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Sustainable Pavement Construction: A Comprehensive Review on the Use of Recycled Materials and their Impact on Performance

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Abstract: The increasing demand for sustainable and environmentally friendly solutions in the construction industry has led to the exploration of using recycled materials in pavement construction. This study reviews the effectiveness of various recycled materials, including recycled concrete aggregates (RCA), coarse recycled aggregates (CRA), rubberized materials, fibers, recovered asphalt pavement (RAP), jarosite, fly ash, and ground granulated blast-furnace slag (GGBS), as potential substitutes for conventional materials. The mechanical properties, durability, and environmental benefits of these materials are assessed in the context of pavement construction. Although the appropriate percentage and treatment of recycled materials must be carefully considered, this review highlights the potential for recycled materials to contribute to sustainable pavement construction without compromising performance. By optimizing the mixtures and developing guidelines for their implementation, the construction industry can promote sustainability, reduce waste, and minimize the environmental impact of pavement construction
Keywords: Recycled Aggregates , Rubberized Materials, Fibers, Recovered Asphalt Pavement, Fly Ash, And Ground Granulated Blast-Furnace Slag

1. Introduction

The use of recycled materials in pavement construction has garnered increasing attention due to the potential for sustainable, environmentally friendly, and cost-effective solutions. Recycled aggregates such as recycled concrete aggregates (RCA) and coarse recycled aggregates (CRA) have demonstrated their effectiveness as a substitute for natural aggregates without significantly compromising essential mechanical properties when used in optimal percentages. Incorporating rubberized materials and fibers, including recycled tire rubber and coir or glass fibers, has been shown to enhance pavement durability and mechanical performance. These materials can help control cracking, improve resilience, and even delay the onset of crack formation. This is particularly important for cement-based pavements, where environmental factors can cause fluctuations in length.

This figure 1 illustrating the different categories of construction and demolition (C&D) waste generated. Categories may include concrete, bricks, wood, metals, asphalt, insulation, gypsum board, and other materials. The chart would show the proportion of each category in the total C&D waste generated. Also, figure 2 showing the amount of C&D waste generated in different countries or regions worldwide. The chart would provide a comparison of C&D waste generation across the globe, highlighting the countries or regions with the highest and lowest waste production. It may also indicate trends in waste generation over time and any waste management initiatives taken by different countries.

Recovered asphalt pavement (RAP) presents another viable option for substituting natural gravel in rigid pavements. When appropriately treated, RAP can offer better workability and compressive strength compared to conventional materials. Additionally, the use of recycled materials like jarosite, fly ash, and ground granulated blast-furnace slag (GGBS) can partially replace cement in pavement construction, contributing to both mechanical strength and reduced environmental impact.

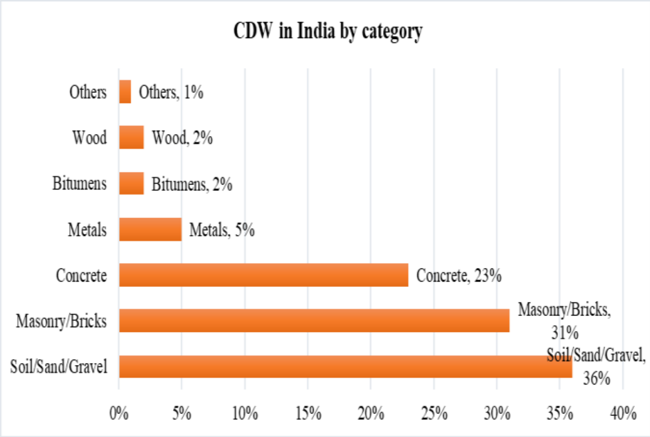

Fig 1: C&D Waste generated category

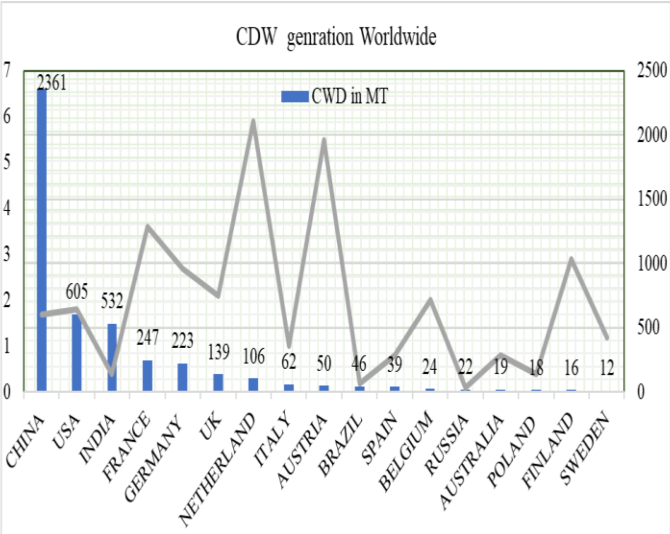

Fig 2: C&D Waste generated World wide

It is crucial to carefully consider the suitable percentages and treatments of these recycled materials to achieve the desired mechanical properties and performance in pavement construction. This requires thorough research and testing to optimize the mixtures and establish guidelines for their implementation. By doing so, the construction industry can promote sustainability, reduce waste, and minimize the environmental footprint of pavement construction, all while maintaining or improving the performance of the pavement structures.

