THE AGE EFFECT ON FIRE SPALLING OF CONCRETE

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Abstract

The age of a test specimen at the time of testing is a factor that is much debated when looking at the spalling sensitivity of concrete. In general when the fire resistance of a test specimen is determined it is assumed to be in equilibrium with the surrounding relative humidity. This is in practice impossible when a dense concrete specimen with a thick cross-section is tested. The option of rapid drying at elevated temperatures has been shown to change the behaviour compared with a specimen that is naturally dried [1] and is, therefore, not a suitable solution when testing the fire resistance of concrete elements.

Complementary tests on concrete specimens from two previous test campaigns [2, 3], that originally included fire tests of more than 60 different concrete mixes tested in over 200 fire tests, have been conducted after an extended storage time of 3-5 years. Included in the new test series are both larg slabs, 1700 × 1200 × 200 mm, and small specimens, 500 × 600 × 200 mm.

The results show that the maximum spalling depth is reduced, to some extent, by longer storage time but the reduction differs between mixes. It is shown that after 5 years storage, severe spalling can occur for some concrete qualities. It was also found that the type of loading arrangement used when testing the spalling behaviour can influence the amount of spalling and the spalling depth to a large extent.

1. INTRODUCTION

The phenomenon behind explosive fire spalling has been discussed for over 100 years, and it is still not fully understood. A factor that is generally pointed out as a major cause of spalling is the amount of water in the concrete, both the free and the chemically bounded water. There are different theories concerning the effect of water on the fire spalling. Commonly in the literature the effect of water is explained in that when it is heated it builds up a high pressure which can lead to spalling. Another theory is that water is transported in the heated concrete and it builds up a zone with liquid water, often defined as a water clog [4]. When this water clog, with very high moisture content, has been established in the concrete the mechanical properties will be affected drastically and the concrete becomes weaker [5]. Due to external loading and thermal stresses spalling can then occur in these weak zones.

Generally only the free water, or the moisture content, is considered when estimating the probability of fire spalling in building codes or handbooks, see for example Eurocode 2 [6]. The limit on the moisture content found in handbooks and codes is often 3 % for conventional vibrated concrete, and for high performance concrete 2,5 %. This is a very coarse (and inaccurate) measure to define whether the concrete is safe or not. One reason is that the moisture content varies through the cross-section of the structure, i.e. the moisture content close to the surface is different from the moisture content in the centre of the structure. It is still not known if it is the moisture content close to the fire exposed surface, or the mean moisture content in the structure that is important for fire spalling. Another reason is that very few studies have been conducted on the subject and it is questionable if there is such a limit on the moisture content to achieve a safe concrete. There are, however, some experimental results available for concrete with low moisture content where spalling was observed, and which indicate that a fixed limit on moisture content does not ensure that the concrete is safe with respect to spalling [7, 8, 9, 10].

In order to establish these relatively low levels of moisture content the concrete must be dried, either stored for a long time or treated in some other way. During this process other characteristics of the concrete change, for instance the strength and stiffness increase. Hence it may be difficult to tell if it is the lower moisture content or the higher strength/stiffness that make the concrete more robust with respect to fire spalling. Nevertheless there seems to be a relationship between the probability of fire spalling and the age of the concrete. The older the concrete, the lower risk and extent of spalling. Whether, this is due to the change in moisture content, or the fact that some other characteristic of the concrete has changed is not known.

The objective of the presented study is to examine the effect of the concrete age on the spalling behaviour. It is outside the scope to determine the reasons why the age has an effect on the spalling since this is a very complex question. It is not only that the spalling phenomenon still cannot be explained physically, but it is also a problem that the test methods used can have a major influence on the resulting spalling behaviour. When fire spalling is studied experimentally it is, therefore, important to be aware of the influence of the test methodology chosen. When fire tests are performed there are several parameters that are solely dependent on the test methodology which can be altered, and which may affect the results more or less, e.g. the specimen geometry, the boundary conditions, how and whether external loads are applied and the heating conditions. In the present study, two different specimen geometries have been used, and the external load has been applied using two different systems.

