



## EVOLUTION OF RUBBER-MODIFIED CONCRETE – A REVIEW

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### Abstract

Concrete stands as the backbone of modern infrastructures, but its quasi-brittle behavior, lower tensile strength and toughness, susceptibility to cracking under dynamic loading and thermal stresses limit its durability and structural reliability. To address the inherent shortcomings of concrete, the late 20<sup>th</sup>-century addition of rubber waste sourced from industrial rubbers, recycled waste tires, etc., has been explored as an effective strategy, resulting in improved ductility, crack and impact resistance, and damping in the concrete matrix. Despite these gains in performance of concrete, weak interfacial interaction due to the hydrophobic characteristic of the rubber surface and the hydrophilic nature of concrete constrained the mechanical strength and durability of concrete. To overcome these challenges, the subsequent research explored the chemical and physical surface treatments for the rubber, which range from NaOH and silane coupling (SCA) treatments to cement coating and polymer coating to enhance the wettability and chemical interaction. These surface modifications significantly enhanced the compressive, flexural, and tensile strengths and durability parameters like resistance to chemical attacks, reduced permeability, and water absorption. This review maps the evolution of rubber-modified concrete from its fundamental origin to the most advanced surface modification techniques and provides an integrated viewpoint on the influence of these innovations on material performance.

*Keywords: rubber-modified concrete, rubber waste, surface modification*

### 1 Introduction

The rapid expansion of highway networks and increasing traffic demand requires durable pavement materials capable of resisting repetitive loading and environmental exposure. At the same time, concrete production raises sustainability concerns due to high cement consumption and depletion of natural aggregates, while large volumes of waste rubber from end-of-life tires create environmental and disposal challenges. These combined pressures highlight the need for sustainable material solutions tailored to highway and pavement engineering. In response, researchers have explored the incorporation of waste materials into concrete pavements as partial replacements for natural aggregates to reduce environmental impact while enhancing performance. Waste rubber, in the form of crumb rubber or shredded tire particles, has emerged as a particularly promising alternative for pavement applications. However, the incorporation of rubber particles in concrete is often associated with reductions in compressive and tensile strength due to weak interfacial bonding and increased porosity. To address these limitations, various strategies have been developed, including surface treatment of rubber particles to improve interfacial transition zone (ITZ) bonding, optimization of mix proportions, and the incorporation of supplementary cementitious materials such as fly ash and slag. These approaches aim to balance mechanical strength with enhanced durability and functional performance suitable for pavement applications.

Accordingly, this paper focuses on the use of rubber-modified concrete in highway and pavement engineering, discussing the types of waste rubber and rubber aggregates, mix design considerations specific to pavement performance requirements, surface modification techniques, and the potential structural and functional applications of RM-C in rigid pavement systems and related transport infrastructure.

## 2 Evolution of rubber modified concrete (RM-C)

The incorporation of rubber in concrete has evolved through various distinct phases, indicating a growing understanding of its compatibility with concrete and a continuous effort to design a high-performance concrete while maintaining sustainability. Initially, before the 1990s, there were scattered reports where rubber was introduced in a crude manner, typically as shredded chips of waste tyres or untreated crumbs to improve the resistance against impact and to reduce density. These early mixes used untreated rubber crumbs as a substitute for fine or coarse aggregates, but resulted in a severe strength loss, poor durability and workability, which limited their application to less important and lightweight structures only. There was no comprehensive research or literature review about the incorporation of rubber at that time since it was relatively isolated, with small-scale industrial trials or experiments. From 1990 onward, academic research on RM-C grew rapidly with dedicated studies on mechanical properties, mix design, durability and microstructure of the matrix.



**Figure 1** Different sorts of rubber aggregates: a) chipped, b) crumb, c) granular, d) fibre (Zrar and Younis) [1]

Initially, rubber and elastomeric materials were added to cement occasionally to improve flexibility, waterproofing and resistance to abrasion, which was largely empirical and lacked standardized protocols for testing. Research suggested that the incorporation of rubber reduced the compressive strength and stiffness of concrete. In the 1960s-1980s, rubber was investigated as a substitute for conventional aggregate rather than as a modifier. These studies were facilitated by the availability of synthetic rubber as waste material and the demand to improve the performance of concrete. Different-sized granulated or chipped forms of rubber were explored during this period and demonstrated a reduced compressive strength and elastic modulus with an increase in percentage of rubber. Classification of crumb rubber on the basis of size is shown in figure 1. Despite these drawbacks, these studies showed an improved ductility, due to which the failure mode shifted from brittle to somewhat ductile. After this duration, due to a large accumulation of waste tires and problems associated with landfilling or incineration, the researchers decided to explore concrete as a recycling solution at large scale. Hence, this period marked a turning point in the systematic and scientific investigation of RM-C. This approach broadly evolved through three phases: Early exploratory phase (1990-2000), intermediate phase included basic mix optimization and surface treatment (2000-2015), and modern phase of high-performance and hybrid system (2015-present) as shown in figure 2.