2. Literature Review

2.1 Supplementary cementitious material

Anandaraj et al. investigated the use of limestone residue (LP) and fly ash (FA) as partial replacements for ordinary Portland cement (OPC) in self-compacting concrete (SCC). The study found that a 10% replacement of cement with LP resulted in improved compressive, flexural, and split tensile strengths. Similarly, the incorporation of FA was found to enhance both the fresh and hardened properties of SCC. C. Singh and Aggarwal examined the performance of concrete mixtures containing marble and granite powders as partial replacements for cement and sand. The study found that concrete with 10% marble powder and 25% granite powder had higher compressive and flexural strengths than the control mix after 7 and 28 days.

Gencel et al. studied the microstructural, mechanical, and transport properties of foamed concrete exposed to high temperatures and freeze-thaw cycles, using rice husk ash (RHA) as a cement substitute and waste marble powder (WMP) as a sand replacement. The mixture with 10% RHA replacing cement and 50%

WMP replacing silica sand exhibited the highest compressive strength after 90 days. Gupta et al. tested M20 grade concrete containing varying percentages of marble dust and steel fibers, finding that the optimal combination for strength was 15% marble dust and 1% steel fiber as cement substitutes.

K Ashish investigated the potential of waste marble powder to partially replace sand and cement in concrete. The study found that the best combination was 10% sand, 10% cement, and 20% marble powder, with improved mechanical and durability properties. Numerous other studies have explored the use of various stone waste materials in concrete production, including Karimipour et al. [6] on self-consolidating concrete, Kumar et al. on Portland pozzolana cement with marble waste powder, Palanisamy et al. on self-compacting concrete with crushed granite and marble waste, and Rajkumar et al. on reinforced concrete beams with metakaolin and marble powder. These studies generally found improved mechanical properties and durability with the incorporation of stone waste materials.

Rashwan et al. explored the effects of ornamental stone muck, , conducting a two-phase experiment with marble and granite sludge as cement binder replacements. They found that compressive strength decreased as sludge content increased but remained within an acceptable range. Concrete containing up to 10% granite sludge exhibited higher flexural and cracking tensile strengths at 28 days. S. Anitha replaced fine aggregates in concrete with waste marble and found that adding marble powder improved concrete's mechanical properties. The optimal concrete mixture contained 10% marble powder, which performed better than ordinary mixtures. Using marble powder as a fine aggregate replacement can enhance concrete performance. Shukla et al. replaced natural sand in concrete with marble dust and examined the effects on compressive strength and microstructure. They found that blended cement with marble dust met the criteria for split-tensile and compressive strength, and the 28-day composite cements were stronger than the 7-day ones.

Singh et al. studied the use of waste marble powder in construction, revealing that replacing 15% of cement with marble powder reduced costs by 9.07%. Additionally, marble powder increased concrete's compressive and split tensile strengths by 15–20% when used at a 10–15% replacement rate. Singh M et al. investigated the long-term effects of using dry waste marble powder slurry as a partial cement replacement. They found that a 15% replacement rate maximized water flow, and the concrete samples exhibited reduced water flow with each curing interval. Varadharajan et al. replaced cement with RHA (0–20%) and fine aggregate in concrete with marble waste powder (MWP) (0–30%). The best blend included 15% RHA, 30% MWP, and 1.5% steel fibers with hooks. Mechanical properties, such as compressive, tensile, and flexural strengths, improved as RHA and MWP replaced cement. Varadharajan also studied the use of Flyash and marble waste powder (MWP) in concrete, showing that mechanical properties greatly improved compared to previous studies. Although the addition of steel fibers and MWP increased costs by 16.8%, this was justified due to the enhanced durability and mechanical properties of the resulting concrete.

2.2 Recycled aggregate

In recent years, the construction industry has witnessed a growing interest in the use of recycled aggregates for sustainable pavement construction. This shift is driven by the need to minimize the environmental impact of construction activities, conserve natural resources, and reduce construction waste. In this context, recycled aggregate derived from construction and demolition (C&D) waste has emerged as a viable alternative to natural aggregates for use in pavement construction.

