them at the average price about 6 €/t. Because of that reason, the price of recycled aggregates should be the 20% lower than the price of the natural ones. Furthermore the concept that recycled aggregates come from wastes meets opposition both from building operators and customers.

3.6.10. Conclusion

According to the ISPRA’s estimates, published on Italian Waste Report 2008, about 52 million tons have been produced in Italy (AA. VV.). Concerning the qualitative characteristics, in 2008 almost the 100% of the wastes sent to the recycling plants were construction and demolition ones, including contaminated soil. Among the above-mentioned, the main categories are:

- EWC 17 09 04 mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03;
- EWC 17 01 07 mixture of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06;
- EWC 17 05 04 soil and stones other than those mentioned in 17 05 03.

Regarding the quantitative aspects, despite this year the plants’ involvement has been limited because the economic situation, so the study cannot totally be considered representative, the Italian situation is strongly rearward if compared with that of other similar European Countries. The recycled CDW are about the 10% of the yearly produced inert wastes. The lack of organized measures between public authority and private sectors makes difficult even the achievement of European recycling purpose (the recycling rate equal to 70% in 2020). Halfway step should be set, for example the achievement of a recycling rate equal to 50% in 2015, to give an impulse to the market.

The failed enforcement of the Ministerial Decree 203/03, concerning the legal requirement for public authorities to use at least the 30% of recycled products, must be report. In this respect, the behaviour of public administrations, especially regarding the use of recycled aggregates in infrastructures and constructions, can be considered disastrous.
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3.7. Recycling in the Netherlands

3.7.1. Existing standards relevant to CDW

Standards have been developed for application, referring to relevant technical properties, as well as to environmental protection properties.

The specification requirements for recycled aggregates are listed in Table 3.26 and Table 3.27.

Table 3.26: PMC recycled concrete aggregate 4/32 as coarse fraction in concrete
<table>
<thead>
<tr>
<th>Items concerning concrete aggregates 4/32 in concrete</th>
<th>Standards</th>
<th>Requirements</th>
<th>Assessment methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>composition:</td>
<td>NEN 5905</td>
<td>&gt; 90 % (m/m)</td>
<td>NEN 5942</td>
</tr>
<tr>
<td>• concrete (≥ 2,100 kg/m³)</td>
<td>NEN-EN 12620</td>
<td>no requirements</td>
<td>NEN-EN 1744-1</td>
</tr>
<tr>
<td>• chlorides</td>
<td>NEN-EN 12620</td>
<td>more requirements</td>
<td>NEN-EN 1744-1</td>
</tr>
<tr>
<td>• acid-soluble sulphate content</td>
<td>NEN-EN 12620</td>
<td>≤ 1 % (m/m)</td>
<td>NEN-EN 1744-1</td>
</tr>
<tr>
<td>• total sulphur content</td>
<td>NEN-EN 12620</td>
<td>more requirements</td>
<td>NEN-EN 1744-1</td>
</tr>
<tr>
<td>• lightweight-organic contaminants</td>
<td>NEN-EN 12620</td>
<td>no requirements</td>
<td>NEN-EN 1744-1</td>
</tr>
<tr>
<td>• constituents causing staining</td>
<td>NEN 5905</td>
<td>no requirements</td>
<td>NEN-EN 1744-1</td>
</tr>
<tr>
<td>• lightweight material</td>
<td>-</td>
<td>no requirements</td>
<td>NEN-EN 1744-1</td>
</tr>
<tr>
<td>grain distribution</td>
<td>NEN 5905</td>
<td>Minimum: 98</td>
<td>NEN-EN 933-1</td>
</tr>
<tr>
<td>flakiness index</td>
<td>NEN-EN 12620</td>
<td>more requirements</td>
<td>NEN-EN 933-3</td>
</tr>
<tr>
<td>shell content of coarse aggregates</td>
<td>NEN-EN 12620</td>
<td>in practice ≤ 10</td>
<td>NEN-EN 933-7</td>
</tr>
<tr>
<td>fines content</td>
<td>NEN-EN 12620</td>
<td>more requirements</td>
<td>NEN-EN 933-1</td>
</tr>
<tr>
<td>fines quality</td>
<td>NEN-EN 12620</td>
<td>more requirements</td>
<td>NEN-EN 933-8</td>
</tr>
<tr>
<td>Los Angeles coefficient</td>
<td>NEN 5905</td>
<td>≤ 40</td>
<td>NEN-EN 1097-2</td>
</tr>
<tr>
<td>polished stone value</td>
<td>NEN-EN 12620</td>
<td>more requirements</td>
<td>NEN-EN 1097-8</td>
</tr>
<tr>
<td>particle density</td>
<td>NEN-EN 12620</td>
<td>no requirements</td>
<td>NEN-EN 1097-6</td>
</tr>
<tr>
<td>water absorption</td>
<td>NEN-EN 12620</td>
<td>in practice 6 % / 24 h</td>
<td>NEN-EN 1097-6</td>
</tr>
<tr>
<td>bulk density</td>
<td>NEN-EN 12620</td>
<td>more requirements</td>
<td>NEN-EN 1097-3</td>
</tr>
<tr>
<td>freeze/thaw resistance</td>
<td>NEN-EN 12620</td>
<td>more requirements</td>
<td>NEN-EN 1367-1</td>
</tr>
<tr>
<td>drying shrinkage</td>
<td>NEN-EN 12620</td>
<td>≤ 0.075 %, if required</td>
<td>NEN-EN 1367-4</td>
</tr>
<tr>
<td>alkali-silica reactivity</td>
<td>NEN 5905</td>
<td>no requirements</td>
<td>CUR-recomm. 89</td>
</tr>
<tr>
<td>environment:</td>
<td>Building Materials Decree</td>
<td>no requirements for aggregates, only for the end product, i.e. concrete</td>
<td>not relevant</td>
</tr>
<tr>
<td>• heavy metals (e.g. barium)</td>
<td></td>
<td></td>
<td>(no assessment of aggregate)</td>
</tr>
<tr>
<td>• anions (e.g. sulphate)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• organic components (e.g. PAHs)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.27: PMC recycled mixed aggregate 0/31.5 as sub-base in road construction
<table>
<thead>
<tr>
<th>Items concerning mixed aggregates 0/31.5 as sub-base in road construction</th>
<th>Standards</th>
<th>Requirements</th>
<th>Assessment methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>composition:</td>
<td>Standard RAW</td>
<td>≥ 50 % (m/m)</td>
<td>Standard RAW</td>
</tr>
<tr>
<td>• concrete and stone (≥ 2,100 kg/m³)</td>
<td>2005</td>
<td>≥ 45 % (m/m)</td>
<td>2005</td>
</tr>
<tr>
<td>• concrete (≥ 2,100 kg/m³)</td>
<td></td>
<td>≥ 50 % (m/m)</td>
<td></td>
</tr>
<tr>
<td>• masonry (≥ 1,600 kg/m³)</td>
<td></td>
<td>≤ 5 % (m/m)</td>
<td></td>
</tr>
<tr>
<td>• other stony materials + asphalt</td>
<td></td>
<td>≤ 1 % (V/V and m/m)</td>
<td></td>
</tr>
<tr>
<td>• asphalt</td>
<td></td>
<td>≤ 0.1 % (m/m)</td>
<td></td>
</tr>
<tr>
<td>• gypsum + non-stony materials</td>
<td></td>
<td>no (visual)</td>
<td></td>
</tr>
<tr>
<td>• organic material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• clamps of clay or soil</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grain distribution</td>
<td>idem</td>
<td></td>
<td>NEN-EN 933-1</td>
</tr>
<tr>
<td>Los Angeles coefficient</td>
<td>idem</td>
<td>≤ 60</td>
<td>NEN-EN 1092-2</td>
</tr>
<tr>
<td>crushed pieces</td>
<td>idem</td>
<td>≥ 90 % (m/m)</td>
<td>NEN-EN 933-5</td>
</tr>
<tr>
<td>round pieces</td>
<td>idem</td>
<td>≤ 3 % (m/m)</td>
<td>NEN-EN 933-5</td>
</tr>
<tr>
<td>flakiness index</td>
<td>idem</td>
<td>≤ 20</td>
<td>NEN-EN 933-3</td>
</tr>
<tr>
<td>CBR&lt;sub&gt;6&lt;/sub&gt;/days</td>
<td>idem</td>
<td>≥ 50 %</td>
<td>NEN-EN 14227-2,</td>
</tr>
<tr>
<td>CBR&lt;sub&gt;8&lt;/sub&gt;/days</td>
<td>idem</td>
<td>≥ 125 % of CBR&lt;sub&gt;6&lt;/sub&gt;/days</td>
<td>annex D</td>
</tr>
<tr>
<td>environment, heavy metals:</td>
<td>Building Materials Decree + Temporary Exemption Regulation</td>
<td>thickness of 70 cm: 16.45 mg/kg d.m. 6.718 mg/kg d.m. others see standard</td>
<td>NEN 7343 (teaching)</td>
</tr>
<tr>
<td>• barium (Ba) (always critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td>NEN 7323 + NEN 7324</td>
</tr>
<tr>
<td>• copper (Cu) (mostly critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• lead (Pb) (mostly critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• mercury (Hg) (always critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• arsenic (As) (always critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• cadmium (Cd) (mostly critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• chromium (Cr) (always critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• thallium (Tl) (always critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• molybdenum (Mo) (mostly critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• nickel (Ni) (mostly critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• selenium (Se) (mostly critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• vanadium (V) (mostly critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• tellurium (Te) (always critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• zinc (Zn) (mostly critical)</td>
<td>NEN EN 5322</td>
<td></td>
<td></td>
</tr>
<tr>
<td>environment, anions:</td>
<td>Building Materials Decree</td>
<td>thickness of 70 cm: 3.43 mg/kg d.m. 1.14 mg/kg d.m. others see standard</td>
<td>NEN 7343 (teaching)</td>
</tr>
<tr>
<td>• sulphate (SO&lt;i&gt;&lt;/i&gt;&lt;sub&gt;4&lt;/sub&gt;) (always critical)</td>
<td>NEN EN-ISO 10304-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• outside reserves</td>
<td>NEN 6589 (content)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• bromide (Br) (always critical)</td>
<td>NEN 5731</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• chloride (Cl) (mostly critical)</td>
<td>NEN 5731</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• fluoride (F) (always critical)</td>
<td>NEN 5731</td>
<td></td>
<td></td>
</tr>
<tr>
<td>environment, organic components:</td>
<td>NEN 5735</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• PAHs total 10 (always critical)</td>
<td>NEN 5733</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• PAHs &lt; 8 mm (always critical)</td>
<td>NEN 5732 + NEN 5734</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• EOCI (mostly critical)</td>
<td>NEN 5734</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• mineral oil (mostly critical)</td>
<td>NEN 5734</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• others: benzene, ethylbenzene, toluene, xyylene, phenol, PCDDs,</td>
<td>NEN 5734</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• organic halogen pesticides</td>
<td>NEN 5734</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• environment, asbestos</td>
<td>NEN 5734</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(as from 2007)</td>
<td>NEN 5734</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building Materials Decree (as from 2007)</td>
<td>NEN 5734</td>
<td>≤ 100 mg (serpentine + amphibole x 10) / kg d.m.</td>
<td>guideline</td>
</tr>
<tr>
<td>guideline</td>
<td>NEN 5734</td>
<td></td>
<td>BRL 2506</td>
</tr>
</tbody>
</table>

Unedited version
3.8. Recycling in Portugal: Overview of CDW

Dr. Isabel Martins, LNEC, Lisboa, Portugal

3.8.1. Introduction

In Portugal, construction and demolition waste (CDW) management was governed by general legislation on waste management but the need of proper managing of this waste stream lead to the publication of specific legislation, Decree Law n. 46/2008 (PORTUGAL-Ministério da Ambiente, do Ordenamento do Território e do Desenvolvimento Regional., 2008), which comes into force in June 2008. This new legal regime for CDW privileges prevention and appeal to sorting at source, recycling and other forms of recovery instead of landfill disposal.

The new Portuguese framework for CDW particularize the operations concerning the management of waste from construction and demolition and its recent implementation evidenced that unlawful acts like incorrect registration of the CDW at their production place and in the Integrated System of Registration of the Portuguese Environmental Agency (SIRAPA), transport by unlicensed operators and dumping of such wastes still exists as reported by the General Inspectorate of Environment and Territorial Planning (IGAOT).

Several training programs have been performed by public and private institutions within the construction sector in order to contribute to the awareness of various actors regarding the issue of construction and demolition waste management. In spite of the long way that there is still to go, some companies in the construction industry have already put into practice an appropriate management system for their construction and demolition waste.

According to the new legal framework the use of the mineral fraction of CDW in public and private construction works is approved if it comply with the requirements of Portuguese or European standards on this subject and, on the lack of these standards, its use is still allowed if these residues fulfil the technical and environmental requisites established in the specifications for CDW developed by the National Laboratory of Civil Engineering (LNEC).

The LNEC specifications provide guidelines and establish the minimum requirements that recycled material from construction and demolition waste must comply with in order to be used as recycled coarse aggregates for concrete, reclaimed asphalt for hot mix asphalt, aggregates for unbound sub-base and base pavement layers and material for embankment and capping layer of transport infrastructures.

3.8.2. Portuguese specifications for CDW application

In agreement with Decree-Law 46/2008 the use of construction and demolition waste in Portugal should comply with the requirements of the Portuguese specifications briefly described hereafter:

- LNEC E 474 – Guide for the use of recycled materials coming from construction and demolition waste in embankment and capping layer of transport infrastructures (LNEC-E474, 2009)

All these specifications present recommendations concerning the practices to be adopted during processing and storage of construction and demolition wastes, requirements for the recycled materials as well as fields of application. A special concern regarding environmental protection is evidenced through the requisite on the release of dangerous substances, which is aligned with the criterion of other European Member States (Böhmer, y otros, 2008)

- **LNEC E 471 – Guide for the use of coarse recycled aggregates in concrete**
  This specification classifies coarse recycled aggregates, within the scope of EN 12620 (CEN. EN 12620: 2002 + A1, 2008), and defines minimum requirements for their use in concrete. The use of fine recycled aggregates for concrete production is excluded. Coarse recycled aggregates to be used in concrete should conform to the classification of Table 3.28, comply with the properties and minimum requirements of Table 3.29 and for special applications meet the requisites of Table 3.30.

Table 3.28 Classification of coarse recycled aggregates in concrete

<table>
<thead>
<tr>
<th>Classes</th>
<th>Constituents (EN 12620 +A1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RC (%)</td>
</tr>
<tr>
<td>ARB1</td>
<td>≥ 90</td>
</tr>
<tr>
<td>ARB2</td>
<td>≥ 70</td>
</tr>
<tr>
<td>ARC</td>
<td>≥ 90</td>
</tr>
</tbody>
</table>

RC – Concrete and concrete products. Mortars
RUJ – Unbound aggregates, natural stone
RA – Bituminous materials
RB – Masonry
RG – Glass
X – Undesirable materials
FL – Floating material, in volume
Table 3.29 Properties and minimum requirements for the use of coarse recycled aggregates in concrete

<table>
<thead>
<tr>
<th>Properties</th>
<th>Standard</th>
<th>Compliance requirement (according EN 12620+A1)</th>
<th>Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate sizes</td>
<td>NP EN 933-1</td>
<td>Fulfil § 4.2</td>
<td>All classes</td>
</tr>
<tr>
<td>Grading</td>
<td>NP EN 933-1</td>
<td>Fulfil § 4.3.2</td>
<td>All classes</td>
</tr>
<tr>
<td>Constituents</td>
<td>pr EN 933-11</td>
<td>Fulfil one class of Table 1 of this specification</td>
<td>All classes</td>
</tr>
<tr>
<td>Shape</td>
<td>NP EN 933-3</td>
<td>$F_{15}$ (§ 4.4 Table 8)</td>
<td>Aggregates class ARB1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$F_{50}$ (§ 4.4 Table 8)</td>
<td>Aggregates class ARB2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Declaration value</td>
<td>Aggregates class ARC</td>
</tr>
<tr>
<td>Fines content</td>
<td>NP EN 933-1</td>
<td>$f_{3}$ (§ 4.6 Table 11)</td>
<td>Aggregates class ARC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_{4}$ (§ 4.6 Table 11)</td>
<td>Aggregates classes ARB1 and ARB2</td>
</tr>
<tr>
<td>Resistance to fragmentation</td>
<td>NP EN 1097-2</td>
<td>$L_{A_{50}}$ (§ 5.2 Table 12)</td>
<td>Aggregates class ARB1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Declaration value</td>
<td>Aggregates class ARB2</td>
</tr>
<tr>
<td>Particle density</td>
<td>NP EN 1097-6</td>
<td>≥2000 kg/m³</td>
<td>Aggregates class ARC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥2200 kg/m³</td>
<td>Aggregates classes ARB1 and ARB2</td>
</tr>
<tr>
<td>Water absorption</td>
<td>NP EN 1097-6</td>
<td>≤7% (§ 5.5)</td>
<td>Aggregates classes ARB1 and ARB2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Declaration value</td>
<td>Aggregates class ARC</td>
</tr>
<tr>
<td>Alkali-silica reactivity</td>
<td>see LNEC E 461</td>
<td>Declared value</td>
<td>All classes</td>
</tr>
<tr>
<td>Volume stability - Drying shrinkage</td>
<td>NP EN 1367-4</td>
<td>≤0.075% (§ 5.7.2)</td>
<td>All classes</td>
</tr>
<tr>
<td></td>
<td>(Annex A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acid soluble chloride</td>
<td>EN 1744-5</td>
<td>Declaration value</td>
<td>All classes</td>
</tr>
<tr>
<td>Water soluble sulphate</td>
<td>NP EN 1744-1, §12</td>
<td>$SS_{0.2}$ (§ 6.3.3)</td>
<td>All classes</td>
</tr>
<tr>
<td>Acid soluble sulphate</td>
<td>NP EN 1744-1, §12</td>
<td>$AS_{0.8}$ (§ 6.3.1)</td>
<td>All classes</td>
</tr>
<tr>
<td>Total sulphur</td>
<td>NP EN 1744-1, §11</td>
<td>$S \leq 1.0%$ (§ 6.3.2)</td>
<td>All classes</td>
</tr>
<tr>
<td>Organic constituents that affect the rate of setting and hardening of concrete</td>
<td>NP EN 1744-1, §15</td>
<td>Fulfil a) e b) §6.4.1</td>
<td>All classes</td>
</tr>
<tr>
<td>Other constituents that affect the rate of setting and hardening of concrete</td>
<td>EN 1744-6</td>
<td>Declaration value</td>
<td>All classes</td>
</tr>
</tbody>
</table>
Release of dangerous substances  | EN 12457-4  | Classification as waste for disposal in landfill for inert waste  | All classes
--- | --- | --- | ---

Table 3.30 Special applications for the use of coarse recycled aggregates in concrete

<table>
<thead>
<tr>
<th>Properties</th>
<th>Standard</th>
<th>Compliance requirement</th>
<th>Scope</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkalis</td>
<td>NP 1382</td>
<td>Value to determine</td>
<td>All classes</td>
<td>Concrete with reactive aggregates</td>
</tr>
<tr>
<td>Light organic contaminants</td>
<td>NP EN 1744-1, §14.2</td>
<td>Fulfil § G4 of Annex G of EN 12620</td>
<td>All classes</td>
<td>Architectural concrete</td>
</tr>
</tbody>
</table>

Regarding application of coarse recycled aggregates LNEC E471 states that:

Coarse recycled materials could not be used on concrete that is in contact with water for human consumption.
ARC coarse recycled materials could only be used for non structural applications (levelling, filling concrete) in non aggressive exposure classes.
ARB1 and ARB2 could be used on concrete elements and on reinforced concrete.
There is no limit for the use of ARB1 and ARB2 coarse recycled aggregates on filling or levelling concrete, in non aggressive exposure classes.
The conditions for application of coarse recycled aggregates in reinforced concrete are expressed below in Table 3.31:

Table 3.31 Fields of application of coarse recycled aggregates in concrete

<table>
<thead>
<tr>
<th>Class</th>
<th>Strength class</th>
<th>Replacement level</th>
<th>Exposure classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARB1</td>
<td>C 40/50</td>
<td>25%</td>
<td>X0, XC1 to XC4, XS1 andXA1(2)</td>
</tr>
<tr>
<td>ARB2</td>
<td>C 35/45</td>
<td>20%</td>
<td></td>
</tr>
</tbody>
</table>

Application of coarse recycled aggregates, under different conditions, call for specific studies to evaluate their influence on the relevant properties for concrete.

- **LNEC E 472 – Guide for the production of recycled hot mix asphalt**
Recommendations and requirements for the manufacture and application of reclaimed asphalt, on recycled hot mix asphalt, within the scope of EN 13108-8 (CEN. EN 13108-8: 2005., 2005) are indicated in LNEC E472. The CDW to be recycled in hot mix plants include: asphalt, reclaimed by milling of asphalt road layers; asphalt reclaimed by crushing of slabs ripped up from asphalt pavements; and asphalt from reject and surplus production.

Reclaimed asphalt is identified as MBR1, MBR2 and MBR3 according to the foreign matter and particle size of reclaimed asphalt, maximum size of aggregates and characteristics of the binder of the reclaimed asphalt.

For the production of recycled hot mix asphalt the properties and minimum requirements and the fields of application are indicated in Table 3.32 and in Table 3.33.
### Table 3.32 Properties and minimum requirements for the reclaimed asphalt to be used in the production of recycled hot mix asphalt

<table>
<thead>
<tr>
<th>Compliance requirements (EN 13108-8)</th>
<th>Reclaimed asphalt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foreign matter on the reclaimed asphalt</strong></td>
<td><strong>Standard</strong></td>
</tr>
<tr>
<td>EN 12697-42</td>
<td>F1</td>
</tr>
<tr>
<td><strong>Binder of the reclaimed asphalt</strong></td>
<td><strong>Type of binder</strong></td>
</tr>
<tr>
<td>EN 12697-3 or EN 12697-4 or EN 1426 or EN 1427</td>
<td>P₁₅ or S₇₀ or P ≥ 15x10⁻¹ mm or S ≤ 70°C</td>
</tr>
<tr>
<td><strong>Particle size reclaimed asphalt</strong></td>
<td>NP EN 933-1</td>
</tr>
<tr>
<td><strong>Aggregate properties</strong></td>
<td><strong>Mean grading</strong></td>
</tr>
<tr>
<td>NP EN 933-1</td>
<td>Declared value</td>
</tr>
<tr>
<td><strong>Maximum size, D</strong></td>
<td>NP EN 933-1</td>
</tr>
<tr>
<td>EN 12697-1</td>
<td>Declared value</td>
</tr>
<tr>
<td><strong>Binder content of reclaimed asphalt</strong></td>
<td><strong>Maximum water content of reclaimed asphalt</strong></td>
</tr>
</tbody>
</table>

### Table 3.33 Applications reclaimed asphalt to be used in the production of recycled hot mix asphalt

<table>
<thead>
<tr>
<th>Classes of reclaimed asphalt (EN 13108-8)</th>
<th>Application</th>
<th>Maximum incorporation</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBR1</td>
<td>Wearing course</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>Base and levelling course</td>
<td>50%</td>
</tr>
<tr>
<td>MBR2</td>
<td>Base and levelling course</td>
<td>25%</td>
</tr>
<tr>
<td>MBR3</td>
<td>Base and levelling course</td>
<td>10%</td>
</tr>
</tbody>
</table>

- **LNEC E 473 – Guide for the use of recycled aggregates in unbound pavement layers**

Recycled aggregates in unbound granular pavement layers obeys to the classification of Table 3.34, and the properties and minimum requirements for the classes B and C, are indicated on Table 3.35. Regarding their application, data is presented in Table 3.36.

<table>
<thead>
<tr>
<th>Classes</th>
<th>Constituents</th>
<th>EN 13242 + A1</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RC+RU+RG</td>
<td>RG</td>
<td>RA</td>
<td>RA</td>
<td>FL</td>
</tr>
<tr>
<td>B</td>
<td>≥90%</td>
<td>≤5%</td>
<td>≤10%</td>
<td>≤5%</td>
<td>≤5%</td>
</tr>
<tr>
<td>C</td>
<td>≥50%</td>
<td>≤5%</td>
<td>≤10%</td>
<td>≤30%</td>
<td>≤5%</td>
</tr>
</tbody>
</table>

Table 3.35 Properties and minimum requirements for recycled aggregates to be used in unbound granular pavement layers

<table>
<thead>
<tr>
<th>Compliance requirements</th>
<th>Recycled aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Properties</td>
</tr>
<tr>
<td>Geometric and nature</td>
<td>Mixture designation</td>
</tr>
<tr>
<td></td>
<td>Oversize</td>
</tr>
<tr>
<td></td>
<td>Grading class</td>
</tr>
<tr>
<td></td>
<td>Fines content</td>
</tr>
<tr>
<td></td>
<td>Fines quality</td>
</tr>
<tr>
<td></td>
<td>Percentage of crushed or broken particles and totally round particles in coarse aggregates (EN 933-5</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Resistance to fragmentation and to wear (EN 1097-2 and EN 1097-1)</td>
</tr>
<tr>
<td>Chemical</td>
<td>Water soluble sulphate (EN 1744-1)</td>
</tr>
<tr>
<td></td>
<td>Release of dangerous substances (EN 12457-4)</td>
</tr>
</tbody>
</table>

Table 3.36 Application of recycled aggregates in unbound pavement layers

<table>
<thead>
<tr>
<th>Category</th>
<th>AGER1</th>
<th>AGER2</th>
<th>AGER3</th>
</tr>
</thead>
</table>

180
For use in embankment and capping layer of transport infrastructure, construction and demolition waste covered by this specification are grouped into three classes (B, C or MB), defined based on the relative proportions of each constituent as shown in Table 3.37. According to geotechnical characteristics these materials are categorized as MAT1 and MAT2 obeying the properties and minimum requirements of Table 3.38. Data in Table 3.39 indicate the corresponding fields of application.

Table 3.37 Classification of recycled materials for embankment and capping layer of transport infrastructure

<table>
<thead>
<tr>
<th>Class</th>
<th>Constituents</th>
<th>RC+RU+RG</th>
<th>RG</th>
<th>RA</th>
<th>RB+RS</th>
<th>FL</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>≥90%</td>
<td>≤10%</td>
<td>≤5%</td>
<td>≤10%</td>
<td>≤5%</td>
<td>≤1%</td>
<td></td>
</tr>
<tr>
<td>MB</td>
<td>≤70%</td>
<td>≤25%</td>
<td>≥30%</td>
<td>≤70%</td>
<td>≤5%</td>
<td>≤1%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>No limit</td>
<td>≤25%</td>
<td>≤30%</td>
<td>No limit</td>
<td>≤5%</td>
<td>≤1%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.38 Properties and minimum requirements for recycled materials for embankment and capping layer of transport infrastructure

<table>
<thead>
<tr>
<th>Compliance requirements</th>
<th>Recycled materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Properties</td>
</tr>
<tr>
<td></td>
<td>Geometrical and nature</td>
</tr>
<tr>
<td></td>
<td>Maximum fines content (below 80 µm)</td>
</tr>
<tr>
<td></td>
<td>Fines quality</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Resistance to fragmentation and to wear</td>
</tr>
<tr>
<td>Chemical</td>
<td>Water soluble sulphate</td>
</tr>
</tbody>
</table>
It must be emphasized that materials type MAT1 are not allowed in the lower part of embankments built in floodable areas and specific studies are foreseen for materials treated with hydraulic binders.

Table 3.39 Application of recycled materials for embankment and capping layer of transport infrastructure

<table>
<thead>
<tr>
<th>Category</th>
<th>MAT1</th>
<th>MAT2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>B</td>
<td>MB</td>
</tr>
<tr>
<td>Capping layer</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Embankment</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

3.8.3. Recycling plants

In Portugal there are between 15 to 20 stationary recycling plants, licensed by the Portuguese Environmental Agency (APA), for recovery of the mineral fraction of CDW and production of materials to be used in the construction sector. Most of these recycling plants are located in the metropolitan areas surrounding the main cities, like Lisbon and Oporto, as denoted by the black dots in the Portugal map, Fig. 3.66, which match the locals of higher construction activity.

A study carried out in 2008 evidenced that in the city of Lisbon the production of CDW
wastes is mainly due to remodelling works and not to new constructions in opposition to what is observed in the neighbouring cities (Braz de Melo, Gonçalves, & Martins, 2011)

Mobile recycling plants are also used to recovery of the mineral fraction of CDW but there is no available information about them.

Actually the recycling plants have had much difficulty in putting on the market their recycled materials. Barriers to their use are mainly dictated by economic aspects, lack of experience, assurance of quality of recycled materials, existence of regular supply/demand systems and environmental concerns.

