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REVIEW **Open Access**

Engineered cementitious composites with recycled rubber particles

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Abstract
Cement-based materials are widely used in construction because of their strength, durability, and flexibility in design. Over the past, researchers have sought strategies to minimize the environmental impact of conventional concrete by adopting industrial waste byproducts and alternative aggregates. In this context, the use of end-of-life tire rubber in the production of engineered cementitious composites (ECC) is viewed as an approach that addresses sustainability in the construction industry. Recycled tire rubber particles can modify the ductility, crack control capabilities, and resilience under different loading scenarios, although challenges remain concerning decreased strength and altered workability. The aim of this paper is to review existing studies on ECC with recycled tire rubber particles and compile findings on fresh properties, mechanical performance, crack behavior, fracture mechanisms, and long-term durability. A combination of bibliometric analysis and thorough screening of experimental investigations is performed to highlight major accomplishments, challenges, and knowledge gaps that merit further research. This review gives an in-depth perspective on the suitability of crumb rubber in ECC mixtures and provides practical insights that aim to help meet industry demands for structural and environmental requirements. The paper focuses exclusively on ECC mixtures containing recycled tire rubber and couples bibliometric mapping of 98 Scopus-indexed publications with a systematic synthesis of fresh-state, mechanical, fracture, impact, and durability responses. The review therefore complements earlier rubber-concrete surveys and rubberized ECC constituent-based reviews by providing an ECC-specific assessment of research gaps and application-oriented recommendations.

Keywords Engineered cementitious composites, Recycled tire rubber, Sustainability, Mechanical properties, Durability

1 Introduction

The continuous expansion of global construction has intensified the reliance on advanced cement-based materials for infrastructure, buildings, and specialized applications [12, 15, 21, 64]. Engineered cementitious composites (ECC) are recognized for their strain-hardening behavior, ductility, and crack control mechanisms [47, 73, 88, 101, 103]. The abilities and usability of these materials have drawn increasing attention in both academic and industrial research, with ongoing studies frequently attempting to modify ECC compositions to meet specific performance and sustainability criteria [77, 82, 93, 94, 108].

In general, rubber used in pneumatic tires belongs to a family of elastomeric polymers whose long-chain molecules can undergo large reversible deformations. Modern tire compounds are typically based on blends of natural rubber (predominantly *cis*-1,4-polyisoprene) and synthetic rubbers such as styrene-butadiene rubber and butadiene rubber, combined with fillers, plasticizers, sulfur-based vulcanizing agents, and stabilizers [64, 79]. During vulcanization, cross-links form between the polymer chains, which converts the initially soft material into a resilient thermoset network with high fatigue resistance under cyclic traffic loads. Carbon black and, increasingly, precipitated silica are introduced as reinforcing fillers that enhance stiffness and wear resistance while influencing heat build-up and durability.

Commercial tire rubbers are commonly classified according to their origin (natural versus synthetic), the base elastomer type (for example, natural rubber, styrene-butadiene rubber, or butadiene rubber), and the functional role of the compound in the tire (tread, sidewall, inner liner). The evolution from early natural-rubber tires in the late nineteenth and early twentieth centuries to current multi-elastomer blends has improved traction and service life but has also produced end-of-life tires that are chemically complex and highly resistant to degradation [79]. Grinding these vulcanized rubbers into crumb particles preserves much of the original cross-linked network, which explains their low water absorption and high chemical stability discussed in later sections on fresh behavior and durability.

At the end of their service life, however, the disposal of rubber tires poses significant environmental and economic challenges. Conventional disposal methods present concerns regarding toxic emissions, extensive land use, and prolonged decomposition periods [13, 79, 85]. Shredded or crumb tire rubber (CR) has therefore been evaluated as fine or coarse aggregates in concrete to mitigate solid waste accumulation and decrease dependence on conventional mineral aggregates [14, 74]. Existing studies have demonstrated that rubberized concrete offers improved toughness and damping capacity while showing reductions in compressive strength and workability remain concerns, particularly at high replacement levels [20, 40, 58, 89]. Previous efforts have also attempted to recycle crumb rubber (CR) into ECC as an alternative way to imply sustainability in the construction industry [47, 65].

Early research on incorporating tire rubber into cementitious materials focused on basic feasibility and highlighted both benefits and drawbacks. Studies in the late 1990s and early 2000s reported reduced density and stiffness but improved toughness and crack resistance when shredded rubber was used in concrete and mortar [20, 37, 64, 72, 73, 88]. Subsequent work examined the synergy between rubber aggregates and steel or polymer fibers in reducing restrained shrinkage cracking and enhancing impact resistance [22, 87]. These foundational findings laid the groundwork for the later development of rubber-modified ECC, where the inherent strain-hardening behavior of ECC is combined with the energy-dissipation capacity of rubber aggregates.

ECC typically consists of a high binder content, controlled fiber dosage, and carefully graded fine particles. The introduction of crumb rubber as a partial replacement for sand or other fine aggregates alters the composite's microstructure and rheological

Fig. 1 Illustration of the approach for converting end-of-life waste tires into aggregates and fibers for construction materials [59]

Fig. 2 Examples of recycled rubber aggregates with varying sizes [40]

characteristics [47, 52, 69]. CR influences density, creates voids, and modifies stress distribution pathways, affecting crack propagation, strain capacity, and impact resistance [11, 46, 60, 86]. Due to its inherent ductility, ECC already exhibits greater deformation capacity than conventional concrete. The inclusion of crumb rubber further influences crack bridging and failure modes. The lower modulus of elasticity in rubber reduces overall stiffness, affecting crack initiation and distribution patterns [12, 47]. This can be advantageous in applications requiring energy absorption, such as protective layers, pavements, or structural elements subjected to impact or seismic activity [28, 57, 104].

The process of converting worn tires into aggregates and fibers is depicted in Fig. 1. Once rubber particles are processed to meet specified gradations, they are classified by mesh size, typically ranging from fine powders to larger particles of several millimeters [16, 17, 40, 72]. Figure 2 provides examples of recycled rubber particles with different gradations, demonstrating the influence of particle size on mixture consistency and hardened properties. Finer crumb rubber particles disperse more effectively in the cementitious matrix and typically result in less pronounced reductions in compressive strength compared to coarser particles, though they still contribute to internal porosity [52, 87].

Another factor influencing performance is the hydrophobic nature of untreated crumb rubber, which can limit its adhesion to the cementitious matrix. The presence of contaminants may further reduce interfacial bonding [19, 66, 100]. Various pretreatment strategies, including chemical and mechanical modifications, have been investigated to enhance rubber compatibility with cementitious phases. Treatments with graphene oxide (GO), sodium hydroxide, or silica fume have been reported to improve both fresh and mechanical properties of rubberized ECC [4, 67, 83, 84]. The inclusion of supplementary fillers or cementitious materials can also counteract the porosity introduced by rubber, improving resistance to aggressive environments while maintaining critical mechanical properties [17, 40, 45, 96].

The adoption of ECC incorporating recycled rubber addresses multiple objectives, including waste reduction, decreased reliance on virgin materials, and enhancement of select mechanical or durability characteristics [10, 62, 68, 88]. These attributes align with sustainable construction initiatives focused on minimizing environmental impact throughout the supply chain [41, 79, 103]. ECC containing crumb rubber has been proposed as a viable alternative for projects seeking to reduce carbon emissions while meeting structural performance requirements [21, 90, 91]. Studies have also indicated that ECC with rubber exhibits improved resistance to spalling at elevated temperatures, making it a potential candidate for high-temperature or fire-resistant applications [8, 60, 80]. Despite these advantages, uncertainties remain regarding optimal mix proportions, performance consistency across different climatic conditions, and cost-effectiveness for large-scale implementation [45, 104].

Applications requiring enhanced energy dissipation, such as protective barriers or seismic dampers, may benefit from the elasticity and crack distribution characteristics imparted by crumb rubber [24, 28, 43, 109]. However, maintaining adequate compressive strength in load-bearing elements presents challenges, particularly at high rubber replacement levels [16, 49, 50, 53]. Increased rubber content may lead to workability issues, necessitating higher dosages of superplasticizers or other chemical admixtures [15, 26]. ECC is inherently more expensive than standard concrete due to its elevated binder and fiber content, and additional pretreatment steps for rubber could further increase costs. A careful balance between performance benefits and economic feasibility must, therefore, be maintained [3, 7, 73, 86].