2. MATERIALS, SPECIMENS AND EXPERIMENTAL STUDIES

Two large research projects on the fire spalling of concrete have been carried out, one on self-compacting concrete and one on concrete for tunnel applications. A large number of different concrete qualities, with different loadings of polypropylene fibres of different geometries, have been examined experimentally. Extra test specimens were manufactured in previous projects, and some of these specimens that have been stored for a long time and that have now been fire tested. It should also be mentioned that tests have also been performed on different concretes with the addition of polypropylene fibres. These concretes did not spall, neither at an early age nor after several years, which was expected.

The recipes for the concretes included in the present study are shown in table 1. The specimens were produced between June 2005 and January 2007. All concrete samples for tunnel applications were stored under water for at least two months after casting and thereafter stored outdoors under cover. All small specimens of concrete for house building applications were stored indoors at 20 ºC, RH 50 %, after casting and until the fire test. The large specimens of house building concrete were stored outdoors under cover.

Table 1: Concrete recipes.

Series	w/c	Cement type	Gravel 0-8 mm [kg/m^3]	Gravel 8-16 mm [kg/m^3]	Gravel 16-25 mm [kg/m^3]	Water [kg/m^3]	Cement [kg/m^3]	Filler limestone [kg/m^3]	Super-plasticizer [kg/m^3]
Self-compacting concrete (Building applications)									
1	0.52	CEM II	1057	621	-	198	380	80	5.5
3	0.40	CEM II	1037	609	-	198	500	-	4.0
10	0.65	CEM II	1035	557	-	230	355	105	4.5
12	0.71	CEM II	1073	631	-	212	300	87	4.1
15	0.40	CEM II	948	745	-	180	450	50	6.7
16	0.52	CEM II	1068	628	-	198	380	60	5.6
46	0.52	CEM II	1035	608	-	198	380	120	5.5
Self-compacting concrete (Civil engineering applications)									
30	0.30	CEM I	936	736	-	168	560	-	5.3
31	0.40	CEM I	976	768	-	168	420	60	5.0
34	0.40	CEM I	884	695	-	168	420	252	7.0
39	0.40	CEM I	846	665	-	168	420	140	6.3
45	0.40	CEM I	1027	603	-	168	420	-	-
Tunnel concrete									
C	0.45	CEM I	871	862	-	182	405	-	2.43
D	0.45	CEM I	880	134	772	171	380	-	2.28

Three different types of specimen were manufactured, two small slab type specimens and one large slab type. The small slabs had the dimensions 600 × 500 × 200 mm with a fire exposed surface of 500 × 400 mm, and the large slabs 1800 × 1200 × 200 mm with a fire exposed surface of 1500 × 1200 mm. The difference between the two types of small specimens was how the external compressive loading was applied. In one type, tubes were placed centrally through the specimens into which post-stressing bars were inserted to which the load was applied, see figure 1. This system was also used for the large specimens. On the other type of small specimens, no tubes were used and the load was applied using an external cradle, see figure 2. The loading with the internally mounted post-stress bars on the small specimens was used in all tests up to an age of one year. The tests on the older, small specimens were made using the external cradle system.

Figure 1: Specimens with internal post-stressing bars. To the left are large slabs and to the right a small slab. Load cells are mounted on the post-stressing bars for load measurements.

Figure 2: A small slab with externally mounted load arrangement or “cradle”.

In all tests, a compressive stress was applied to the test specimens. The stress level varied depending on the concrete quality (strength class), and was within 3-10 % of the 28 days compressive strength.

All tests performed on the building concrete specimens were carried out with a heat exposure in accordance with the standard fire curve (EN 1363-1 [11], ISO 834-1 [12]). The tunnel concrete specimens were tested using different fire curves. All small specimens were tested with the standard fire curve, while the large specimens were heated in accordance with the hydrocarbon curve (EN 1363-2 [13]).

3. TEST RESULTS

3.1 Tests with large specimens

The test results showed in figures 3-4 were obtained with the large test specimens and present the maximum spalling depth of the fire exposed surface measured after the specimens had been removed from the furnace. Figure 3 presents the spalling depth for self-compacting civil engineering concrete used in, for instance, tunnels and figure 4 show the results for self-compacting concrete for building applications.

