International Journal of Engineering Research and Science & Technology

IJERST

www.ijerst.org

ISSN : 2319-5991

Vol. 21 No. 3 (1) 2025

ijerst.editor@gmail.com
editor@ijerst.com

ISSN 2319-5991 www.ijerst.com
Vol. 21, No. 3(1), 2025

Research Paper

DEVELOPMENT OF SUSTAINABLE RUBBERIZED CONCRETE FOR ENHANCE DURABILITY AND STRUCTURAL APPLICATION

[1] P.MANIKANTA, [2] S.DEEPIKA, [3] N.SANDHYA, [4] P.INDRAKUMARI, [5] G.ANUSHA

[1] Assistant Professor, Department Of Civil Engineering, Princeton Institute of Engineering & Technology for Women, Hyderabad, India

[2,3,4,5] B.Tech Students , Department of Civil Engineering , Princeton Institute of Engineering & Technology for Women, Hyderabad, India

Abstract:

The increasing demand for sustainable construction materials has motivated researchers to explore alternatives to conventional concrete ingredients that are environmentally responsible, cost-effective, and structurally reliable. Rubberized concrete, developed by partially replacing fine or coarse aggregates with waste tire rubber particles, has emerged as a promising solution that addresses two critical global issues: the depletion of natural aggregate resources and the environmental hazards caused by the disposal of end-of-life tires. This innovative composite not only contributes to sustainable waste management but also enhances certain mechanical and durability properties, including resistance to impact, abrasion, freeze-thaw cycles, and chloride penetration. However, challenges such as reduced compressive strength compared to normal concrete can be mitigated through supplementary cementitious materials like fly ash, silica fume, and ground granulated blast furnace slag, along with surface treatments and optimized mix proportions. The development of sustainable rubberized concrete opens new pathways for its application in structural and non-structural elements, especially in areas requiring energy absorption, vibration damping, and enhanced durability. Thus, rubberized concrete is an important step toward achieving a circular economy in the construction industry, providing both environmental and structural benefits.

Received: 08-7-2025 Accepted: 16-8-2025 Published: 23-8-2025

I.INTRODUCTION

Concrete is the most widely used construction material worldwide, but its production significantly contributes to the depletion of natural aggregates and high carbon emissions due to cement manufacturing. At the same time, the global disposal of waste tires has become a pressing environmental concern, as millions of tons of used tires accumulate in landfills, contributing to soil and groundwater pollution, fire hazards, and other ecological problems. Against this backdrop, researchers have been motivated to integrate waste tire rubber into concrete as an aggregate replacement, giving rise to rubberized concrete.

Rubberized concrete offers the dual advantage of sustainable waste management and enhanced durability performance. Although the incorporation of rubber particles tends to lower compressive strength due to their elastic and hydrophobic nature, it significantly improves other properties such as flexural strength, tensile strength, ductility, energy absorption, toughness, resistance to cracking, and durability against aggressive environments. Additionally, rubberized concrete exhibits superior acoustic insulation, vibration damping, and impact resistance, making it highly suitable for applications in pavements, retaining walls, sound barriers, bridge decks, shock-resistant structures, and buildings located in seismic zones.

The use of rubber in concrete also aligns with the principles of green construction, sustainable materials management, and the circular economy, promoting the reuse of industrial and municipal wastes in a productive manner. Recent advances in material science and nanotechnology have further enhanced the performance of rubberized concrete by introducing surface modification techniques such as rubber pre-treatment with sodium hydroxide (NaOH), cement slurry coating, or the inclusion of nano-silica and fibers, which improve the bond between rubber and the cement paste. These modifications have paved the way for expanding rubberized concrete from being merely experimental to being a potential candidate for large-scale structural applications.

II.RELATED WORKS

Numerous studies have been conducted to evaluate the feasibility of using waste rubber in concrete mixes and its long-term performance. Topçu (1995) was among the pioneers who demonstrated that incorporating rubber aggregates could reduce unit weight and increase energy absorption capacity of concrete. Later, Siddique and Naik (2004) highlighted that although compressive strength was reduced, rubberized concrete displayed enhanced toughness, ductility, and improved resistance to freeze-thaw cycles. Similarly, Eldin and Senouci (1993) investigated crumb rubber as fine aggregate replacement and observed improved crack resistance, making it suitable for pavements and road applications.

Recent works have focused on the durability aspect of rubberized concrete, with Gupta et al. (2016) reporting higher chloride resistance and reduced permeability when rubber was combined with supplementary cementitious materials like fly ash and silica fume. Li et al. (2018) highlighted that NaOH-treated rubber improved the interfacial transition zone (ITZ) between rubber and cement paste, mitigating the strength reduction issue. Mohamed et al. (2020) further emphasized the role of hybrid mixes containing steel fibers and rubber aggregates in enhancing flexural performance and post-cracking behavior.