In evaluating fresh properties, standard tests such as slump flow, V-funnel time, and rheological stability are commonly employed to characterize mixture behavior during mixing and placement [17, 49, 50, 52]. The presence of crumb rubber generally reduces flowability, particularly if untreated or used in significant quantities. The inclusion of polymeric fibers, such as polyethylene or polyvinyl alcohol, further influences the workability of the paste [42, 68]. Strategies to mitigate these issues include modifying sand-to-binder ratios, incorporating highly efficient superplasticizers, or utilizing physically or chemically treated rubber particles [45, 71].

The mechanical performance of rubberized ECC is frequently assessed under compression, tension, flexure, and cyclic loading. A consistent trend observed in studies is the reduction in compressive strength proportional to rubber content, while improvements in fracture toughness and ductility have also been documented [16, 28, 47, 74]. A defining feature of ECC is the strain-hardening behavior under flexural and tensile loads. Instead of forming a single dominant crack, multiple microcracks develop, enhancing overall ductility [46, 69, 103]. The presence of crumb rubber in ECC can refine this behavior when adequate bond characteristics and fiber dispersion are maintained [45, 66]. The formation of numerous microcracks with smaller widths may also contribute to improved self-healing when moisture activates residual cement hydration [51, 75, 82].

Durability in aggressive environments remains a key concern. Studies have examined rubberized ECC performance under sulfate attack, acidic conditions, and freeze–thaw cycles [7, 8, 65, 72]. Although rubber inclusion increases porosity, the ductile matrix and enhanced crack control can mitigate the ingress of harmful agents when mix design and surface treatments are optimized [45, 71, 78]. Evaluations at elevated temperatures indicate that melted rubber creates vapor escape channels, which may reduce the risk of explosive spalling [8, 60, 80]. These findings suggest the potential benefits of rubberized ECC in applications where fire safety is a major concern.

This study aims to perform a bibliometric and systematic review of existing research on ECC with recycled rubber, providing a comprehensive assessment of current findings, material improvements, and future research needs. Previous reviews on rubberized cementitious composites have mainly addressed conventional concrete or fiber-reinforced composites in general rather than ECC with its strain-hardening behavior [9, 79]. A more recent review on rubberized ECC concentrates on the role of constituent materials and mix ingredients, without combining bibliometric mapping with a detailed performance-based synthesis of fresh properties, fracture behavior, impact resistance, and durability [2]. The present work focuses specifically on ECC formulations that incorporate recycled tire rubber, links the bibliometric trends for 98 Scopus-indexed studies to their reported fresh, mechanical, fracture, and durability outcomes, and summarizes practical implications for mix proportioning and application-specific use. Studies have reported various mechanical properties, surface treatments, durability considerations, and self-healing behaviors. A critical evaluation of these investigations is necessary to determine the practical feasibility of rubberized ECC in construction, particularly regarding cost, standardization, and long-term stability. Subsequent sections will examine fresh properties, mechanical responses, crack control mechanisms, durability, and high-temperature performance in greater detail. The discussion will outline existing challenges and potential strategies to enhance performance, including surface treatment methods, optimized dosage rates, and improved compatibility with supplementary cementitious materials.

2 Bibliometric analysis

This section presents the bibliometric analysis conducted to examine the existing body of research on rubberized engineered cementitious composite (ECC). A total of 98 publications were retrieved from the Scopus database, with search terms including "engineered cementitious composite" and "rubber" appearing in the title, abstract, or keywords. Accordingly, the search was performed in the Scopus database using the query string "engineered cementitious composite" AND "rubber" applied to titles, abstracts, and author keywords. Only journal articles, conference papers, and book chapters written in English were considered. Records were screened to retain studies that either (i) investigated ECC mixtures incorporating recycled tire rubber or closely related rubber aggregates, or (ii) provided review or overview material explicitly covering rubberized ECC; duplicates and documents that mentioned ECC and rubber only tangentially were

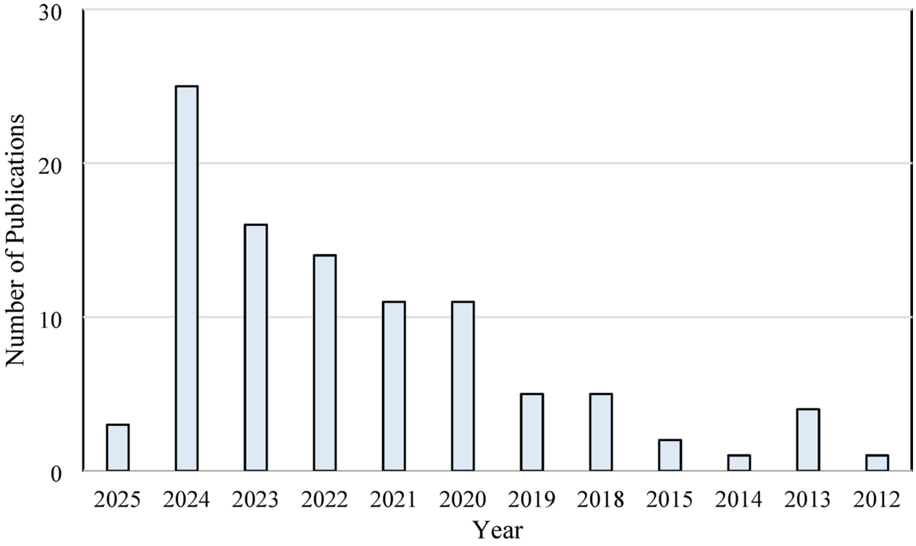


Fig. 3 Number of yearly publications about recycling rubber in ECC in Scopus database

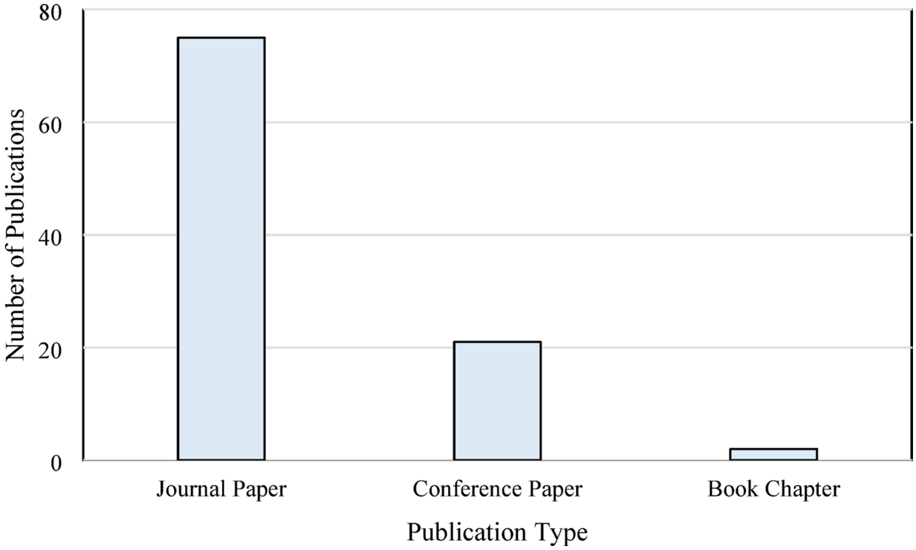


Fig. 4 Types of journal articles and conference papers on recycling rubber in ECC

excluded. The analysis is therefore limited by the coverage and indexing practices of Scopus and by the chosen keywords, so some relevant contributions that use different terminology or appear in other databases may not be captured. The dataset was processed using VOSViewer software to identify patterns, publication trends, and research focus areas. The annual distribution of research articles and conference papers on the topic is shown in Fig. 3. The data indicates a growing interest in rubberized ECC, particularly in recent years. The highest number of publications occurred in 2024, with 25 articles, followed by 2023 and 2022 with 16 and 14 publications, respectively. A noticeable increase can be observed after 2018, suggesting a shift in research priorities toward sustainability in construction materials. Earlier studies were sparse, with only a few papers published before 2015. The categorization of publication types is displayed in Fig. 4, where journal papers constitute the majority, accounting for 75 publications. Conference papers make up a smaller proportion with 21 contributions, while book chapters are limited to only two entries. The predominance of journal publications suggests that the topic has gained significant traction in peer-reviewed scientific discussions, reflecting the depth of investigation in this area.