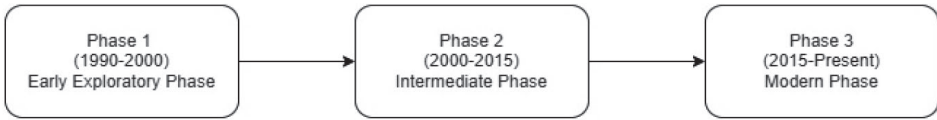


Figure 2 Evolution of RM-C

## 2.1 Early exploratory phase (1900-2000)

The pioneering work of comprehensive evaluation of RM-C incorporating scrap tires to replace both fine and coarse aggregate was provided by Eldin et al. [2]. Their work demonstrated a reduction in tensile and compressive strength with an increase in rubber content, but improved ductility and impact resistance. In continuation, an empirical relation between strength loss and rubber content was developed. Later, this matrix was investigated as a 3-phase composite consisting of cement, aggregate and rubber particles [3,4]. These studies observed a reduction in strength and elastic modulus, confirming rubber as a low-stiffness phase. This mismatched stiffness in rubber and surrounding concrete resulted in early initiation of microcracks under compressive loading. However, RM-C contributed positively under tensile, dynamic or flexural loading by dissipating the energy. Later, the dual behavior – strength reduction in compression and improved ductility became the defining characteristics of RM-C. An improved impact resistance and freeze-thaw durability were demonstrated in studies highlighting the potential of RM-C for rigid pavement application and other structures experiencing dynamic or cyclic loading. Rubber, being hydrophobic and chemically inert in nature, shows poor adhesion with cement [5]. Microstructural analysis of the composite showed the weak bonding at ITZ caused strength loss, early microcracks and premature debonding in the rubber-concrete matrix [6]. By the end of this phase, researchers investigated the feasibility of the incorporation of rubber in concrete and demonstrated the improved toughness, ductility and impact resistance along with the decrease in compressive strength and stiffness. One of the major limitations during this phase was observed as the weak interfacial bond resulting in strength degradation, which further directed the research to be more focused on surface treatment, material optimization and durability enhancement.

## 2.2 Intermediate phase (2000-2015)

The earlier phase studied the feasibility of adding rubber in the concrete matrix, along with the challenges associated with a reduction in strength and weak ITZ. Research after the 2000s focused more on systematic development of material and performance-based evaluation; hence, during the intermediate phase, researchers focused on evaluating the mechanical behavior and durability characteristics. Studies in this phase began considering the RM-C as a 3-phase composite instead of just rubber as a substitute for aggregates.

Using rubber as chips or fibre in RM-C resulted in a consistent reduction in elastic modulus, compressive strength and stiffness, etc., with increasing rubber content regardless of the form of rubber [7]. Their work confirmed that the rubber acts as a low-stiffness phase in the composite, which disturbs the load transfer, resulting in a reduced load-bearing capacity and delayed crack propagation. While the reduction in strength remained consistent, rubber incorporation also offered significant improvement in toughness, impact resistance, ductility and sustainability, leading to optimization of rubber content rather than abandoning the concept. Similar outcomes related to a reduction in compressive strength, which is associated with decreased stiffness and density due to increasing rubber content (usually < 5-10%), were reported [8, 9].

It was found that a finer size of rubber results in less strength loss than a coarser one, highlighting the importance of optimization of particle size. Incorporation of rubber in self-compacting concrete resulted in a significant decrease in elastic modulus but increased strain capacity that led to a delay in crack initiation due to reduced stiffness [10]. Wang et al. replaced 30-40% of fine aggregates with rubber in their study and found that acceptable mechanical performance and workability could be achieved [11].

During this phase, one of the most noteworthy contributions of the researchers was the detailed analysis of toughness, energy absorption and ductility characteristics, which were further adopted as the defining criteria of RM-C. Fracture mechanics the matrix was explored and a higher fracture energy of modified concrete as compared to conventional mix was reported [12]. According to the developed microcracks, which were evenly distributed in the matrix and failure shifted from sudden brittle to ductile. Other researchers also observed an increased energy absorption and ductility, which led to a reduction in crack width and a delay in the propagation and initiation of cracks. Further, a study demonstrated a superior behavior of modified concrete in impact resistance and enhanced fatigue life under the influence of cyclic or repeated load [13]. Weak ITZ bonding led to microcracks, loss in strength, and debonding at the interface, which results in increased porosity and reduces the durability and overall performance. To improve the ITZ bonding, researchers explored surface treatment techniques and surface coating techniques, which ultimately improve the durability and performance of the composite. Several studies were conducted on surface treatment and coating, which reported an improvement in bonding, reduced porosity and water absorption, and enhanced chemical attack resistance.

