RELEVANCE of STAR 279-WMR

Road pavements have been successfully constructed using a variety of waste materials, including plastic, crumb rubber, steel slag, and construction and demolition waste, which indicate positive environmental and economic effects. However, based on the data currently available, this is mainly at the research level or restricted to a few nations; as a result, solutions need to be developed and widely demonstrated to encourage the market uptake of such alternative materials. TC 279-WMR offered a platform for international cooperation to handle all aspects pertaining to the utilization of waste and marginal materials for roads; TC 279-WMR established a solid and seminal framework for the assessment of selected waste and marginal materials, through interlaboratory experiments, and the development of standard procedures for their selection, preparation, and implementation.

STAR in a nutshell 279-WMR
"Valorisation of Waste and Secondary Materials for Roads"

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The structure of this STAR follows the organization of the TC that was divided into Task Groups, and their related areas of investigation: 1) implementation of plastics in binder and mixture; 2) application of crumb rubber in asphalt binder; 3) use of construction demolition waste, recycled concrete, and steel slag as aggregates in asphalt mixture; 4) life cycle assessment.

Bituminous binder and bituminous mixture modified with waste polyethylene (PE)

Although several types of waste plastics were initially considered, waste Polyethylene was selected for the experimental work, as the softening point of PE is around 125°C, which is lower than the temperature of production of hot bituminous mixtures (around 150°C). PE was expected to be easily and evenly mixed in the bituminous binder and mixture. In this work, two types of PE applications were performed:

Bituminous binder modified with waste PE - The materials used for this inter-laboratory study were straight-run bituminous binder 70/100 with a penetration of 82 mm^{-1} and softening point of 50 °C and two types of polyethylene waste (pellets and shreds). The experimental program included conventional characterization, rheological testing with the Dynamic Shear Rheometer (DSR), Differential Scanning Calorimetry (DSC), and Fourier Transform Infrared Spectroscopy (FTIR) for chemical analysis. The following conclusions can be drawn:

- At high temperatures, the binder blends modified with PE were less sensitive to permanent deformation compared to the non-modified binder.
- At intermediate temperatures, the fatigue performance of the PE blends could withstand more loading cycles under low strain levels; however, it could sustain fewer loading cycles under high strain levels due to the increase in brittleness.

Bituminous mixture modified with waste PE – Eleven laboratories from nine countries prepared and characterized a dense graded bituminous mixture with a 16 mm maximum aggregate size and containing different amounts of waste PE. Each laboratory used its own aggregates and 70/10 penetration bituminous binder, whereas waste PE was the same for all. The bituminous mixture was designed according to the dry process, and a series of mechanical tests were conducted to determine stiffness, strength, and resistance to permanent deformation. The following conclusions can be drawn:

- The addition of waste PE did not significantly affect the workability of asphalt mixtures.
- Samples with higher PE dosage have higher Indirect Tensile Strengths due to the improved cohesion of the plastic-modified mastic.
- The stiffness experiments showed an improved performance with a lower time dependence and a higher elasticity when PE was added.
- The cyclic compression tests demonstrated a reduced creep rate along with a higher creep modulus when PE shreds were added; similar conclusions can be drawn from the wheel tracking test.

- Acceptable and often improved moisture resistance was observed for PE-modified mixtures.

As binder modified with PE specimens can have the disadvantage of segregation and inhomogeneity, dry addition of plastics in mixtures should be preferably used. A balanced mix design that considers the low and high temperature performance could be considered.

Crumb Rubber Modified Binders (CRMB)

This study used four types of Crumb Rubber (CR) obtained from different procedures: mechanical grinding, cryogenic process, waterjet pulverization, and reacted and activated rubber. Three penetration-grade bitumens (46, 55, and 69 mm/10) were used. Five laboratories performed mechanical and chemical tests on the modified bitumen. The characterization of CRMB included: Scanning Electron Microscopy (SEM), penetration value, softening point temperature, viscosity, Fourier Transform Infrared Spectroscopy (FTIR), complex shear modulus, and black space diagram. The results are the following:

- From the FTIR analysis, the interaction between bitumen and CR was mainly a physical phenomenon.
- The incorporation of CR material provided a stiffening effect to the CRMB in the high-temperature/low-frequency domain. Simultaneously, a comparable decrease in stiffness was observed on the other end of the spectrum (low-temperature/high-frequency).
- Despite some differences in the non-mechanical tests, i.e., penetration, softening point, and viscosity, the results of the mechanical tests (complex shear modulus) suggested that the bitumen's penetration grade ultimately dictates the CRMB response.