The keyword co-occurrence network, illustrated in Fig. 5, highlights key themes in prior research. The most frequently occurring terms include “engineered cementitious composites”, “rubber”, “crumb rubber”, “compressive strength”, and “tensile strength”. Other recurring terms, such as “fly ash” and “silica sand”, indicate common supplementary materials used in ECC mixtures. Emerging terms like “graphene oxide” suggest a growing interest in advanced treatments to modify rubber properties for better compatibility with cementitious matrices. The visualization of keyword relationships provides insight into the dominant research topics and potential gaps that may require further investigation. A citation analysis of leading journals publishing in this field is presented in Fig. 6. The most frequently cited sources include *Construction and Building Materials*, *Journal of Building Engineering*, *Lecture Notes in Civil Engineering*, *Cement and Concrete Composites*, and *Case Studies in Construction Materials*. The prominence of these journals underscores the interdisciplinary nature of the research, covering aspects of material science, structural performance, and sustainability. The clustering of citations also reveals the key sources that have shaped the direction of studies on rubberized ECC.

The bibliometric analysis confirms that research on rubberized ECC has gained momentum in the last decade, with an increasing number of publications and a strong presence in high-impact journals. The frequent occurrence of specific keywords suggests that mechanical properties, material optimization, and durability aspects are central to ongoing investigations. The analysis of citations further reflects the interconnected nature of studies, with established journals serving as primary platforms for disseminating findings in this domain. Finally, within the obtained dataset, journal articles account for the majority of contributions, while conference papers and book chapters form a

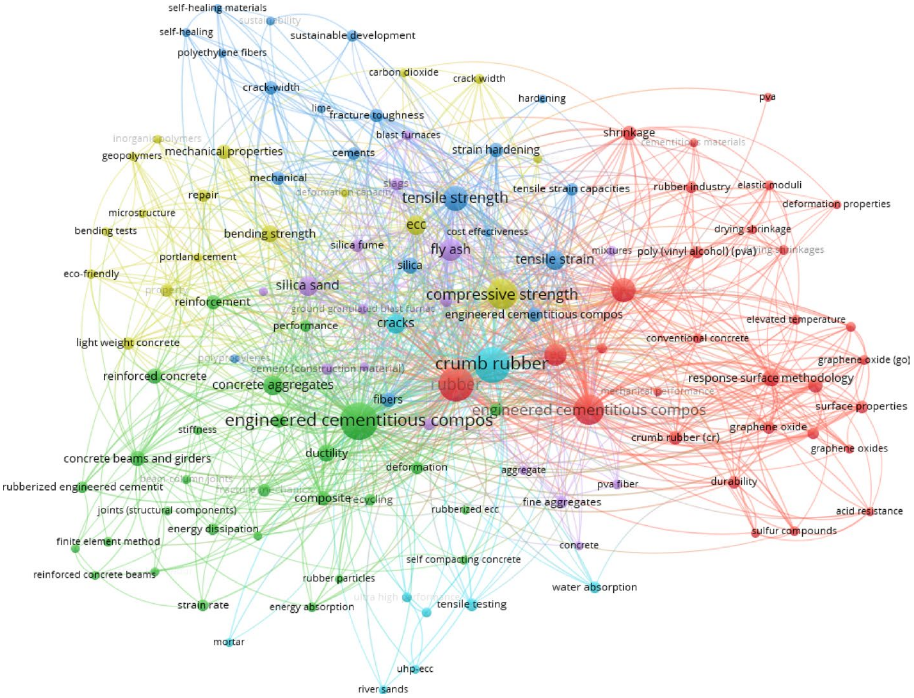


Fig. 5 Co-occurrence of keywords in previous research on recycling rubber in ECC

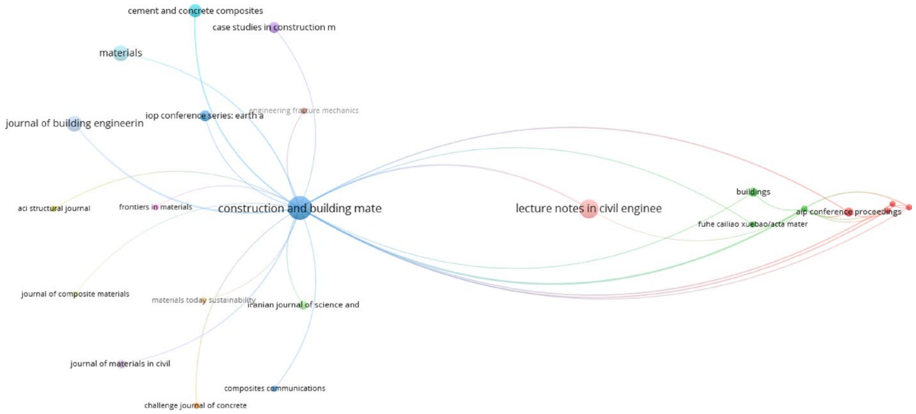


Fig. 6 Citation analysis of influential journals in the area of recycling rubber in ECC

smaller fraction. The dataset is also dominated by individual experimental or numerical investigations, and only a very small number of review-type papers were identified, most of which consider rubberized cementitious composites in general or concentrate on constituent materials rather than ECC as a distinct class. The combination of a marked increase in publications after 2018 and the scarcity of ECC-focused reviews underscores the need for the present synthesis of rubberized ECC mixtures.

3 Fresh properties

The workability of ECC incorporating recycled CR particles directly influences their placement and compaction efficiency [17, 42]. The fresh properties of these mixtures depend on factors such as rubber content, particle shape and size distribution, fiber dosage, and chemical admixtures [40, 49, 50, 86]. As rubber dosage increases, a reduction in fluidity is observed, primarily due to its hydrophobic nature and irregular morphology, which increases viscosity and disrupts flow [9, 12, 19]. Figure 7 illustrates this trend, showing a steady decline in slump flow with higher rubber substitution, while fiber incorporation further amplifies this effect [109].

Table 1 summarizes investigations that assess the impact of crumb rubber on ECC workability. Previous findings indicate that replacing fine aggregate with CR reduces slump flow and increases viscosity, necessitating adjustments in superplasticizer dosage or water content to maintain a workable consistency [1, 5, 16, 45]. Minor additions (1–5%) of fine crumb rubber particles under 1 mm typically exert minimal influence on flowability when paste volume remains sufficient [11]. However, higher CR fractions exceeding 15–20% result in considerable reductions in flow due to increased interparticle friction, which can hinder placement in reinforced sections unless mix proportions are optimized [30, 52].

The mechanisms behind these fresh-state trends are primarily linked to the surface and volumetric characteristics of tire rubber. Crumb rubber particles exhibit very low water absorption compared to mineral aggregates, so mixing water is not stored inside the particles but remains in the paste phase; however, the hydrophobic and often rough surface of rubber interferes with the dispersion of cement grains and reduces the efficiency of polycarboxylate-based superplasticizers [40, 64, 73]. The resulting paste-aggregate interface behaves almost like a lubricated, non-bonding boundary that increases interparticle friction rather than improving flow. When angular or fiber-like rubber

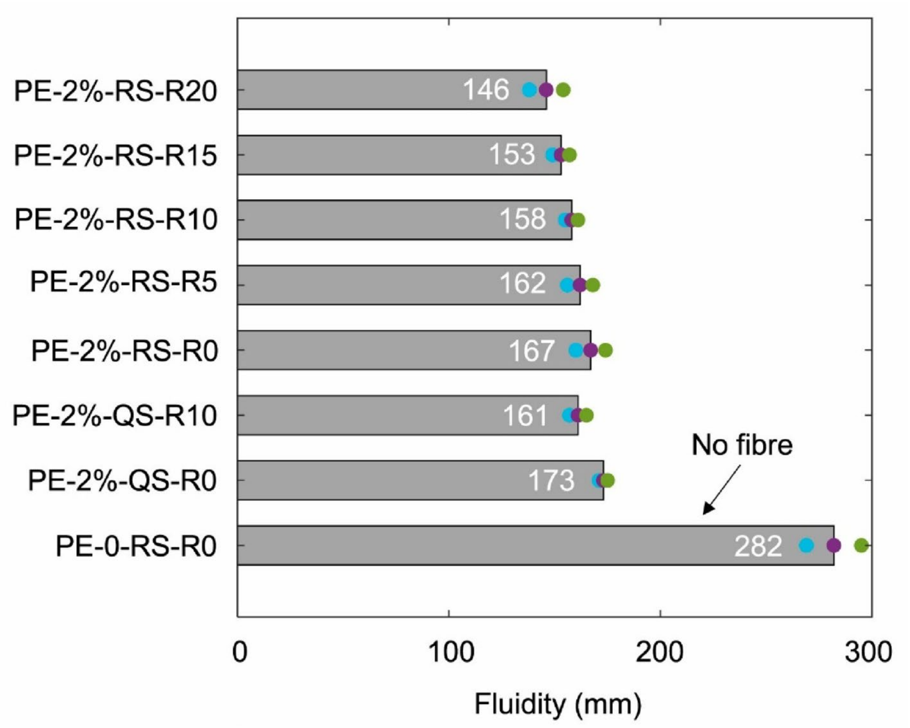


Fig. 7 Fluidity measurements of ECC mixtures with various rubber contents (R), including quartz sand (QS) or river sand (RS) and polyethylene fiber (PE), showing a drop in the workability as rubber particles are added [109]

particles are used, their geometry promotes mechanical interlocking and flocculation, which further raises yield stress and plastic viscosity. These effects are amplified when fibers are present, because fibers and rubber particles compete for space in the mortar matrix, increasing the probability of clusters or “balls” that resist flow [49, 50, 52].