In terms of sustainability, researchers such as Ali et al. (2019) have pointed out the environmental and economic benefits of using rubberized concrete, noting its potential for large-scale adoption in infrastructure projects. Applications in shock-absorbing structures, vibration-reducing railway slabs, impact-resistant flooring, and seismic-resistant buildings have been successfully tested. Studies by Khatib and Bayomy (1999) and Thomas et al. (2016) also demonstrated improvements in long-term durability, particularly in resisting sulfate attack, thermal stresses, and shrinkage cracking.

The cumulative evidence from past and ongoing research suggests that with proper mix design, pre-treatment of rubber particles, and combination with mineral admixtures, rubberized concrete can evolve into a mainstream construction material that not only addresses environmental waste management but also enhances structural durability.

III. MATERIAL USED

The development of sustainable rubberized concrete requires a careful selection of materials that not only maintain the fundamental characteristics of conventional concrete but also incorporate waste rubber in a way that promotes both performance and sustainability. The basic constituents include **cement, fine aggregates, coarse aggregates, water, waste rubber particles, and supplementary cementitious materials (SCMs)**.

- **Cement**: Ordinary Portland Cement (OPC) is the most widely used binder due to its availability, strength-giving properties, and compatibility with other materials. In

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advanced studies, blended cements such as Portland Pozzolana Cement (PPC) or Portland Slag Cement (PSC) are often preferred to enhance durability and reduce carbon footprint. Additionally, supplementary cementitious materials like **fly ash, silica fume, ground granulated blast furnace slag (GGBS), and metakaolin** are incorporated to improve the interfacial bond, minimize strength reduction, and enhance durability against sulfate, chloride, and freeze-thaw attacks.

- **Fine Aggregates**: River sand or manufactured sand (M-sand) forms the fine aggregate fraction of the mix. However, in rubberized concrete, a portion of this fine aggregate is replaced with **crumb rubber** (typically 0.6 mm to 4.75 mm in size). The proportion of replacement varies between 5% to 30% depending on the intended application. Crumb rubber improves ductility, toughness, and impact resistance but may reduce compressive strength. Surface treatments like **NaOH soaking, cement paste coating, or silica fume modification** are often used to improve bonding with cement paste.
- **Coarse Aggregates**: Natural crushed stone (typically 10 mm to 20 mm size) remains the primary coarse aggregate. In some cases, shredded tire chips (larger than 5 mm) can partially replace coarse aggregates, especially in lightweight or shock-absorbing concretes. This inclusion reduces density, enhances vibration damping, and improves thermal insulation.
- **Waste Tire Rubber**: The primary sustainable component of this concrete is **recycled tire rubber**, which is available in different forms such as crumb rubber, tire chips, and powdered rubber. These particles act as partial replacements for natural aggregates. By incorporating rubber, large volumes of discarded tires are diverted from landfills, reducing environmental pollution and contributing to the circular economy.
- **Admixtures**: Chemical admixtures such as **superplasticizers** are used to improve workability, while **air-entraining agents** may be added to enhance freeze-thaw resistance. Additionally, fibers (steel,

polypropylene, or glass fibers) can be introduced to counteract strength losses and further improve ductility and post-cracking behavior.

- **Water**: Potable water, free from organic impurities and harmful salts, is required to ensure proper hydration of cement. The water–cement ratio is carefully controlled, as rubberized concrete often requires a slightly higher water content due to the hydrophobic nature of rubber particles.

Together, these materials form a **composite concrete** that is not only environmentally friendly but also capable of providing enhanced **durability, resilience, and energy absorption capacity**, making it suitable for a wide range of structural and non-structural applications.

IV. SUSTAINABLE APPROACHES RELATED WITH THE CONCRETE MATERIAL

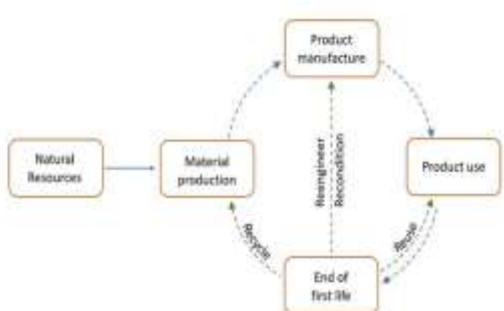

Fig 4.1 Approaches based on the phases of the concrete material life-cycle

The methodology to assess the environmental impact of a material, includes the calculation of the related emissions generated and energy required in the different phases of the material life-cycle, i.e. from the extraction of raw materials to the end of the first life. Therefore, the use of the life-cycle phases of the concrete material results especially useful to analyse different contributions to more sustainable alternatives of this massive use material.

Evaluating the energy consumption and generated emissions of material alternatives allows to quantify sustainable benefits at different stages of the life-cycle. For instance, in the material production stage, alternatives can be generated to reduce the amount of cement and natural aggregates used in the concrete mix. And in the product manufacture stage, benefits can be achieved by implementing optimised design and construction procedures that reduce the amount of concrete or alternatives with less demanding maintenance interventions, or with better thermal insulation and then less demanding of heating energy. Furthermore, more durable concrete can be produced in such a way that at the end of the first life the material can be reused.