### 3.8.4. Recycling rates

The existing data regarding construction and demolition waste production in Portugal is provisional. According to the Portuguese Environmental Agency the total waste, listed in chapter 17 of the List of Wastes, received at the recycling plants in 2009 was approximately 2 million tonnes. However CDW generation must be higher since the CDW reused or recycled on site in civil works is not registered on the Portuguese electronic database.

Fig. 3.67 presents the total production of waste within the chapter 17 of the List of Waste, expressed as percentage, including soils and excluding dangerous wastes, received at recycling plants. CDW classified as 17 01 of List of Wastes – concrete, bricks, tiles, ceramics, and gypsum-based materials – constitute about half of the total waste from chapter 17 and 32% of it was subject to recovery operations. Nevertheless the available data show that only 4% has been effectively processed and is available to be used as inorganic material in the construction sector; most of the remainder was stored for further processing.

Fig. 3.67: Production and recovery of waste within the chapter 17 of the List of Wastes in 2009

In spite of the impossibility of knowing the total production of CDW in Portugal and the difficulty to point a value or a range of values for the recycling rate it is necessary a better marketing of recycled materials from CDW and the adoption of additional measures in order to increase the recycling and meet the European goals for 2020 for this waste flow. In 17th June 2011 a new Portuguese legislation, Decree-Law 73/2011 (PORTUGAL-Ministério da
Ambiente e do Ordenamento do Território., 2011) transposing the Waste Framework Directive 2008/98/EC (OJEU. 2008/98/CE., 2008), foresees that, whenever technically feasible, it is mandatory the use of at least 5% of recycled materials in the hiring of construction works and maintenance of infrastructure under the Code of Public Contracts, with a view to preserve natural resources and promote waste recovery.

3.8.5. Case studies

Regardless of incomplete implementation of the new law for CDW management successful recycling cases in Portugal could be mentioned. All these cases involve previous development of appropriate environmental management plans, investment on employee training and extensive sorting of waste in situ in order to minimize the costs of waste management.

![Fig. 3.68: Construction of pier north of Lisbon airport](image)

Between 2008 and 2010 the construction of the new pier north of Lisbon airport, with a gross area of 13000 m², produced a total of 15650 tonnes of CDW and the concrete slabs of the existing pavement after grinding and characterisation were used in situ as recycled aggregates for the layer beneath the wearing course of the new pier. A recycling rate of 96% was achieved in this project.

In 2009/2010 during construction of Estoril-Sol Residence, with a gross floor area of buildings around 30000 m², about 4250 tonne of CDW was generated, being 2400 tonnes of concrete, classified within the code 17 01 01 of the List of Waste, that were recovered by licensed operators. The total recycling rate of 99% evidenced the adequate CDW management.

Also in 2009 the demolition of a set of industrial and office buildings in Lisbon, occupying an area of 7000 m², were entirely demolished resulting in the production of 32700 tonnes of inert waste, partially recycled in situ. About 25000 tonnes of recycled material were transported to other works to be used in infrastructures. In this process only 0.3% of CDW were eliminated, corresponding to a recycling rate of 99.7%. 
Acknowledgments
The author wishes to thank the National Laboratory for Civil Engineering (LNEC), the Portuguese Environmental Agency (APA), the Construction Group EDIFER and Demolition Enterprise DEMOTRI, for their collaboration on the data presented.

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3.9. Recycling in Spain: Overview of CDW

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3.9.1. Introduction

The information presented in this overview is mostly obtained with the GEAR Project and complemented with the projects RECNHOR and CLEAM. The Project "Spanish Guide on Recycled Aggregates" (GEAR Project) is a technical and scientific project subsidized by the Ministerio de Medio Ambiente, y Medio Rural y Marino, of the Spanish Government, with 2.5 M€ within the framework of the National Plan of Scientific Research, Development and Technological Innovation.

Coordinated by the GERD (Spanish Association of the Recycling Industry), the GEAR Project, possesses the direct participation of 73 CDW recycling plants of Spain, 4 Universities:

• Universitat Politècnica de Catalunya (UPC)
• Universidad de Oviedo (UNIOVI)
• Universidad d’A Coruña (UDC)
• Universidad Politécnica de Valencia (UPV)

and 3 Technological Centers:

• Instituto Tecnológico de la Construcción (AIDICO), Valencia
• Instituto Tecnológico de Rocos Ornamentales y Materiales de Construcción (INTROMAC), Caceres
• Asociación para la Investigación y Desarrollo Industrial de los Recursos Naturales (AITEMIN), Madrid

Under the scientific direction of Prof. E. Vázquez (UPC, Barcelona), the technical direction of E. Varela (UPC) and the Management of A. Güell (GERD), the GEAR Project aims the normalization of CDW recycled products and its uses in civil construction across the elaboration of the "Spanish Guide on Recycled Aggregates". The first stage of the project consists of the accomplishment of a technical and statistical field study to characterize the situation of the Spanish Recycling Plants. This diagnosis study consists on the analysis of data from 73 Spanish recycling plants, chosen by their importance and location, production systems and uses. The aim is that the final document reflects the reality of the Spanish recycling market, considering all its technical, scientific and environmental aspects, presents several real controlled applications, analyses future possibilities and offer recommendations and limits based on European standards and the Spanish research projects.

3.9.2. Diagnosis Method

The diagnosis consisted in collecting technical information from the Spanish CDW recycling plants, mainly considering the methods of production of recycled aggregates, the results of control tests conducted and the uses proposed by the companies. The collection of this information has been done during technical visits, applying specification sheets.

In order to complement the information, the recycling companies have executed a specific
plan of tests for the Project defined by the Coordination. The planning of the tests and their frequency of accomplishments has been defined by the needs of the project and the conditions of production of each plant. In order to fulfil this plan, all participants have received indications and specifications on how to correctly carry out tests plan so to guarantee its representativeness and strictness. The Table 3.40 presents the laboratory tests carried out in this stage of the project.

Table 3.40: Characterization Tests adopted for the diagnosis stage.

<table>
<thead>
<tr>
<th>Property</th>
<th>Control Test</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical</td>
<td>Granulometry</td>
<td>UNE EN 933-1:1998</td>
</tr>
<tr>
<td></td>
<td>Particle shape/Flakiness index</td>
<td>UNE EN 933-3</td>
</tr>
<tr>
<td>Physical</td>
<td>Composition</td>
<td>EN 933-11:2009</td>
</tr>
<tr>
<td>Mechanical and Physical</td>
<td>Sand equivalent test</td>
<td>UNE EN 933-8</td>
</tr>
<tr>
<td></td>
<td>Methylene blue test (when applicable)</td>
<td>UNE-EN 933-9:1999</td>
</tr>
<tr>
<td></td>
<td>Cleaning (organic impurity content)</td>
<td>UNE 146130</td>
</tr>
<tr>
<td></td>
<td>Resistance to fragmentation (Los angeles test)</td>
<td>UNE EN 1097-2</td>
</tr>
<tr>
<td>Chemical</td>
<td>Plasticity (Atterberg limits)</td>
<td>UNE 103104</td>
</tr>
<tr>
<td></td>
<td>total sulfur content</td>
<td>UNE EN 1744-1:1999</td>
</tr>
<tr>
<td></td>
<td>Organic contaminants</td>
<td>UNE EN 1744-1:1999 (APDO 15.1)</td>
</tr>
<tr>
<td></td>
<td>Salts</td>
<td>NLT 114</td>
</tr>
<tr>
<td></td>
<td>Water Soluble Sulfate content</td>
<td>UNE EN 1744-1:1999</td>
</tr>
<tr>
<td></td>
<td>Acid Soluble Sulfate content</td>
<td>UNE EN 1744-1:1999</td>
</tr>
<tr>
<td></td>
<td>Gypsum</td>
<td>NLT 115</td>
</tr>
</tbody>
</table>

Every University and Technological Centre has verified the results obtained in the assigned correspondent territory by the accredited laboratories used by the companies, and executed a random part of the tests presented to control the good execution.

In the second stage of the Project, the tests plan will be applied with more specific tests for the analysis of the recycled aggregate application. Based on the present diagnose results, the project adopted the following research lines for the next stage: roller compacted concretes, non-structural concretes, pre fabricated elements, fillings / drainages, aggregates for roads bases and gravel and soil cement.

![Fig. 3.69: Task flow of GEAR Project’s Diagnosis Stage.](image)

All the obtained information has been registered in the project database. The Fig. 3.69 presents the task flow of the activities that correspond to the stage of diagnosis of the GEAR Project.
3.9.3. Production of recycled aggregates in Spain

In Fig. 3.70 we present the distribution of the analyzed plants in the Spanish Autonomies.

From 73 plants investigated from 2008 to 2011, 35 were direct participants of the Project and 38 were incorporated later as collaborators. The total number of plants in Spain in 2011 was 156.

The total amount of CDW estimated in 2008 by the “Ministerio de Medio Ambiente” was about 38 million tones. This amount has diminished dramatically in the last two years and we don’t have precise data. In 2008, 15% of waste was processed. In 2008, 1.5 million tones were produced and commercialized. The most used recycled product has been the mixed recycled aggregate, in the all-in-one fraction (47.1% of total commercialized tones in 2008, object of this analysis), followed by concrete recycled aggregate, also in the all-in-one fraction (17.95% of total). The distribution in different types of aggregates produced can be seen in the Fig. 3.71.

Only a small proportion of concrete coarse aggregates >4mm, were used in structural concrete in emblematic constructions as the bridges in Barcelona and Valencia and in housing near Madrid.
The 59% of the 0/40mm size of Concrete Recycled Aggregates was used in road sub base unbounded or as soil cement mixtures. Most of the 0/40mm size of Mixed Aggregate is used in environmentally controlled fills and small country roads, but there are some cases of use in soil cement. The fine fraction of those aggregates was mostly used as fill or non-identified applications. The 42% of the aggregates >40mm, concrete and mixed were used in fills and 35% in country roads.

The different types of plants are presented in Fig. 3.72.

Mobile plants are only present in Catalonia, Madrid, Murcia and Valencia. General distribution of mobile, semi mobile and steady plants can be seen in Fig. 3.73.
The proportion of plants with pre treatment and pre elimination of fines can be seen in Fig. 3.74.

In Fig. 3.75 we can see the situation of plants with classification and cleaning.
In general as we can deduce from the obtained data the production scheme of a recycling plant in Spain generally consists of all or some of the stages presented. The design criteria of a recycling plant can change a lot for each plant depending of the place and demand of products. In the most complete plants the production flow is as can be seen in Fig. 3.76.

**Fig. 3.75:** Plants with classification and cleaning.

**Fig. 3.76:** Production flow of a Spanish type recycling plant.
3.9.4. Properties of Spanish recycled aggregates

We include in this overview only the most relevant properties. The analysis of the size distribution detected excess of fines in an important proportion of the recycled aggregates commercialized (Fig. 3.77).

![Fig. 3.77: Fines in recycled aggregates.](image)

The flakiness index was clearly related with the proportion of masonry elements present (Fig. 3.78).

![Fig. 3.78: Flakiness index related with % of masonry aggregates.](image)
The composition was evaluated with EN 933-11. Fig. 3.79 shows the minimum and maximum ranges, and the average found for each type of material identified in recycled aggregates analyzed during the experimental campaign.

Absorption is an important parameter of quality of material in aggregates. Although ceramic materials usually present higher water absorption than concrete materials, it is the presence of stone materials that most influence the values of these parameters. Both the presence of concrete and mortar as ceramic elements contribute to increasing the water absorption of recycled aggregate. (Fig. 3.80, Fig. 3.81, Fig. 3.82).
Fig. 3.80: Absorption related with % masonry aggregates.

Fig. 3.81: Absorption related with % concrete aggregates.

Fig. 3.82: Absorption related with % of stony aggregates.
The Los Angeles value was in average better than expected. This can be related with the considerable quantity of natural stone present in Spanish CDW and the good quality of ceramics. (Fig. 3.83)

Only 16% of values >40% were detected considering all types and samples.

![Fig. 3.83: Los Angeles coefficient.](image)

Sufficient good values were obtained in sand equivalent for mixed aggregates 0/40mm, (Fig. 3.84) for his use in sub bases and soil cement.

![Fig. 3.84: Sand equivalent.](image)

The cleanness coefficient of Spanish recycled aggregates is in average a weak point. Only 52% of the products and samples are under 2, the limit established in the Spanish Road Code PG3 for all kind of aggregates.

The good values are related with plants that select the material before processing or plants provided with air and water cleaning systems.

The proportion of soluble salts in the recycled aggregates is another weak point considering all the compositions. The limit established for the use in contact with soil is <1% of soluble salts different from gypsum. Only 43% are under this limit (Fig. 3.85)
As in the case of cleanliness coefficient, the good values are related with plants that select carefully the material before processing or plants provided with air and water cleaning systems.

The presence of gypsum is a weak point in relation with the use of the recycled aggregate in concrete or soil cement, because in the average gypsum content in recycled concrete aggregate (with minimum 90% concrete) is of 0.6% only, with maximum values of 2%, which is produced in fewer plants. In contrast, the mixed type aggregate, with a minimum concrete content of 70%, which is the most widespread, has an average of 2.5% and varies between 0.5% and 6.7%, always in weight. In general the plants cleaning with water have the lowest gypsum content.

### 3.9.5. The proposed classification of the recycled aggregates

The Gear Project proposed a classification of the recycled aggregates based on the predominant components.

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Proportion of constituent (% total weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar H</td>
<td>Recycled concrete aggregate</td>
<td>≥ 90% ≤ 10% ≤ 5% ≤ 1%</td>
</tr>
<tr>
<td>ArM H</td>
<td>Mixed recycled concrete aggregate</td>
<td>≥ 70% ≤ 30% ≤ 5% ≤ 1%</td>
</tr>
<tr>
<td>ArM C</td>
<td>Mixed recycled ceramic aggregate</td>
<td>&lt; 70% &gt; 30% ≤ 5% ≤ 1%</td>
</tr>
<tr>
<td>ArM A</td>
<td>Mixed recycled asphalt aggregate</td>
<td>- - 5%-30% ≤ 1%</td>
</tr>
</tbody>
</table>
3.9.6. GEAR-PRT-02: Technical specifications and recommendations for aggregates from construction and demolition waste, to use as a granular material in pavements

Table 3.42: Usage classes for recycled graded-aggregate, according to technical specifications degree

<table>
<thead>
<tr>
<th>Class</th>
<th>Usage classes for recycled graded-aggregate, according to technical specifications degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>Bases, subbases and shoulders for traffic routes T0</td>
</tr>
<tr>
<td>Class 2</td>
<td>Bases, subbases and shoulders for traffic routes T1 y T2</td>
</tr>
<tr>
<td>Class 3</td>
<td>Bases, subbases and shoulders for traffic routes T3 y T4</td>
</tr>
<tr>
<td>Class 4</td>
<td>Bases and subbases for roads with lower traffic category T4</td>
</tr>
</tbody>
</table>

Table 3.43: Viability of application by category of aggregate and usage class.

<table>
<thead>
<tr>
<th>Usage class</th>
<th>Recycled aggregate category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>X</td>
</tr>
<tr>
<td>Class 2</td>
<td>X</td>
</tr>
<tr>
<td>Class 3</td>
<td>X</td>
</tr>
<tr>
<td>Class 4</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 3.44: Limits of the size distribution for recycled aggregates

<table>
<thead>
<tr>
<th>Category a</th>
<th>Cumulative percent of aggregate sieved (%mass min-max) b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td>ZA25</td>
<td>100</td>
</tr>
<tr>
<td>ZA20</td>
<td>—</td>
</tr>
<tr>
<td>ZAD20</td>
<td>100</td>
</tr>
</tbody>
</table>

a The graded-aggregate type designation is based on the nominal maximum size, according to the range of % passing, set in the corresponding Limits of the size distribution.
b The sieve sizing is defined by UNE-EN 933-2.

Table 3.45: Summary of recommended technical requirements

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Class / Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granulometry</td>
<td>Table 3.44</td>
</tr>
<tr>
<td>Flakiness index</td>
<td>Table 3.44</td>
</tr>
<tr>
<td>Grounded particles</td>
<td>Table 3.44</td>
</tr>
<tr>
<td>Compositio(*)</td>
<td>ArH ó ArM A</td>
</tr>
<tr>
<td>Los Angeles coefficient</td>
<td>≤ 35%</td>
</tr>
<tr>
<td>Liquid limit</td>
<td>Non-plastic</td>
</tr>
<tr>
<td>Plasticity</td>
<td>Non-plastic</td>
</tr>
<tr>
<td>Sand equivalent</td>
<td>&gt; 40%</td>
</tr>
<tr>
<td>Clay content (*)</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>≤ 0.2 %</td>
</tr>
<tr>
<td>Sulphur compounds</td>
<td>≤ 1 %</td>
</tr>
<tr>
<td>Water soluble sulphate</td>
<td>≤ 0.5 %</td>
</tr>
</tbody>
</table>

(*) Orientative and not restrictive requirement.
3.9.7. GEAR-PRT-04: Technical specifications and recommendations for aggregates from construction and demolition waste, to use as a granular material in pavement surfaces, treated with hydraulic binders.

Table 3.46: Usage classes in the current technical recommendations, according to technical specifications degree

<table>
<thead>
<tr>
<th>Classes</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil cement</td>
<td>SC20 Soil-cement applicable to pavements and shoulders T3 y T4</td>
</tr>
<tr>
<td></td>
<td>SC40 Soil-cement applicable to pavements and shoulders T00 a T2</td>
</tr>
<tr>
<td>Gravel cement</td>
<td>GC20 Gravel-cement applicable to pavements T00 a T2</td>
</tr>
<tr>
<td></td>
<td>GC25 Gravel-cement applicable to pavements T3 y T4 and shoulders, replacing SC40</td>
</tr>
</tbody>
</table>

Table 3.47: Viability of application by category of aggregate and usage class.

<table>
<thead>
<tr>
<th>Viability of application</th>
<th>Recycled aggregate category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ar H</td>
</tr>
<tr>
<td>Soil cement</td>
<td>SC20</td>
</tr>
<tr>
<td></td>
<td>SC40</td>
</tr>
<tr>
<td>Gravel cement</td>
<td>GC20</td>
</tr>
<tr>
<td></td>
<td>GC25</td>
</tr>
</tbody>
</table>

Table 3.48: Limits of the size distribution for soil cement application

<table>
<thead>
<tr>
<th>Class</th>
<th>Cumulative percent of aggregate sieved (%mass min-max) a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>SC40</td>
<td>100</td>
</tr>
<tr>
<td>SC20</td>
<td>100</td>
</tr>
</tbody>
</table>

* The sieve sizing is defined by UNE-EN 933-2. (mm)

Table 3.49: Limits of the size distribution for gravel cement application

<table>
<thead>
<tr>
<th>Class</th>
<th>Cumulative percent of aggregate sieved (%mass min-max) a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td>GC25</td>
<td>100</td>
</tr>
<tr>
<td>GC20</td>
<td>100</td>
</tr>
</tbody>
</table>

* The sieve sizing is defined by UNE-EN 933-2. (mm)

Table 3.50: Summary of recommended technical requirements

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Class / Usage</th>
<th>SC20</th>
<th>SC40</th>
<th>GC20</th>
<th>GC25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granulometry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flakiness index</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grinded particles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition(*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Los Angeles Coefficient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasticity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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3.9.8. GEAR-PRT-05: Technical specifications and recommendations for aggregates from construction and demolition waste, to use as a granular material in precast concrete units, treated with hydraulic binders.

The applications considered are the following:

- Kerbs (BD)
- Concrete blocks/concrete hollow bricks (BV)
- Benches (BNC)
- Blocks (BLQ)

This proposal is in accordance with the following technical standards, and adapts those requirements to the recycled aggregates specifications:

- EN 1340:2004 Concrete kerb units. Requirements and testing methods.
- EN 127340 Concrete kerb units. Requirements and testing methods. National complement to the standard UNE-EN 1340
- prEN 15037-2 Precast concrete products Beams and floor systems Part 2: Concrete blocks.
- DIN 483 Terms of delivery and testing standards of concrete kerb units
- NFP-98302 precast concrete kerb units and channels
- BS 340 British Specification for “Precast concrete: Kerbs, channels, edgings and quadrants”

Table 3.51: Usage classes in the current technical recommendations, according to technical specifications degree

<table>
<thead>
<tr>
<th>Class</th>
<th>Application</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>Kerbs</td>
<td>Kerbs type R6, R5 y R3,5</td>
</tr>
<tr>
<td></td>
<td>Concrete blocks/concrete hollow bricks</td>
<td>Concrete blocks/concrete hollow bricks for floor slabs.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flexural strength ≥ 4KN</td>
</tr>
<tr>
<td></td>
<td>Benches</td>
<td>Benches for seating on public roads and parks.</td>
</tr>
<tr>
<td></td>
<td>Blocks</td>
<td>Concrete blocks/concrete hollow bricks for walling</td>
</tr>
<tr>
<td>Class 2</td>
<td>Kerbs</td>
<td>Kerbs type R5 y R3,5</td>
</tr>
<tr>
<td></td>
<td>Made from Ar H or ArM H.</td>
<td></td>
</tr>
</tbody>
</table>
### Table 3.52: Limits of the size distribution for recycled aggregates

<table>
<thead>
<tr>
<th>Application</th>
<th>Granulometry - EN 933-1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cumulative percent of aggregate sieved (% mass min-max)</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Class 1</td>
<td></td>
</tr>
<tr>
<td>BD-1</td>
<td></td>
</tr>
<tr>
<td>BV-1</td>
<td></td>
</tr>
<tr>
<td>BNC-1</td>
<td></td>
</tr>
<tr>
<td>BLQ-1</td>
<td></td>
</tr>
<tr>
<td>Class 2</td>
<td></td>
</tr>
<tr>
<td>BD-2</td>
<td></td>
</tr>
<tr>
<td>BV-2</td>
<td></td>
</tr>
<tr>
<td>BNC-2</td>
<td></td>
</tr>
<tr>
<td>BLQ-2</td>
<td></td>
</tr>
<tr>
<td>Class 3</td>
<td></td>
</tr>
<tr>
<td>BD-3</td>
<td></td>
</tr>
<tr>
<td>BV-3</td>
<td></td>
</tr>
<tr>
<td>BNC-3</td>
<td></td>
</tr>
<tr>
<td>BLQ-3</td>
<td></td>
</tr>
<tr>
<td>Class 4</td>
<td></td>
</tr>
<tr>
<td>BD-4</td>
<td></td>
</tr>
<tr>
<td>BV-4</td>
<td></td>
</tr>
<tr>
<td>BNC-4</td>
<td></td>
</tr>
<tr>
<td>BLQ-4</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3.53: Composition of recycled aggregates

<table>
<thead>
<tr>
<th>Material</th>
<th>% substitution percentage of recycled aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% ≤50%</td>
</tr>
<tr>
<td></td>
<td>% ≤100%</td>
</tr>
<tr>
<td>Asphalt</td>
<td>≤1%</td>
</tr>
<tr>
<td>Or the sum of them three does not exceed 5%</td>
<td>≤2%</td>
</tr>
<tr>
<td>Lightweight particles (L)</td>
<td>≤3%</td>
</tr>
<tr>
<td>Or the sum of them three does not exceed 3%</td>
<td>≤2%</td>
</tr>
<tr>
<td>Other materials (X)</td>
<td>≤3%</td>
</tr>
</tbody>
</table>

### Table 3.54: Summary of recommended technical requirements

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granulometry</td>
<td>Table 3.52</td>
<td>Table 3.52</td>
<td>Table 3.52</td>
<td>Table 3.52</td>
</tr>
<tr>
<td>Flakiness index</td>
<td>&lt; 35%</td>
<td>&lt; 35%</td>
<td>&lt; 35%</td>
<td>&lt; 35%</td>
</tr>
</tbody>
</table>
### Table 3.55: Viability of application by category of aggregate and usage class.

<table>
<thead>
<tr>
<th>Viability of application</th>
<th>Recycled aggregate category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ar H</td>
</tr>
<tr>
<td>Usage class</td>
<td></td>
</tr>
<tr>
<td>Class 1</td>
<td>X</td>
</tr>
<tr>
<td>Class 2</td>
<td>X</td>
</tr>
<tr>
<td>Class 3</td>
<td>X</td>
</tr>
<tr>
<td>Class 4</td>
<td>X</td>
</tr>
</tbody>
</table>

(*) Orientative and not restrictive requirement.

### Table 3.56: Viability of application by category of aggregate and usage class.

<table>
<thead>
<tr>
<th>Viability of application</th>
<th>Recycled aggregate category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ar H</td>
</tr>
<tr>
<td>Usage class</td>
<td></td>
</tr>
<tr>
<td>Soil cement</td>
<td></td>
</tr>
<tr>
<td>SC20</td>
<td>X</td>
</tr>
<tr>
<td>SC40</td>
<td>X</td>
</tr>
<tr>
<td>Gravel cement</td>
<td></td>
</tr>
<tr>
<td>GC20</td>
<td>X</td>
</tr>
<tr>
<td>GC25</td>
<td>X</td>
</tr>
</tbody>
</table>

3.9.9. **GEAR-PRT-07:** Technical specifications and recommendations for aggregates from construction and demolition waste, to use as a granular material treated with hydraulic binders in roller compacted concrete

The applications considered in these technical specifications and recommendations, refer to binded structural layers of pavements with roller compacted concretes, using recycled aggregates. The applications are the following:

- Pavement layers
- Pavement bases
This proposal is in accordance with the following technical standards, and adapts those requirements to the recycled aggregates specifications.

- UNE-EN 12620:2009: Aggregates for concrete
- EHE-08, anejo 15: Hormigones con árido reciclado (recycled aggregate concretes), and anejo 18: Hormigones de uso no estructural (non-structural concretes).

### Table 3.57: Viability of application by category of aggregate and usage class.

<table>
<thead>
<tr>
<th>Usage class</th>
<th>Recycled aggregate category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ar H</td>
</tr>
<tr>
<td>Class 1</td>
<td>X</td>
</tr>
<tr>
<td>Class 2</td>
<td>X</td>
</tr>
</tbody>
</table>

### Table 3.58: Limits of the size distribution for recycled aggregates

<table>
<thead>
<tr>
<th>Class</th>
<th>Granulometry - EN 933-1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cumulative percent of aggregate sized (mass min-max)*</td>
</tr>
<tr>
<td></td>
<td>32</td>
</tr>
<tr>
<td>Class 1</td>
<td>100</td>
</tr>
<tr>
<td>Class 2</td>
<td>100</td>
</tr>
</tbody>
</table>

* The sieve sizing is defined by UNE-EN 933-2. (mm)

### Table 3.59: Composition of coarse recycled aggregate

<table>
<thead>
<tr>
<th>Component</th>
<th>Porcentaje en masa (%)</th>
<th>Categoría según UNE 12620:09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rc (hormigón, productos de hormigón, mortero, elementos de albañilería de hormigón)</td>
<td>Re+Ru &gt; 50%</td>
<td>R&lt;sub&gt;ext&lt;/sub&gt;</td>
</tr>
<tr>
<td>Ru (árídos no ligados, piedra natural, árido ligado hidráulicamente)</td>
<td>Rb &lt; 50%</td>
<td>R&lt;sub&gt;sp&lt;/sub&gt;</td>
</tr>
<tr>
<td>Rb (elementos de albañilería de arellla, de silicato cálcico y hormigón, unidos no flotante)</td>
<td>Ra &lt;5%</td>
<td>R&lt;sub&gt;g&lt;/sub&gt;</td>
</tr>
<tr>
<td>Ra (materiales bituminosos)</td>
<td>X+Rg&lt;1%</td>
<td>XR&lt;sub&gt;g&lt;/sub&gt;</td>
</tr>
<tr>
<td>X (arellla, tierra, yeso, plástico, madera y otros)</td>
<td>FL&lt;sub&gt;2&lt;/sub&gt;</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3.60: Summary of recommended technical requirements

<table>
<thead>
<tr>
<th>Technical requirements</th>
<th>Class 1</th>
<th>Class 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granulometry Minimum particle size</td>
<td>4 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>Flakiness index</td>
<td>≤ 30%</td>
<td>≤ 35%</td>
</tr>
<tr>
<td>Composition(*)</td>
<td>Table 3.58</td>
<td>Table 3.58</td>
</tr>
<tr>
<td>Absorption</td>
<td>≤ 10%</td>
<td>≤ 10%</td>
</tr>
<tr>
<td>Density</td>
<td>≥ 2100 kg/m³</td>
<td>≥ 2100 kg/m³</td>
</tr>
<tr>
<td>Los Angeles Coefficient</td>
<td>≤ 35%</td>
<td>≤ 40%</td>
</tr>
<tr>
<td>Cleanness coefficient</td>
<td>≤ 2%</td>
<td>≤ 2%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>≤ 1%</td>
<td>≤ 1%</td>
</tr>
<tr>
<td>Sulphur compounds</td>
<td>≤ 1%</td>
<td>≤ 1%</td>
</tr>
<tr>
<td>Acid soluble sulphate</td>
<td>≤ 0.8%</td>
<td>≤ 0.8%</td>
</tr>
<tr>
<td>Oxidizable sulphurs</td>
<td>Must not contain</td>
<td>Must not contain</td>
</tr>
<tr>
<td>Water soluble compounds</td>
<td>≤ 1%</td>
<td>≤ 1%</td>
</tr>
</tbody>
</table>

(*) Orientative and not restrictive requirement.
3.9.10. GEAR-PRT-06: Technical specifications and recommendations for aggregates from construction and demolition waste, to use as a granular material treated with hydraulic binders in mass concrete.