Some studies suggest that finer rubber particles disperse more uniformly in the cementitious matrix, reducing flow loss compared to coarser particles that tend to form bridging points [69, 74].

Chemical and physical modifications have been explored to counteract the adverse effects of rubber on fresh consistency [19, 67, 71]. Chemical treatments, such as sodium hydroxide exposure, roughen the rubber surface and improve wettability, potentially enhancing rubber-cement bonding [92, 100]. However, improper dispersion of chemically modified rubber may disrupt fluidity. Physical modifications, such as grinding or surface abrasion, have been found to remove contaminants that interfere with cement paste integration, promoting better dispersion [45, 65]. The combination of physically treated rubber with supplementary cementitious materials has also demonstrated improvements in fresh behavior [7, 16, 70].

The introduction of polyethylene, polyvinyl alcohol, or steel fibers in ECC mixtures affects workability by increasing viscosity, particularly when combined with CR [17, 47, 48]. Each crumb rubber particle acts as a non-absorptive boundary, further thickening the mixture [104, 105]. The interaction between rubber and fiber geometry influences dispersion, as similarly sized components tend to cluster, leading to non-uniform distribution or “balling” [52]. Figure 8 presents slump flow variations in mixtures containing untreated and treated rubber, emphasizing the role of rubber type and modification in altering workability [45]. Among the tested treatments, ground glass powder

Table 1 Effect of crumb rubber inclusion on the workability of ECC

Study	Crumb rubber content (%)	Additional modifiers	Workability parameters	Observation
Abdulkadir et al. [5]	5–15	Graphene Oxide (GO)	Slump flow, T500, V-funnel time, L-box ratio	Increased crumb rubber and GO reduced flowability but maintained self-consolidating properties. Optimal mix achieved slump flow of 645–800 mm, T500 of 2.4–5.2 s, and L-box ratio of 0.8–0.98
Ismail et al. [49, 50]	0–50	Fly ash, silica fume, metakaolin	Slump flow, workability index	Higher rubber content reduced slump flow and increased viscosity. Up to 30% CR maintained self-consolidating behavior, but 40–50% required increased superplasticizer dosage
Helal et al. [45]	10–30	Waste Quarry Dust (WQD)	Slump flow, V-funnel time	Increased rubber reduced slump flow and increased V-funnel time. Physically treated CR improved flowability compared to untreated rubber
Zhao et al. [105]	10–30	Fly ash	Slump flow, rheological behavior	Higher rubber content increased viscosity and reduced slump flow. Fly ash compensated for flowability loss, ensuring better workability at high rubber levels
Abdulkadir et al. [7]	1–5	Graphene Oxide (GO)-treated crumb rubber	Slump flow, viscosity index	GO-treated rubber reduced viscosity and improved slump retention compared to untreated rubber. High GO content resulted in excessive thickening
Mohammed et al. [60]	0–5	Polyvinyl Alcohol (PVA) fibers	Slump flow, compactability	Low rubber content (≤ 5%) had minimal impact on workability, but higher fiber content increased viscosity, requiring mix adjustments
Khed et al. [52]	Up to 60	Hybrid fiber-reinforced ECC	Slump flow, viscosity index	Finer crumb rubber (30 mesh) improved workability, while larger rubber particles (1–3 mm) increased viscosity and reduced flowability
Adesina and Das [10, 11]	0–100	None	Slump flow, mid-span deflection	Full replacement (100% CR) resulted in extremely low slump, requiring superplasticizers. Partial replacement (≤ 30%) retained acceptable workability
Siad et al. [78]	0–40	Powder Rubber Sand (PRS)	Slump flow, water absorption	PRS improved workability compared to standard crumb rubber, allowing higher rubber replacement levels
Hassan [42]	0–30	Powder Rubber (PR)	Slump flow, fresh mix behavior	PR mixes up to 30% retained good slump, while CR mixes exhibited faster slump loss. PR was preferred for maintaining flowability

modification achieved the highest slump values, indicating its effectiveness in preserving fluidity. Adjustments such as gradual rubber introduction, partial pre-wetting, and controlled fiber distribution during mixing have been investigated to address these challenges [14, 60].

Supplementary cementitious materials, including fly ash, silica fume, and metakaolin, are frequently incorporated into rubberized ECC to offset the porosity introduced by CR and mitigate water demand [7, 49, 50, 81]. Fly ash enhances paste cohesion through pozzolanic reactions, while silica fume improves pore structure by filling voids at the microscale [30, 45, 105]. These additions help maintain self-consolidating properties, which are essential for ECC applications. Some studies have also examined the effects of GO and other nanomaterials in modifying rubber surfaces, demonstrating improvements in workability due to reduced interfacial friction and improved dispersion [1, 23].

Experimental studies commonly employ rheometers to evaluate viscosity and yield stress in rubberized ECC, confirming that rubber presence increases both parameters [52, 78]. The matrix must retain sufficient free water for lubrication, which can be achieved through optimized mix proportions. Fine fillers such as quarry dust or recycled

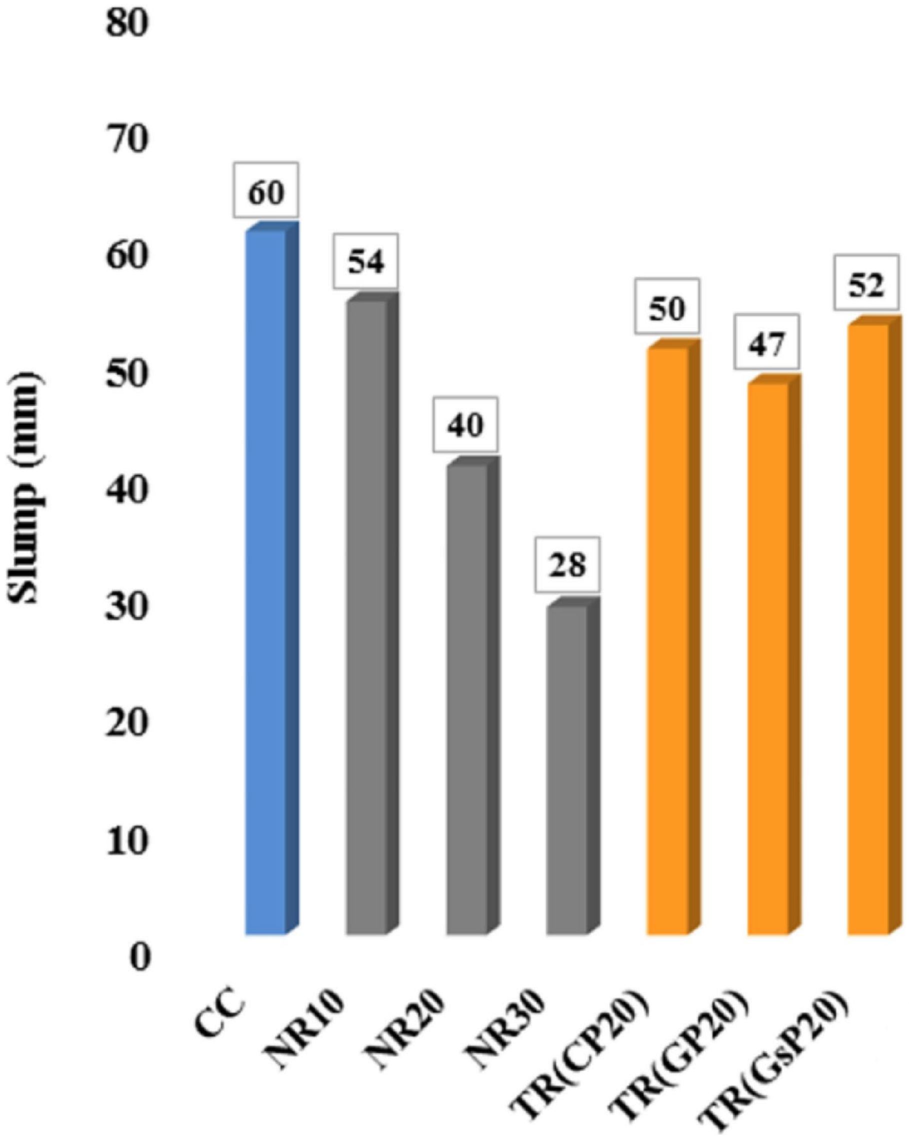


Fig. 8 Measured slump values of ECC showing the control mixtures (cc), the non-treated rubber (NR) mixtures, and the treated rubber (TR) mixtures with ceramic powder (CP), granite powder (GP), and ground glass powder (GsP) at various percentages, showing a drop in the workability as untreated rubber particles are added but when treated particles are used the pattern changes and the workability is much improved with the GSP case being the best [45]

glass have been investigated as a means to counteract void formation due to rubber inclusion, supporting a stable mixture [45, 70, 102]. Certain mix design strategies adjust paste volume or incorporate silica-based fillers to maintain flowability [45, 68, 78].