Numerous studies have been conducted to investigate the mechanical properties, durability, and environmental benefits of using recycled aggregates in pavement construction. Generally, recycled aggregates can be classified into two categories: recycled concrete aggregates (RCA) and coarse recycled aggregates (CRA). These materials have shown promise in replacing a portion of natural aggregates in various pavement applications, such as base and subbase layers, rigid and flexible pavements, and pervious concrete pavements.

Afonso et al. found that cold mix asphalt with modified granite aggregates and cementitious grout containing 30% milled glass performed best mechanically in grouted macadam pavements. Ali et al. discovered that concretes with 0.25% GF (glass fibers) and varying amounts of CWA (crushed waste aggregate) demonstrated improved flexural strength, hardness, and residual strength compared to conventional concrete. The cost and environmental impact of these fiber-reinforced concretes were found to be significantly lower.

Gared and Gaur's study on jarosite, a hazardous industrial waste, showed that partially replacing cement with jarosite can increase the mechanical strength of concrete while decreasing porosity and abrasion loss.

Krishna et al. examined the effects of replacing OPC (ordinary Portland cement) with silica sand and GGBS (ground granulated blast furnace slag) in stiff concrete. They found that removing more than 50% of silica sand negatively impacts concrete performance. Mikhailenko et al. studied the use of recycled concrete aggregates (RCA) in low-noise Semi-Dense Asphalt (SDA) mixtures, finding that incorporating 15% of RCA in the control mixture led to favorable results.

Mohammadinia et al. investigated mixtures of soft and hard aggregates for permeable pavements, concluding that an optimal mixture of heterogeneous granular materials can provide the necessary flexibility for tree growth and reactive sub-grade layer movement without failing under moderate traffic. Muthaiyan and Thirumalai evaluated the effects of replacing cement with fly ash and coarse aggregate with fine aggregate in pervious concrete. They found that fly ash replacement decreased compressive strength but also reduced voids in the concrete due to its micro-filler effect. Olivares et al. found that recycled tire rubber-filled concrete (RRFC) can be used for rigid highway pavements on elastic subgrades based on fatigue load data and analytical analysis. Pham et al. suggested that rubberized cement-based materials, when combined with a solution to improve rubber-cement matrix adhesion, can be used in various types of pavements to recycle used rubber tires. These materials can delay cracking, control crack spread, and limit crack mouth openings without significantly weakening the composite's strain capacity and post-peak residual behavior.

Poongodi developed pavement-quality fiber-reinforced concrete with coarse recycled aggregate (CRA) and coir fiber, finding that a combination of 25% CRA substitution of granite aggregate and 1% coir fiber didn't affect compressive or splitting tensile strengths while providing a stronger bond in concrete. Sadati and Khayat conducted field testing of recycled concrete aggregate (RCA) for rigid pavement, showing that replacing 30% and 40% of RCAs resulted in a slight decrease in compressive strength, MOE, splitting tensile, and bending strengths, but the values were still comparable to the reference concrete.

Singh et al. found that by replacing up to 50% of natural gravel with cleaned recycled asphalt, the compressive strength of rigid pavement can be improved by 20%. However, water-washed reclaimed asphalt can weaken the concrete. Tabatabaie Shourijeh et al. analyzed the strengthening of clay soil reinforced with recycled tire polymer fibers and glass fibers with the addition of recycled concrete aggregates. They found that increasing RCA content and curing time improved compressive and tensile strengths in the composite clay soils. Ungureanu et al. applied recovered asphalt pavement (RAP) recycling technique to a standard road surface by replacing the base course with a recycled one. Their accelerated pavement testing (APT) demonstrated that RAP recycling technology can be effective for road network enhancement, and APT loading linearly modified the compressive and tensile strengths of stabilized subgrade, aggregate, and RAP materials.

3. Conclusions

In conclusion, various studies have demonstrated the potential of using recycled materials, such as tire rubber, recycled concrete aggregates (RCA), and recovered asphalt pavement (RAP), in pavement construction. These recycled materials can contribute to the development of more sustainable and environmentally friendly pavements without significantly compromising their mechanical properties, such as compressive strength, tensile strength, and modulus of elasticity. Additionally, the use of recycled materials in pavements can lead to significant cost savings and reductions in carbon emissions. However, it is essential to carefully consider the appropriate percentages of recycled materials to ensure the desired mechanical properties are achieved. In some cases, using certain recycled materials may require additional treatments or additives to improve their performance. Overall, the integration of recycled materials in pavement construction offers promising prospects for enhancing the sustainability and cost-effectiveness of the infrastructure while minimizing environmental impacts.

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