The applications considered in these technical specifications and recommendations are the following:

- Structural concretes (HE) up characteristic compressive strength \( f_{ck} \) = 30 MPa.
- Non-Structural concretes (HNE) up characteristic compressive strength \( f_{ck} \) = 20 MPa
- Lean Concrete (HL) with a minimum cement content= 150 kg/m³.

This proposal is in accordance with the following technical standards, and adapts those requirements to the recycled aggregates specifications.

- EHE-08, anejo 15: Hormigones con árido reciclado (recycled aggregate concretes), y anejo 18: Hormigones de uso no estructural (non-structural concretes).
- UNE-EN 12620:2009: Aggregates for concrete

- **Structural concretes (HE)**

  Are subjected to Structural Concrete Instruction EHE-08 and especially its Annex 15. This Annex is the result of the Group's investigations GT2 / 5, for RECNHOR project coordinated by Dr. Pilar Alaejos (from CEDEX), and also involving the CEDEX polytechnic universities of Catalonia (Universitat Politécnica de Catalunya), and Madrid (Universidad Politécnica de Madrid), the universities of A Coruña (Universidade da Coruña), the Spanish Institute of cement and its applications (Instituto Español del Cemento y sus Aplicaciones-IECA) and the University of Cantabria (Universidad de Cantabria).

The most important points regarding materials are reflected in the Table 3.61 and Table 3.62

### Table 3.61: Maximum content of impurities

<table>
<thead>
<tr>
<th>Element</th>
<th>Max. cont of impurities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic material</td>
<td>5</td>
</tr>
<tr>
<td>Light particles</td>
<td>1</td>
</tr>
<tr>
<td>Asphalt</td>
<td>1</td>
</tr>
<tr>
<td>Others materials (glass, plastic, metal, etc)</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 3.62: Frequency of testing production control

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granulometry</td>
<td>UNE-EN 933-1:98</td>
<td>1/week</td>
</tr>
<tr>
<td>Flakiness index</td>
<td>UNE-EN 933-4:00</td>
<td>1/month</td>
</tr>
<tr>
<td>Fines content</td>
<td>UNE-EN 933-2:96</td>
<td>1/week</td>
</tr>
<tr>
<td>Los Angeles coefficient</td>
<td>UNE-EN 1097-2:99</td>
<td>1/month</td>
</tr>
<tr>
<td>Absorption</td>
<td>UNE-EN 1097-6:01</td>
<td>1/week</td>
</tr>
<tr>
<td>Estability in front of MgSO₄(*)</td>
<td>UNE-EN 1367-2:99</td>
<td>1/ 6 months</td>
</tr>
<tr>
<td>Soft particles</td>
<td>UNE 4134:58</td>
<td>1/month</td>
</tr>
<tr>
<td>Clay lumps</td>
<td>UNE 7133:58</td>
<td>1/week</td>
</tr>
<tr>
<td>Light particles</td>
<td>UNE 7244</td>
<td>1/month</td>
</tr>
<tr>
<td>Sulphur compounds</td>
<td>UNE-EN 1744-1</td>
<td>1/3 months</td>
</tr>
<tr>
<td>Acid soluble sulphate</td>
<td>UNE-EN 1744-1</td>
<td>1/3 months</td>
</tr>
<tr>
<td>Total chlorides</td>
<td>UNE-EN 1744-1</td>
<td>1/3 months</td>
</tr>
<tr>
<td>Impurities</td>
<td>PrEN 933-11</td>
<td>1/week</td>
</tr>
</tbody>
</table>

(*) Only applicable in frost environment and deicing salts.
• **Non-structural concretes (HNE)**

According to Structural Concrete Instruction EHE-08, Annex 18, for the manufacture of the non-structural concrete may be used up 100% of coarse recycled aggregate, provided it meets the specifications defined for it in Annex No. 15 of this Instruction.

The minimum characteristic compressive strength ($f_{ck}$) of non-structural concretes will be 15 N/mm². Due to the low resistance which requires these concretes and consequently low content of cement, inside its requirements do not appear any reference to exposure conditions.

### 3.9.11. Associated works to GEAR project ("Pre-normative research on the use of recycled aggregate")

Unbound recycled aggregate

- Rural roads, forestry, bases for sports fields: 17 works
  - Bases and sub-bases in urban paving: 7 works
  - Bases and sub-bases in different traffic roads: 10 works

Recycled aggregates for soil-cement: 5 works

Recycled aggregates for precast concretes: 5 companies
- Kerbs
- Concrete blocks/ concrete hollow bricks
- Blocks for walls
- Benches (urban furniture)

Mass concrete: 4 works
- Sidewalks
- Foundations
- Non-structural concrete in buildings

Recycled aggregate for dry compacted concrete: 1 paved road.

Demonstration projects associated with other projects
- 1 bridge in Valencia (CEDEX)
- 1 bridge in Barcelona (UPC) - (board)
4. Recycled Concrete.

4.1. Methods in mixture proportioning and his influence in the properties.

Prof. Dr. Enric Vazquez, Universitat Politecnica de Catalunya, Materials Section of the Department of Construction Engineering, Barcelona, Spain

In the 2nd International Conference on Waste Engineering and Management held in Shanghai I 2010, A.G. Razaqpur et al. (Razaqpur, Fathifazl, Isgor, Abbas, Fournier, & Foo, 2010) presented a new method of concrete mix design for concrete made with recycled aggregate. The method is based on considering the concrete recycled aggregate as a two phase material, the old natural aggregate and the old mortar, and taken the old mortar as a part of the total mortar content of the new concrete. The key to the system is to design a reference concrete with natural aggregate, having the desired compressive strength (ACI method), and design the new recycled concrete with the same total mortar volume as the reference concrete. After an extensive experimental verification, the authors conclude that the designed new recycled concrete can satisfy the strength, the durability and all the requirements of a structural concrete with less cement.

The first step is the determination of the volume fractions of the original natural aggregate, and the residual mortar in the RCA (recycled coarse aggregate). Knowing the RMC (residual mortar content), and the bulk specific gravity of the RCA (recycled coarse aggregate) and the original natural aggregate, can be determined the bulk specific gravity of the RMC, and consequently, the volume fractions of residual mortars and original natural aggregate (Razaqpur, Fathifazl, Isgor, Abbas, Fournier, & Foo, 2010).

\[
V_{RCA-concrete}^{RCA} = \frac{V_{NA-concrete}^{NA} \times (1-R)}{(1-RMC) \times \frac{SG_{b-RCA}}{SG_{b-OVA}}} 
\]

Where, \(V_{RCA-concrete}^{RCA}\) is the volume fraction of coarse RCA in RCA-concrete; \(V_{NA-concrete}^{NA}\) is the volume fraction of fresh natural aggregate in the companion normal concrete; \(RMC\) is the residual mortar content of RCA; \(R\) is the replacement ratio which represents the volumetric ratio of the fresh natural aggregate in RCA-concrete to fresh natural aggregate in the companion NA-concrete; \(SG_{b-RCA}\) and \(SG_{b-OVA}\) are the bulk specific gravities of RCA and original virgin aggregate, respectively.

As second step a reference concrete mix proportions, with natural aggregates only, are determined using the ACI method to satisfy a specified strength and other properties. Based on the composition of the RCA, the minimum amount of coarse natural aggregate required in the RCA concrete is determined.

Third step is the determination of the required volume of RCA and NA in RCA concrete.

Fourth step is to calculate the required oven dry weight of RCA and NA in RCA concrete.

Fifth step is to calculate the required new mortar volume in RCA concrete.

Sixth step is to calculate the required water, cement and fine aggregate proportions in RCA.
concrete.

The validity is verified with two RCA sources and using the same OPC and sand in all mixes. The w/c ratio and air content of all mixes were held at 0.45 and 6%.

Using the new proportioning method, resulted 6% and 13% higher compressive strength for all the mixes with recycled aggregate, compared with the reference concretes. Using the conventional method of mix proportioning resulted lower elastic modulus for the concretes with RCA.

Using the new method resulted 11% and 14% higher elastic moduli than the reference concretes. The observed higher moduli can be attributed to the equality of the total natural aggregate volumes of the recycled and reference concretes.

**Creep at 305 days** was 3% and 11% lower in the recycled concretes proportioned with the new method than the reference concretes. The RCA mixes proportioned with the conventional method had higher creep than the reference concretes. Since all the factors affecting creep where kept constant, the higher total mortar content, compared with those proportioned by the new method are identified as the main reason for the higher creep.

**Shrinkage at the age of 224 days** with RCA, concretes proportioned with the new method were lower as the shrinkage of the reference concretes. As in creep, the total mortar content can be considered the main reason.

**The Freeze and Thaw resistance** is related to the difference in the proportioning of RCA in the two types of mixes, and the RCA concrete mixes proportioned with the new method had higher resistances to freeze and thaw than the mixes proportioned with the conventional method.

**The Chloride Penetration** was tested with the ASTM C 1556-06. The Chloride concentration on the exposed surface were below the limit of the ACI in all the concretes, but differences between the TWO RCA concretes can be related with different salt contaminations of the old concrete.

The RCA concrete specimen proportioned with the new method had level carbonation limit then the concrete proportioned with the conventional method, and similar level then the reference concrete.

Other tests showed that there was no major difference between the observed **flexural** behaviour of reinforced RCA concrete beams and reference concrete beams. The same was observed for **shear** performance. In the **Bond** performance the RAC concrete designed by the new method presented the best results.

Jimenez et al. (Jiménez, Barra, Valls, & Vázquez, 2011) have worked with the EMV method and Spanish recycled aggregates in the materials laboratory of UPC (Universitat Politècnica de Catalunya). An experimental campaign has been performed in order to examine different concrete mix proportioning methods, taking into account the use of recycled concrete aggregates. With this purpose, two different mixes, each one of them using 0.45 and 0.6 water/cement ratios (w/c), were prepared. The mixes were prepared using ACI proportioning methodology (ACI 211.1-91, 2002) and the design method proposed by Razaqpur and
Fathifazl, based on the fact that the recycled concrete aggregate (RA) is a two phase material comprising old mortar on the one hand, and natural aggregate on the other. The first of these two mixes was prepared using clean recycled concrete aggregates (A) and the second one was prepared using mixed recycled aggregate with predominance of concrete (B). The chosen cement was CEM I 42.5 R.

Other mixes are being studied, after the verification of the novel method on the initial mixes, using Bolomey mix proportioning method (Fernández, 2007) and an adaptation of the novel method to Bolomey. The results of this part will be published later.

In order to prepare the different mixes, a characterization campaign over the aggregates was performed. The recycled aggregates bulk densities were 2.31 [g/cm³] and 2.33 [g/cm³], and the attached mortar amounts of them were 39% and 32% for aggregates A and B respectively. The natural aggregates bulk densities were 2.67 [g/cm³] and 2.65 [g/cm³] for limestone and sand respectively.

To obtain the mortar content of the RA, a thermal shock methodology was used (Barra, Estudio de la durabilidad del hormigón de árido reciclado en su aplicación como hormigón armado. Dissertation, 1996). This consists on subjecting the recycling aggregate to cycles of water submersion and high temperature shock, in order to create stresses by the rapid evaporation of the absorbed water of the aggregate and also by throwing the heated aggregate back to the water. Its purpose is to crumble down the attached mortar by the appearance of cracks, which will debilitate the bond between the natural aggregate and the mortar.

After the aggregates characterization, the mix proportions were calculated. The results are shown in Table 4.1

<table>
<thead>
<tr>
<th>Identification</th>
<th>w/c</th>
<th>RA [%]</th>
<th>Water [kg]</th>
<th>Cement [kg]</th>
<th>Sand [kg]</th>
<th>Limestone [kg]</th>
<th>RA (A) [kg]</th>
<th>RA (B) [kg]</th>
<th>HRWRA [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMV-A</td>
<td>0.45</td>
<td>65</td>
<td>140</td>
<td>311</td>
<td>577</td>
<td>421</td>
<td>782</td>
<td>-</td>
<td>2176</td>
</tr>
<tr>
<td>ACI-A</td>
<td>0.45</td>
<td>100</td>
<td>184</td>
<td>409</td>
<td>752</td>
<td>-</td>
<td>786</td>
<td>-</td>
<td>1227</td>
</tr>
<tr>
<td>EMV-B</td>
<td>0.45</td>
<td>68</td>
<td>145</td>
<td>323</td>
<td>600</td>
<td>369</td>
<td>-</td>
<td>788</td>
<td>1939</td>
</tr>
<tr>
<td>ACI-B</td>
<td>0.45</td>
<td>100</td>
<td>184</td>
<td>409</td>
<td>746</td>
<td>-</td>
<td>-</td>
<td>798</td>
<td>1227</td>
</tr>
<tr>
<td>EMV-A</td>
<td>0.60</td>
<td>65</td>
<td>140</td>
<td>233</td>
<td>644</td>
<td>421</td>
<td>782</td>
<td>-</td>
<td>1632</td>
</tr>
<tr>
<td>ACI-A</td>
<td>0.60</td>
<td>100</td>
<td>184</td>
<td>307</td>
<td>839</td>
<td>-</td>
<td>786</td>
<td>-</td>
<td>613</td>
</tr>
<tr>
<td>EMV-B</td>
<td>0.60</td>
<td>68</td>
<td>145</td>
<td>242</td>
<td>669</td>
<td>369</td>
<td>-</td>
<td>788</td>
<td>1454</td>
</tr>
<tr>
<td>ACI-B</td>
<td>0.60</td>
<td>100</td>
<td>184</td>
<td>307</td>
<td>833</td>
<td>-</td>
<td>-</td>
<td>798</td>
<td>613</td>
</tr>
</tbody>
</table>

The designation of the mixes corresponding to EMV, are the ones using the Razaqpur method, which was named after Equivalent Mortar Volume. The letter after, corresponds to the type of aggregate used.

A number of different tests were performed in order to verify the quality and characteristics of the concrete. In Table 4.2 the results of the compressive strength and elasticity modulus are shown. The compressive strength tests were performed over cubic specimens (10x10 cm) and the elasticity modulus over cylindrical specimens (10x20 cm). For the compressive strengths, a conversion factor has been used in order to present the results based on a cylindrical
specimen of 15x30 cm (Fernández, 2007)

Table 4.2: Average values of compressive strengths and modulus of elasticity of ACI and EMV mixes.

<table>
<thead>
<tr>
<th>Concrete Mix</th>
<th>Compressive Strength [N/mm²]</th>
<th>Modulus of Elasticity [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/c ratio 0.45</td>
<td>0.6</td>
</tr>
<tr>
<td>ACI-A</td>
<td>31.6</td>
<td>20.7</td>
</tr>
<tr>
<td>EMV-A</td>
<td>32.9</td>
<td>21.1</td>
</tr>
<tr>
<td>ACI-B</td>
<td>33.1</td>
<td>22.1</td>
</tr>
<tr>
<td>EMV-B</td>
<td>39.2</td>
<td>28.5</td>
</tr>
</tbody>
</table>

It can be noticed that, in general terms, the results of the compressive strengths of the novel method are similar or better than the conventional methods, in both 0.45 and 0.6 w/c ratios. This was achieved using less cement in all of the cases, going up to around 24% reduction in weight when comparing ACI-A with EMV-A mixes, and around 21% reduction when comparing ACI-B with EMV-B mixes.

The elasticity modulus showed the same tendency of the compressive strength results, but with higher differences in both 0.45 and 0.6 w/c ratios. This higher difference is a result of the total natural aggregate in the mixes, because this property is based on this issue, and EMV method achieves higher amounts by replacing the old mortar by natural aggregates.

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4.2. Durability

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4.2.1. Sulfates

The four most significant applications of recycled aggregate are in unbound road base layers, bounded overlays with a low lime or cement content, in mass concrete and in various structural concrete applications. Their necessities, from a durability standpoint, are different in each application. Although they share some characteristics, they do it with a different level of demand.

A sulfate attack can originate from the same components of the recycled aggregate. The sulfates that will act are of the sum of all sulfates present in the system. In all cases, there is a common necessity to prevent the formation of ettringite and thaumasite. From an environmental point of view, it is also important to prevent the excessive leaching of the sulfates. The need to limit the presence of sulfates in recycled aggregate is a common necessity; nonetheless, the environment surrounding the material is of particular importance as it varies from place to place affecting the overall product and leaching release.

In recycled concrete aggregates, sulfates can be present as gypsum and as sulfates from admixtures or binders. In mixed aggregates and CDW in general, their presence is attributed to residues of plasterwork, insulation prefabricated pieces, drywall, etc.

This contamination of final products is of particular concern in countries with wide use of gypsum, such as Spain (Vazquez, Varela, & Güell, 2011) and Germany (Müller, Schnellert, &
Kehr, 2010). As a construction material, gypsum is good, efficient and economic, which means that the percentage of gypsum in building rubble can be expected to increase in the future. But this can make the re-use of building rubble difficult, and even call it into question altogether. Data from Germany and Spain confirm this trend.

In eastern Germany (Müller, Schnellert, & Kehr, 2010) the average gypsum content in recycled aggregates is 2.73 mass % and varies between 1.8 and 5.35 mass %. In Spain (Vazquez, Varela, & Güell, 2011), the average gypsum content in recycled concrete aggregate (with minimum 90% concrete) is of 0.6% only, with maximum values of 2%, which is produced in fewer plants. In contrast, the mixed type aggregate, with a minimum concrete content of 70%, which is the most widespread, has an average of 2.5% and varies between 0.5% and 6.7%, always in weight.

Regulation limits for sulfates vary according to application and are virtually the same within the EU. Yet, there has been pressure in changing them coming from two sides: some researchers are of the opinion that tolerance of sulfate in recycled aggregates should be lower, while complaints to the contrary were heard from producers in the EQAR 2011 congress (Dupré, 2011). In any case, the removal of gypsum constituents from recycled aggregates during their processing seems indispensable. This can be achieved with jigging machines, in which asymmetrical jig stroke diagrams can be implemented (Müller, Schnellert, & Kehr, 2010). A significant reduction in the gypsum content in processed crushed concrete can be achieved by jig sorting, fulfilling requirements even with input material that contains gypsum. As A. Müller et al. have proved, with medium and high input levels of gypsum, two passes through the jigging machine are needed to comply with the requirements specified by the DIN 4226-100. This can be achieved either by intermediate stockpiling of the material and feeding it through the machine again or by two jigging machines connected in series.

Another effective technique for reducing gypsum content is selection by means of near infrared spectroscopy. This newly developed technique has been successful in Spanish Basque processing plants, among others.

Whatever the technique chosen, the improvement of gypsum removal in processing facilities is for many a must if they want to survive in today's market.

4.2.2. Frost-susceptible recycled concrete aggregates.

Frost resistance appears as another durability issue discussed in both concrete applications and road base. Demolished concretes to be recycled show great diversity in properties with regard to the potential to resist environmental effects, such as frost action, when they are used in a new concrete as aggregate.

Ch. Hendriks (Hendriks, Nijkerk, & Van Koppen, The Building Cycle, 2000) was of the opinion that recycled aggregate concrete is frost resistant unless moisture content is extremely high. The combination of frost and the use of de-icing salts (chlorides) also result in damage when the porosity of recycled aggregate is very high.

It should be discussed if appropriate test methods exist to evaluate the specific characteristics of recycled concrete aggregates with respect to frost durability. Many authors think that this fact raises another important prejudice against the performance of recycled concrete aggregates compared to natural aggregates.

Gokce et.al (Gokce, Nagataki, Saeki, & Hisada, 2011) concluded after a long series of tests,
that the direct unbound frost soundness test offers more realistic testing conditions to judge the soundness of recycled concrete aggregates. In this test, there is no chemical process decomposing the adhered mortar. In comparison with existing standard procedures, which condition the aggregate at 110 °C, a moderate pre-drying process at 50 °C is proposed. This seems to be more appropriate to the cement-bonded characteristic of the recycled concrete aggregates, as it eliminates the uncontrolled damage of test material that the usual conditioning at 110 °C causes.

The sulfate soundness test fails to predict the frost susceptibility of the recycled concrete aggregate. This is because the procedure of the test severely decomposes the mortar adhering to the original coarse aggregate regardless of its quality or air void system. Thus, the sulfate soundness test would be applicable for only natural (inert) aggregates as a rapid indication of durability.

Due to the presence of adhered mortar, recycled concrete aggregate has a significantly higher absorption compared to natural coarse aggregate. In general, the frost susceptibility of an ordinary concrete aggregate is judged by its physical properties. Although high moisture absorption is often used as an index for unsoundness, many aggregates can absorb large amounts of water but remain sound. Unsoundness is therefore related to pore size distribution, rather than to the total porosity of the aggregate (Mehta & Monteiro, 2006).

Here, we reproduce a part of the important study of Gokce. In his research, Gokce used three air-entrained type concretes with low, medium and high water–cement ratios; and a non-air-entrained type concrete with a medium water–cement ratio; as the starting material to produce recycled coarse aggregate.

<table>
<thead>
<tr>
<th>Type</th>
<th>Code</th>
<th>W/C</th>
<th>Air content (%)</th>
<th>Compressive strength at 28 days (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-entrained</td>
<td>HQC-AE</td>
<td>0.35</td>
<td>4.4</td>
<td>60.7</td>
</tr>
<tr>
<td></td>
<td>MQC-AE</td>
<td>0.45</td>
<td>4.0</td>
<td>49.0</td>
</tr>
<tr>
<td></td>
<td>LQC-AE</td>
<td>0.63</td>
<td>4.5</td>
<td>28.3</td>
</tr>
<tr>
<td>Non-air-entrained</td>
<td>MQC-NON-AE</td>
<td>0.45</td>
<td>1.2</td>
<td>55.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Process level</th>
<th>Code</th>
<th>Adhered mortar content (%)</th>
<th>Density S.S.D. (g/cm³)</th>
<th>Absorption (%)</th>
<th>JIS crushing value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>–</td>
<td>VC</td>
<td>0</td>
<td>2.65</td>
<td>0.68</td>
<td>3.0</td>
</tr>
<tr>
<td>HQC-AE</td>
<td>1</td>
<td>A1</td>
<td>52.3</td>
<td>2.42</td>
<td>4.88</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>A3</td>
<td>30.2</td>
<td>2.51</td>
<td>3.14</td>
<td>1.5</td>
</tr>
<tr>
<td>MQC-AE</td>
<td>1</td>
<td>B1</td>
<td>55.0</td>
<td>2.41</td>
<td>5.58</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>B3</td>
<td>32.4</td>
<td>2.50</td>
<td>3.19</td>
<td>1.7</td>
</tr>
<tr>
<td>LQC-AE</td>
<td>1</td>
<td>C1</td>
<td>52.3</td>
<td>2.37</td>
<td>6.27</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>C3</td>
<td>32.3</td>
<td>2.48</td>
<td>3.76</td>
<td>2.3</td>
</tr>
<tr>
<td>MQC-NON-AE</td>
<td>1</td>
<td>B’1</td>
<td>55.7</td>
<td>2.44</td>
<td>5.57</td>
<td>3.7</td>
</tr>
</tbody>
</table>
The concrete mixtures were proportioned to give a slump of 80 ± 20 mm and air content of 4.5 ± 1.5% with water-cement ratio of 0.55. The mixture proportions and measured fresh concrete properties are shown in Table 4.5. The freeze-thaw test procedure was performed in accordance with JSCE-G 501, corresponding to ASTM C 666 Procedure A. The durability factor (DF) was calculated at the end of 300 cycles. The weight, dynamic modulus of elasticity and length change measurements continued up to 500 cycles.

Table 4.5: Mixture proportions and fresh properties of concretes

<table>
<thead>
<tr>
<th>Mixture code</th>
<th>W/C</th>
<th>Water (kg/m³)</th>
<th>Cement (kg/m³)</th>
<th>Fine agg (kg/m³)</th>
<th>Coarse agg (kg/m³)</th>
<th>Admixture AE-WR</th>
<th>Admixture SP</th>
<th>Air cont (%)</th>
<th>Slump (mm)</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VC-VS</td>
<td>0.55</td>
<td>165</td>
<td>300</td>
<td>813</td>
<td>1039</td>
<td>0.72</td>
<td>0.94</td>
<td>4.3</td>
<td>90</td>
<td>17.0</td>
</tr>
<tr>
<td>A1-VS</td>
<td>0.55</td>
<td>160</td>
<td>291</td>
<td>819</td>
<td>959</td>
<td>0.47</td>
<td>0.91</td>
<td>4.5</td>
<td>90</td>
<td>16.8</td>
</tr>
<tr>
<td>A3-VS</td>
<td>0.55</td>
<td>157</td>
<td>285</td>
<td>825</td>
<td>1002</td>
<td>0.46</td>
<td>0.89</td>
<td>4.0</td>
<td>65</td>
<td>16.0</td>
</tr>
<tr>
<td>B1-VS</td>
<td>0.55</td>
<td>160</td>
<td>291</td>
<td>819</td>
<td>955</td>
<td>0.47</td>
<td>0.91</td>
<td>4.1</td>
<td>80</td>
<td>16.1</td>
</tr>
<tr>
<td>B3-VS</td>
<td>0.55</td>
<td>157</td>
<td>285</td>
<td>825</td>
<td>998</td>
<td>0.46</td>
<td>0.89</td>
<td>3.8</td>
<td>65</td>
<td>16.0</td>
</tr>
<tr>
<td>C1-VS</td>
<td>0.55</td>
<td>160</td>
<td>291</td>
<td>822</td>
<td>940</td>
<td>0.46</td>
<td>0.91</td>
<td>4.5</td>
<td>65</td>
<td>19.4</td>
</tr>
<tr>
<td>C3-VS</td>
<td>0.55</td>
<td>158</td>
<td>287</td>
<td>826</td>
<td>988</td>
<td>0.46</td>
<td>0.90</td>
<td>4.7</td>
<td>75</td>
<td>20.3</td>
</tr>
<tr>
<td>B’1-VS</td>
<td>0.55</td>
<td>160</td>
<td>291</td>
<td>851</td>
<td>939</td>
<td>0.47</td>
<td>0.91</td>
<td>4.7</td>
<td>85</td>
<td>25.5</td>
</tr>
<tr>
<td>B’3-VS</td>
<td>0.55</td>
<td>156</td>
<td>284</td>
<td>817</td>
<td>996</td>
<td>0.57</td>
<td>0.89</td>
<td>4.1</td>
<td>80</td>
<td>21.5</td>
</tr>
</tbody>
</table>

The following experimental procedure was implemented in the direct testing of the freeze-thaw resistance of recycled coarse aggregates and natural crushed stone:

1) Drying of the sample at 50 °C and 60% R.H. until reaching constant weight.
2) Saturation of the sample with 3% NaCl solution for 24 h.
3) Removing the saturated sample from the solution and wiping the particles with a towel to bring them into SSD condition.
4) Weighing the sample prior to frost test ($W_0$).
5) Re-immersion of the sample into the NaCl solution for 30 min due to the immediate loss of solution in the aggregate surface after weighing.
6) Removing the saturated sample from the solution without allowing the surface to lose wetness.

Next, the testing sample, in saturated and slightly surface wet condition, was placed into a double wall bag made of two plies of poly. Then, all the bags containing the aggregate samples were sunk into the freezing pool.

One freezing and thawing cycle took about 5 h. The freeze-thaw equipment was set to ensure a temperature not lower than −20 °C at freezing, and not higher than 15 °C at thawing, at any point of the chamber. The saturated samples were subjected to up to 90 freeze-thaw cycles. Every 30 cycles, the weight loss of the test samples was checked according to the following procedure:

1) Roughly sieving the wet sample to remove the particles under 5 mm as much as possible.
2) Wiping the sample with a towel without causing a further weight loss.
3) Sieving the surface dry sample again to remove the remaining particles finer than 5 mm.
4) Determining the new weight of the sample over 5 mm at the end of $N$ cycles.
5) Re-immersion of the sample into the NaCl solution for 30 min, due to the loss of the solution on the aggregate surface, before starting the test for the next 30 cycles. The calculation of the frost soundness (FS) after $N$ cycle was done as follows:

$$FS_N = \frac{W_0 - W_N}{W_0} \times 100(\%)$$

where FS = freeze-thaw soundness loss of the aggregate tested after N cycles (%), $W_0$ = weight of the saturated-surface dry sample prior to the frost test (g) and $W_N$ = weight of the saturated-surface dry sample after N cycles (g).