An increase in the water-to-binder ratio can improve flow but may negatively impact mechanical performance [63, 69, 73]. Superplasticizers offer a more effective solution, with polycarboxylate-based variants proving superior to naphthalene-based alternatives in controlling slump retention [40]. Other approaches include refining the mixing sequence by gradually introducing rubber or soaking it in solutions that enhance compatibility. A combination of chemical and physical pretreatment methods has also been explored to improve consistency [7, 67].

The extent to which rubber affects flow varies based on dosage, particle size, and modification method [11, 12, 60]. Although minor additions (under 10%) of fine CR are generally well tolerated, particularly when paste volume is adjusted, larger dosages or untreated rubber above 20% significantly increase viscosity, complicating placement [30, 52]. Several studies have proposed solutions, including advanced admixtures, finely ground mineral powders, and optimized mixing procedures [19, 45, 92].

Ensuring fresh workability is fundamental to achieving uniformity in the hardened composite. Poor dispersion of rubber and fibers can result in clustering, leading to weak zones and reduced mechanical performance [52, 69]. Research on rubber pretreatment continues to focus on improving rubber-cement bonding, which not only benefits mechanical properties but also maintains a more stable fresh mixture [19, 67, 95]. However, the cost and environmental implications of such treatments must be considered, as more advanced chemical or nanomaterial modifications introduce production expenses and technical challenges [83, 84, 96]. While mild sodium hydroxide treatment can be implemented on a moderate scale, more complex chemical or nanomaterial approaches require further economic assessment before large-scale adoption.

For ECC to retain its self-consolidating and crack-controlling capabilities, precise mix adjustments are necessary. Proper CR pretreatment, optimized admixture dosages, and carefully designed mix proportions ensure even distribution of rubber and fibers [45, 104]. Researchers have quantified the slump reductions associated with crumb rubber incorporation and proposed effective countermeasures, yet further refinements are required for practical field applications where complex casting conditions introduce additional variables [16, 64]. The next section examines the influence of these mixture adjustments on mechanical performance and failure characteristics, assessing their implications for structural applications.

4 Mechanical performance and failure behavior

Crumb rubber in ECC matrices substantially modifies mechanical behavior under compression, tension, flexure, and dynamic loading [11, 13, 33–35, 47, 74, 103]. Conventional ECC typically exhibits strain-hardening and multiple cracking under tension, producing an elevated strain capacity compared to normal concrete. CR addition can boost flexibility and impact resistance but typically lowers compressive strength if introduced in higher volumes [17, 45, 46, 78]. This section examines how crumb rubber affects compressive, tensile, and flexural performance, fracture behavior, self-healing, and high-impact responses.

4.1 Compressive, tensile, and flexural strength

Previous research consistently indicates that compressive strength decreases as CR content increases due to the lower stiffness of rubber and the formation of pores at the matrix-rubber interface [78, 82, 86]. Figure 9 presents dynamic compressive stress–strain curves for ECC incorporating varying amounts of rubber and polyethylene fiber [98]. The results confirm a reduction in peak compressive strength compared to control mixtures without rubber, although the material retains ductile behavior.

Several factors influence the extent of strength reduction. Fine crumb rubber generally causes less pronounced strength loss compared to coarser particles, likely due to its more uniform dispersion within the matrix [11, 13, 52]. Higher rubber content, particularly

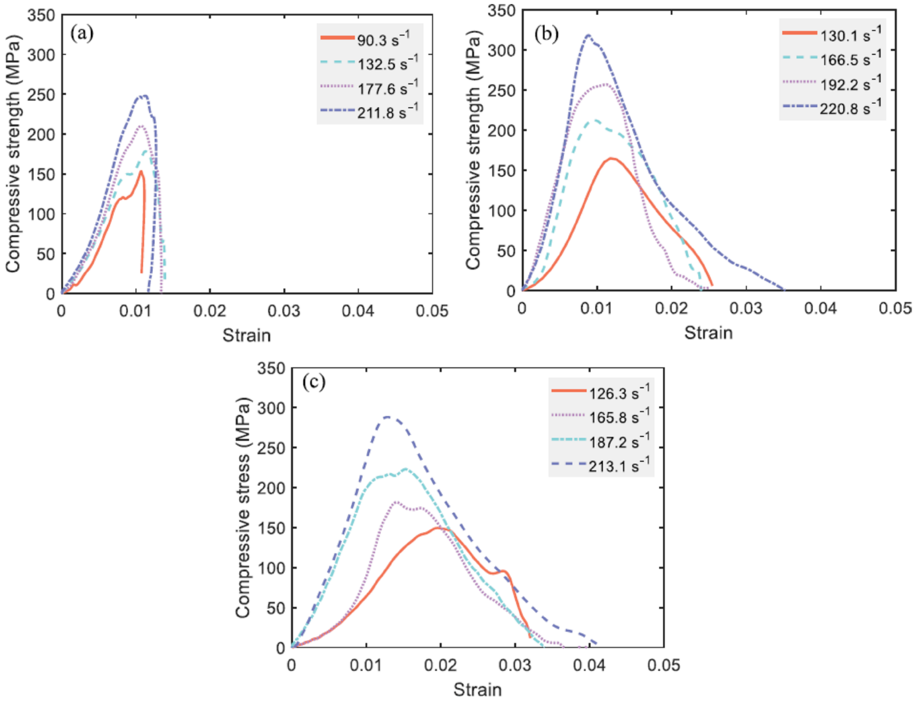


Fig. 9 Dynamic compressive stress–strain curves of engineered cementitious composite mixtures with various recycled rubber (R) and polyethylene fiber (PE) contents: **a** PE-0-R0, **b** PE-2%-R0, and **c** PE-2%-R10, showing a drop in the compressive when rubber particles are added without changing the stress–strain behavior from ductile to brittle [98]

beyond 20–30%, tends to exacerbate strength loss [8, 49, 50, 65]. Surface modification or chemical pretreatment of CR enhances interfacial bonding and reduces void formation, mitigating compressive strength reduction [3, 19, 45]. Additionally, incorporating supplementary cementitious materials such as fly ash, silica fume, or metakaolin refines the matrix and counteracts porosity introduced by rubber [17, 81, 105].

Thermal effects on rubberized ECC have also been investigated. Adamu et al. [8] examined behavior across temperatures up to 1000 °C, reporting a gradual compressive strength decline with increasing temperature, though CR improved resistance to spalling [60]. Helal et al. [45] demonstrated that physically treated crumb rubber combined with waste quarry dust mitigated some strength losses. Table 2 summarizes representative data on the influence of crumb rubber on compressive, tensile, and flexural strengths in various studies.

The observed strength reductions can be interpreted in terms of both local and global load-transfer mechanisms. At the microscale, replacing stiff mineral sand with low-modulus rubber introduces compliant inclusions surrounded by relatively weak interfacial transition zones (ITZs), where microcracks tend to initiate under compression and tension [69, 96, 103]. These ITZs act as preferred paths for crack growth, lowering peak compressive and tensile strengths even when the overall matrix composition remains unchanged. Under multiaxial or cyclic loading, stress concentrations around rubber particles are relieved through local deformation of the rubber, which contributes to improved toughness and higher post-peak strains but reduces the maximum load that can be carried before microcrack coalescence.