V. METHODOLOGY

The methodology for developing sustainable rubberized concrete involves a series of systematic steps starting from material selection, mix proportioning, and specimen preparation to testing and performance evaluation. Each step is designed to ensure that the negative effects of rubber inclusion are minimized while the beneficial properties are maximized.

1. **Collection and Processing of Waste Rubber**:
   End-of-life tires are collected from landfills, automobile workshops, or recycling facilities. The tires are shredded into chips or ground into crumb rubber using cryogenic or mechanical processes. The size distribution is controlled depending on whether the rubber will replace fine or coarse aggregates. Pretreatment processes such as **NaOH soaking, surface roughening, or cement slurry coating** are performed to improve the interfacial bond between rubber and cement paste.
2. **Material Characterization**:
   Before mix design, all constituent materials are tested for their physical and chemical properties. Cement is tested for consistency, setting time, and compressive strength; aggregates are checked for gradation, specific gravity, and water absorption; rubber is analyzed for particle size distribution and density; and SCMs are characterized for pozzolanic activity.
3. **Mix Proportioning**:
   The mix design is formulated based on standards such as IS 10262, ACI 211, or ASTM guidelines, with modifications to incorporate rubber. Trial mixes are prepared with varying percentages of rubber replacement (commonly 5%, 10%, 15%, 20%, and 30% by volume of sand or coarse aggregate). In addition, SCMs like fly ash or silica fume are included to compensate for strength losses. Superplasticizers may be added to maintain adequate workability.
4. **Preparation of Concrete Mix**:
   The mixing process is carried out in a laboratory concrete mixer. Aggregates and rubber particles are first dry mixed to ensure uniform distribution. Cement and SCMs are then added, followed by water and

admixtures. The mixing process is carefully controlled to prevent segregation and ensure homogeneous dispersion of rubber particles throughout the matrix.

5. **Casting of Specimens**: The fresh mix is placed into standard molds (cubes, cylinders, and beams) and compacted either manually using tamping rods or mechanically with vibrators. Surface finishing is done to achieve smoothness, and molds are kept under laboratory conditions for initial setting.
6. **Curing Process**: After 24 hours, the specimens are demolded and subjected to curing, typically in water tanks maintained at 27 ± 2 °C. The curing period generally extends to 7, 28, and 56 days to study the short- and long-term performance of rubberized concrete. Alternative curing techniques such as steam curing or accelerated curing may also be tested.
7. **Testing of Properties**:
   - **Fresh Properties**: Slump test, compaction factor test, and V-funnel tests are conducted to evaluate workability.
   - **Mechanical Properties**: Compressive strength, split tensile strength, and flexural strength tests are performed at different curing ages.
   - **Durability Properties**: Resistance to chloride ion penetration, sulfate attack, carbonation depth, water absorption, and freeze-thaw cycles are studied to assess long-term performance.
   - **Special Properties**: Impact resistance, energy absorption capacity, and dynamic modulus of elasticity are evaluated for structural applications.
8. **Data Analysis and Optimization**: Test results are compared against control concrete mixes. Statistical analysis and regression modeling may be applied to establish the relationship between rubber content and mechanical/durability performance. Based on this analysis, the optimum rubber replacement percentage is identified for structural and non-structural applications.

9. **Practical Implementation and Feasibility Study**: Finally, the performance of rubberized concrete is compared with conventional concrete in terms of cost, sustainability benefits, and lifecycle performance. Pilot studies or small-scale structural elements (e.g., pavement blocks, beams, or slabs) may be cast and tested to validate laboratory findings.

VI.CONCLUSION

The development of sustainable rubberized concrete is an innovative approach to addressing both environmental challenges and the need for durable construction materials. By incorporating waste tire rubber as a partial replacement for natural aggregates, this concrete not only reduces the burden of non-biodegradable waste in landfills but also contributes to sustainable construction practices. Although the inclusion of rubber particles can result in some reduction in compressive strength compared to conventional concrete, these drawbacks are effectively compensated through the use of supplementary cementitious materials, surface treatments for rubber particles, and optimized mix designs. The resulting concrete exhibits enhanced impact resistance, ductility, toughness, sound insulation, and vibration damping capacity, which make it highly suitable for pavements, earthquake-resistant structures, noise barriers, and lightweight applications.

Furthermore, the addition of rubber improves freeze–thaw resistance, abrasion resistance, and long-term durability, ensuring that such composites can be used in harsh environments. The structural applications of rubberized concrete extend beyond traditional uses, as it is particularly promising in sustainable urban infrastructure, resilient housing, and eco-friendly pavements. Importantly, this material represents a pathway toward a circular economy, where industrial waste is transformed into valuable resources for construction.

In conclusion, sustainable rubberized concrete is not just a replacement for conventional concrete but a step forward in the integration of waste management with structural engineering solutions. Future research should focus on nano-modifications, hybrid composites, and large-scale field trials to fully establish its potential for mainstream construction applications. Thus, rubberized concrete holds immense promise for creating durable, cost-effective, and environmentally responsible structures for the next generation.

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