The results summarized in Table 4.6 reveal that the concretes produced with the recycled coarse aggregates belonging to air-entrained type of source concretes were highly durable against freezing and thawing (DF > 91), and were even slightly superior than the reference concrete produced with virgin aggregates.

<table>
<thead>
<tr>
<th>Concrete mixture</th>
<th>No. of cycles at which the exposure ended</th>
<th>300 cycles</th>
<th>End of cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DF</td>
<td>Weight loss (%)</td>
<td>Length change ($\times 10^{-6}$)</td>
</tr>
<tr>
<td>VC-VS</td>
<td>500</td>
<td>87</td>
<td>2.10</td>
</tr>
<tr>
<td>A1-VS</td>
<td>500</td>
<td>91</td>
<td>1.39</td>
</tr>
<tr>
<td>A3-VS</td>
<td>500</td>
<td>92</td>
<td>1.41</td>
</tr>
<tr>
<td>B1-VS</td>
<td>500</td>
<td>96</td>
<td>2.68</td>
</tr>
<tr>
<td>B3-VS</td>
<td>500</td>
<td>97</td>
<td>2.07</td>
</tr>
<tr>
<td>C1-VS</td>
<td>500</td>
<td>92</td>
<td>2.58</td>
</tr>
<tr>
<td>C3-VS</td>
<td>500</td>
<td>93</td>
<td>3.10</td>
</tr>
<tr>
<td>B’1-VS</td>
<td>90</td>
<td>17</td>
<td>–</td>
</tr>
<tr>
<td>B’3-VS</td>
<td>180</td>
<td>35</td>
<td>–</td>
</tr>
</tbody>
</table>

While the frost soundness loss of the non-air-entrained type recycled aggregate ranged between 34.2% and 37.1%. The results for the virgin aggregate and air-entrained type recycled aggregates were below 10%, except for one with 16.4%, originated from low quality source concrete with a high adhered mortar content (C1). In the opinion of the author it is not possible to propose a certain limit value for the frost soundness loss with the limited data of this study. A further quantitative assessment based on the statistical interpretation of a large number of test results, to be obtained from a broad range of demolished concrete sources in terms of quality, air-entrainment characteristics and damage accumulation during past service life, would be favorable to establish an exact durability criteria.

J. Mehus et al. (Petkovic, Mehus, & Myren, 2003), from the Norwegian Building Research Institute, present an overview of research conducted as a part of the Norwegian Roads Recycled Materials R&D Program. A proposed adjustment of the test method specified in EN 1367-1 avoiding pre-drying of the recycled aggregate, has been evaluated. Furthermore, various exposure conditions with recycled aggregate, including submersion and saturation in deicing salts, have also been investigated. This has resulted in the proposal of a revised test
method based on EN 1367-1, for documentation of freeze-thaw properties of recycled aggregate. The specimen preparation procedure in EN 1367-1 specifying pre-drying affects the recycled aggregate freeze-thaw durability.

A. Richardson et al, (Richardson, Coventry, & Bacon, 2010) have shown that the use of air entrainment and polypropylene fibers in concrete made with recycled aggregate are equally effective at providing freeze-thaw durability when compared with concrete made with natural aggregates, air entrainment and polypropylene fibers.

The results show that the concrete samples made with recycled aggregate were slightly more durable than those made with virgin aggregate. The samples made with recycled aggregate and an addition of polypropylene fibers were found to have an average compressive strength of 13.8 N/mm², while the samples made with natural aggregate with polypropylene fibers had an average compressive strength of 12.9 N/mm² -which is a difference of 7% and within normal batching tolerances. The concrete samples made with recycled aggregates were more durable than plain samples made with natural aggregate by 68%. This data may be explained by the variability of the good quality recycled aggregate and curing procedure using soaked aggregate. Overall, the results show that recycled aggregates, with the aid of additives, can be used for applications where concrete is subject to freezing and thawing while still providing the durability that natural aggregates offer.

4.2.3. Chloride penetration

As is well known, corrosion of reinforcing steel as consequence of penetration of chlorides through concrete, from sea water, marine environment, de-icing salts, have serious implications for structures and represents important economic damages for many countries. Should not be ruled out the presence of chlorides in some components of concrete, but this is easily avoidable with a correct control of materials.

Different physical mechanisms may be distinguished with respect to the driving force. These mechanisms may be referred to the permeation of a salt solution, the capillary absorption or chloride-containing liquids, and the diffusion of free chloride ions. J.Kropp (Kropp & Hilsdorf, (1995)) describes the transport of chloride ion as the result of the action of three mechanisms: permeation, capillary absorption and diffusion. The diffusion will exist only if there is not flow of water in the concrete. In reality it is very difficult, if not impossible, to quantify the partial contributions of each mechanism and the combined effects of them. In the determination of diffusion coefficients by some rapid methods, overlaps an external electric potential that causes a migration transport.

All these mechanisms act only on the free chlorides. The chlorides can be chemically binded by the C₃A present in the hydrated cement, forming the chloroaluminate or Friedel’s salt (3CaO.Al₂O₃.CaCl₂.10H₂O) and can be binded too by adsorption by the CSH. Blast furnace slag and fly ash in blended cements, reduce the concentration of C₃A and generally chlorides binding capacity (Kropp & Hilsdorf, (1995))

Other publications suggest that the cements with high slag content, increases the ability of chlorides to bind (Kropp & Hilsdorf, (1995)). There are factors that can affect retention, such as type of chlorides and moisture. Tuutti (Tuutti, 1982) indicates that chlorides from the addition of CaCl₂ are combined in larger quantities than those from KCl. The pH of the liquid in the pores, the water/cement ratio and especially the type of test used, should also be taken into account.
It is considered that only the free chlorides are able to reach the reinforcing steel, and therefore, bound chlorides are innocuous with respect to corrosion. It should be noted that physically bound chlorides, can be released by carbonation or entry of sulphates (Tang & Nilsson, Chloride binding capacity, penetration and pore structure of blended cement pastes with slag and fly ash. Proc. of the International Conference on Blended cements in Construction, 1991). Likewise, the chloroaluminate can be decomposed by the same agents, producing calcium carbonate, aluminum oxide and releasing chloride. This may mean that in a carbonate matrix, could be free the most of chlorides. Despite this argument, be bound, strongly retards the transport and the ability of chloride to reach the reinforcing steel, and therefore, the effect should always be considered when determining the transport of chlorides in the concrete. The complete mechanism requires even more research and experimental determinations.

These processes also apply to recycled aggregate concretes. They must be take into account the presence of adhered mortar from the original concrete, and even aggregates that are pure mortar. Thus, it is necessary consider not only the porosity of the new mortar, but also the possible contribution from the mortar from the recycled aggregate. A common simplification of the problem is to consider only the possible contribution of recycled aggregate porosity, ignoring the contribution of other factors that may influence the final result of changing behavior in chlorides.

These factors include prior contamination of recycled aggregates by chlorides and / or sulfates, the water/cement ratio in mortar of the new concrete, pre-wetting, the ability of binding chlorides, and the test used to determine the diffusion coefficient. A review of recent publications about the transport of chloride in recycled concrete, allows an assessment of the importance of each one of these factors. If the recycled concrete aggregate is contaminated by chlorides, the new concrete will have an additional quantity of chlorides. L. Friedl et al. (Friedl, Volkwein, & Schiebl, 2003) established that the pretreatment of recycled aggregate (e.g. moistening), has a large effect on the quantity and the speed of redistribution of chlorides between recycled aggregate and the new matrix. Additional tests with conventional concrete corrosion cells, where individual chloride contaminated recycled aggregates were placed near the embedded steel, showed intense pitting corrosion after 90 days. For these investigations the composition of the recycled aggregate concrete, especially the type and the proportion of recycled aggregate, were varied. The results indicate that the quantity of recycled aggregate has a minor influence on chloride ingress. However, the concrete composition and the type of recycled aggregate can enhance the chloride ingress into the recycled aggregate concrete. Y.A. Villagran et al. (Villagrán-Zaccardi, Zega, & Di Maio, 2008) analyzed in his work, the influence of coarse recycled concrete aggregate on the chloride penetration rate and binding capacity, of concrete under marine exposure. Concrete specimens were molded and exposed to a natural marine atmosphere. After exposure periods of 6, 12, and 18 months, ingress profiles of total and water-soluble chlorides were measured. Results indicate that recycled aggregate incorporation had two opposed effects in concrete:

- It increases its chloride penetration rate
- The chloride binding capacity. Therefore, water-soluble free chloride contents in conventional and recycled concrete series had similar values.

The diffusion coefficient D is a chloride parameter considered useful to evaluate the transport of chloride in a concrete. Tests are available to accelerate the transport of chloride, either by
means of an external electric field, a concentrated solution of chloride or with rising temperature

The immersion test NT BUILD 443, as for non-steady-state diffusion, the RCM test, as for non-steady-state migration, the UNE 83987, as for steady state and non-steady-state migration and the resistivity test were selected for a final evaluation in the European project CHLORTEST. In parallel an international inter-laboratory comparison was organized by RILEM TC 178-TMC (Huang Y. , Deng, Luo, & Yang, 2010), and other comparisons were made by Tang Luping et al (Tang, Nilsson, & Basheer, Resistance of concrete to chloride ingress, 2011) . The values obtained of the non-steady-state migration from the UNE 83987 are comparable with those obtained with NT BUILD 443 for relative porous concretes, but deviate for dense concrete. For the same 2 tests the steady state diffusion coefficient obtained from UNE 83987 is smaller then the non-steady-state coefficient from the NT BUILD 443. These and other relations must be taken into account if we want to draw valid conclusions, comparing studies on chloride penetration into concrete with recycled aggregates made with immersion tests, dissemination and migration respectively.

V.A. Ulloa et al. (Ulloa, Barra, Serna, Pelufo, Aponte, & Vazquez, 2011) studied the influence of the use of recycled aggregates in the chloride penetration coefficient, determined according to UNE 83987. The type of aggregates, the water/cement ratio in new concrete and the age of this at the beginning of the attack, are the three variables. For the part of the study focused on the use of recycled concrete aggregate (ArH), were used recycled aggregates from a plant in Valencia, with absorptions of 5.26% and 4.51% respectively. The effective w/c ratio of the concretes were 0.40 and 0.50, and dosages for cement CEM I 42.5/SR were 380 y 330 kg/m³

Non-standard concretes with mixed recycled aggregates were studied, with 21% ceramic aggregate and absorption of 8.6%. The dosages were carried out by the method of Bolomey. For the study of the penetration of chlorides, diffusion coefficients for the hardened concrete for stationary and nonstationary states are determined. Cores of 7.5 x3cm obtained from cylindrical specimens of 15x30cm were tested. The results obtained for the compressive strength and the diffusion coefficients are shown in the graphs.

<table>
<thead>
<tr>
<th>Dosage /m³</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/c ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of recycled aggregate</td>
<td>AN</td>
<td>ArH</td>
</tr>
<tr>
<td>Water</td>
<td>152</td>
<td>152</td>
</tr>
<tr>
<td>Cement</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>Sand 0/4mm</td>
<td>920</td>
<td>751</td>
</tr>
<tr>
<td>Medium aggregate 7/12mm</td>
<td>418</td>
<td>0</td>
</tr>
<tr>
<td>Coarse aggregate 12/20mm</td>
<td>591</td>
<td>0</td>
</tr>
<tr>
<td>Recycled aggregate GRB</td>
<td>1076</td>
<td>875</td>
</tr>
<tr>
<td>Recycled aggregate TECREC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical Density (kg/m³)</td>
<td>2461</td>
<td>2359</td>
</tr>
</tbody>
</table>
Fig. 4.1: Compressive strength in the short and mid-term, for concretes performed with different types of coarse aggregates and two water–cement ratios.

Fig. 4.2: Non-Stationary Chloride Diffusion Coefficient $D_{ns}$, analyzed for concretes in the short and mid-term.

Fig. 4.3: Stationary Chloride Diffusion Coefficient $D_s$, analyzed for concretes in the short and mid-term.

For recycled aggregates ArH, with the above-mentioned porosities, the chloride penetration is affected by the water-cement ratio into the cement matrix of new concrete. To water-cement ratio of 0.4, resultant concretes do not experiment significant losses of durability, in terms of chloride penetration, even in this case, which ArH aggregate is used in the entire fraction.
>4mm. For concretes with ARMH, chloride penetration values are significantly higher.

Table 4.8: Concrete mixes

<table>
<thead>
<tr>
<th>Materials</th>
<th>Concrete mixes (kg/m³)</th>
<th>0%-0.45</th>
<th>20%-0.45</th>
<th>50%-0.45</th>
<th>100%-0.45</th>
<th>0%-0.60</th>
<th>20%-0.60</th>
<th>50%-0.60</th>
<th>100%-0.60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement CEM I 52.5 SR</td>
<td>385.0</td>
<td>385.0</td>
<td>385.0</td>
<td>385.0</td>
<td>325.0</td>
<td>325.0</td>
<td>325.0</td>
<td>325.0</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>173.0</td>
<td>173.0</td>
<td>173.0</td>
<td>173.0</td>
<td>178.7</td>
<td>178.7</td>
<td>178.7</td>
<td>178.7</td>
<td></td>
</tr>
<tr>
<td>w/c</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Fine Agg.</td>
<td>813.8</td>
<td>698.2</td>
<td>741.7</td>
<td>746.1</td>
<td>874.9</td>
<td>799.4</td>
<td>831.3</td>
<td>824.9</td>
<td></td>
</tr>
<tr>
<td>Coarse Agg.</td>
<td>870.9</td>
<td>747.9</td>
<td>431.7</td>
<td>0.0</td>
<td>754.9</td>
<td>627.5</td>
<td>367.1</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Medium Agg.</td>
<td>167.6</td>
<td>143.9</td>
<td>83.1</td>
<td>0.0</td>
<td>253.9</td>
<td>211.0</td>
<td>123.4</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Recycled Agg.</td>
<td>0.0</td>
<td>222.9</td>
<td>514.8</td>
<td>963.2</td>
<td>0.0</td>
<td>209.6</td>
<td>490.5</td>
<td>923.4</td>
<td></td>
</tr>
<tr>
<td>Superplas.</td>
<td>3.85</td>
<td>3.85</td>
<td>3.85</td>
<td>1.85</td>
<td>3.25</td>
<td>3.25</td>
<td>3.25</td>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2414.2</td>
<td>2374.8</td>
<td>2333.3</td>
<td>2371.2</td>
<td>2390.8</td>
<td>2354.7</td>
<td>2319.2</td>
<td>2255.3</td>
<td></td>
</tr>
</tbody>
</table>

M.Barra et al (Barra, Aponte, Pielarisi, & Vazquez, 2011), have performed an extensive experimental program in order to evaluate the repercussions of the recycled aggregates content in the properties and in the durability of concrete. Two series of concrete mixes were tested, with a water-cement ratio (w/c) of 0.45 and 0.50. Each series was consisted of 4 mixes with 0%, 20%, 50% and 100% substitution of conventional aggregate by recycled aggregate, as shown in Table 4.8. Notice that the nomenclature used to represent each mix indicates the percentage of substitutions of conventional aggregate by recycled aggregate in volume and the water-cement ratio (w/c).

Calcareous aggregate (coarse, medium and fine) and one type of coarse recycled aggregate were used. The bulk density and water absorption of recycled aggregate was 2.33 g/cm³ and 4.6%, respectively. The visual characterization (UNE EN 933-11) of the former showed the following results: concrete 55.9%, aggregates 34.5%, bituminous material 8.5%, masonry 0.7%, gypsum 0.4% and others 0.005%.

The average compressive strength at 28 days measured in cylindrical specimens with 150 mm of diameter and 300 mm of height are summarized in Table 4.9 for all mixes.

Table 4.9: Compressive strength at 28 days

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Compressive Strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%-0.45</td>
<td>71</td>
</tr>
<tr>
<td>20%-0.45</td>
<td>61</td>
</tr>
<tr>
<td>50%-0.45</td>
<td>56</td>
</tr>
</tbody>
</table>
Additional tests were conducted to assess the capillary suction, the penetration depth and profile (NTBuild 443:1995). The capillary suction test was performed at 28 days from the casting of the specimens. The results obtained were then used to assess the absorptivity of the different concrete mixes, as illustrated in Fig. 4.4.

<table>
<thead>
<tr>
<th>Content of Recycled Aggregate</th>
<th>Absorptivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% 0.45</td>
<td>50</td>
</tr>
<tr>
<td>20% 0.55</td>
<td>62</td>
</tr>
<tr>
<td>50% 0.55</td>
<td>55</td>
</tr>
<tr>
<td>100% 0.55</td>
<td>48</td>
</tr>
</tbody>
</table>

For the same w/c, the absorptivity estimated for the mixes with low content of recycled aggregate (0% and 20%) are similar. Higher percentages of substitutions of conventional aggregate (50% and 100%) lead to an increase in the absorptivity estimated. For instance, the difference between the absorptivity of the mix without recycled aggregate and with 100% of substitution are 27.5% for a w/c of 0.45 and 49.1% for a w/c of 0.55. Such result may be attributed to the higher porosity of the recycled aggregate used that facilitates the entrance of liquids in the microstructure.

On the other hand, the chloride penetration profile measured according with the NTBuild 443:1995 test was used to estimate the total non-stationary chloride diffusion coefficient by means of an interactive procedure. Fig. 4.5 shows the results obtained depending on the w/c and on the content of recycled aggregate.

The diffusion coefficient of mixes with the same w/c and low recycled aggregate content (0% and 20%) show very similar diffusion coefficients. The same is observed between mixes with high recycled aggregate content (50% and 100%). Furthermore, it is observed that the substitution of conventional aggregates in a percentage superior to 20% produces a decrease of 18% and 80% on the average diffusion coefficient for mixes with w/c equal to 0.55 and 0.45, respectively.
Such results show a tendency that goes against the expected due to the permeability of concrete. Indeed, if only the permeability affected the diffusion process, the mixes with higher recycled aggregate content should present higher chloride diffusion coefficients since they tend to be more permeable. Therefore, it is clear that another phenomenon acting in parallel to the simple diffusion of chlorides is responsible for the results shown in Fig. 4.5. This phenomenon is the chloride retention by the aluminates of the paste, which should be bigger in the mixes with more recycled aggregates thus compensating the effect of a bigger permeability of the matrix. Therefore, according to the estimation performed, the use of a high recycle aggregate content had a positive repercussion, leading to a concrete less permeable to chlorides.

It was also observed that the change on the w/c from 0.45 to 0.55 produces an increase on the diffusion coefficient. Such increase is approximately of 49% in mixes with low recycled aggregate content (0% and 20%) and of 227% in mixes with high aggregate content (50% and 100%). Consequently, the latter appear to be more sensible to variations in the w/c.

To understand the practical repercussion of the results of chloride diffusion, the durability estimation was performing using the models proposed by the EHE-08 and by Helene. In both of them, the induction and the propagation time was calculated and summed to obtain the total life of a standardized structure. This structure considered in this estimation is constructed with reinforced concrete that present conventional steel bars with 16 mm of diameter with a 35 mm concrete cover. The surficial, the internal and the critical chloride content are 0.25%, 0.03% and 0.20% by weight of cement, respectively.

Fig. 4.6 shows the total life predicted considering the use of each concrete mix tested previously. It is observed that, for the same w/c, the total life is bigger for mixes with higher content of recycled aggregate. Nevertheless, in this case, the difference in favor of mixes with higher recycled aggregate content is of approximately 0.75% according to the Helene Model and 4.75% according to the EHE-08 model, respectively.
This result demonstrates that the use of recycled aggregates in substitution of more than 50% of the conventional aggregate, may lead to an improvement of the durability of concrete if the mix is properly designed.

Otsuki (Otsuki, 2003) found that chloride penetration was higher in the conventional aggregate concrete, than in recycled aggregate concrete. Limbachiya et al. (Limbachiya, Leelawat, & Dhir, 2000) studied concretes of 50 MPa and 370 kg/m³, and concluded that even for concretes with 100% of recycled coarse aggregate, the values of D decrease compared to conventional aggregate concrete.

Other studies start from the idea that chloride penetration increases with the recycled aggregate content. They attribute the effect to cracks and fissures produced during the production of recycled aggregate, and that this effect can be compensated using active mineral admixtures.

V. Corinaldesi and G. Moriconi (Corinaldesi & Moriconi, 2009) showed that when fly ash was added to recycled aggregate concrete the pore structure was improved, and particularly the macro pores volume was reduced causing benefits in terms of mechanical performance. From the serviceability point of view, the drying shrinkage of recycled aggregate concrete did not appear to be a problem since the same risk of crack formation resulted in ordinary concrete. As far as corrosion aspects were concerned, the use of fly ash appeared very effective in protecting galvanized steel reinforcement in porous concrete, as it could occur when recycled aggregates are used, even with cracked concrete. Resistance to chloride ion penetration was investigated concerning the durability of recycled aggregate concretes containing high volumes of fly ash. The Concrete mixture proportions are shown in the next two tables (Table 4.10 and Table 4.11).

Table 4.10: Concrete mixture proportions

<table>
<thead>
<tr>
<th>Mixture</th>
<th>NAT-0.6</th>
<th>REC-0.3</th>
<th>REC-WRA-0.3</th>
<th>REC-FA-0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/C</td>
<td>0.60</td>
<td>0.30</td>
<td>0.30</td>
<td>0.60</td>
</tr>
<tr>
<td>W/CM</td>
<td>0.60</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Mixture proportions, kg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>230</td>
<td>230</td>
<td>165</td>
<td>230</td>
</tr>
<tr>
<td>Cement</td>
<td>380</td>
<td>760</td>
<td>550</td>
<td>380</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>380</td>
</tr>
<tr>
<td>Natural Sand</td>
<td>314</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aggregate</td>
<td>1338</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 4.11: Physical properties of the aggregate fractions

<table>
<thead>
<tr>
<th>Aggregate Fractions</th>
<th>Bulk Specific Gravity</th>
<th>Water Absorption</th>
<th>Passing 75 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Sand</td>
<td>2620</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>Crushed Aggregate</td>
<td>2680</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>Fine Recycled Fraction</td>
<td>2150</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>Coarse Recycled Fraction</td>
<td>2320</td>
<td>8</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The chloride penetration into concrete was evaluated through the AgNO3 and fluoresce test (Collepardi et al. 1972) in concrete specimens exposed to a 10% NaCl aqueous solution after a wet curing of 1 week and an air curing of 3 weeks at a temperature of 20°C.

Table 4.12: Diffusion coefficients of chloride ions into different concretes at 20°C

<table>
<thead>
<tr>
<th>Mixture</th>
<th>NAT-0.6</th>
<th>REC-0.3</th>
<th>REC-0.3+</th>
<th>REC-FA-0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>D (cm² · s⁻¹ · 10⁻8)</td>
<td>1.90</td>
<td>0.87</td>
<td>0.72</td>
<td>0.46</td>
</tr>
</tbody>
</table>

The strong beneficial effect of fly ash on the chloride penetration depth measured from concrete sample REC-FA-0.6 is quite evident. In fact, the diffusion coefficient of chloride ions into REC-0.3 concrete doubled with respect to REC-FA-0.6, the only difference being the replacement of 50% of cement with fly ash.

Lower water/cement ratios also influence positively the concrete resistance against chloride penetration: the diffusion coefficient of chloride ions into NAT-0.6 concrete more than doubled with respect to REC-0.3, even though recycled aggregate was used.

The apparent chloride diffusion coefficients for all RCA-concrete specimens made of mixtures proportioned by the new EMV method were found by Abbas et al (Abbas, Fathifazl, Isgor, Razaqpur, Fournier, & Foo, Durability of Recycled Aggregate Concrete Designed with Equivalent Mortar Volume Method. Special Issue of the Journal of Cement and Concrete Composites on Sustainability of Civil Engineering Structures - Durability of Concrete, 2009) to be of the same order of magnitude as the specimens made of conventional structural-grade concrete (i.e. 10⁻¹² m²/s). The chloride penetration of RCA-concrete was investigated by conducting the acid soluble bulk diffusion test as per ASTM C 1556-04. This test method covers the laboratory determination of the apparent chloride diffusion coefficient for cementitious mixtures by measuring the acid soluble (total) chloride content. In fact, the apparent chloride diffusion coefficients for the RCA-concrete specimens proportioned by the EMV method were lower than those of the specimens made of mixture proportioned by the conventional method. The measured acid soluble initial chloride concentration of the RCA-concrete proportioned by the EMV method was found to be lower than the limits specified by the current standards.

There is a need for research that provides more data on the penetration of chloride in real conditions in situ. The miscellany of recently published papers, with results based in laboratory studies with accelerated tests led to conclusions relatively optimistic about the use of concrete with recycled concrete aggregates in environments with chlorides.
The use of low enough water/cement ratio and quality recycled aggregate free of chlorides and sulfates in the new concrete or the use of mineral admixtures, led to believe that it is possible to use concretes with high contents of recycled aggregate in media containing chlorides.

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5. Use of fine fraction

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5.1. Introduction

The increased concern on the reuse and beneficial application of construction and demolition waste (CDW) lead to a significant number of research studies mainly related to the use of the coarse fraction leaving behind the fine fraction for which there is little or no market at the moment.

Nowadays, the fine fraction, which accounts for 20% to 50% of the CDW stream, depending on the characteristics of the processing unit, is usually disposed off but with the increase of building activity this scenario has to be changed in order to avoid depletion of natural aggregates, divert construction and demolition waste from landfill and close the life cycle of building materials.

It is well known that fine recycled aggregates, e.g. from crushed concrete, have a higher content of mortar adhered to its surface than the coarse fraction and this characteristic will influence several properties like absorption or density, that restrict its use. Envisaging the removal of the binder attached to CDW different processing techniques, more or less committed to the fine fraction, have evolved.

Regarding its application, the use of fine recycled aggregates in the manufacturing of concrete is usually not allowed or very restricted owing to its high absorption capacity that could result in loss of workability, larger shrinkage and creep deformations, low durability and high permeability of the cement paste (Etxeberria, Mari, & Vázquez, 2007) (Hansen T. C., 1986) (Poon, Azhar, & Kou, Recycled aggregates for concrete applications, 2003). Depending on the composition of the fine fraction of CDW applications like back-filling material, road material or cement burning material have been proposed (YANAGIBASHI, A new concrete recycling process for coarse aggregate to be used in concrete structure., 2004). In recent years the use of the fine fraction in mortars and in paving blocks has also been subject of research.

From an environmental point of view fine recycled aggregate are more susceptible to contamination with foreign materials than the coarse fraction. Some measures applied during CDW collection, like selective demolition, are essential to control this feature. Minimization of contamination could also be achieve in recycling plants through implementation of adequate practises, for instance separation of fines coming from primary screening from those of crushing because of the higher content of contaminants, such as gypsum, organic materials
5.2. Processing fine recycled aggregates

The main constraint for producing high quality recycled aggregates from CDW relates to the chosen processing technology. In most countries recycling of construction and demolition waste usually relies on simple technologies, like crushing and screening, which are not efficient for taking away the binder stuck on the recycled aggregate surface, leading to low quality aggregates. This problem is much more evident in the fine fraction of construction and demolition waste hindering their application.

Advances in technologies based on mechanical scrubbing lead to the production of recycled concrete aggregates of improved quality. In the mechanical scrubbing – eccentric rotor type, crushed concrete lumps are fed into an eccentric tubular mill unit (Fig. 5.1) and the cement and mortar are removed from the surface of aggregates by eccentric rotation of two cylinders leading to coarse recycled concrete aggregates that comply with the requirements of Japanese standards for natural aggregates. Regarding the properties of concrete manufactured with these coarse aggregates they are similar to those of a concrete using natural aggregates (YANAGIBASHI, A new concrete recycling process for coarse aggregate to be used in concrete structure, 2004). Fine recycled aggregate produced by this technology does not have the adequate characteristics to be used in structural concrete.