Table 2 Influence of crumb rubber on the mechanical performance of ECC

Study	Crumb rubber content (%)	Temperature range	Compressive strength impact	Tensile strength impact	Flexural strength impact	Ductility impact	Key observations
Siad et al. [78]	0–40	Normal conditions	Lowered	–	Enhanced	Increased flexibility	Powder rubber improved transport properties, reducing chloride permeability
Adamu et al. [8]	0–5	23–1000 °C	Gradual reduction with increased temperature	–	–	–	Crumb rubber provided moisture venting, preventing explosive spalling
Mohammed et al. [60]	0–5	100–1000 °C	No catastrophic failure observed	–	–	Maintained integrity despite strength decline	Crumb rubber inclusion prevented spalling at high temperatures
Jiangtao et al. [51]	100	Normal conditions	Lowered due to reduced matrix toughness	Reduced tensile strength, but improved crack management	–	Enhanced self-healing through hydration	Wet-dry cycles activated binder hydration, restoring mechanical integrity
Abdulkadir et al. [1]	1–5	Normal conditions	Increased with the addition of graphene oxide	Increased due to improved fiber-matrix bonding	–	Decreased drying shrinkage	Graphene oxide offset the porosity introduced by crumb rubber, leading to lower shrinkage
He et al. [44]	10	Normal conditions	Decreased by 8.9%	Increased strain hardening capacity	Reduced by 15.6%	Maintained	Dynamic strength increased at higher strain rates, indicating good impact resistance
Helal et al. [45]	10–30	Normal conditions	28.1% reduction with untreated crumb rubber, but 20.1% increase with treated rubber	Increased with physically treated crumb rubber	Reduced flexural strength at high levels	Enhanced	Quarry dust and treated crumb rubber improved bonding and mechanical properties
Hasibuan et al. [41]	2.5–12.5	Normal conditions	Decreased but remained above structural viability (≥ 17 MPa)	–	–	Increased	Palm shell ash compensated for some of the strength loss from crumb rubber
Ye et al. [98]	10	High strain rate conditions	No significant reduction in peak compressive stress	Increased strain energy density	Slightly reduced flexural strength	Enhanced under dynamic loading	Crumb rubber increased strain energy density by 20.2%, improving impact resistance
Rahman et al. [74]	10–30	Normal conditions	Decreased with higher crumb rubber content	–	–	Increased	Ground palm oil fuel ash and crumb rubber combined resulted in reduced density and thermal conductivity
Teng et al. [82]	0–30	Normal conditions	Reduced at early ages, improved later	Increased tensile strain capacity	Crack width reduced by 52.79%	Long-term ductility enhanced	Early-age ductility loss was mitigated by improved fiber bridging at later ages

Table 2 (continued)

Study	Crumb rubber content (%)	Temperature range	Compressive strength impact	Tensile strength impact	Flexural strength impact	Ductility impact	Key observations
Zhu et al. [109]	0–15	25 °C to − 196 °C	Reduced at room temperature	Increased due to improved crack bridging	Increased impact toughness	Higher at lower temperatures	Ice formation at low temperatures altered fiber bridging, affecting tensile performance

At the composite level, the reduction in elastic modulus due to rubber alters the balance between matrix cracking and fiber bridging. In conventional ECC, strain-hardening relies on a carefully tuned relationship between matrix fracture toughness, fiber pull-out resistance, and crack-tip stress intensity [101, 104]. When rubber is added, the softer matrix and modified ITZ reduce the stress transmitted to individual fibers, which explains the modest reductions in tensile and flexural strengths. At the same time, the compliant inclusions promote crack deflection and branching, so more microcracks form at lower individual crack openings. This explains why many studies report lower peak strength yet equal or higher ultimate strain and deflection capacities [45–47].

Since this strength-ductility trade-off appears consistently across many experimental programs, subsequent sections refer back to these mechanisms and focus primarily on how rubber content and treatment affect fracture patterns, impact resistance, and durability, rather than repeating numerical strength reductions.

In general, strain-hardening in ECC under tension is primarily governed by fiber bridging and the development of multiple microcracks [68, 101, 104]. The presence of CR reduces matrix stiffness, influencing crack initiation and propagation [47, 73, 97]. Figure 10 illustrates that tensile strength decreases as rubber content rises, but the capacity to sustain multiple cracking remains a defining characteristic [47, 66]. Certain studies indicate that a small CR fraction (2–5%) leads to only a minor reduction in tensile strength while refining crack patterns [16, 46]. Crack width reduction contributes to improved durability and self-healing capacity [46, 51].

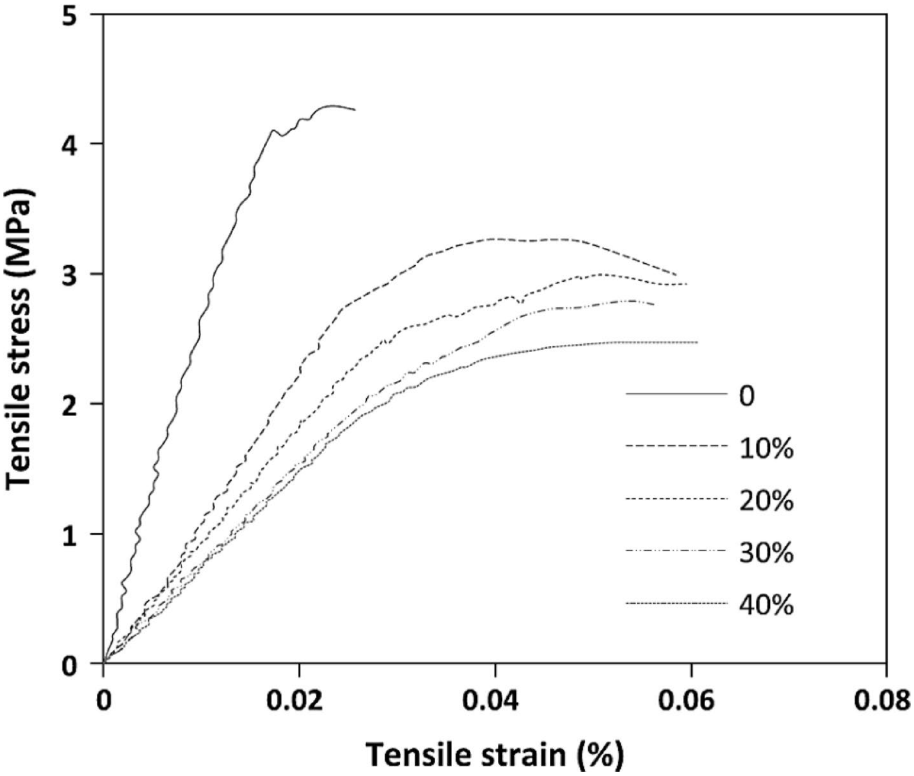


Fig. 10 Tensile stress–strain curve of engineered cementitious composite mixtures at various rubber replacement percentages, showing a considerable drop in the strength when rubber particles are added with improvement in the ductile [47]

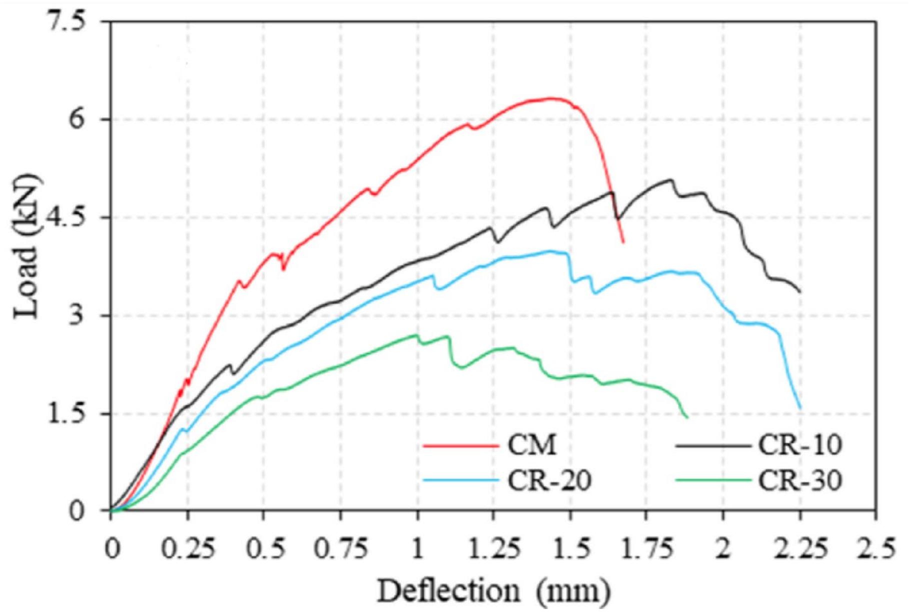


Fig. 11 Effect of crumb rubber content on the load–deflection response of ECC, showing a drop in the load carrying capacity as rubber particles are added [74]

Fig. 12 Failure pattern of ECC with various rubber contents under compression, showing improved behavior with the inclusion of rubber compared to the control case [106]

In flexural testing, ECC typically exhibits deflection-hardening with delayed crack localization [46, 69, 104]. The elastic nature of rubber extends pre-peak deformation, though peak load capacity declines. Figure 11 presents a representative load–deflection response for varying levels of crumb rubber replacement [74]. As CR content increases, peak load decreases, but deflection capacity and energy absorption improve, which is beneficial in high-impact or seismic applications [16, 24, 28]. Studies on moderate rubber substitution report an acceptable balance between flexural strength and ductility [42, 43].