When comparing the results between the self-compacting concretes of series 39 and 45, figure 3, it is clear that concrete 45 shows less spalling. The reason for this is probably that no limestone filler was used in concrete 45, i.e. the concrete does not include as much fine material and is therefore not as dense as concrete 39. When comparing these two concretes the maximum spalling depth decreases to some extent with the age of the concrete for the large specimens. It is not a significant decrease, although it does indicate a trend.

Results obtained with the self-compacting house building concretes are presented in figure 4. The difference between the two concretes investigated is the amount of fine material. Concrete 46 had a lower water-cement ratio and also had a higher content of limestone filler. Hence the spalling was expected to be more severe for this concrete, which the test results also confirm. These house building concretes show a more significant decrease of the maximum spalling depth with increasing age for the large specimens.

The test results show that for all four concrete qualities tested, spalling occurred even after four years, in some cases severe spalling.

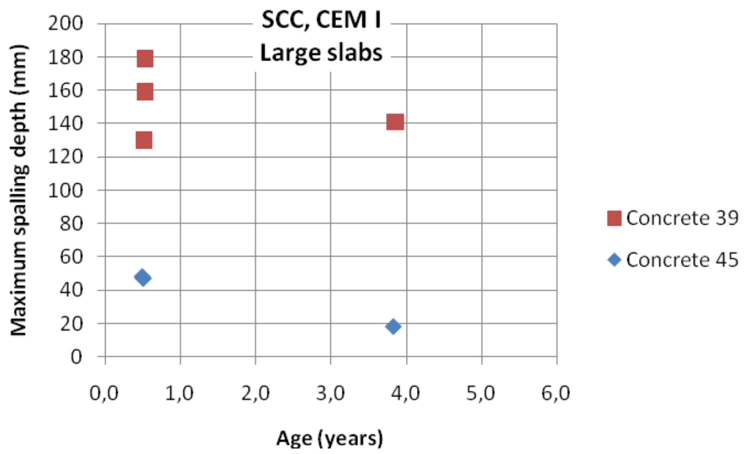

Figure 3: Maximum spalling depth of self-compacting concretes with cement type CEM I.

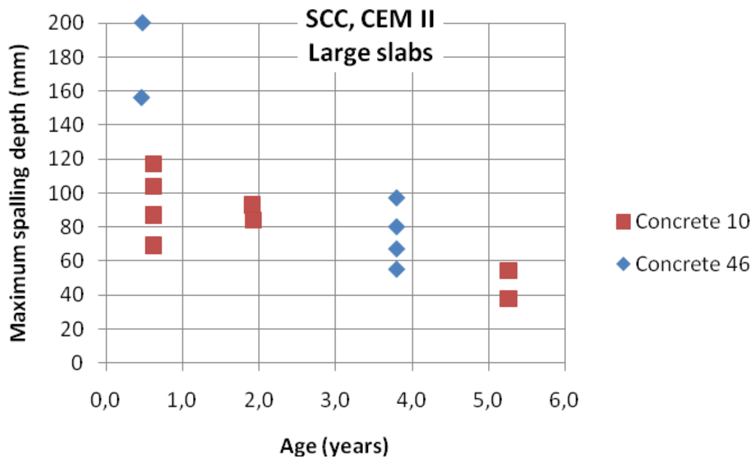

Figure 4: Maximum spalling depth of self-compacting concretes with cement type CEM II.

3.2 Tests with small specimens

In figures 5-7, test results are shown for tests performed with small slab specimens. Concretes for civil engineering applications are presented in figures 5-6 and for house building applications in figure 7.

When looking on the maximum spalling depth of the small specimens, there is no significant difference of the spalling depth with age. Instead, it seems that the spalling depth may increase with age. This phenomenon is almost certainly not an effect of age but more likely an effect of the test set-up. An important difference between the tests performed at young age and the later tests was the loading system used. The experiments performed up to an age of one year were conducted with the post-stressing bars mounted in tubes placed centrally through the specimens, while the tests performed after longer storage were loaded using an externally mounted cradle.