Another type of mechanical scrubbing named screw-type is also used for the production of recycled (Fig. 5.2). The partition plates along the drum allow the separation of coarse and fine recycled fractions and attrition will promote reduction of the cement paste stick on aggregate surface.
An heating scrubbing method based rely on the use of hot air, at 300 ºC, to heat the concrete rubble and dehydrate cement paste, followed by a mechanical treatment, in which rubbing separates the brittle paste from the aggregates (Fig. 5.1) have been developed to enhance the properties of recycled aggregates. The generated coarse and fine recycled concrete aggregate can be used in ready mixed concrete while fine powder can be recycled as raw material for cement, as cement admixture, or as soil stabilizer (SHIMA, TATEYASHIKI, MATSUHASHI, & YOSHIBA, 2005).

Based on the experiments of Mitsubishi, TNO and KEMA Mulder et al. proposed a sorting process for concrete from CDW that combine a thermal and a mechanical procedure (MULDER, DE JONG, & FEENSTRA, Closed cycle construction: An integrated process for the separation and reuse of C&D waste, 2007). Heating at temperatures above 700ºC will remove the adhered the cement paste and almost all the constituents of the concrete waste will be recovered allowing closing the material life-cycle.
With the aim of improving the quality of fine recycled aggregates Weimann and Müller treated, in a pilot plant, uncontaminated crushed concrete fines from selective demolition by mixing with water and feeding the mix into a stirring unit, to remove the adhered mortar. This processing technology also include a hydrocyclone that allow elimination of particles sized under 100 μm, and a jig that promote the separation of the material into a heavy fraction, with density closer to that of natural fine aggregates, and a light fraction. This separation is based on the difference of materials densities, for example natural aggregates like quartz or dolomite have higher densities (quartz: 2.65 t/m³ and dolomite: 2.85-2.95 t/m³) than concrete (2.2-2.5 t/m³) and hardened cement paste (1.5 - 1.8 t/m³) (WEIMANN & MÜLLER, Effects of wet processed crushed concrete fines as secondary aggregates in building materials., 2008). This treatment changed the grading of the fines and the heavy fraction evidenced a reduction on binder content and an improvement in water absorption allowing a higher replacement level of fine recycled aggregates in concrete (WEIMANN & MÜLLER, Properties of building materials gained from wet processed crushed concrete fines, 2004).

![Flow scheme of the wet treatment process for crushed concrete fines](image)

**Fig. 5.5: Flow scheme of the wet treatment process for crushed concrete fines (WEIMANN & MÜLLER, 2008).**
MÜLLER, Effects of wet processed crushed concrete fines as secondary aggregates in building materials., 2008).

Yamasaki et al. developed a technique for removal of the mortar adhered to fine aggregate from waste concrete comprising direct carbonation with high pressure CO2 and ball mill crushing (Fig. 5.4). In addition to the recycling of fine aggregate this process can also be seen as a new measure for CO2 sequestration (YAMASAKI, y otros, 2006)

![Diagram of carbonation process](image)

Fig. 5.6: Recycling of fine aggregate using carbonation with high pressure CO2 (YAMASAKI, y otros, 2006)

Another approach for removal of the cement paste from the aggregates relies on a proactive methodology that relies on applying new procedures in the design phase of construction works that will lead to a closed lifecycle of the used materials. Noguchi and Tamura (NOGUCHI & TAMURA, Concrete design towards complete recycling, 2001) proposed that reducing the adhesive strength of original aggregates to cement paste, which is achieved through chemical or physical coating of the virgin aggregates, will facilitate aggregate recovery and lead to a completely recyclable concrete. Since this procedure for aggregate recycling could conflict with the mechanical behaviour of concrete Noguchi et al. (NOGUCHI, KITAGAKI, NAGAI, & TSUJINO, 2009) proposed as alternative the modification of coarse aggregate surface using silica fume and a dielectric material that allow increase of concrete strength up to 20% and after microwave heating recovery of 90% of high quality aggregate.

### 5.3. Characteristics of fine recycled aggregates

The variability of the characteristics of the fine fraction of construction and demolition waste has a great influence on the possible applications of this residue. According to Van der Wegen and Haverkort (VAN DER WEGEN & HAVERKORT, 1998) this fraction collected in different processing phases, after sieving or after crushing, shows diverse characteristics that will influence the performance of the building materials where they are applied. This chapter is devoted to the fine recycling aggregates resulting from CDW crushing, excluding the fine particles from primary screening. A brief review of the main properties for this fraction is presented hereafter.
5.3.1. Content of cement paste and fines

Cement paste content adhered to the surface of recycled aggregates plays a key role on prescribing their field of application. Cement mortar will affect the quality of recycled aggregates by lowering density, increasing water absorption and sulphate content (SÁNCHEZ DE JUAN & ALAEJOS, 2009).

The content of old cement paste can be as high as 45-65% in the 0 - 0.3 mm fraction of the fine recycled aggregate (Hansen T. C., 1986). Engelsen et al. (ENGELSEN, VAN DER SLOOT, WIBETOE, PETKOVIC, STOLTENBERG-HANSSON, & LUND, 2009) reported a cement paste content around 28% in fine recycled concrete aggregates, 0-4 mm, prepared in laboratory. Angulo et al. (ANGULO, ULSEN, JOHN, KAHN, & CINCOTTO, 2009) found an average of 17.7% of cement paste in the fine fraction of mixed CDW and 38% in the power sized below 0.150 mm.

Zega et al. (ZEGA, SOSA, & DI MAIO, Propiedades de los agregados finos reciclados procedentes de hormigones elaborados con diferentes tipos de agregados gruesos naturales., 2010) studied the properties of fine recycled aggregates prepared from crushing of concretes produced with different types of coarse natural aggregates. The content of cement paste was lower, 28%, on the fine recycled aggregates with origin on concrete with quartzite aggregates in relation to those of concretes with granite and basalt aggregates source, 39 and 36% respectively, and this fact affect the properties like water absorption and sodium sulphate attack.

Tseng (TSENG, 2010) also verified the increase of cement paste content with the decrease of particle size of recycled concrete aggregates, processed with jaw and impact crushers, by relating the calcium oxide content plus the loss on ignition to the binder percentage, in the absence of limestone aggregates (Fig. 5.7).

Reduction of cement paste attached to the surface of fine recycled aggregates could be achieved through processing. Mulder (MULDER, DE JONG, & FEENSTRA, Closed cycle construction: An integrated process for the separation and reuse of C&D waste., 2007)
reported a cement paste content of 2% on the sand grains from concrete recycled by a thermal process. Using mining engineer techniques, Ulsen (ULSEN, 2011) achieved high quality fine concrete aggregates with contents of cement paste lower than 10%.

According to Hansen and Narud (HANSEN & NARUD, 1983) the material finer than 75µm ranges from 0.8 to 3.5% in fine concrete aggregates below 4mm. Recycled fine aggregates obtained from crushed waste concretes, corresponding to the fraction 0 - 4.75 mm, presented a content of 4.3% of material finer than 75µm (ZEGA & DI MAIO, Comportamiento de hormigones elaborados con agregado fino reciclado, 2006). This percentage result lower than the limit indicated for natural fine aggregates on the Reglamento Argentino de Estructuras de Hormigón (CIRSOC 201), which is of 5.0%.

5.3.2. Density and water absorption

The density of recycled aggregates is lower in relation to fine natural aggregates and the water absorption is higher for recycled versus natural aggregates. These properties reflect not only the composition but also the processing operations during CDW recycling.

Evangelista and Brito (EVANGELISTA & BRITO, 2010) reported densities of 1.94 g/cm³ and 2.55 g/cm³ for fine recycled concrete aggregates and fine natural aggregate respectively. Zega and Di Maio (ZEGA & DI MAIO, Comportamiento de hormigones elaborados con agregado fino reciclado, 2006) also presented values for density of fine recycled aggregate, 2.48 g/cm³, which is inferior of that of natural fine aggregate, 2.59 g/cm³. Densities of 2.05 g/cm³, 2.34 g/cm³ and 2.65 g/cm³ were found for fine crushed bricks, fine recycled concrete and natural sand (KHATIB, Properties of concrete incorporating fine recycled aggregate, 2005). Densities of 2.0 to 2.5 g/cm³ (SOLYMAN, 2005).

Water absorption ranging from 8.3 to 12.1% for fine recycled aggregates were presented by Hansen (Hansen T. C., 1986). According to Solyman (SOLYMAN, 2005) this range is more extended, it goes from 3.8% to 11.5% in 10 min water absorption test. Fung (FUNG, 2005) quoting De Pauw et al. reported that for recycled CDW with grain sizes between 2-4 mm water absorption in 30 min amount over 90% of water absorption in 24 h, 10.12% and 10.95% respectively.

Water absorption has significant implication on water/cement ratios for concrete mixes so it is very important to have accurate results. Evaluation of water absorption of recycled fine aggregates is usually difficult to perform. According to Hansen (Hansen C., 1992) this difficulty is related to the amount of cement paste adhered to the surface of fine CDW. Solyman (SOLYMAN, 2005) pointed out some conditions, like the exclusion of particles below 125µm or achieving saturated particle surface dry, that lead to inaccurate measurements of water absorption and proposed an equation to predict water absorption (WA) from the water demand (MWD) of a mortar with recycled fine aggregates that have the same spread of a standard mortar prepared according to EN 196-3:

\[ WA = 0.059 \times MWD - 12.4 \]

\[ R^2 = 0.90 \]

5.3.3. Shape

Aggregate shape has an important effect in workability and water requirement of concrete.
According to Rashwan and Abourizk (RASHWAN & ABOURIZK, 1997) the crushing operation of the mineral fraction of CDW results in recycled aggregates having an angular shape that impair the workability when they are used owing to the higher internal friction (RASHWAN & ABOURIZK, 1997). For crushed fine recycled aggregates Hansen (Hansen T. C., 1986) reported that they are coarser and more angular than it is advantageous for having good concrete mixes.

Using a computer-aided particle analysis system Solyman (SOLYMAN, 2005) studied the length-width ratio (L/W) and the spherically (S) values of recycled sands and noticed that the former is similar to that of natural aggregates however spherically values of recycled fine aggregates diverge from those of natural aggregates and have a good correlation with water absorption up to 8%. Concerning surface texture, assessed by scanning electron microscopy (SEM), the smooth surface of natural aggregates no longer exists in recycled fine aggregates, Fig. 5.8. The texture of the recycled sands could be related to the loss of workability of concrete mixes incorporating these aggregates

By use of a vertical shaft impactor, VSI, tertiary crusher, Ulsen (ULSEN, 2011) increased the roundness of high quality fine concrete aggregates. The particles shape were evaluated by dynamic image analysis on QICPIC real time particle analyzer to appraise the influence of the attrition and abrasion crushing on particles sphericity as well as to compare the effect of the rotor speed as depicted in Fig. 5.9.

5.3.4. Deleterious substances

Deleterious substances represent major drawbacks for the reuse of the fine fraction of CDW, in particular the finest particles, below 75μm, which have a higher level of contaminants. The level of contamination is more or less significant depending on the delivery requirements of CDW at processing plants as well as on the operations that it will be subjected during processing.

As it is well known contaminants like gypsum or clay materials adversely affect the strength properties and durability of concrete so it is essential to reduce their contents. Owing to the lower density of these contaminants it is possible to minimize its content using separation techniques based on density. According to Montero et al. (MONTERO, y otros, 2010) for mixed construction and demolition waste gypsum is concentrated on densities between 1.59 to 2.28 g/cm³ so removal of material within this range will improve the contamination level.
5.4. Technical specifications for fine recycled aggregates

Gonçalves (GONÇALVES, 2007) analysed the specifications for recycled aggregates to be used on concrete and summarized some restrictions on their use. In Table 5.1 an updated overview of the limits regarding the use of the fine fraction of construction and demolition waste for that application in several countries is presented. As indicated a few number of countries permit that fine recycled aggregates can be used in concrete, namely Brazil, Denmark, Russia and Switzerland, and only two countries consent 100% substitution of fine natural aggregates for non-structural concrete, with a maximum allowed strength of 15 MPa. As detailed in 5.5.1 the research regarding application of fine recycled aggregates in concrete foresee a better implementation. Detailed information can be found on the cited specifications.

In recent years the Japanese Standards Association has established standards for high quality recycled aggregate for concrete, H, that are produced using some of the more advanced processing technologies and for concrete with low quality recycled aggregates, L, respectively JIS A5021 and JIS A 5023 (JSCE, 2007.). The physical requirements for fine aggregate and the limits of deleterious substances for high quality aggregates are listed in Table 5.2 and in Table 5.3.

Table 5.1 – Overview of the use of fine recycled aggregates
## Specification Classes

<table>
<thead>
<tr>
<th>Specification</th>
<th>Classes</th>
<th>Fine aggregate replacement level</th>
<th>Application clauses</th>
<th>Maximum allowed strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GGBS-II (RCA)</td>
<td></td>
<td></td>
<td>C30/37</td>
</tr>
<tr>
<td>Brazil (ABNT. NBR 15116:2004, 2004)</td>
<td>RCA</td>
<td>100%</td>
<td>Non-structural concrete. Recycled aggregates must be pre-saturated</td>
<td>15 MPa</td>
</tr>
<tr>
<td></td>
<td>RMA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>GP1 with or without testing (RCA)</td>
<td>20%</td>
<td>In non aggressive exposure classes</td>
<td>40 MPa</td>
</tr>
<tr>
<td></td>
<td>GP2(RMA)</td>
<td></td>
<td></td>
<td>20 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany (DIN 4226-100:2002-02, 2002)</td>
<td>1 (RCA)</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 (RCA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 (RMA)</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 (RMA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hong-Kong (EPD. WBTC No. 12/2002. , 2002)</td>
<td>RCA</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Netherlands (CUR, 1986)</td>
<td>RCA</td>
<td>20%</td>
<td>Combined with coarse natural aggregates in non aggressive exposure classes.</td>
<td>C40/50</td>
</tr>
<tr>
<td></td>
<td>RMA</td>
<td></td>
<td></td>
<td>C20/25</td>
</tr>
<tr>
<td>Portugal (LNEC-E471, 2009)</td>
<td>RCA1</td>
<td>0%</td>
<td>For concrete production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RCA2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Russia</td>
<td>RMA</td>
<td>100%</td>
<td>Not allowed in prestressed concrete</td>
<td>15 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50%</td>
<td></td>
<td>20 MPa</td>
</tr>
<tr>
<td>Spain (EHE, 2008)</td>
<td>RCA</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swiss (SIA., 2010)</td>
<td>RC-B (RCA)</td>
<td>N.d</td>
<td>Accept the use of fine recycled aggregate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RC-M (RA)</td>
<td>100%</td>
<td>Non-reinforced concrete</td>
<td>N.d</td>
</tr>
<tr>
<td>United Kingdom (BSI. BS 8500-2, 2006)</td>
<td>RCA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RA (RMA)</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RILEM (RILEM, 1994)</td>
<td>I (RMA)</td>
<td>N.d</td>
<td>Comply with specifications for natural fine aggregates</td>
<td>C16/20</td>
</tr>
<tr>
<td></td>
<td>II (RCA)</td>
<td></td>
<td></td>
<td>C50/60</td>
</tr>
<tr>
<td></td>
<td>III (M)</td>
<td></td>
<td></td>
<td>No limit</td>
</tr>
</tbody>
</table>

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Table 5.2 – Physical requirements for high quality fine recycle aggregate, H (JSCE, 2007.)

<table>
<thead>
<tr>
<th>Items</th>
<th>Fine aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven dry density (g/cm$^3$)</td>
<td>Not less than 2.5</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>Not more than 3.0</td>
</tr>
<tr>
<td>Abrasion (%)</td>
<td>NA</td>
</tr>
<tr>
<td>Solid volume percentage for shape determination (%)</td>
<td>Not less than 53</td>
</tr>
<tr>
<td>Amount of material passing test sieve 75 $\mu$m (%)</td>
<td>Not more than 7.0</td>
</tr>
<tr>
<td>Chloride ion content (%)</td>
<td>Not more than 0.4</td>
</tr>
</tbody>
</table>

Table 5.3 – Limits of deleterious substances for high quality recycled aggregate, H (JSCE, 2007.)

<table>
<thead>
<tr>
<th>Category</th>
<th>Deleterious substances</th>
<th>Limits (mass %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Tile, brick, ceramics, asphalt</td>
<td>2.0</td>
</tr>
<tr>
<td>B</td>
<td>Glass</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>Plaster</td>
<td>0.1</td>
</tr>
<tr>
<td>D</td>
<td>Inorganic substances other than plaster</td>
<td>0.5</td>
</tr>
<tr>
<td>E</td>
<td>Plastics</td>
<td>0.5</td>
</tr>
<tr>
<td>F</td>
<td>Wood, paper, asphalt</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3.0</td>
</tr>
</tbody>
</table>

5.5. Fine recycled concrete aggregates and fine recycled mixed aggregates

The application of CDW aggregates in the construction and building sector is largely related with the technology used in its processing. A general approach point to the use of recycled aggregate in concrete, in mortars and in roads but taking in account their specific properties some limits for incorporation have been indicated.

In some studies the lack of information about the type of fine recycled aggregates and their condition – dried, pre-wetted, pre-saturated - at the moment of mixing could influence the drawn conclusions when intercomparisons were performed.

5.5.1. Concrete

Studies regarding the combined used of fine recycled concrete aggregates and coarse recycled concrete aggregates in the manufacture of concrete evidence that the fine fraction, in
particular the one below 2mm, has a negative effect on mechanical properties and also on durability of concrete and so its use have been restricted or even prohibited for this purpose. (BUYLE-BODIN & HADJIEVA-ZAHARIEVA, 2002) (FRAAIJ, PIETERSEN, & DE VRIES, 2002) (Hansen T. C., 1986)

For concrete produced with coarse, fine or a mixture of coarse and fine recycled concrete aggregates. Kenai et al. (KENAI, DEBIEB, & ASSOUZ, 2002.) reported that for constant slump an increase of mixing water is needed, resulting on a decrease of mechanical performance and superior shrinkage in relation to a reference concrete. For 100% replacement of natural sand by recycled aggregate the compressive strength decrease 30% and shrinkage increase 70%. In order to overcome durability problems a maximum limit of 50% of fine recycled aggregates was indicated.

According to Corinaldesi and Moriconi (Corinaldesi & Moriconi, 2009) the lower mechanical performance of concrete incorporating mixed recycled aggregates, coarse and fine fraction, can be surpassed by the use of mineral additions. In this research, fly ash or silica fume replaced 15% or 30% by weight of cement and natural aggregates are totally replaced by recycled aggregates, with fine fraction reaching 26% of the whole aggregate. The mixing water is added in two steps, “two stage mixing procedure”, allowing the development an initial layer of cement slurry on the surface of recycled aggregates that strengthen the interfacial transition zone (TAM, GAO, & TAM, 2005.). The mechanical performance of concrete with recycled aggregate is similar to the reference concrete, with natural aggregates and without mineral additions. By decreasing the w/c ratio and maintaining the workability with a superplasticizer it is possible to achieve compressive strengths similar or better than those of the conventional concrete.

The difficulties associated with the combined use of fine and coarse fraction of CDW are partially overcome when only the fine fraction is replaced by recycled concrete aggregates. Dhir et al. (DHIR, LIMBACHIYA, & LEELAWAT, 1999) found that substitution of 20% of sand by fine recycled concrete aggregates on concrete production does not influence compressive strength. Regarding carbonation depth, freeze-thaw resistance and expansion due to sulphate exposure the achieved results do not compromise the intended use.

Masood et al. (MASOOD, AHMAD, ARIF, & MADHI, 2002) produced concrete with partial replacement, 10%, 20% and 30%, of the fine aggregate fraction of mixed CDW (lime concrete and lime mortar). Concretes with 30% substitution of the sand have a decrease around 26% on the 28 day compressive strength and 20% on modulus of elasticity. Flexural strength is also lower in relation to a conventional concrete but, according to the authors, the results allow the use of fine recycled aggregates in concrete in a defined range for replacing natural aggregates. Partial replacement of cement by demolished waste, up to 30%, evidence larger decreases on compressive strengths and modulus of elasticity, mainly for the higher level.

Evangelista and Brito (EVANGELISTA & BRITO, Criteria for the use of fine recycled concrete aggregates in concrete production., 2004) evaluated the replacement of fine recycled concrete aggregates in the production of concrete and verify that it is viable to replace up to 30% of the fine aggregates without significant differences on shrinkage and on water absorption by capillarity in relation to a reference concrete produced with natural aggregates with the same grading curve. Concerning compressive strength there were only small differences even for total replacement of the fine fraction. The lack of a significant effect of
concrete crushed fines on compressive strength was previously stated by Hansen (Hansen T. C., 1986). Data regarding splitting tensile strength and modulus of elasticity show a reduction of 5.2% and 3.7% respectively for a replacement level of 30%, but with entire substitution of fine aggregates the decrease reaches 30.5% and 18.5% (EVANGELISTA & BRITO, Mechanical behaviour of concrete made with fine recycled concrete aggregates, 2007). Regarding durability further studies, including assessment of carbonation resistance and non-steady-state chloride migration coefficient, highlight the feasibility of producing concrete with 30% fine recycled concrete aggregate (EVANGELISTA & BRITO, 2010).

Similar results on compressive strength were obtained when crushed concrete was used as fine recycled aggregates in concrete production: a decrease in compressive strength reaching 30% occurs when an integral substitution of fine aggregates is performed (KHATIB, Properties of concrete incorporating fine recycled aggregate., 2005). An increase on shrinkage and expansion was observed upon substitution of natural aggregates by crushed concrete fines.

According to Solyman (SOLYMAN, 2005) when recycled sand, mainly composed by crushed concrete and brick, replace natural fine aggregates on concrete production the reduction on compressive strength can be predicted, for w/c ratios between 0.48 and 0.66, by the equation:

\[ R = 97.5 \left( \frac{w}{c} \right)^2 - 112.5 \left( \frac{w}{c} \right) + 5.3 A_s - 2.6 A_b + 6.7 A_b + 31.3 \]

where: w/c - water to cement ratio (0.48 to 0.66)

\[ A_s \] - recycled concrete volume / total sand volume

\[ A_b \] - recycled brick volume / total sand volume

Fig. 5.10 depicts the reduction on compressive strength when only crushed concrete, \( A_s \), was used, with water to cement ratio ranging from 0.48 to 0.66.
This research also highlighted the possibility of producing concretes up to C35/45 when recycled concrete fines were used to replace natural sand, with a considerable decrease on consistency using pre-wetted recycled aggregates. Regarding the splitting-tensile strength, fsp, and the dynamic modulus of elasticity, $E_{\text{dyn}}$, the following relations with compressive strength, $f_{cm}$, apply:

$$\text{fsp} = 0.3 f_{cm}^{2/3} \quad \text{and} \quad E_{\text{dyn}} = 5400 f_{cm}^{0.551}$$

Concrete durability in the presence of recycled fine aggregates, addressed through the carbonation depth after one year and the frost de-icing salt resistance, was not noticeable when compared to reference concrete.

Concretes made with fine recycled concrete aggregate, in percentage higher than 25%, replacing the natural fine aggregate, showed a significant decrease of the slump, despite the increase in the dosage of plasticizer additive (ZEGA & DI MAIO, Comportamiento de hormigones elaborados con agregado fino reciclado, 2006). The compressive strength of recycled concretes made with 25, 50 and 75% in volume, of fine recycled aggregates, obtained from crushed waste concretes with unknown characteristics, determined at the age of 7, 28 and 70 days, was similar or higher than that of concrete made totally with natural aggregates and the static modulus of elasticity of recycled concretes was similar to that of reference concrete.

To assess the effect of fine recycled aggregates on reinforced concrete Reis et al. performed pull-out tests on concrete with 10mm and 16mm bars, incorporating 25% and 50% of fine recycled concrete aggregates, and. The bond strength decrease up to 30% in relation to a reference concrete, being this effect more noticeable when using higher diameter bars. (REIS, LEITE, & LIMA, 2009).

Durability studies concerning concrete with partial replacement of fine aggregates, up to 30%, by crushed concrete fines was performed by Zega and Di Maio (ZEGA & DI MAIO, Use of recycled fine aggregate in concretes with durable requirements, 2011). The effective water to cement ratio of recycled concretes is lower in relation to the control concrete and this condition justify the similar compressive strengths, carbonation depths and water penetration under pressure achieved. Compressive strength at 28d was 43.6 MPa for control concrete and 41.4 MPa for recycled concrete with 30% of fine recycled aggregate. Analogous drying shrinkage results, at 180 days, were attained for control concrete and recycled concrete with 20% of fine crushed concrete and a slightly lower value is observed with 30% of fine recycled aggregates. From the quantification of capillary absorption by sorptivity it was concluded that recycled concretes comply with the Argentinean Regulation requisites, i.e., below 4 g/m²/s¹/².

The use of the fine fraction of concrete waste can also be beneficial in the production of self-compacted concrete (SCC). Corinaldesi et al (CORINALDESI, MORICONI, & TITTARELLI, SCC: a way to sustainable construction development, 2005) found that the use as filler of the finest fraction of mixed CDW, below 90 µm, in self-compacting concrete (SCC) improve flowability as well as viscosity and segregation resistance as evidenced by
slump and L-box tests. Ultra-sonic pulse velocity measurements corroborate these findings. The use of this mineral addition in combination with coarse recycled aggregates could also lead also to the development of a sustainable SCC.

Kou and Poon (KOU & POON, 2009) produced SCC with 100% replacement of coarse recycled concrete aggregates and increasing level of replacement of the fine fraction and found that the mechanical properties present a maximum for substitutions between 25% and 50%. Regarding resistance to chloride penetration it increases with increase of fine recycled aggregates, probably owing to a filler effect caused by the fraction below 300 µm. Drying shrinkage also increase with the content of fine recycled aggregate but it can be controlled by the water to binder ratio.

Kim et al. (KIM, CHUN, PARK, & RYOU, 2011) used recycled fines from waste concrete, with a fineness modulus of 2.8, to replace 25, 50, 75 and 100% of fine aggregate on SCC. The workability decrease with increased substitution of the aggregate and the mechanical properties, compressive and flexural strength, indicate the viability of using up to 50% of recycled fine aggregates.

Corinaldesi and Moriconi (CORINALDESI & MORICONI, The role of industrial by-products in self-compacting concrete., 2011) evaluated the use of powder, below 150 µm, from concrete and masonry waste on SCC as an alternative to the use of a viscosity modifying agent. Rheological studies on cement pastes with rubble powder showed an increase on yield strength and plastic viscosity and a reduction of thixotropy, in relation to a reference cement paste, which evidence the relevance of this addition for application in SCC. Preparation of distinct SCC, regarding the type of addition and aggregates used, confirm the effectiveness of using the rubble powder mainly when coarse recycled aggregates replace natural aggregates. SCC mixes were proportioned to attain a volume, in the order of 190l/m³, of very fine particles. On the fresh state superior flowability and flow segregation resistance were achieved while on the hardened state there is no significant change on compressive strength. For SCC with total replacement of fine natural aggregates by fine recycled aggregates combined with the use of rubble powder poor 28 day compressive strengths were achieved.

5.5.2. Mortar

The use of the fine fraction of CDW in the production of mortars has been explored by several researchers. In order to improve the performance of rendering mortars made up with construction and demolition waste Miranda and Selmo (MIRANDA & SELMO, CDW recycled aggregate renderings: Part I - Analysis of the effect of materials finer than 75 [µm on mortar properties., 2006) (MIRANDA & SELMO, CDW recycled aggregate renderings: Part II - Analysis of the effect of materials finer than 75 [µm under accelerated aging performance., 2006) used a mix design based in two parameters, “aggregates and plasticizing materials to cement ratio” and “total materials finer than 75µm”. The results of this research show that mortars with 25% of finer particles or more are prone to cracking and that low levels of these particles lead to good workability.

Improvement of the quality of crushed concrete fines by a wet treatment, developed within the European project RECDEMO, was analysed through studies on mortars incorporating 100% of processed concrete fines with the same particle size, 0.1 to 4 mm, and different densities (WEIMANN & MÜLLER, Effects of wet processed crushed concrete fines as secondary
aggregates in building materials., 2008). For the heavy fraction a decrease of the cement paste stuck on the particle surface takes place and therefore the water absorption decrease, in opposition to what was observed on the light fraction. The decrease on binder content of the heavy fraction lead to an enhancement of the dynamic modulus of elasticity at 28 days for mortars prepared with this fraction as depicted on Fig. 5.11.

Further tests on concrete mixes using 20 and 50% of the same heavy fraction demonstrate improvements on compressive strength, dynamic modulus of elasticity and shrinkage, Fig. 5.12, evidencing the advantage of the wet treatment.