The testing program in this work provided a pathway for more research on the CRMB's physical and mechanical properties, but further studies should focus on the chemical aspects. Another focus for research is the emerging treated crumb rubber for the dry process. An additional aspect to consider for further analysis is the link across the different testing methods adopted during the investigation: conventional, rheological, chemical, and microscopy. Artificial Intelligence and Machine Learning have a high potential for revealing hidden relationships, enabling more sophisticated links across material properties.

Waste Aggregates in Asphalt Mixtures

The feasibility of replacing natural virgin aggregates with different types of by-products, such as Steel Slag (SS), Construction and Demolition Waste (CDW), and Recycled Concrete Aggregate (RCA), was studied through interlaboratory investigations (namely nine European laboratories and one laboratory from Canada). All participants used limestone aggregates as reference virgin material except for one laboratory, which selected sandstone. Optimized mixtures were subjected to a performance characterization study to assess the effect of the different waste types and contents on volumetrics, strength, stiffness, water resistance, and anti-rutting potential. The following can be concluded from this multi-laboratory investigation:

- All steel slag aggregates (SS) had a particle density roughly 30% higher than virgin aggregate, with a better fragmentation resistance.
- CDW showed the worst characteristics among all other waste materials. Extremely high water absorption and low abrasion resistance may be two limiting factors for the application of CDW in new asphalt mixtures.
- RCA materials mostly had poorer propertyes than limestone and sandstone aggregates and SS, but slightly better than CDW.
- The volumetric and mechanical investigation results showed that more binder was required in comparison to the control mixture, in most cases.
- The Marshall Stability (MS) values generally increased when waste aggregates were used.
- Waste aggregate addition did not have a detrimental effect on the indirect tensile strength (ITS).
- The general trend was that lower permanent deformation was observed for mixtures with waste aggregates even though binder contents were higher.

The current technical specifications for aggregates prescribe specific properties for water absorption and resistance to abrasion that are hard to meet for some alternative aggregates. However, most mixtures examined here fulfilled the performance criteria in terms of stiffness, permanent deformation resistance and moisture susceptivity, while more research could be necessary about their cracking resistance.

Life Cycle Assessment of asphalt mixtures with waste and secondary materials for roads (WMR)

The environmental impact of asphalt mixtures can be evaluated using Life Cycle Assessment (LCA) techniques. Here, the exercise was carried out with a process-based attributional LCA limited to cradle-to-gate to gain information on the impact of asphalt mixture up to the road construction stage. First, benchmarks were generated through the LCA of reference asphalt mixtures using the data provided by the participating organisations. Then, these values were compared, in terms of Climate Change and Energy Use, with the results of the LCA of asphalt mixtures containing alternative materials. Keeping in mind that the analysis was limited to cradle-to-gate, the following conclusions are made:

- Raw materials supply, particularly bitumen, is the most relevant life cycle stage for Climate Change and Energy Use, unless transport distances are particularly long. In this regard, if the environmental impact of asphalt mixtures is to be decreased, practitioners should focus on reducing the impact of the extraction of raw materials or focus on increasing the use of recycled materials in asphalt mixtures.
- Stone Matrix Asphalt (SMA) mixtures show higher environmental impact than Asphalt Concrete (AC) mixtures in terms of materials. Therefore, although not part of this study, it can be speculated that designers should try to use more recycled materials in SMAs and/or possibly compensate with greater durability.
- Selected WMR mixtures seem to be a more environmentally friendly option when compared to benchmark values of SMA. This is not always as clear as when the selected WMR mixes are compared to conventional ACs.

TC 279-WMR was active for five years. The results obtained during the intense research activity must be considered exploratory while establishing the basis for a new research direction. The open research questions identified by TC 279-WMR demonstrate the need for continuing the scientific investigation on waste and secondary materials for roads, possibly expanding the research beyond the combination with traditional paving materials, such as asphalt binders, toward an enhanced circularity vision.

RELATED DOCUMENTS:

Poulikakos, L. D.; Pasquini , E. .; Tušar, M. . .; Pais , J. .; Cannone Falchetto , A. .; Moreno Navarro , F. .; Lo Presti , D. .; Jiménez del Barco Carrion, A. .; Wang , D. . Summary of Rilem Technical Committee TC 279-WMR Activities. *RILEM Tech Lett* **2024**, *8*, 176-181.