4.2 Fracture behavior and self-healing

Indeed, fracture behavior and self-healing are influenced by the presence, size, and surface characteristics of crumb rubber particles. Previous researchers have observed that rubberized ECC offers the ability to form fine multiple cracks instead of a single critical macrocrack [22, 45, 46, 69]. Figure 12 shows an example of how the presence of CR influences compressive failure patterns, producing more diffuse cracking rather than brittle splitting [106]. Figure 13 demonstrates that CR leads to smaller yet more numerous cracks [109]. Digital image correlation results highlight the distribution of microcracks,

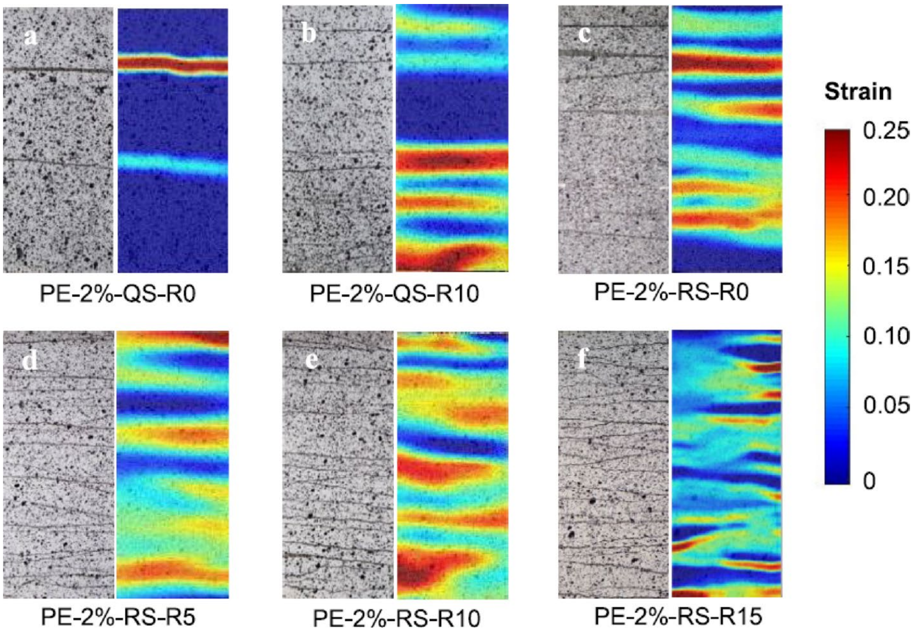


Fig. 13 Crack patterns and digital image correlations of engineered cementitious composite mixtures with various rubber contents (R), including quartz sand (QS) or river sand (RS) and polyethylene fiber (PE), showing smaller yet more cracks when rubber particles are added [109]

differing from standard concrete, where cracks typically coalesce into a primary fracture plane [87, 102].

From a fracture mechanics viewpoint, rubber particles modify both crack initiation and crack propagation conditions in ECC. The presence of compliant inclusions and associated ITZs increases crack-path tortuosity, so propagating cracks are repeatedly deflected or arrested at rubber–matrix interfaces [22, 46, 69]. Each deflection event effectively reduces the mode I stress intensity at the crack tip, which delays unstable crack growth and favors the formation of new microcracks elsewhere in the matrix. The micro-CT and digital image correlation observations of diffuse crack patterns [102, 109] are therefore consistent with a reduction in effective fracture toughness at the local level but an increase in global energy absorption due to a larger fracture surface area. The resulting multiple-cracking response aligns with established strain-hardening criteria for ECC, where the bridging stress-crack opening relationship of fibers must exceed the matrix cracking resistance over a range of small crack widths.

Under tensile or flexural loading, fibers can act alongside CR to sustain load, delaying crack localization [44, 82, 103]. Figure 14 provides scanning electron microscope images of microcracks in ECC with and without rubber [99]. The bridging action from polyethylene fibers is maintained, but cracks are more dispersed when CR is present. This phenomenon is partially attributed to the ability of rubber particles to deflect or blunt cracks before they become large [27, 46].

Multiple cracks with narrow widths can be more likely to close over time if moisture or other healing agents are available, since narrower cracks provide smaller paths for external fluid infiltration [51, 65]. Rubber's lower elastic modulus can contribute to crack refinement, which in turn supports hydration product deposition or crystallization within cracks [10, 69]. Figure 15 shows how rubber particles themselves can act as crack bridges, a process that is particularly relevant when the matrix remains cohesive

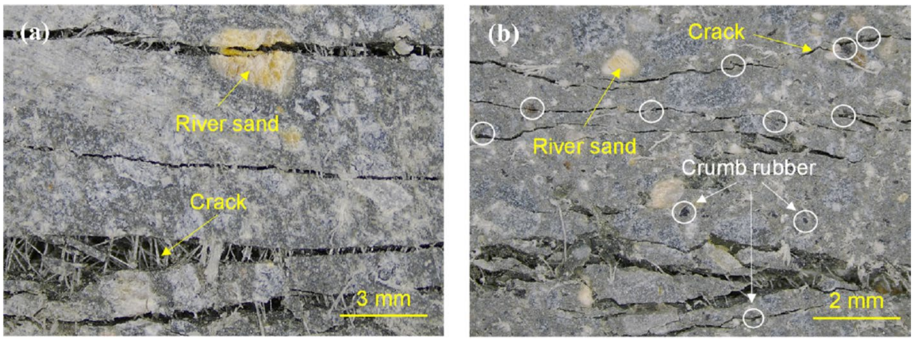
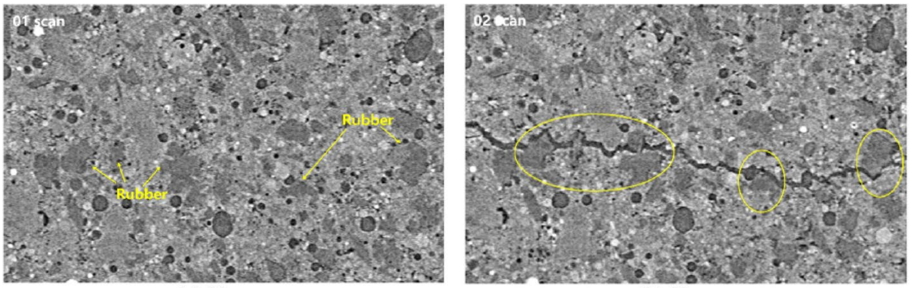
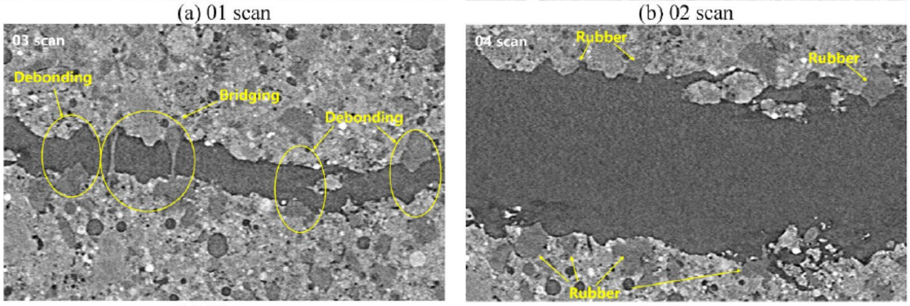


Fig. 14 Scanning electron microscope images of microcracks in ECC with recycled rubber (R) and polyethylene fiber (PE) under dynamic splitting tensile testing: **a** PE-2%-R0, and **b** PE-2%-R10 [99]



(a) 01 scan (b) 02 scan



(c) 03 scan (d) 04 scan

Fig. 15 Scanning electron microscope images showing the crack bridging process of rubber particles in ECC under tension: **a** before matrix crack, **b** rubber particles intercept and bridge crack faces, **c** stretching of rubber particles across the opening crack, and **d** ruptured rubber particles [46]

[46]. The sequence shows rubber inclusions intercepting crack faces and deforming until rupture. This can improve ductility but only if the interfacial zone remains secure. Table 3 summarizes various studies on crack control and self-healing in rubberized ECC. For instance, Teng et al. [82] utilized Zn^{2+} ionic clusters for self-healing and recorded a 36.8% reduction in crack width at 28 days with significant ductility gains, suggesting synergy between rubber's elasticity and ongoing hydration processes.