Studies regarding durability of mortars with fine recycled aggregates were evaluated by
testing the sulphate resistance, in sodium and magnesium sulphate solutions, of mortars produced with fine recycled concrete aggregates up to 100%. Better sulphate resistance was achieved on mortars with 50% replacement of fines in relation to a conventional mortar; the worst situation occurs for a 100% replacement level in which the observed deterioration is associated with gypsum and thaumasite formation. The level of mortar deterioration increase for fine recycled aggregates with higher water absorption (LEE, Influence of recycled fine aggregates on the resistance of mortars to magnesium sulfate attack, 2009) (LEE, SWAMY, KIM, & PARK, 2008).

Corinaldesi and Moriconi studied the use of fine recycled aggregates in bedding mortars in relation to a mortar with natural aggregate and observed that there was a decrease on the compressive and flexural strength of mortars containing fine recycled aggregate. However, the bond strength of the interface recycled mortar/brick was improved probably owing to the anti-thixotropic effect achieved by the decrease on yield stress and plastic viscosity of the cement paste in the presence of fine recycled aggregates, as evaluated by rheological tests. Because the enhanced adhesion is more important than mechanical behaviour in bedding mortars this can be a suitable application for the fine fraction of CDW (CORINALDESI, Mechanical behavior of masonry assemblages manufactured with recycled-aggregate mortars, 2009) (CORINALDESI & MORICONI, Behaviour of cementitious mortars containing different kinds of recycled aggregate, 2009a).

Mix design of mortars are dependent on the type of fine aggregate used (DE SCHUTTER & POPPE, 2004). Leite et al. (LEITE, LIMA, & SANTOS, 2009) analysed the feasibility of incorporating 50% and 100% of fine recycled aggregates on mortars using compensations rates for water absorption between 50% and 100%. The best balance between workability and compressive strength was achieved using a mortar mix design with a water compensation ratio of 80% but restrain on the use of fine recycled aggregates on mortars could occur for compensation ratios below 70% owing to loss of consistency.

Vegas et al. (VEGAS, AZKARATE, JUARRERO, & FRIAS, 2009) observed that water absorption of fine recycled concrete aggregates and also sulphur content are critical for their use on masonry mortars and replacement of natural sand by these recycled aggregates, up to 25%, is not unfavourable regarding mechanical performance, workability and shrinkage.

Dapena et al. (DAPENA, ALAEJOS, LOBET, & PÉREZ, 2011) incorporated fine recycled concrete, from structural concrete with compressive strengths in the range 15 to 35 MPa, in cement mortars to replace siliceous sand and limestone sand. Mortars with siliceous sand and fine recycled aggregates, up to 20%, could be adequately compacted and their compressive strengths are reduced in relation to a reference mortar, by 0.7 times the aggregate replacement percentage. For mortars using limestone sand and fine recycled aggregate a similar decrease on the compressive strength also occurs. Regarding flexural strength of mortars with partial replacement of aggregates by fine recycled aggregate a more accentuated drop was observed in the presence of siliceous sand when compared to those with limestone sand. On concrete specimens with up to 100% of recycled aggregates the substitution by 10% fine recycled aggregate has no relevant effect on compressive strength and on modulus of elasticity.

5.5.3. Blocks

The grading of aggregates required for the production of concrete blocks makes this application suitable for fine recycled aggregates. Soutsos et al (SOUTSOS, MILLARD,
Bungey, Jones, Tickell, & Gradwell (2004) studied the replacement of natural aggregates by recycled concrete aggregates in precast concrete blocks and observed that the substitution of 30% of the fraction 0 to 4 mm by recycled aggregates has a detrimental effect on compressive strength but increasing the cement content will allow to keep the level strength (Fig. 5.13). Recent studies indicate that 20% replacement of natural fine aggregates by concrete or masonry recycled aggregates have no significant influence on concrete block production (Soutsos, Tang, & Millard, Concrete building blocks made with recycled demolition aggregate., 2010).

Poon et al (Poorn, Kou, & Lam, Use of recycled aggregates in molded concrete bricks and blocks, 2002) used coarse and fine recycled aggregates to replace natural aggregates on concrete bricks and paving blocks and concluded that substitution up to 50% of the coarse and fine fraction has little influence on compressive strength but for higher replacement level this strength will be reduced. Regarding the flexural strength it increases with the increase on the recycled aggregates content.

Poon and Chan (Poorn & Chan, Paving blocks made with recycled concrete aggregate and crushed clay brick., 2006) also studied different compositions with recycled concrete aggregate and crushed clay bricks to be used as paving blocks. The paving blocks produced only with aggregates sized below 5 mm show an increase on tensile splitting strength and on water absorption and a reduction on density and on resistance to abrasion in relation to paving blocks produced using the fine and coarse fraction of recycled concrete aggregates, with the same replacement level by crushed clay bricks. Despite these changes the paving blocks made only with fine fraction comply with the requirements of Hong-Kong for paving blocks to be used in traffic areas.

A study regarding the feasibility of using fine aggregates from construction waste on the production of paving blocks, for residential applications, was performed by Chan and Poon (Poorn, Qiao, & Chan). Comparison of the results of compressive strength tests with the strength requirements of the Hong Kong and Australian/New Zealand standards, for the above application, allowed establishing recommendations on the maximum amount of waste to be used. As expressed in Table 5.4 only the use of recycled concrete aggregates is not restricted.
Fig. 5.13: Compressive strength against cement content for concrete blocks with replacement of the fine fraction (SOUTSOS, MILLARD, BUNGEY, JONES, TICKELL, & GRADWELL, 2004)

Table 5.4: Maximum allowable construction waste contents in paving blocks (CHAN & POON, 2006)

<table>
<thead>
<tr>
<th>Materials</th>
<th>Maximum % by weight of total aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled concrete aggregate</td>
<td>100.00</td>
</tr>
<tr>
<td>Clay brick</td>
<td>15.00</td>
</tr>
<tr>
<td>Ceramic tile</td>
<td>20.00</td>
</tr>
<tr>
<td>Recycled concrete masonry</td>
<td>20.00</td>
</tr>
<tr>
<td>aggregate</td>
<td>0.50</td>
</tr>
<tr>
<td>Lightweight aggregate</td>
<td>0.25</td>
</tr>
<tr>
<td>Timber</td>
<td>0.25</td>
</tr>
<tr>
<td>Bamboo</td>
<td></td>
</tr>
</tbody>
</table>

Comparison of paving blocks performance produced with fine recycled concrete aggregates and with fine recycled aggregates contaminated with crushed clay brick, crushed tile, crushed waste glass, and wood chips aggregate allow to advise an increase on contaminant to 10% for this application (POON & CHAN, Effects of contaminants on the properties of concrete paving blocks prepared with recycled concrete aggregates, 2007).

Dosho (Dosho, 2007) found that it is feasible the use of fine recycled aggregates on precast concrete products after improving their characteristics through adequate processing, wet grinding with an eccentric rotor. A relative absorption index that typify the aggregate quality,
estimated from the absorption and absolute volume of recycled aggregate, must be used in concrete design with these aggregates. The precast concrete products with fine recycled aggregates using steam curing meet the requirements of strength and durability.

Recycled aggregates from concrete precast elements can be incorporated in prefabricated units for non-structural applications. Substitution of crushed aggregates 0/4 by recycled aggregates up to 50%, with a similar size distribution, resulted in concrete with comparable properties (PELUFO, SERNA, JACQUIN, ULLOA, & LÓPEZ, 2009).

5.5.4. Roads

The large quantities of aggregates used on road construction along with the increase of CDW led to the sustainable practice of incorporating these residues as substitutes of natural aggregates. Reports on recycling construction and demolition wastes in road layers usually cover the use of the fine and the coarse fraction.

Huang et al studied the fine fraction of construction and demolition waste, coming from a mechanical sorting plant of C&DW, through sieve analysis, LA abrasion test, freezing test, organic content test, and fineness test and concluded that it is appropriate as a material for roadbeds if contamination is removed in advance or it could be used to cover daily waste streams disposed in landfills (HUANG, LIN, CHANG, & LIN, 2002).

Cho and Yeo analyzed the use of coarse and fine recycled aggregates in concrete pavement and verified that the important decrease in flexural strength prevented its use in this application; however the strength requirements for lean concrete base are fulfilled using coarse and fine aggregates if the level of impurities can be controlled below 25% (CHO & YEO, 2004).

The use of different recycled sands, up to 21% of total aggregate mass, in hot bituminous mixtures evidenced the feasibility of their use in base and binder courses (SOLYMAN, 2005). Reduction on density, increase on mix stability and decrease of voids on mineral aggregate were observed. The optimum binder content is directly proportional to the water absorption of recycled aggregates.

Poon and Chan (POON & CHAN, Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base., 2006) researched the use of recycled concrete and crushed clay bricks as coarse fraction mixed with fine recycled concrete aggregate or fine crushed clay bricks as unbound sub-base materials for use in road construction. Blends with fine recycled concrete were more susceptible to moisture changes and exhibit higher maximum dry densities, lower optimum moisture content and higher CBR values toward those with fine crushed clay bricks, Fig. 5.14. The recycled sub-bases fulfil the minimum strength requirements of Hong-Kong.

It has been observed that the combined use of coarse and fine recycled concrete aggregates as unbound sub-base materials is sometimes coupled with an increase of strength over the time. This self-cementing capability, noticed by Arm (ARM, 2001) after triaxial tests in laboratory and FWD tests in the field with crushed concrete in unbound layers, was analysed by Poon, Qiao and Chan (POON, QIAO, & CHAN). These authors studied the size fractions <0.15, 0.15–0.30, 0.3–0.6, 0.6–1.18mm and <5mm of fine recycled concrete aggregates and ascribed the self-cementing characteristic primarily to the fractions <0.15 and 0.3–0.6 mm. The
withdrawn conclusion was based on evidence, from XRD experiments, that the particles sized below 0.15 mm have a higher C₂S content, and from that the fraction 0.3–0.6 mm in contact with water have a higher pH indicating a higher content of amorphous hydration products possibly supplying lime for supplementary reaction. The dominating factors associated to self-cementing properties are the age, grade and mix proportions of the original concrete as well as compaction and grading of the sub-base materials.

Fig. 5.14: Trend in maximum dry density and optimum moisture content: Serie I with fine recycled concrete aggregate; Serie II with fine crushed clay bricks (POON & CHAN, Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base., 2006)

The recycled fine powder from recycling concrete aggregates was used by Chen, Lin and Wu (CHEN, LIN, & WU, 2011) as filler in asphalt mixtures to replace limestone powder. Testing results evidenced a better water sensitivity and resistance to fatigue in relation to the control mix. The asphalt mixture with recycled powder complies with China specification for pavement construction even with a lower temperature performance.

5.5.5. Other applications

In a laboratory study Plaza C. et al (PLAZA, XU, TOWNSEND, BITTON, & BOOTH, 2007) verified that the recycled concrete, with particle size less than 2.5 cm, can be used as a cover layer in CDW landfill to reduce the emission of hydrogen sulphide, H₂S, generated from biological reduction of sulphate from gypsum drywalls. The authors suggest that the sorption of H₂S into the fine fraction followed by conversion to sulphide minerals could be the mechanism underlying the decrease of emissions, higher than 99%.

Shui et al (SHUI, XUAN, WAN, & CAO, 2008) assessed the use of fine recycled concrete aggregates after thermal treatment and grinding below 75 µm as cementitious constituent of mortars. After dehydration, on heating up to 500 ºC, the fine recycled aggregates and the hardened cement paste were used to produce mortars and the rehydrated phases were
investigated. The new phases, calcium silicate hydrate (C-S-H gel), ettringite and portlandite (CH), present a looser microstructure in relation to those of the original hardened cement paste that is partially responsible for the low values of mortar compressive strength. Enhanced mechanical response could be achieved by fly ash and Portland cement addition.

An alternative use of the fine fraction of CDW is based on hydrothermal curing. Hlawatsch et al. (HLAWATSCH, SCHLUTTER, BERGER, & KROPP, 2009) developed their research on construction products obtained by autoclave hardening fine aggregates under elevated temperature on an atmosphere of saturated water vapour. The main material under investigation were crushed concrete fines but other fine recycled aggregates gained from crushed clay bricks, hard fired clay bricks and calcium silicate bricks were also studied. Addition of lime or silica was used as a process to increase the fines reactivity.

On Fig. 5.15 the compressive strength resistance for some of the products after autoclave hardening at 200ºC during 12 h is presented. The strength values reached by autoclaved hardened pure concrete fines are attractive for producing construction products such as masonry units. For a finer grain size distribution, i.e. 40% of grains lower than 0.125 mm at a maximum grain size of 4 mm, the observed compressive strength increase up to 18.2 MPa. On carbonated concrete crushed fines the hardening process does not take place owing to the unavailability of calcium oxide; however upon addition of white lime the hydrothermal treatment was successful. Assessment of the pore structure by mercury intrusion porosimetry evidenced that augmenting the duration of the hardening period using concrete fines increase the total porosity and coarser pores with a decrease on compressive strength.

![Graph showing compressive strength of fine fractions of CDW](image_url)

**Fig. 5.15:** Strength characteristics of fine fractions of CDW with or without additions after autoclave hardening at 200 °C for 12 hours (HLAWATSCH, SCHLUTTER, BERGER, & KROPP, 2009)

The chemical composition of concrete fines includes siliceous fines and cement hydration products. Under hydrothermal conditions these compounds become reactive and microscopical observation on thin sections evidenced that the surface zones of quartzitic grains exhibited reaction rims where the quartz entered into reactions with CaO and water to
form calcium silicate hydrates, as illustrated in Fig. 5.16. The new calcium silicate hydrate phases (CSH) were formed with different CaO/SiO$_2$ ratios, which depend on the treatment duration, explaining the formation of the crystalline phases like tobermorite and gyrolite, observed in X-ray diffraction analysis.

![Quartzitic grain](image)

Fig. 5.16: Inner and outer reaction rims around a quartzitic grain with different CaO/SiO$_2$ ratios (HLAWATSCH, SCHLUTTER, BERGER, & KROPP, 2009)

The autoclave hardening of crushed concrete fines was also used by Al-Otaibi, El-Hawary and Abdul-Jaleel (AL-OTAIBI, EL-HAWARY, & ABDUL-JALEEL, 2010) for production of silica-lime bricks with promising results. Reference bricks, with 100% of crushed concrete fines, or mixtures of this residue with different supplementary cementitious materials and water, allowing enough consistency, were moulded and cured at 190-200°C under an adequate pressure program. Bricks using 20 and 40% of ground granulated blastfurnace slag (GGBS) or fly ash are within the water absorption limit of the standard specification for calcium silicate brick ASTM C73 (ASTM. C73, 2010). Regarding compressive strength it was principally enhanced when GGBS up to 40% replace crushed concrete fines.

Achtemichuk et al. (ACHTEMICHUK, HUBBARD, SLUCE, & SHEHATA, 2009) found that it is feasible to produce controlled low strength materials (CSLM) using fine recycled concrete aggregates combined with slag or high-calcium fly ash instead of Portland cement. The increase of strength is related to hydraulic and pozzolanic reactions of the industrial by-products, being the last ones promoted by the alkalies present on the cement paste adhered to recycled aggregates surface. Some applications like permanent structural fill and road bases not requiring short hardening time and bedding for conduits with small spacing were envisaged for CLSM. If the coarse fraction on recycled concrete aggregates is also used the field of application become enlarged.

### 5.6. Recycled ceramics

According to Oikonomou (OIKONOMOU, 2005) ceramic waste represents approximately 30% of demolition wastes. For Juan et al (JUAN, y otros, 2010) the ceramic materials – bricks, wall tiles, sanitary ware, etc – constitute the major fraction of construction and demolition waste, around 54%. Even with this discrepancy the fact is that ceramic wastes correspond to an important part of CDW.
Research on the application of fine ceramic wastes relates to waste generated by the construction sector and by the ceramic industry so that the literature presented hereinafter cover wastes from these different sources.

The high proportion of clay minerals on ceramic wastes makes them a useful source of addition for the production of blended cements. Firing, with adequate temperatures, during fabrication of ceramic products could activate some clay minerals that become pozzolanic materials (MEDINA, SANCHEZ DE ROJAS, FRÍAS, & JUAN, 2011.). The use of glazed ceramic tiles for the production of blended cement was analyzed by Ay and Ünal (AY & UNAL, 2000). After grounding the tiles they were mixed with cement in percentages between 25 and 40%. The ground ceramic waste conforms to Turkish standard regarding pozzolanic properties. Results from bending and compressive strength, at 7 and 28 days, indicate the viability of producing cement with grounded waste tiles up to 35% addition.

Turanli, Bektas and Monteiro (TURANLI, BEKTAS, & MONTEIRO, 2003) researched the influence of 10, 20 and 30% of crushed clay brick, used as partial cement substitute, on alkali-silica reaction (ASR) of mortars using a reactive fine aggregate. Reference mortar bars, tested according to ASTM C1260 (ASTM. C1260, 2006), evidenced a severe cracking pattern in comparison to mortars containing crushed bricks. The expansion curves prove that the decline of ASR increase with the increase of cement replacement, achieving reductions around 70%, after 30 days, for the maximum incorporation of crushed clay bricks.

Lin et al. (LIN, WU, SHIE, HWANG, & AN, 2010) used waste brick, with particle size lower than 75 µm, as cement replacement in cement pastes and verified that pozzolanic reactions begin to develop after 28 days curing with a decrease on portlandite content and a densification of the cementitious matrix.

Red roof tiles waste, non glazed, natural glazed and black glazed, were powdered below 44 µm and were analyzed to evaluate their feasibility of being used as additions in blended cements, on percentages between 20 and 40% (LAVAT, TREZZA, & POGGI, 2009). Results from the Fratini pozzolanic test were positive and they were corroborated by reduction on the Ca-OH peak, related to portlandite content, on infrared spectra acquired by FTIR spectroscopy. Compressive strength results point to 20 to 30% replacement of cement by these wastes without compromising the mechanical resistance.

Waste bricks, from brick manufacture, were used to replace 5 to 20% of clinker (NACERI & HAMINA, 2009) on cement to be used in mortars. The increase of brick waste reduced the cement grinding time up to 10%, which represents a decrease on energy consumption. Cement pastes show a decrease on setting time with increase of waste content that is related to the higher water absorption of the residue. Compressive and flexural tests on mortars indicate that similar resistances were achieved at 90 d for a substitution of clinker by 10% of ceramic bricks suggesting that this is the adequate level of replacement.

Replacement of ceramic wastes, fired at different temperatures, as fine recycled aggregate on mortar, substituting 20% of sand, resulted in slight differences on flexural and compressive resistances (FRIÁS, MARÍN, RIVERA LOZANO, & SÁNCHEZ DE ROJAS, 2001). The total porosity does not undergo great changes and in the most unfavourable situation, ceramic fired at higher temperature, the difference on porosity does not reflects on the apparent density neither on the average pore size of mortar. Data from a ceramic factory of concrete
tiles in which ceramic wastes replaced 5 and 10% of the siliceous sand show a maximum loss of 5% on transversal flexion strength for the high level of sand replacement. Freeze and thaw and impermeability tests results comply with the requirements of the European standard. EN 490 - Concrete roofing tiles and fittings for roof covering and wall cladding - Product specifications.

Khatib (KHATIB, Properties of concrete incorporating fine recycled aggregate, 2005) researched the use of crushed bricks as fine recycled aggregates for concrete. Using crushed bricks no compressive strength reduction was observed for a 50% level of replacement and for a 100% level of replacement a reduction of only 10% occurs. Higher shrinkage and expansion were recorded for concrete with fine crushed brick.

Poon and Chan (POON & CHAN, The use of recycled aggregate in concrete in Hong Kong., 2007) studied the use of fine crushed bricks and tiles in concrete and verified that for 20% replacement of fine aggregates there is a decrease in mechanical strength, in relation to a reference concrete, that could be partially overcome using a double mixing procedure, i.e., mixing recycled aggregates, addition of half of the water, mixing step, addition of cement, mixing step, addition of the rest of the water and another mixing step. Non structural concrete applications, such as road curbs and road barriers are suggested for the application of concrete with fine crushed bricks and tiles aggregates.

Debieb and Kenai (DEBIEB & KENAI, 2008) produced concrete mixes using different replacement levels of coarse and of fine recycled brick aggregates and, from the decrease on the performance of concrete, set up limits for the use of the coarse fraction and of the fine fraction, respectively 25% and 50%, and restrict the application of concrete to pavement blocks and other manufactured elements.

Precast concrete paving blocks, produced at laboratory using vibration and compaction to simulate industrial processing, were used to investigate the feasibility of total replacement of natural aggregates by simultaneous use of recycled ceramic wastes sized 0 - 4 and 4 - 8 mm, with or without superplasticizer (MARTINS & GONÇALVES, 2008). Water absorption, abrasion resistance and tensile splitting strength tests allowed to verify the conformity of the fabricated blocks with the requirements for paving blocks of EN 1338 (COPRÓ. PTV 406.Version 2.0:2003, 2003). The water absorption was recognized as a critical characteristic but the use of chemical admixture allowed surpassing this issue.

Durability studies of mortars with crushed clay bricks partially replacing the aggregates, evidenced a decrease on flowability with the increase on bricks content, no significant effect regarding compressive strength, up to 20% replacement, a decrease on shrinkage, in a narrow range, with augmenting crushed clay bricks from 10% to 20% and a better freeze-thaw resistance for higher replacement level (BEKTAS, WANG, & CEYLAN, 2009). Alkali silica reaction was positive with these recycled aggregates when the mortar bar test was performed (ASTM. C1260, 2006) (ASTM. C73, 2010) and the worst result was assigned to a crushed brick content of 30%, nevertheless there is no similar report on the literature on this subject so it should be further investigated.

The use of recycled ceramic aggregates, bricks and tiles, on plastering mortar was studied by Silva et al. (SILVA, DE BRITO, & VEIGA, 2010). The authors reported that 50% substitution of sand by brick waste resulted in mortars performing as well as a reference mortar, exception made to dimensional stability. For the modified mortar with 20% brick waste the main advantages rely on flexural and compressive strength and water permeability due to capillary action in relation to the reference mortar.
Pacheco-Torgal and Jalali (PACHECO-TORGAL & JALALI, 2010) studied the use of different ceramic wastes in concrete as cement and as aggregate substitutes. In the first case concretes with 20% of cement replaced by ceramic powder, sized less than 75 µm, evidenced a slight decrease on compressive strength, no relevant effect on oxygen permeability and an improvement on water permeability and on resistance to chloride penetration in relation to a reference concrete. Concrete mixes with ceramic wastes taking the place of sand present a gain on compressive strength along with a superior durability performance.

Puertas et al. (PUERTAS, y otros, 2008) found that the use of white and red ceramic waste as raw materials for Portland cement clinker increase reactivity and burnability in relation to conventional raw mixes when particle size is lower than 90 µm, in particular for red ceramic waste.

5.7. Conclusions

Recycling of the fine fraction from construction and demolition waste is essential since the increased use of the recycled coarse fraction result in massive quantities of the former that is still disposed of in landfill.

Similarly to other materials the fine recycled aggregates characteristics, mainly the cement paste content, influence their uses in the production of materials to be applied in civil engineering works but do not inhibit it. Within a recycling perspective the environmental issues cannot be set aside. This subject is of special concern regarding the fine fraction from construction and demolition waste owing to the potential presence of contaminants in the particles sized below 75 µm.

The research concerning the fields of application of the fine fraction of CDW highlights the feasibility of replacement of a considerable mass of fine natural aggregates by fine recycled concrete or fine mixed aggregates on different segments, with special emphasis in concrete, mortars, blocks and roads.

For concrete production most of the studies deal with fine recycled concrete aggregates, in percentages up to 30%, without significant loss of mechanical properties and similar durability characteristics in comparison to a reference concrete. Improvement of concrete characteristics could be attained in the presence of fine recycled aggregates by adjusting the mixing procedure. Self-compacted concrete prepared with recycled concrete or mixed aggregates is also a valid option for fine recycled aggregates, with replacement levels around 50%, as verified through the rheological behaviour.

Mortars produced with fine recycled aggregates up to 25% could have adequate properties depending on the type of aggregates. Improved durability and enhanced adhesion are some valuable characteristics for rendering and bedding mortars.

The production of blocks allows that fine recycled aggregates be successfully applied, alone or combined with coarse recycled aggregates, being viable to replace the whole natural aggregates when recycled concrete aggregates were used.

In roads vast quantities of fine recycled aggregates can be incorporated in base and sub-base
layers, with the advantage that fine crushed concrete could present self-cementing properties resulting on strength increase over time. Application on hot bituminous mixtures used as base and binder course represents another alternative.

Some special applications for the fine fraction of CDW such production of masonry units by hydrothermal curing or production of controlled low strength materials is under development. For fine ceramic wastes the viability of their use as a pozzolanic material for production of cement blends could be regarded as an opportunity to attain a decrease on the clinker factor, with the consequent reduction on CO₂ emissions. In general, cement substitution up to 30% result on structure densification and possible prevention of alkalis-silica reaction without compromising compressive strength. The use of fine ceramic wastes in partial replacement of natural aggregates, in percentages in the range 20 to 50%, on mortars, concrete and precast concrete products revealed to be practicable.

Regardless of the opportunities identified for the use of the fine fraction of CDW and of the environmental advantages that could be achieved the lower prices of fine natural aggregates, the lack of dissemination of reliable scientific information and the absence of particular specifications are some factors that still compromise the use of fine recycled aggregates and must be overcome.

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6. Quality assurance of recycled aggregates

Recycled aggregates differ from the natural aggregates in several properties (density, absorption, LA coefficient, etc), making their quality lower in general, but good enough in many cases to be used in different applications inside the construction field.

The composition and the nature of its components are the principal parameters affecting the final quality of the recycled aggregates. This quality can be controlled mainly by means of density and absorption characteristics, as different International Standards establish (Table 6.1).

Table 6.1: Density and absorption specifications of different International Standards

<table>
<thead>
<tr>
<th>STANDARD</th>
<th>Density</th>
<th>Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rilem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type I</td>
<td>≥1500 kg/m³</td>
<td>≤20%</td>
</tr>
<tr>
<td>Type II</td>
<td>≥2000 kg/m³</td>
<td>≤10%</td>
</tr>
<tr>
<td>Type III</td>
<td>≥2400 kg/m³</td>
<td>≤3%</td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine aggregate (low quality)</td>
<td>≥2000 kg/m³</td>
<td>≤13%</td>
</tr>
<tr>
<td>Fine aggregate (medium quality)</td>
<td>≥2500 kg/m³</td>
<td>≤10%</td>
</tr>
<tr>
<td>Fine aggregate (high quality)</td>
<td>≥2500 kg/m³</td>
<td>≤3%</td>
</tr>
<tr>
<td>Coarse aggregate (low quality)</td>
<td>≥2200 kg/m³</td>
<td>≤7%</td>
</tr>
<tr>
<td>Coarse aggregate (medium quality)</td>
<td>≥2500 kg/m³</td>
<td>≤5%</td>
</tr>
<tr>
<td>Coarse aggregate (high quality)</td>
<td>≥2500 kg/m³</td>
<td>≤3%</td>
</tr>
<tr>
<td>Belgium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GBSB-I</td>
<td>≥1600 kg/m³</td>
<td>≤18%</td>
</tr>
<tr>
<td>GBSB-II</td>
<td>≥2100 kg/m³</td>
<td>≤9%</td>
</tr>
<tr>
<td>Australia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>≥2100 kg/m³</td>
<td>≤6%</td>
</tr>
<tr>
<td>Hong Kong</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Tipo II)</td>
<td>≥2000 kg/m³</td>
<td>≤10%</td>
</tr>
<tr>
<td>Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>≥2000 kg/m³</td>
<td>≤10%</td>
</tr>
<tr>
<td>Type 2</td>
<td>≥2000 kg/m³</td>
<td>≤15%</td>
</tr>
<tr>
<td>Type 3</td>
<td>≥1800 kg/m³</td>
<td>≤20%</td>
</tr>
<tr>
<td>Type 4</td>
<td>≥1500 kg/m³</td>
<td>-</td>
</tr>
<tr>
<td>Brasil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCA</td>
<td>-</td>
<td>≤7%</td>
</tr>
<tr>
<td>MRA</td>
<td>-</td>
<td>≤12%</td>
</tr>
<tr>
<td>Portugal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ARB1</td>
<td>≥2200 kg/m³</td>
<td>≤7%</td>
</tr>
<tr>
<td>ARB2</td>
<td>≥2000 kg/m³</td>
<td>≤7%</td>
</tr>
<tr>
<td>ARC</td>
<td>≥2000 kg/m³</td>
<td>-</td>
</tr>
<tr>
<td>Spain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCA</td>
<td>-</td>
<td>≤7%</td>
</tr>
</tbody>
</table>
Table 6.1 shows different grade qualities of recycled aggregates depending on the country: densities may range from 1500 kg/m$^3$ to 2500 kg/m$^3$ and absorption from 20% to 3%. Best qualities are related to aggregates consisting mainly of stone particles, while the low qualities include those mixed aggregates with high contents of porous ceramic particles.