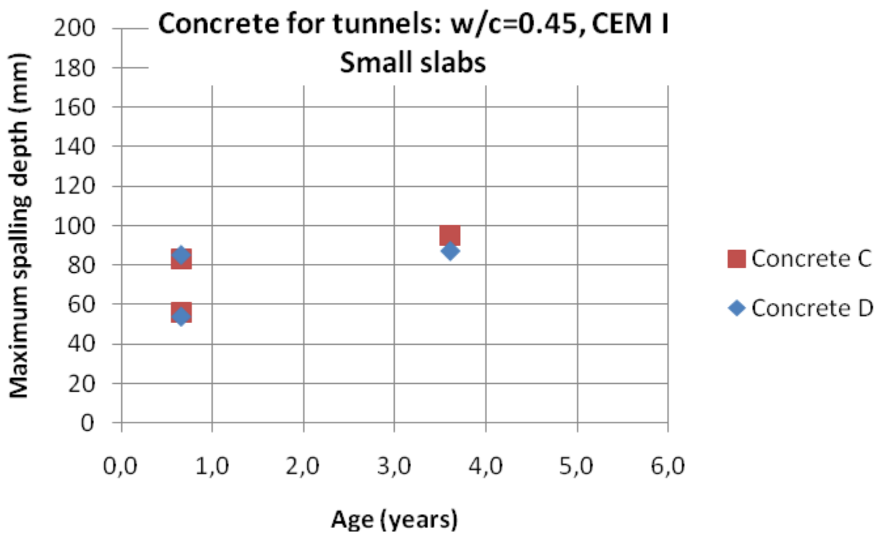

Figure 5: Maximum spalling depth of conventional tunnel concrete.

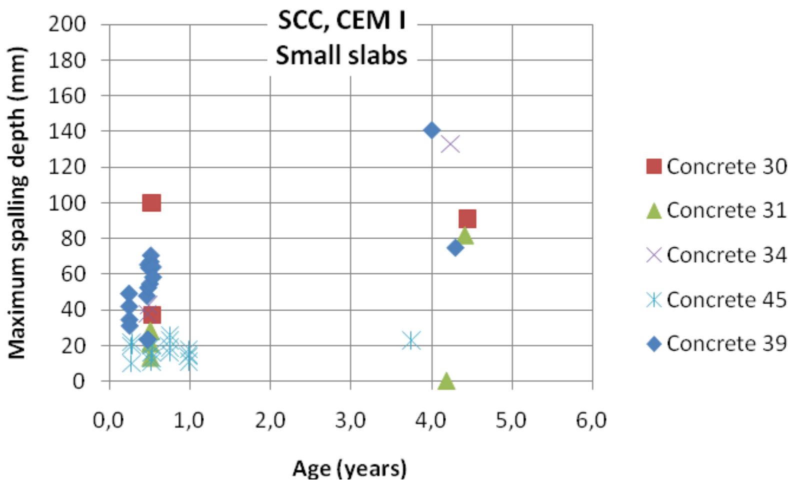

Figure 6: Maximum spalling depth of self-compacting tunnel concrete.

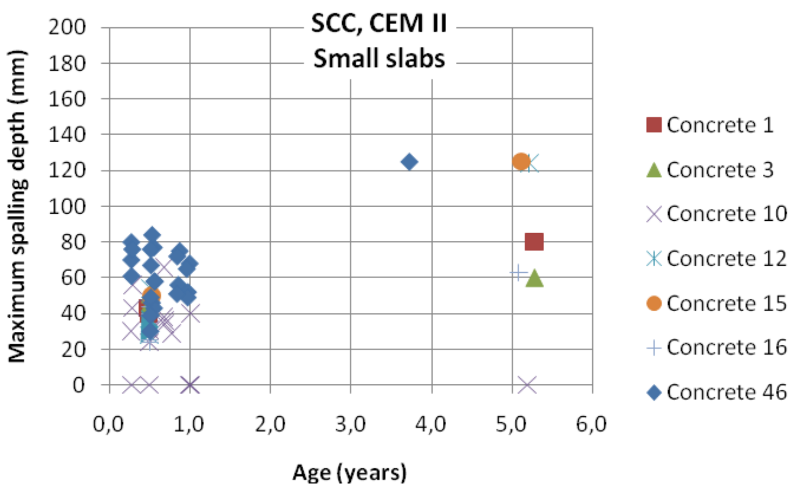

Figure 7: Maximum spalling depth of self-compacting house building concrete.