Durability performance was observed as a major research focus during this phase, and investigation on freeze-thaw resistance, water absorption and permeability revealed a mixed response. Several studies reported an increase in permeability due to poor bonding between cement and rubber surfaces, while others demonstrated that particle size and optimum rubber content can mitigate these effects [6, 14]. A comprehensive study on durability concluded that a durable and workable composite can be produced despite a loss in strength [9]. These observations further led to surface treatment to improve the ITZ in modified concrete. Similarly, laboratory work done by researchers working on mechanical strength and permeability observed that a balanced performance of the modified concrete can be achieved by controlling the rubber content (usually < 10-15%). Impacts of RM-C on the environment were investigated and highlighted its potential to reduce the stockpiles of waste tires and landfill waste to produce low-density and resilient concrete composite [15]. This phase was mainly about the transition of RM-C from an experimental composite to a performance-characterized and durable-driven material. While loss in strength remained in this phase, a superior ductility, toughness, dynamic damping, energy absorption, free-thaw resistance and environmental benefits were observed as the major outcomes of this phase.

### **2.3 Modern phase (2015- Present)**

Weak ITZ bonding holds a significant share in weakening the matrix and reducing the durability and performance in long-term as reported in phase 2. To overcome these effects and to strengthen the ITZ bond, research in this duration focused more on surface treatment of rubber particles to make them compatible with the concrete matrix. Researchers used surface-treated rubber, did advanced microstructural analysis, refined the mix designs, and conducted long-term durability assessment under dynamic loading in an aggressive environment. Since 2015, studies shifted their interest from conventional characteristic strength to optimization of performance and a mechanistic approach. Across various studies, it was found that the inclusion of rubber as a partial replacement of aggregates leads to a loss in strength due to weak bonding at the interface and low stiffness of rubber [16].

However, recent research observed that the loss in strength can be attenuated by grading rubber particles, optimizing the mix design and using surface treatment for rubber particles to improve the bonding with cement [17, 18]. As mechanical strength reduction is seen with increasing the rubber content, but alkali pre-treatment, proper curing techniques and optimized rubber content can significantly improve the strength without compromising the ductility imparted by rubber in the composite [19]. So, the use of rubber particles of finer size and hybrid reinforcement have significant contribution in improving the mechanical strength and durability characteristics in RM-C [20]. With increasing rubber content, post-peak deformation and strain capacity increase while the compressive strength reduces [21].

Out of all, surface treatment is the most critical consideration to improve ITZ. NaOH-treated rubber crumbs show a better polarity and roughness, resulting in improved mechanical interlocking and hydration [22]. An increase in compressive strength by 12-18% and split tensile strength by 15-25% is observed in experimental reports of the investigation. Dou et al. reported an increase in compressive strength up to 25-30%, while in flexural strength up to 20% as compared to untreated crumbs [23]. Durability characteristics also showed an improvement, with a reduction in water absorption by 20-35% and chloride penetration by 30-40%, highlighting the significance of surface coating. Silica-rich slurry-coated rubber particles resulted in reduced microcracking and improved hydration. Increase in compressive strength by 10-22% and electric conductivity around 40%, decrease in depth of carbonation by 15-20% as compared to untreated rubber crumbs [18, 24]. Most studies concluded that optimized rubber content (usually < 15%) along with moderate intensity of treatment on the rubber surface can result in balanced mechanical performance and durability characteristics of rubber-modified concrete.

Recent life cycle-based studies report cradle-to-gate embodied CO<sub>2</sub> reductions of approximately 5–15% when recycled rubber replaces natural aggregates under optimized sourcing conditions [25-27]. However, these studies clearly indicate that transport distance and rubber pre-treatment energy (e.g. grinding or chemical modification) significantly influence net environmental performance [28]. Integrated durability–sustainability investigations further demonstrate that reductions in chloride permeability (≈ 20–40%) and improved crack resistance can extend pavement service life, resulting in whole-life carbon reductions in the range of 8–18% [29]. Overall, in this recent phase of evolution, it was reported that the surface treatment is an effective approach for transforming RM-C from a strength-compromised composite to a performance-engineered material. Improvement in mechanical strength, durability, and reduced permeability highlights the central and most important role of ITZ.

### 3 Conclusion

This review has outlined the evolution of rubber-modified concrete (RM-C) across three phases, demonstrating its progression toward pavement and highway applications. Despite significant improvements in mechanical behavior, durability, and surface treatment techniques, important gaps remain before large-scale implementation in transport infrastructure can be realized. The absence of pavement-specific standards and performance-based specifications remains a major limitation, as current guidelines are primarily strength-oriented and developed for conventional concrete. Furthermore, optimization of rubber surface treatment, validation in structural pavement systems, and comprehensive life cycle assessment linked to service-life performance require further investigation. Addressing these gaps is essential to advancing RM-C as a resilient and sustainable material for highway infrastructure.

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