Other properties are also important regarding the final behaviour of recycled aggregates, as the presence of impurities (plastic, gypsum plaster, glass, etc) which can affect both mechanical and durability properties of concrete. The content of these contaminants (see section 3.1.3) must be controlled to reach a suitable quality level.

### 6.2. Variation in the properties of recycled aggregates

Recycled aggregates are quite more heterogeneous compared to natural aggregates, varying their characteristics along the production. This variation is present even when the aggregate comes from pure crushed concrete, mainly due to the different quality of the concrete debris stocked at the recycling plant, but also to the incidental presence of contaminants.

For masonry wastes, this heterogeneity also affects to the composition of the aggregate and can be appreciated even at first sight (Fig. 6.1)

![Fig. 6.1: Heterogeneous composition of recycled aggregates (Mueller, Determination of the composition of C&D recycled aggregates, 2008)](image-url)
Table 6.2 and Table 6.3 show variations measured in different properties of both concrete and mixed recycled aggregates, taken from the references indicated.

### Table 6.2: Variation of concrete recycled aggregates properties

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>Mean value</th>
<th>Standard Deviation</th>
<th>Coefficient of variation (%)</th>
<th>Sampling period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption (%)</td>
<td>5.44 [4.7-6.5]</td>
<td>0.52</td>
<td>9.6</td>
<td>6 months (11 samples)</td>
<td>(Sagoe-Crentsil &amp; Brown, 1998)</td>
</tr>
<tr>
<td></td>
<td>4.87 [4.4-5.28]</td>
<td>0.30</td>
<td>6.2</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>5.79 [1.75-10.07]</td>
<td>*</td>
<td>*</td>
<td>12 months (15 samples)</td>
<td>(Karlsen, Petkovic, &amp; Lahus, 2002)</td>
</tr>
<tr>
<td>Granulometric modulus (%)</td>
<td>6.48 [6.34-6.57]</td>
<td>0.09</td>
<td>1.4</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>6.85 [6.64-7.21]</td>
<td>*</td>
<td>*</td>
<td>12 months (15 samples)</td>
<td>(Karlsen, Petkovic, &amp; Lahus, 2002)</td>
</tr>
<tr>
<td></td>
<td>[6.7-7.2]</td>
<td></td>
<td>1.7</td>
<td></td>
<td>(Sánchez de Juan &amp; Alaejos Gutiérrez, Estudio sobre las propiedades del árido reciclado: utilización en hormigón estructural, 2006)</td>
</tr>
<tr>
<td>Saturated surface-dry density (kg/m³)</td>
<td>2.394 [2.319-2.494]</td>
<td>0.06</td>
<td>2.6</td>
<td>6 months</td>
<td>(Sagoe-Crentsil &amp; Brown, 1998)</td>
</tr>
<tr>
<td></td>
<td>2.462 [2.440-2.450]</td>
<td>0.12</td>
<td>0.8</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>[2.38-2.48]</td>
<td></td>
<td>1.77</td>
<td>12 months (15 samples)</td>
<td>(Sánchez de Juan &amp; Alaejos Gutiérrez, Estudio sobre las propiedades del árido reciclado: utilización en hormigón estructural, 2006)</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>2.400 [1.330-1.540]</td>
<td>0.08</td>
<td>5.7</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td>Crushing value (%)</td>
<td>23.3 [21.2-25.7]</td>
<td>1.39</td>
<td>6.0</td>
<td>6 months</td>
<td>(Sagoe-Crentsil &amp; Brown, 1998)</td>
</tr>
<tr>
<td>Attached mortar (%)</td>
<td>12.8</td>
<td>1.2</td>
<td>9.4</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>[27.2-54.3]</td>
<td></td>
<td>19.6</td>
<td>12 months (15 samples)</td>
<td>(Sánchez de Juan &amp; Alaejos Gutiérrez, Estudio sobre las propiedades del árido reciclado: utilización en hormigón estructural, 2006)</td>
</tr>
<tr>
<td>Lightweight particles (%)</td>
<td>2.79 [0.55-5.02]</td>
<td>1.75</td>
<td>62.7</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>[0.0-5.85]</td>
<td></td>
<td>151</td>
<td>12 months (15 samples)</td>
<td>(Sánchez de Juan &amp; Alaejos Gutiérrez, Estudio sobre las propiedades del árido reciclado: utilización en hormigón estructural, 2006)</td>
</tr>
</tbody>
</table>
Table 6.3: Variation of recycled aggregates composed of ceramic waste and concrete

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>Mean value</th>
<th>Deviation</th>
<th>Coefficient of variation (%)</th>
<th>Sampling period</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption (%)</td>
<td>7.49</td>
<td>1.43</td>
<td>19.1</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>[4.5-9.7]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granulometric modulus (%)</td>
<td>5.5</td>
<td>3.07</td>
<td>*</td>
<td>13 samples</td>
<td>(Mueller &amp; Winkler, Characteristics of Processed Concrete Rubble, 1998)</td>
</tr>
<tr>
<td></td>
<td>[0.6-11.8]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satured surface-dry density (kg/m³)</td>
<td>2.362</td>
<td>0.06</td>
<td>2.5</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>[2.226-2.462]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>1.300</td>
<td>0.07</td>
<td>5.4</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>[1.180-1.420]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attached mortar (%)</td>
<td>19.7</td>
<td>2.3</td>
<td>11.7</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td>Lightweigt particles (%)</td>
<td>7.55</td>
<td>4.17</td>
<td>55.2</td>
<td>3 months (10 samples)</td>
<td>(Yanagi, Nakagawa, Hisaka, &amp; Kasai, 1988)</td>
</tr>
<tr>
<td></td>
<td>[2.24-15.88]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For aggregates coming from masonry debris, the composition is an important characteristic to be controlled and that can be related to a great dispersion. Thus, the tests show that the coefficient of variation can reach up to 17.6% (Fig. 6.2).

Some standards establish limits to the variation of specific properties of recycled aggregates. DIN 4226-100 Standard requires for density a tolerance of ±150 kg/m³ and BRE 433 is more
strict as requires a variation ±1%.

In Belgium the BENOR volunteer mark requires the following tolerances for density and absorption both for natural and recycled aggregates (Table 6.4).

<table>
<thead>
<tr>
<th>Gravillons selon NBN EN 1097-6, §8</th>
<th>Sables alluvionnaires ou marins selon NBN EN 1097-6, §9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masse volumique réelle P&lt;sub&gt;25&lt;/sub&gt;</td>
<td>Tollerence max. admise valeur individuelle</td>
</tr>
<tr>
<td>Valeur moyenne = valeur déclarée</td>
<td>± 70 kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Absorption d'eau W&lt;sub&gt;AW&lt;/sub&gt;</td>
<td>Valeur moyenne = valeur déclarée</td>
</tr>
</tbody>
</table>

### 6.3. Factors affecting the quality of the recycled aggregate

#### 6.3.1. Influence of the production process

To obtain recycled aggregate properties suitable for use in higher value applications, operations should be put in place to (Wrap):

- Restrict the type of CDEW that is used.
- Separate materials before crushing.
- Screen out oversize materials.
- Crush twice: using primary and secondary crushers.
- Separate out impurities.
- Wash aggregates.

The following chart (Fig. 6.3) shows the complete process from a case study of a Recycling Plant Process to obtain high value aggregates (40, 20, 10 mm and sand).
Apart from the basic treatment (crushing, screening, use of magnets), some specific aspects to improve the quality of the aggregate are:

- The use of a log washer to eliminate clay
- Plastic removed by air knives.
- After washing the aggregate, the use of a thickener where a flocculent is added. The resulting water is then recycled by means of a Diemme clay press, obtaining a puddle clay which is a saleable end product used for landfill linings.
- Following the washing process, the material is sent to a static screening unit consisting of a 12 x 5 screen with a 3-way split. The 3-way split allows products of 10/10mm, 20/20mm and 40/40mm to be collected. In addition, sand of 0/4mm is collected.

### Aspects related to the incoming wastes

An initial basic measure to be taken in order to avoid an excessive heterogeneity in recycled aggregates is the control of the incoming deliveries to the recycling plant, clearly separating the different wastes depending on its nature: pure concrete, mix with ceramic, asphalt, etc.

In practice, the recycling plants usually distinguish the truck load depending on its weight at the entrance. Three possible classes can be used (Gestora de Runes):
Class I: Wastes with a bulk density over 1.45 t/m³
Class II: Wastes with a bulk density over 1.10 t/m³
Class III: Wastes with a bulk density under 1.10 t/m³

Different Waste Taxes apply for each case as the low density loads usually involve wastes more contaminated, which require a more complex processing to eliminate impurities and an additional cost to carry the rejected material to dump.

At the same time of weighing, the truck must be inspected at the entrance, both the visual inspection and the weight helps for a correct and uniform stocking (Fig. 6.4). Finally, also a visual inspection is recommended at the discharging point, to check the nature of the whole load.

Many of the leading recycled aggregate producers in Europe have recognised that in order to obtain RA with properties suitable for use in higher-value applications it is necessary to restrict the type of wastes put through the crushing plant. An example of good practice in Europe is to separate all materials arriving at a recycling centre into three distinct colour-coded groups (Wrap):

- Black: Asphalt (Fig. 6.5 (a))
- White: Concrete (Fig. 6.5 (b))
- Red: Mixed waste, but generally comprised of brick (Fig. 6.5 (c))

![Image of recycling centre]

![Image of recycling centre invoice]

![Image of recycling centre invoice details]

![Image of recycling centre invoice details]
Fig. 6.4: Image of the truck load on the mirror at the entrance cabin of the recycling plant and weight data of the computer with an estimation of the load bulk density.

Fig. 6.5: Materials separated into distinct colour-coded groups

The activities of contractors bringing construction and demolition wastes to the recycling centre could be monitored (sometimes using CCTV), and any contractors found to be violating the rules be banned. The success of these operations is marked by the lack of asphalt and concrete in the “red” pile. Clearly, the success of such an operation is dependent on demolition and excavating contractors to separate materials at source.

The recycled concrete aggregate (RCA) is created from the “white waste”. The recycled aggregate (RA) is produced from the “red waste” and is largely brick-based. RCA may sometimes be added to brick-based RA to improve the performance of the product.

Clearly, reliance on external contractors imposes an element of risk in ensuring the consistent and overall quality of recycled aggregates. For this reason some large demolition contractors produce recycled aggregates using only CDEW sourced from their own work. The resulting RCA and RA are usually of very high quality (Wrap).

Whilst best-practice leads to good separation of CDEW and good quality end-products, many smaller recycling companies are unable to put sufficient pressure on contractors to segregate materials at source, nor the capability to police the contractors on-site. Therefore RA produced in many operations, whilst nominally brick based often has an asphalt content too high for use in cement bound applications.

Moreover, in order to have confidence in the final RCA products with respect to dangerous substances and thus to avoid extensive testing of the final product, it is also important to have as much knowledge as possible of the construction and demolition material to be recycled. Chapter 4 gives the minimum data that should be collected for every incoming load to the Recycling Plant, according to European Standards. However, if a high grade quality of recycled aggregate wants to be achieved, it is also advisable to obtain complete information from the waste source (Yanagi, Nakagawa, Hisaka, & Kasai, 1988) (Karlsen, Petkovic, & Lahus, 2002):

- Demolition site details, at least type of structure: building, bridge, pavement, marine structure, etc.
- Reason of the demolition
- Original concrete characteristics:
  - Type: mass, reinforced, prestressed
Compressive strength
Possible use of aluminous cement

This information may be useful with different purposes:

- To identify original concretes that can produce low quality aggregates (possible existence of chemical concrete pathologies, concrete affected by fire, etc).
- To separate recycled aggregates that should not be used for high grade applications.
- To separate incoming wastes that can be supplied for certain categories of end use with little or no processing (Wrap, 2005).
- To optimize the potential use of the recycled aggregates (for example high quality recycled aggregates obtained from original prestressed concrete could be specifically used for the production of a new structural concrete).

**Influence of the crushing process**

To achieve the most desirable grading curves and shape for recycled aggregates, a series of successive crushers (or crushes) and screening should be used; with oversized material returned to the respective crusher (Wrap).

Both the jaw crushers (usually called primary crushers as they can handle larger fragments) and impact crushers (secondary crushers) may be suitable to process CDEW, depending on different factors: presence of impurities, nature of the waste (stone, concrete, bricks, etc), size of the incoming blocks, kind of final product (Kleemann GmbH).

The main characteristics of impact crushers are as follows (Kleemann GmbH):

- They give RA a more rounded shape which is beneficial for engineering performance (Wrap).
- They provide aggregates with very good grading.
- The modern equipment allows the same incoming size block than the jaw crushers obtaining up to 75% artificial graded aggregate in one step.
- On the contrary, the impact crushers require more maintenance as they suffer more wearing than the jaw crushers.

The jaw crushers main characteristics are (Kleemann GmbH):

- Longer service life, as they suffer less wearing.
- They admit a size block up to 1500 mm but do not reduce the maximum size under 60 mm.
- The efficiency is better as they just reduce the particle size.
- They give a RA with low fines content (5% to 8% 0-40 mm), making necessary to use an impact crusher to produce an artificial graded aggregate for roads.

Table 6.5 shows a summary of the main characteristics of the different crushers for the production of recycled aggregates (Kleemann GmbH) (European Demolition Association (EDA), 1992):

| Table 6.5: Characteristics of different crushers to produce recycled aggregates |
Taking into account the previous characteristics, the selection of the equipment for a recycling plant (jaw crusher, impact crusher or a combination) will depend on (Kleemann GmbH):

- The original waste: if it is hard and abrasive or the input block size is higher than 600 mm, the best option is a combination of primary (jaw) and secondary (impact) crushing.
- The final product: if an artificial graded aggregate is desired an impact crushing will be necessary.

Some frequent combinations are shown in Table 6.6 (Kleemann GmbH). An example of good practice for a high quality recycled aggregate is to use primary crushers (usually jaw crushers due to its high efficiency and low cost) to reduce the blocks of wastes to 50mm, and secondary crushers (either impact or cone crushers) to reduce the particle size to 32mm or less (Wrap) (Kleemann GmbH).

### Table 6.6: Frequent combinations of equipments to produce recycled aggregates

<table>
<thead>
<tr>
<th>PRIMARY CRUSHING</th>
<th>SECONDARY CRUSHING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaw crusher</td>
<td>Impact crusher</td>
</tr>
<tr>
<td>Impact crusher</td>
<td>Impact or Cone crusher</td>
</tr>
</tbody>
</table>

Magnets, air knives (directed blasts of air) and hand picking are usually used between the two crushes to remove impurities. Pre-screens and eddy currents are also occasionally used, whilst use of additional magnets after the secondary crusher will aid removal of wire reinforcement (Wrap).

Screens are used at various stages within the crushing process although usually the main separation by size takes place after the second crusher. It is increasingly common however to screen off the fines before the primary crusher as a preponderance of fines can reduce crushing performance. Care should be taken when crushing recycled aggregate containing a large proportion of brick since this produces more fines than crushing of concrete or primary aggregates (Wrap).

Soil, silt and clay can be particular problems and care is usually taken to avoid these materials.
entering the stream at source. Where they are present some contractors use a scalping screen ahead of the primary crusher to remove soil and clay balls. Other practices rely on the soil and clay being removed during washing processes. To avoid the resulting soil, silt and clay being directed to landfill, a number of producers use innovative methods to create products for this material. One example is the creation of filter cakes for use in drainage (Wrap).

- **Systems to eliminate impurities**
  - **Impurities content**
  
  Many of the leading recycled aggregate producers in Europe have recognised that in order to obtain RA with properties suitable for use in higher-value applications it is necessary to restrict the type of demolition waste put through the crushing plant, and create RA with a low content of impurities. Most importantly, many recycled aggregate producers have recognised that to use RA in higher-value applications there is a need to limit the asphalt content (and indeed the proposed EN 12620 classification of constituents for recycled aggregate for use in concrete will limit asphalt content to a maximum of 10% by mass) (Wrap).

In the following tables a comparison in different countries of the maximum content of impurities allowed (and the test standard applied) is shown, both for RCA (Table 6.7 and Table 6.8) and RA (Table 6.9):

### Table 6.7: International Requirements for recycled concrete aggregate

<table>
<thead>
<tr>
<th>Density of material ≤1800 kg/m³</th>
<th>Rilem (Type II)</th>
<th>Japan Fine aggregate</th>
<th>Japan Coarse aggregate</th>
<th>Australia</th>
<th>DIGEST 433 (RCA II)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤10%</td>
<td>≤10% (b)</td>
<td>≤10% (b)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>ASTM C123</td>
<td>Experimental method</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Density of material ≤1000 kg/m³</th>
<th>≤0.5%</th>
<th>≤2% (c)</th>
<th>≤2% (c)</th>
<th>≤0.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASTM C123</td>
<td>Experimental method</td>
<td>-</td>
<td>BS 812-101</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impurity content (metals, glass, soft materials, asphalt)</th>
<th>≤1%</th>
<th>-</th>
<th>≤1%</th>
<th>≤1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>-</td>
<td>Visual</td>
<td>BS 812-101</td>
<td></td>
</tr>
</tbody>
</table>

| Lightweight particles | - | - | - | - |

<table>
<thead>
<tr>
<th>Fines content (&lt;0.063 nm)</th>
<th>≤2%</th>
<th>≤8%</th>
<th>≤1%</th>
<th>-</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UNE-EN 933-1</td>
<td>JIS 5308</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sand content (&lt;4 mm)</th>
<th>≤5%</th>
<th>-</th>
<th>-</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UNE-EN 933-1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sulphate content (SO₃)</th>
<th>≤1%</th>
<th>-</th>
<th>-</th>
<th>≤1%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BS 812-118</td>
<td>-</td>
<td>-</td>
<td>BS EN 1744-1</td>
</tr>
</tbody>
</table>

| JIS 5308 | - | - | |

### Table 6.8: (continue) International Requirements for recycled concrete aggregate

<table>
<thead>
<tr>
<th>Hong Kong (Type II)</th>
<th>Brasil (RCA)</th>
<th>Portugal (ARB1)</th>
<th>Spain</th>
<th>United Kingdom (RCA)</th>
</tr>
</thead>
</table>

337
### Table 6.9: International Requirements for recycled aggregate

<table>
<thead>
<tr>
<th></th>
<th>United Kingdom (RA)</th>
<th>Holland (e)</th>
<th>Brazil (MRA)</th>
<th>Portugal (ARB2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤1800 kg/m³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Density of material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤1000 kg/m³</td>
<td>≤0,5%</td>
<td>BS 812-101</td>
<td>-</td>
<td>BS 812-101</td>
</tr>
<tr>
<td>Impurity content</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(metals, glass, soft</td>
<td>≤1%</td>
<td>BS 812-101</td>
<td>NP EN 933-11</td>
<td>BS 812-101</td>
</tr>
<tr>
<td>materials, asphalt)</td>
<td>≤3%</td>
<td>-</td>
<td>UNE-EN 933-1</td>
<td></td>
</tr>
<tr>
<td>Lightweight particles</td>
<td></td>
<td></td>
<td>BS EN 933-1</td>
<td></td>
</tr>
<tr>
<td>Fines content</td>
<td>≤4%</td>
<td>BS EN 933-1</td>
<td>NBR NM 46</td>
<td>BS EN 933-1</td>
</tr>
<tr>
<td>(&lt;0.063 mm)</td>
<td>≤10% (&lt;75 µm)</td>
<td>NBR 9917</td>
<td>NP-EN 1744-1</td>
<td></td>
</tr>
<tr>
<td>Sand content</td>
<td>≤5%</td>
<td>BS EN 933-1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>(&lt;4 mm)</td>
<td>≤5%</td>
<td>-</td>
<td>UNE-EN 933-1</td>
<td></td>
</tr>
<tr>
<td>Sulphate content</td>
<td>≤1%</td>
<td>BS 812-118</td>
<td>NBR 9917</td>
<td>BS 1881-124</td>
</tr>
<tr>
<td>(SO₃)</td>
<td>≤1%</td>
<td>NBR 9917</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

(a) Limit established in the Japanese guide revision, the limit in the first version is 13%  
(b) Density material <1950 kg/m³ in the Japanese guide, <1600 kg/m³ in Belgium  
(c) Density material <1200 kg/m³ in the Japanese guide  
(d) El límite de absorción del The 7% limit of absorption in Spain en España se aplica para sustituciones del árido natural por árido reciclado de hormigón de hasta un 20%. Para tasas de sustitución superior, el límite de absorción es de 5%  
(e) En Holanda, el árido reciclado mixto se puede utilizar en sustitución del árido natural inferior al 20%

In Germany, a very detailed group of requirements is applied to constituents of the recycled aggregates, as can be seen in the following Table 6.10
The limits for impurities content are very strict all over the standards, making the producers have included different systems in the process to eliminate the non desirable substances, as will be described as follows.

- **Basic treatments**
  All the stationary recycling plants include hand picking cabins (Fig. 6.6(a)), where the biggest impurities are thrown into specific containers: metal, glass, plastic, wood and papers (Fig. 6.6(b)).

  ![Fig. 6.6: (a) Hand picking cabin; (b) Containers for specific materials (Kleemann GmbH).](image)

Also, the use of magnets to remove reinforcement from the concrete is a basic usual treatment in recycling plants (Fig. 6.7(a)).

The elimination of lightweight particles is usually carried out by knife airs, being the limit particle size of removal a function of the pressure and direction of the air jet (Fig. 6.7(b)).
Advanced methods to improve the quality

Grinding of the recycled aggregate to reduce the paste content: In Japan, there have been attempts to further improve the quality of recycled aggregate via, for example the methods briefly stated below (Parekh & Modhera, 2011).

1. Heating and rubbing: where by the recycled aggregates are heated to 300°C to remove weaker mortar and cement particles from the aggregate.
2. Eccentric – shaft rotor method: in which the recycled aggregates are passed between two cylinders eccentrically rotating at high speed which separates coarse aggregates from mortar via a grinding effect.
3. Straightforward mechanical grinding: in which aggregates are placed in a rotating drum containing iron balls.

In the production of recycled aggregate concretes, 55-73% of the concrete waste can be used as recycled coarse aggregate; the remaining could also be used as recycled fine aggregate for precast concrete products. As this fine fraction contains a large amount of original mortar that detrimentally affects its properties, a wet grinding treatment process could be applied to improve the quality, in particular to reduce the absorption of the sand. The process is shown in Fig. 6.8. The aggregate is ground by the rotation of a rotor positioned inside a cylindrical shell. Recycled fine aggregate and fine powder of 5 mm or less is manufactured by passing through a screen. Impurities such as fine powder aggregate and wood chips are removed by a wet-type high-speed centrifuge, or cyclone. By means of this treatment, the absorption can be reduced from 11.2% to 7.45%, and the density increased from 1.98 to 2.21 (g/cm³) (Dosho, 2007).
Dry density separation of mixed recycled aggregate (air jigs) (De Jong, Fabrizi, & Kuilman, 2006): This system employs a pulsating air jet that causes a stratification of a bed of mixed material producing differential displacement of light and heavy particles. The lightest material separated mainly consists on wood, plastics, porous masonry and gypsum (Fig. 6.9). This system has a minimum feed size of 1 mm, and maximum feed size of 50 mm, with a maximum capacity of about 50 tons per meter width per hour.

Systems to remove impurities: Together with recently developed new sensors and advanced industrial image processing, different systems have been developed using X-ray, optical and electromagnetic sensors.

- Colour sorting. Scan & Sort The Sense Combi 1200 (Fig. 6.10) developed in Germany consists of an optical system that incorporates a high resolution camera and a special conductivity sensor permitting the identification of materials according to the size, shape, color or position of the particles in the tape. This information is transmitted to a system that generates impulses instructing the nozzles to blow out single particles or allow them to pass. This system is particularly suitable to remove wood, glass and gypsum\textsuperscript{26}.
X-ray sorting. More recently, a new technology has arisen aiming to a greater separation of the gypsum fraction, based on automatic infra-red detection systems and a subsequent elimination of the gypsum and other impurities using a blower (Vegas, Lisbona, Sánchez de Juan, & Carvajal, 2009). Fig. 6.11 illustrates this separation system.

Stationary plants versus mobile plants (Wrap)
Recycling of construction and demolition waste can take place either at the site from which the material is sourced using mobile crushers, or the material may be transported to a fixed recycling centre (sometimes referred to as urban quarries) where large stockpiles may be accumulated.

Mobile crushers (Fig. 6.12) whilst often more economical in that they avoid transporting construction and demolition wastes away from site, are rarely sophisticated enough to remove all impurities. For this reason, recycled aggregates produced from mobile crushers are usually used as site fill or capping layers, and used at, or close to, the location they were crushed.

Mobile impact crushers are usually the most economic option regarding licences, set up, production, etc; so they are increasingly used for in situ processing. The modern equipments allow the removal of ferric materials, obtaining high production rates up to 400 t/tour, depending on the original waste and final product. They are also used for furnace slag recycling.
In contrast, recycled aggregates from central recycling facilities undergo a number of processes to ensure higher quality, always depending on the cleanliness of the waste. This may include: magnets, picking stations, trash screen, screens, log washers, water pumps and sludge tanks (Fig. 6.13).

Furthermore central recycling facilities take great care to control the type of C&D waste that is allowed to be stockpiled.

### 6.3.2. Influence of the original concrete

Recycled aggregates obtained crushing a high strength original concrete (and subsequently with a low water/cement ratio and porosity) usually have a lower absorption, as can be observed in Fig. 6.14.
6.3.3. Influence of the maximum size on the quality of the aggregate

The maximum size of the recycled aggregate has a great influence on its final properties. In the particular case of the coarse recycled aggregate, the less coarse the fraction is, the lowest density (Fig. 6.15 and Fig. 6.16), highest attached mortar content (Fig. 6.17), and highest absorption (Fig. 6.18) is obtained. This behaviour is even more intense in the case of the recycled sand, which makes it unadvisable to use it for structural concrete (Sánchez de Juan M., 2004).
Fig. 6.15: Density versus maximum size of concrete recycled aggregate

Fig. 6.16: Saturated surface-dry density versus maximum size of concrete recycled aggregate

Fig. 6.17: Attached mortar content versus maximum size of concrete recycled aggregate.
For mixed recycled aggregates, the amount of ceramic particles has an influence of the shape index (Fig. 6.19) and Los Angeles coefficient (Fig. 6.20). Crushing of bricks produces a high content of flake particles, so the shape index decreases. On the other hand, ceramic bricks are harder than concrete, so they help to decrease the Los Angeles coefficient (Sánchez de Juan, y otros, 2011).
6.4. Quality assurance of the production

The main aim for developing a certification protocol of recycle aggregates is to give users confidence in the material, having properties satisfying requirements, and also with defined tolerances on variation throughout a delivery.

Requirements of the recycled aggregates are set depending on the final use (roads, concrete, etc). As far as the use of recycled aggregates in the production of concrete concerns, in the European Union they should satisfy, as a minimum, the requirements included in “EN 12620:2002 Aggregates for concrete”. However, as the standard itself points out, additional requirements might be needed to cover completely recycled aggregates, which should be established in accordance with local regulations valid at the place of use.

In some countries, as Netherlands and United Kingdom, the European standard has been amended in order to cover specific aspects of recycled aggregates (NEN 12620:2002+A1:2006 and BS EN 12620:2002+A1:2008). Other countries, however, have published independent standards for these aggregates, such is the case of Germany where a specific standard has been developed: DIN 4226-100:2002 “Aggregates for mortar and concrete. Part100: Recycled aggregates”. In this section those specific aspects included in all these standards will be detailed.

In the European Union, all the aggregates for concrete must have an EC Declaration of conformity, which entitles the producer to affix the CE marking. The system of attestation of conformity of aggregates for concrete is 2+ and 4, for uses with and without high safety requirements respectively. System 2+ includes an initial certification of the factory production control, and a subsequent continuous surveillance. System 4 only requires the existence of a factory production control and the execution of type initial tests. All these considerations also apply for recycled aggregates.
EN 12620 specifies requirements for the evaluation of conformity and the implementation of a quality control system in the production, which should also be satisfied by recycled aggregates for concrete. Thus, the recycling plants must have in place a system of factory production control consisting of procedures for internal control of the production to ensure that recycled aggregates placed on the market conform the requirements of the standard. Apart from the regulated aspects that the system of production control must accomplish, there are also other measures during processing that could be taken to improve the final quality of the aggregates. All these aspects will be detailed in the following sections, applied to the case of recycled aggregates.