4. DISCUSSION

4.1 Influence of test arrangement on the fire spalling

When testing the small slab specimens two different systems for compressive loading was used. One system was based on post-stress bars going through the centre of the specimen, and the other on an external cradle. The external cradle was used when testing the specimens at an old age, while the internal bars were used when testing the young concrete. Unfortunately, no comparable results are available using the two methods of load application, i.e. tests performed with the same concrete quality at the same age. Nevertheless, it is expected that the amount of spalling will decrease with the age of the concrete, although these test results indicate the opposite. Further, there is reason to believe that the concrete samples would have spalled more at a young age had the external loading cradle been used in the initial tests. Indeed, some tests were made with large slabs, using the same loading system and at different age. These results indicate that the spalling decreases with the age of the concrete. Hence it is fair to assume that the loading arrangement has an important effect on the amount of spalling.

A possible explanation to the fact that the specimens with internal post-stressing bars show less spalling is that more boundaries are introduced into the specimen. It is possible for the water to mitigate through the area around the pipes, which could also be seen when carrying out the tests where water and steam were observed coming out of the pipes. Further, extra crack development during heating, releasing stresses, might be introduced which may reduce the amount of spalling with this loading arrangement.

It has been shown in other studies [14] that the amount of spalling obtained on small slab specimens is less compared to the amount obtained on large slab specimens, which was also the case in this study. This is probably due to boundary effects. In the small specimens, water mitigates more easily to the edges and the shape of the isotherms in the concrete will be different due to the small distance to the boundaries during such tests compared to larger specimens. Further, based on the discussion of the internal load system above, one should keep in mind that the inclusion of tubes to post-stressing bars will probably reduce the overall spalling of the concrete specimen due to the introduction of additional pathways for the removal of moisture from the specimen during fire exposure.

4.2 Effect of age on the spalling

It has not been possible to analyse the effect of age on the amount of spalling in the small specimens due to the different loading systems used. The tests made with the large specimens indicate that the amount of spalling decreases with age, especially for the concrete for house building applications, although in almost all cases there was still a significant amount of spalling even four years after casting. Even if the results obtained with the small specimens cannot be compared, they also result in severe spalling in most cases even several years after casting.

According to the present study most of the concrete qualities tested did show significant spalling even after aging for four years and more. Since the building elements used shall have the required fire resistance immediately when mounted in a building or other structure, it is questionable if these types of concretes can be used without protection, i.e. insulation, in constructions with requirements on fire resistance.

5 CONCLUSIONS

The experimental series presented included self-compacting concretes for building as well as civil engineering applications, and two typical concretes used in tunnels in Sweden. In principle all concretes spalled to a degree that would not be acceptable, even after more than four years of storage. These concretes were relatively dense and it is known that water transportation is very slow [15]. It will, therefore, take a long time to dry out free water in the concrete.

An important question to ask is at what age the concrete could be expected to be safe? According to the Swedish building regulations, and probably in many other countries, the requirements on fire resistance shall be fulfilled from day one, i.e. when the construction starts to be used. Although, there are generally no requirements on fire spalling when classifying a building element, for instance in accordance with EN 13501-2 [16] (the European classification standard). The requirements in EN 13501-2 only consider the primary functions: loadbearing capacity, integrity and insulation. The test methods used for determining the fire resistance of concrete elements allow spalling as long as no failure of the primary functions occurs during the classification time.

It is, however, also possible to certify concrete elements based on calculations in accordance with Eurocode 2. In this case it is specified that spalling shall be avoided by appropriate measures or the influence of spalling on the performance requirements shall be taken into account. It is pointed out in Eurocode 2 that explosive spalling is unlikely to occur when the moisture content is less than k % (where k is defined nationally but a recommendation is 3 %). The Eurocode does not specify whether it is the moisture content at the surface, a mean moisture content of the whole element or the maximum moisture content in the element. Accordingly it is unclear how to interpret the standard, which can lead to very different results. The present results show that explosive spalling occurs even after a very long curing period, which may be due to the very slow drying of these dense concretes. With the present Eurocode it would be possible to classify and certify building elements composed of these concretes. It is of course possible that the concretes tested in the present study do not spall when the moisture level has decreased further, but with the present, unclear definition in the Eurocode, they would certainly pass a certification process and hence be out on the market.

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