6.4.1. Incoming debris

As part of the production control of aggregates for concrete, there must be a documentation of the raw material incoming to the factory. This requirement, when applied to recycling plants, means to document the construction and demolition wastes origin, including the following information (NEN and BS EN 12620):

- nature of the raw material
- source (processing depot) and place of origin
- supplier and transporting agent

Additional data, recommended by WRAP (Wrap, 2005) includes also the date of each load, description of the quality of the incoming material and its quantity (by weighing/volume).

DIN 4226 also requires organoleptic checks of the material before and after dumping to establish whether its composition is as given on the delivery note. Other necessary information of the incoming debris that should be documented is:

- type of material (e.g. concrete, bricks, etc)
- name and address of haulage contractor
- information of any suspected contaminants
- details regarding former use of the material (e.g. office building, sugar factory, etc)
- results obtained from previous tests (e.g. effects of chlorides or alkali-silica reactions)
- supplier’s declaration that the material conforms to the data given in the delivery note

The Japanese standard for the use of recycled aggregate and recycled concrete establishes the following recommendations about the stockpile of recycled aggregate:

- To keep separately recycled aggregates from different concrete qualities.
- To keep separately coarse and fine recycled aggregates.
- To keep separately natural and recycled aggregates.
- As the absorption of coarse recycled aggregate is high, it is advisable to use it saturated so the aggregate hopper may have a sprinkler system in order to keep it in moisture conditions.
- Fine aggregate should not be stockpiled for a long time, because it may solidify.

To ensure that only inert waste is accepted, the producer should have a specific procedure on the “acceptance criteria”, depending on the local waste management licence. The criteria should describe which types of wastes are accepted and the method of acceptance. An
example of flow chart for accepting and processing of inert waste is shown in the following Fig. 6.21, taken from WRAP (Wrap, 2005).

![Flow chart for accepting and processing of inert waste](image-url)

**Fig. 6.21: Flow chart for accepting and processing of inert waste**

The control of the incoming material must be done by means of a visual inspection to be carried out on every load, on initial receipt and after tipping, rejecting the consignment whenever the percentage of any contaminant or foreign material is higher than that defined in the acceptance criteria (Wrap, 2005).

It is also important that staff responsible for reception inspection be specially trained for this job. In a certification scheme of the recycling plant, this training should be documented (Karlsen, Petkovic, & Lahus, 2002).

### 6.4.2. Processing

To optimize the use of recycled aggregate, the Japanese Industrial Standards (JIS) recently issued Recommendations on the use of recycled aggregate concrete, classifying it into three types: H, L and M. The requirements for each class, are shown in Table 6.11. (Tam, 2009).

**Table 6.11: Classification of recycled aggregates (classes H, L and M) in Japan** (Tam, 2009)

<table>
<thead>
<tr>
<th>Class of recycled aggregate</th>
<th>Requirements of recycled aggregate</th>
<th>Suggested concrete applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class H</td>
<td>Recycled aggregate which performs advanced processing of a separation, grinding down by friction and classification form the concrete mass generated by demolition of the structures.</td>
<td>It can be used in the main structure part of a concrete structure object on a par with natural river gravel and sand, and the macadam and crushed sand.</td>
</tr>
<tr>
<td>Class L</td>
<td>Recycled aggregate which crushed and</td>
<td>It can be use don concrete without</td>
</tr>
</tbody>
</table>

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manufactured concrete waste which arises when a concrete structure object is mainly demolished by the machines for beating and crushing and which has not performed advanced wastewater treatment.

Three types of concrete are suggested: a stock item, a salt regulation article, and a technical specification order article.

It can be used for components which cannot be easily influenced by drying shrinkage or freezing and thawing such as a stake, withstand pressure version, a footing beam and steel-tubing in filled concrete.

<table>
<thead>
<tr>
<th>Class M</th>
<th>Recycled aggregate which is processed by demolition, grinding down by friction and classification.</th>
</tr>
</thead>
</table>

6.4.3. Recycled aggregates stockpiling

Stocking and storage locations identification of the recycled aggregates has to be done in a controlled manner. Also, procedures must be applied to ensure that materials are put into, and taken from the stock in such a way that they do not suffer deterioration. This point is of special importance to recycled aggregates, as they are friable materials, so an unsuitable handling can easily alter the grading or fine contents of the aggregates at the stockpiles.

DIN 4226 specifies that there shall be in the recycling plant procedures to monitor stockpiling and to identify storage sites and their stocks. The products shall be identifiable up to the point of sale as regards source and type.

Some helpful recommendations for correct stockpiling and material handling procedures in order to avoid segregation, contamination or degradation of the aggregates during processing, are shown in the following Fig. 6.22 to Fig. 6.26 (USA Guide for aggregate certification).
Fig. 6.22: Stockpiling techniques for clean stone

Fig. 6.23: Improper load out methods
Fig. 6.24: Load out from stockpiles

Fig. 6.25: Bin contamination
When recycled aggregates are transported in bulk, it may be necessary to cover or enclose the material so as to prevent contamination. If aggregates are packaged, the system shall not cause the aggregates to be contaminated or segregated (DIN 4226).

### 6.4.4. Sampling procedures

In Angulo and Müller (Angulo & Müller, Determination of construction and demolition recycled aggregates composition in considering their heterogenity, 2008), it is pointed out that the regulations applied for natural aggregates sampling may be not sufficient, and must be supplemented considering the content of foreign materials. Thus, according to the European Standard EN 932-1, the minimum mass of a sample of aggregates should be calculated only by two parameters: the maximum grain size and the loose bulk density. This means that the composition heterogeneity, typical in recycled aggregates is not considered as a parameter. This study concludes that the mass sample for recycled aggregates should be higher than that recommended by the EN 932-1, especially for the determination of foreign materials such as gypsum and organic materials. For example, for a maximum particle size of 32 mm the standard establishes a representative mass of 50 kg, that gives a coefficient of variation higher than 5% in the composition determination when the concentration of the organic materials is lower than 3% or the concentration of gypsum is lower than 7%. So, the content of such danger foreign components in the recycled aggregates are not determined precisely.

On the other hand, the collection of the sample according to EN 932-1 can be done randomly in a three dimensional lot (conic pile). Reference 20 compares the results of dispersion applying this procedure to those when the collection is made of all section material taken from the conveyor belt, and then a homogenization by horizontal mixing piles. As can be observed in Fig. 6.27, the standard procedure gives higher coefficient of variation.
6.4.5. Tests and frequency of sampling

The frequency of sampling and the tests to be carried in the producer control system are shown in Table 6.12, for the general properties of both natural and recycled aggregates, according to EN 12620.

The European Standard establishes three levels of requirement to classify the result of the test:

- Just as a declared value, not under requirement
- It belongs to a specific Category
- The result Pass or Fail a threshold value

Few properties are controlled applying a threshold value, and most of them classify the aggregate in different categories. Depending on the end use of the aggregate, one category or another will be required. In the case of recycled aggregates, due to its nature usually are classified in the lower categories, in special for some properties (LA coefficient, absorption, etc).

Table 6.12: Minimum test frequencies for general properties. Producers control. (European Standard)
Additional controls, specific for recycled aggregates, are also included in BS EN 12620: influence on setting time of cement, constituents, particle density, absorption and water soluble sulfates, sulphur compounds and chloride content. Minimum test frequency to be carried by the producer is shown in Table 6.13. When the measured value is close to a specific limit, the frequency may need to be increased.

Similar minimum frequencies are recommended by WRAP (Wrap, 2005) for recycled aggregates, with the exception of constituents, where the test frequency is more strict (1 per week), as can be observed in the following Table 6.14.

Table 6.13: Minimum test frequencies for aggregates from particular sources. Producers control. (European Standard)
DIN 4226 includes a wide factory production control testing, as can be seen in the following Table 6.15. For specific uses, additional controls should be taken as shown in Table 6.15 (general properties) and Table 6.16 (specific uses).

Table 6.14: Minimum test frequencies. Producers control. (WRAP)
Table 6.15: Minimum test frequencies. Producers control. (German Standard)

<table>
<thead>
<tr>
<th>Line</th>
<th>Item/Property</th>
<th>Cf. subclause</th>
<th>Notes</th>
<th>Relevant test method(s)</th>
<th>Minimum frequency of testing for aggregate type(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Processing equipment</td>
<td>A.3</td>
<td>Visual check</td>
<td>Daily</td>
<td>Daily</td>
</tr>
<tr>
<td>2</td>
<td>Source of material (receiving inspection)</td>
<td>A.4</td>
<td>Visual check</td>
<td>Each consignment</td>
<td>Each consignment</td>
</tr>
<tr>
<td>3</td>
<td>Grading</td>
<td>4.3 (DIN 4226-1)</td>
<td>–</td>
<td>DIN EN 933-1</td>
<td>Weekly</td>
</tr>
<tr>
<td>4</td>
<td>Particle shape (coarse aggregate)</td>
<td>4.4 (DIN 4226-1)</td>
<td>–</td>
<td>DIN EN 933-3-1</td>
<td>Weekly</td>
</tr>
<tr>
<td>5</td>
<td>Fines content</td>
<td>4.6 (DIN 4226-1)</td>
<td>–</td>
<td>DIN EN 933-1</td>
<td>Weekly</td>
</tr>
<tr>
<td>6</td>
<td>Assessment of fines</td>
<td>4.8 (DIN 4226-1)</td>
<td>If conditions set out in Annex D of DIN 4226-1 are met.</td>
<td>DIN EN 933-8, DIN EN 933-9</td>
<td>Weekly</td>
</tr>
<tr>
<td>7</td>
<td>Composition</td>
<td>4.3</td>
<td>–</td>
<td>Weighing of constituents separated manually</td>
<td>Daily</td>
</tr>
<tr>
<td>8</td>
<td>Particle density</td>
<td>4.4</td>
<td>–</td>
<td>DIN EN 1097-6</td>
<td>Weekly</td>
</tr>
<tr>
<td>9</td>
<td>Water absorption</td>
<td>4.4</td>
<td>–</td>
<td>Cf. Annex D.</td>
<td>Daily</td>
</tr>
<tr>
<td>10</td>
<td>Acid-soluble chloride content</td>
<td>4.5</td>
<td>–</td>
<td>Cf. Annex E.</td>
<td>Twice a year</td>
</tr>
<tr>
<td>11</td>
<td>Sulfur/sulfate content</td>
<td>6.3 (DIN 4226-1)</td>
<td>–</td>
<td>DIN EN 1744-1</td>
<td>Twice a year</td>
</tr>
<tr>
<td>12</td>
<td>Organic matter content</td>
<td>6.4.1 (DIN 4226-1)</td>
<td>–</td>
<td>DIN EN 1744-1</td>
<td>To be specified by inspection body, at least once a year.</td>
</tr>
<tr>
<td>13</td>
<td>Harmful substances</td>
<td>4.8</td>
<td>–</td>
<td>Cf. Annex G.</td>
<td>Twice a year</td>
</tr>
</tbody>
</table>

1) Not required if performed as part of third party inspection.
Table 6.16: Minimum test frequencies for specific uses. Producers control. (German Standard)

<table>
<thead>
<tr>
<th>Line</th>
<th>Property</th>
<th>Cf. subsection(s) of DIN 4126-1</th>
<th>Intended use</th>
<th>Relevant test method(s)</th>
<th>Minimum frequency of testing for aggregate type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Resistance to fragmentation</td>
<td>6.2</td>
<td>–</td>
<td>DIN EN 1097-2</td>
<td>Twice a year</td>
</tr>
<tr>
<td>2</td>
<td>Resistance to wear</td>
<td>5.4</td>
<td>Wearing courses</td>
<td>DIN EN 1097-1</td>
<td>Once every two years</td>
</tr>
<tr>
<td>3</td>
<td>Resistance to corrosion</td>
<td>5.5.1</td>
<td>–</td>
<td>DIN EN 1097-8</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>Resistance to abrasion</td>
<td>5.5.2 and 5.5.3</td>
<td>Wearing courses</td>
<td>DIN EN 1097-9, DIN EN 1097-9</td>
<td>Once every two years</td>
</tr>
<tr>
<td>5</td>
<td>Frost resistance</td>
<td>5.8.1</td>
<td>–</td>
<td>DIN EN 1097-1</td>
<td>Twice a year</td>
</tr>
<tr>
<td>6</td>
<td>Resistance to freezing and thawing</td>
<td>5.8.1</td>
<td>–</td>
<td>DIN EN 1097-1, DIN EN 1097-2</td>
<td>Twice a year</td>
</tr>
<tr>
<td>7</td>
<td>Calcium carbonate content</td>
<td>6.5</td>
<td>Fine aggregate for concrete wearing surfaces</td>
<td>DIN EN 166-21</td>
<td>Once every two years</td>
</tr>
<tr>
<td>8</td>
<td>Alkali-silica reaction</td>
<td>To be assessed by an expert in accordance with the DIN 1045-169, über rohbaugende Maßnahmen gegen schädigende Alkalinitätsreaction in Beton.</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Note: 5) See table 6.1 for 6).

Frequency of tests for bound and unbound use are shown in the following Table 6.17 according to Norway recommendations:

Table 6.17: Minimum test frequencies. Producers control. (Norway recommendations)

<table>
<thead>
<tr>
<th>Property to be tested</th>
<th>Test method</th>
<th>To be tested by (type of lab.)</th>
<th>Test frequency at continuous production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Financial sector, industry or laboratories</td>
</tr>
<tr>
<td>Grading</td>
<td>EN 933-1</td>
<td>L i</td>
<td>One per week or min. per 2000 tons</td>
</tr>
<tr>
<td>Fines content (materials &lt; 0.063 mm or in sand on materials &lt; 0.63 mm)</td>
<td>EN 933-1</td>
<td>L i</td>
<td>One per week or min. per 2000 tons</td>
</tr>
<tr>
<td>Content of materials 0.026 mm or in sand on materials &lt; 0.63 mm</td>
<td>L i</td>
<td>-</td>
<td>If required</td>
</tr>
<tr>
<td>Material composition</td>
<td>prEN 933-11</td>
<td>L i</td>
<td>One per week or min. per 2000 tons</td>
</tr>
<tr>
<td>Organic materials 0.6</td>
<td>EN 1744-1</td>
<td>L i</td>
<td>One per week or min. per 5000 tons</td>
</tr>
<tr>
<td>Stone - Flakiness index of materials &gt; 8 mm</td>
<td>EN 933-3</td>
<td>L/C/E i</td>
<td>One per month</td>
</tr>
<tr>
<td>Mechanical properties (Los Angeles)</td>
<td>EN 1097-2</td>
<td>L/C/E i</td>
<td>-</td>
</tr>
<tr>
<td>Density</td>
<td>EN 1097-6</td>
<td>L/C/E i</td>
<td>One per two weeks or min. per 10 000 tons</td>
</tr>
<tr>
<td>Water absorption</td>
<td>EN 1097-9</td>
<td>L/C/E i</td>
<td>One per two weeks or min. per 10 000 tons</td>
</tr>
<tr>
<td>Chloride content</td>
<td>EN 1744-1</td>
<td>L/C/E i</td>
<td>One per two weeks or min. per 10 000 tons</td>
</tr>
<tr>
<td>Sulfur-containing compounds</td>
<td>EN 1744-1</td>
<td>L/C/E i</td>
<td>If required</td>
</tr>
<tr>
<td>Chemical analyses</td>
<td>EN 1744-3</td>
<td>A i</td>
<td>One per two weeks or min. per 10 000 tons</td>
</tr>
</tbody>
</table>

i) Should be tested at the production site to be able to manage the production on basis of the test results
ii) Might be tested either locally, at a central laboratory or external laboratory
iii) To be tested either at a third party approved or accredited laboratory
iv) Alternative methods might be accepted
v) The test frequency might be reduced by 50 % if it is carried out pre-evaluation of the building according to Publication no. 26 from the Norwegian Concrete Association
The frequency of testing should be increased or additional tests carried out in the following circumstances (DIN 4226):

- In case of severe variation in composition of the incoming material.
- When the source of the material changes, this being a function of the results of receiving inspection.
- When visual checks indicate any non-conformance indicated
- When measures values are close to a specified limit

On the other hand, the frequency of testing may be reduced (properly documenting the case) under special conditions (DIN 4226):

- highly automated production equipment
- long-term experience as regards constancy of special properties
- a high uniformity of the material supplied
- running an exceptional quality management system

It is considered very important that the producer has a certain minimum of laboratory equipment either on site or nearby, to make use of the results to manage the production (Karlsen, Petkovic, & Lahu, 2002). It is mandatory (EN 12620) that the producer be responsible of the calibration and maintenance of the test equipment. Calibration records shall be retained.

As far as external inspections of the producer control system concerns, EN 12620 makes it mandatory for aggregates with high safety requirements (under certification System 2+), but no details can be found about how the surveillance of the production control must be carried out. DIN 4226-100, however, establishes minimum frequency of testing (general and specific use) carried out by a third party inspection body, as is shown in the following tables (Table 6.18 and Table 6.19)

Table 6.18: Minimum test frequencies for general properties. External control. (European Standard)
The inspection body shall check whether the test results conform to the requirements for the relevant category, and whether they are in compliance with those obtained from factory production control tests.

### 6.4.6. Document and data control

It is mandatory according to EN 12620 that the producer keeps documents concerning purchasing, processing, inspection of materials and in general all those affecting the factory production control system. In particular, recording of sampling locations, dates and times and product tested and other relevant information (e.g. weather conditions).
Of particular importance are those records related to the incoming wastes and the final products, which shall be kept by the producer.

NEN EN 12620 specifies that the recycled aggregates shall be identified by:

- the source and the manufacturer (if the material has been re-handled in a depot both the source and depot shall be given).
- Type of aggregate (recycled in this case)
- The category according constituents

The basic information to be provided by the supplier of the recycled aggregate according to DIN 4226 includes:

a) Source of supply
b) Material designation
c) Aggregate type and size
d) Average particle density
e) Average water absorption

The purchaser should inform the supplier, at the time of ordering, of any special requirements for a particular end use and of any additional information needed of any property shown in Tables 4.4 and 4.5.

When requested by the purchaser, the producer should provide (Wrap):

a) test results
b) test procedures
c) outline details of the factory production control manual

Based on the experience from his production and the test results, the producer shall work out a document of declared values for the requested properties dependent on the end use. This document shall also state within tolerances or maximum/minimum levels the user can expect his material to be delivered.

All cases of non-conformity shall be recorded by the producer, investigated and if necessary corrective action shall be taken (EN 12620), controlling its effectiveness (DIN 4226). If the producer obtains results outside the declared values, he has to inform his customer (Karlsen, Petkovic, & Lahus, 2002).

Non conforming aggregates shall be reprocessed, assigned to another application for which be suitable or rejected. The manufacturer shall document and investigate the cause of nonconformity checking if the tests have been carried out properly, analyzing the processes, operations, quality records, etc (DIN 4226).

6.5. Control tests for recycled aggregates

The type of control tests for quality assurance of recycled aggregates, as for the natural aggregates, depends on its final utilization: roads, concrete, etc. According to WRAP (Wrap, 2005) Recommendations, the following test methods may be used as a means of either
deciding or illustrating suitability for a particular end use (Table 6.20).

Many of the controlled properties of recycled aggregates apply the same tests procedures than the natural aggregates, but some specific tests should also be carried out (DIN 4226-100):

- Determination of ten minutes water absorption
- Determination of acid-soluble chloride content
- Evaluation for harmful substances
- Verification of the frost resistance of aggregate by testing concrete
- Effect of recycled aggregates on soil and groundwater

Table 6.20: Test methods for particular end uses

<table>
<thead>
<tr>
<th>Test Reference</th>
<th>DS EN</th>
<th>DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>All end uses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>particle Density</td>
<td>1007-6</td>
<td></td>
</tr>
<tr>
<td>resistance to Fragmentation:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>los Angeles</td>
<td>1097-2</td>
<td></td>
</tr>
<tr>
<td>bulk Density</td>
<td>1097-3</td>
<td></td>
</tr>
<tr>
<td>Use in Concrete/hydraulically bonded materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Absorption</td>
<td>1097-6</td>
<td></td>
</tr>
<tr>
<td>magnesium Sulphate</td>
<td>1367-2</td>
<td></td>
</tr>
<tr>
<td>Abrasion Resistance</td>
<td>1007-8</td>
<td></td>
</tr>
<tr>
<td>friable Shrinkage</td>
<td>1367-4</td>
<td></td>
</tr>
<tr>
<td>Chlorides</td>
<td>1744-1</td>
<td></td>
</tr>
<tr>
<td>Sulfate and Sulfides</td>
<td>1744-1</td>
<td></td>
</tr>
<tr>
<td>Alkali silica reaction*</td>
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<tr>
<td>organic Contamination</td>
<td>1744-1</td>
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<tr>
<td>*All RSA must be classified as highly reactive</td>
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<tr>
<td>Use as Fill</td>
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<td>Water Absorption</td>
<td>1097-6</td>
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<tr>
<td>Dry</td>
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<td>1377: Part 4</td>
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<tr>
<td>Plasticity of fines</td>
<td>1377: Part 2</td>
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<tr>
<td>Use as unbound, pipe bedding</td>
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<td>particle Density</td>
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<td>resistance to Fragmentation:</td>
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<td>los Angeles</td>
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<td>Plasticity of fines</td>
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<td>1377: Part 2</td>
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<tr>
<td>Fines</td>
<td>81: Part 2</td>
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<td>Water Soluble Sulfate</td>
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<td>Magnesium Sulfate</td>
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<td>Use in asphalt</td>
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<td>particle Density</td>
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<tr>
<td>Abrasion Resistance (AAV)</td>
<td>1007-8</td>
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<tr>
<td>Polishing resistance</td>
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<tr>
<td>Resistance to Heat</td>
<td>1367-3</td>
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</table>
NEN 12620 indicates that new test methods necessary for recycled aggregates are at an advanced stage of preparation. On the other way some specific tests, different from those used for natural aggregates, are applied to recycled aggregates:

- Acid-soluble chloride content EN 1744-5 (instead of water–soluble chloride content of EN 1774-1:1998, clause 7)
- Inorganic constituents that may adversely affect the rate of setting and hardening of concrete may be inorganic in recycled aggregates, so the procedure given in EN 1744-6 should be used.
- The magnesium sulphate test EN 1367-2 is unsuitable for recycled aggregates with cemen-bound fractions. Resistance to freezing-thawing must be carried out under EN 1367-1 or using a test on concrete.
- To prevent alkali-silica reaction when using recycled aggregates, it will be necessary to ascertain that the original concrete does not contain reactive (or reacting) aggregate, and its alkali content will be determined and taken into account. The possibility of unpredictable compositional variability should be considered.

Regarding the control of the composition of recycled aggregates, the test based on visual analysis can introduce errors due to a wrong identification of particles: between mortar and concrete; between gypsum lumps and plaster, mortar calcium silica bricks, etc.; errors due to unknown materials. This test requires experience of the laboratory technician who carries out it.

Reference 19 points out that a more accuracy results could be obtained if the control is carried out by means of the determination of the oven dry density of the aggregate instead of a visual analysis of its composition.

Moreover, a density distribution of particles could give the most complete information of the quality of the aggregate. Next Fig. 6.28 shows an example of the average cumulative oven dry density distribution for concrete, mortar and lightweight material particles of one sample of recycled aggregate.
Fig. 6.28: Average cumulative OD density distributions and span of the measurements for densities and cumulative masses

The distribution of densities was done by a sequential sink float density separations, using sodium politungstate solutions of different densities.

6.6. Voluntary marks for high grade recycled aggregates

Several countries have developed certification systems aimed to the production of high grade recycled aggregates.

In Belgium, the BENOR-mark certifies the conformity of the aggregates for concrete, including the recycled aggregates themselves and testifies that the product is in accordance with the European Standard for aggregates (EN 12620). In order to obtain this voluntary quality mark, the aggregates must already have been certified under the CE-Mark level 2+. The BENOR mark includes an autocontrol system for the producers, periodically confirmed by external certified bodies. There are more strict frequency control tests and also described procedures to manage non conformity products.

In the region of Flanders, Certipro® (a certification body with representatives of the authorities, research institutes and the sector) manages the Quarea certification system. This is an integrated environmental management system, which aims at production and application of secondary aggregates with minimal effect on man and the environment. Quarea-certification evaluates the processing of the material and management of the installation. The system is based on the principles of ISO14001. Technical measures for the installations are based on the selection of Best Available Techniques. The produced secondary aggregates are considered secondary raw materials and may be handled as a product. As such they lose their status of a waste material. The system is operational since September 2007.

In the United Kingdom, WRAP (Waste and Resources Action Programme) has developed a Quality Protocol (Wrap, 2005) (QP) for the production of aggregates from inert waste. The Protocol covers several aspects in the production system:

- Waste management legal requirements
- Acceptance criteria of incoming waste
- Mandatory Factory Production Control, including
  o Manual of procedures
  o Manager responsible of FPC
  o Trained personnel
  o Records of all the quality control activities
  o Identifiability of the product up to the point of sale
  o Procedures to maintain the quality of the product during handling, storage, transport and delivery.
  o Minimum testing requirements – Frequencies

The Michigan Department of Transportation's (MDOT) strategy for the recycling and reuse of concrete aggregate is to use it if it enhances or equals the performance of virgin material in the final product. Statewide use of recycled concrete aggregate (RCA) is permitted in the
Standard Specifications of Construction, 2003, Aggregate section 902.03 part B, 902.04, and 902.06. It allows the use of RCA as coarse aggregate for Portland cement concrete for curb and gutter, valley gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps, and shoulders. RCA is also allowed as coarse aggregate in hot mix asphalt and as dense-graded aggregate for base course, surface course, shoulders, approaches and patching. RCA was widely in the pavement structure during the 1980's.

MDOT and local aggregate suppliers have been using RCA for over 19 years and have overcome some barriers. Recommendations given by MDOT and Detroit Metro region for using RCA in state highways for durability, bonding, and strength are:

- Quality assurance and quality control of materials is needed to assure meeting specifications.
- Normally commercial sources of concrete are not allowed for recycling in the crushing plants. Most recycled material comes from the MDOT's reconstruction projects. This assures a consistent source of original aggregate.
- Certification of recycling aggregate producers and the approval of stockpiles, when the primary source is the concrete from highways.
- Changes in the design on the permeable base allow RCA to be used when the density of material is increased and the design of the drainage system is modified.

Finally, in Singapore an accreditation scheme for Recycled Aggregate Supplier has been implemented, as an industrial led effort initiated by the Waste Management and Recycling Association of Singapore (WMRAS). The scheme applies for recycling plants supplying recycled concrete aggregates meeting requirements of SS EN 12620: Specification for Aggregates for Concrete. The accreditation protocol aims to improve the quality and consistency of the waste processors serving the construction industry. The final objective is to increase the Industry Professional and Users’ confidence in specifying the use of recycled products in their projects.

The accreditation criteria are based on the following areas:

1. Company Financial Status
   - Requirement for minimum NTA (Net Tangible Asset) investment of S$250,000
   - Land Lease for a Minimal Period throughout the Accredited duration with Landlord and/or NEA approved usage for Recycling Activities (minimum of 2 years).

2. Facilities & Equipment
   - Production Crushing Facility equipped with input, crushing, transfer, output and selective separation device
   - Proper processing plant
   - Proper weighing facility (with calibration certificate)
   - Proper dispatch system for issuance of delivery records
   - Production Facility with Relevant Authority Approval or Support with regards to Pollution Control, Sewerage Discharge and WSHA requirements.
   - Declaration of Waste Stockpile Limit Set by Landlord (Declaration only)

3. Human Resource
   - Qualified Full-Time Trained Personnel to be employed
Manager (At least with Diploma in any discipline)
Production Supervisors (Experienced / In House OJT* – On the Job Training Programme)
QC / QA Supervisors (Experienced / In House OJT* – On the Job Training Programme)
*OJT Programme to be submitted for auditing

4. Quality Assurance Testing
- Company should have a Quality Assurance Testing Program for regular checking and periodic testing of End Product by Accredited Laboratories
- Level of impurities (not more than 5% for Class 1 Recyclers) & Chemical composition of end product generated from plant to comply with Authority Requirement (Test Report to be submitted for Assessment)
- End Product Quality must Comply with SS EN 12620* and other relevant Codes/Guidelines in accordance to Project requirements as imposed by authorities from time to time (Quarterly conduct of Prescribed Test, please refer to Specifications and details in Application Form)
- Product Subject to Periodic Sampling Tests by Authority

5. Quality Management System & Documentation
- Company should have a Quality Management Plan for the Management of Incoming Waste, Processing and End Product incorporating disposal and segregation of hazardous and non-recyclable material with Proper Documentation and Tracking of Quantities
- Company should have a nominated personnel for the preparation and submission of documentation and relevant data to the Authorities on a monthly basis (consistency of submission shall be a criteria for subsequent renewal of certification) (ISO Certification will be implemented in the future)

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