4.3 High-impact resistance and energy absorption

Impact resistance is a primary consideration when incorporating CR into ECC. The elasticity of rubber contributes to energy dissipation, while the fiber network continues to distribute loads [28, 76, 104, 109]. This effect is particularly relevant in structures exposed to dynamic or impact loads, where maintaining ductility and minimizing brittle failure are essential [36, 38]. The ability of rubberized ECC to sustain repeated shocks without significant strength loss has been examined under various temperature

Table 3 Crack control and self-healing potential of ECC containing crumb rubber

Study	Crumb rubber content (%)	Self-healing mechanism	Crack width	Key observations
Jiangtao et al. [51]	100	Wet–dry cycles promoting hydration	Reduced crack width due to matrix toughness reduction	Self-healing was enhanced through crack refinement, despite strength loss
Hou et al. [46]	Varying	Crumb rubber bridging model	39–68 μm	Smaller crumb rubber particles enhanced crack control through particle bridging
Teng et al. [82]	0–40	Zn^{2+} ionic clusters for self-healing	36.8% reduction in crack width at 28 days	Ionic cluster-treated rubber accelerated self-healing via continued hydration and managed to increase ductility by 27.11%
Zhao et al. [105]	15–35	Fly ash and crumb rubber interactions	Reduced crack width with higher crumb rubber content	Reduced permeability due to tight crack formation improved water resistance
Huang et al. [47]	0–40	Restrained drying shrinkage mitigation	Increased free shrinkage but reduced crack formation	Lower elastic modulus of rubber-enhanced engineered cementitious composite prevented large shrinkage cracks
Zhang and Qian [101, 102]	10–15	Rubber powder influence on matrix toughness	52.79% reduction in tensile fracture width	Rubber powder facilitated multiple microcracks, refining crack behavior

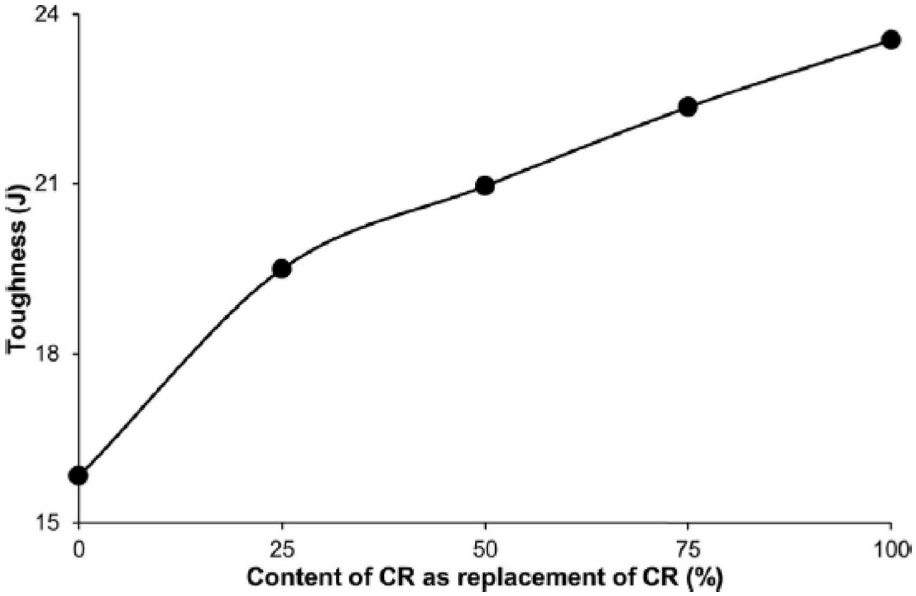


Fig. 16 Effect of rubber content on the toughness of ECC, showing an significant improvement in the toughness as rubber particles are added [10, 11]

conditions [32, 107]. Figure 16 presents data illustrating how toughness evolves with increasing rubber dosage [10, 11]. These results show that ECC containing crumb rubber demonstrates improved energy absorption capacity, though this enhancement is accompanied by a reduction in compressive strength [49, 50, 65]. The trade-off between these properties requires careful balance in structural applications. Zhu et al. [109] observed that ultra-high-performance ECC with CR maintained steady energy absorption at sub-zero temperatures, a feature particularly beneficial for cold climates [103].

Figure 17 provides an overview of energy dissipation coefficients across a temperature range from – 50 to 150 °C [28]. Findings confirm that rubberized ECC exhibits higher energy absorption than conventional ECC, especially in low-temperature environments [48, 105]. The ability of CR to delay crack propagation under abrupt loads is one of its advantages, though considerations such as chemical stability and potential thermal degradation at elevated temperatures must be accounted for [8, 60].

Experimental investigations frequently employ strain-rate-sensitive testing methods, including the split Hopkinson pressure bar and drop-weight impact tests, to assess the mechanical response of rubberized ECC [42, 99, 104]. Ye et al. [98] reported an increased dynamic compressive energy absorption capacity of ECC when rubber particles are added, Fig. 18. Ye et al. [99] found that rubber particles, acting as pseudo-pores, allowed the material to withstand greater strains without catastrophic cracking, contributing to increased dynamic splitting tensile strength and more dispersed crack patterns [27, 29]. Residual mechanical capacity after multiple impact cycles was higher than that of control ECC mixtures [28, 46, 90, 91].

Rubber particle characteristics, including density, shape, and compatibility with the cement matrix, play a role in ensuring consistent performance under high-impact conditions [16, 25, 87]. Larger rubber particles may improve cushioning properties, but they can also interfere with fiber bridging or introduce localized weaknesses in the matrix. Finer CR generally integrates more effectively within ECC, which is a mortar-based composite [45, 49, 50, 70]. Some researchers propose hybrid approaches that combine crumb rubber with synthetic fibers in varying proportions to improve ductility while minimizing strength reduction [11, 52, 68].

The experimental programs reviewed in Sects. 3 and 4 cover a wide range of mixture designs and testing protocols. While the main text emphasizes mechanisms and

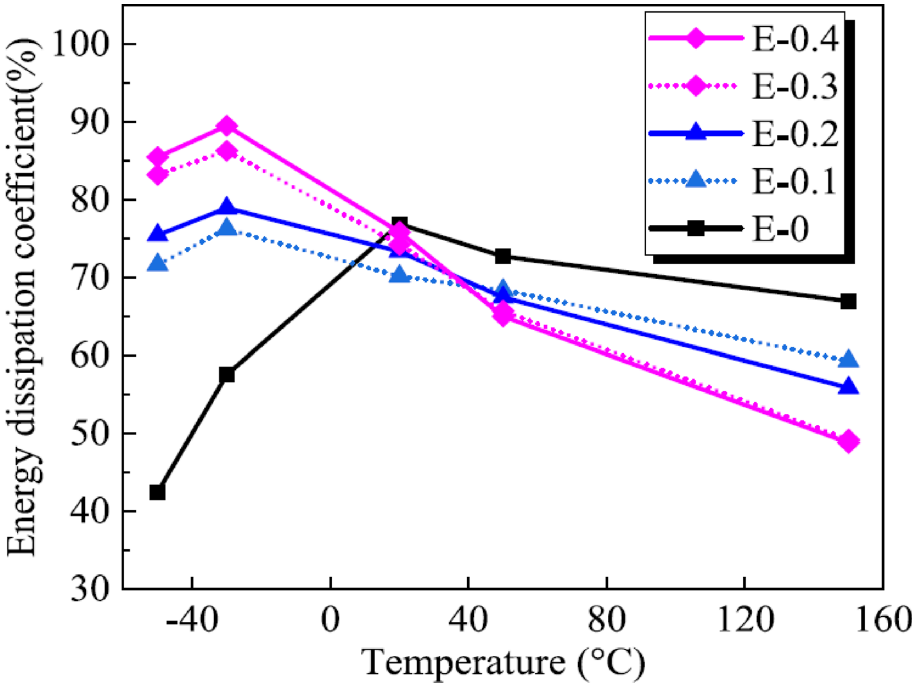


Fig. 17 Energy dissipation coefficient of ECC with rubber practices at various temperatures, showing a huge impact in the behavior with respect to the temperature as rubber particles are added [28]

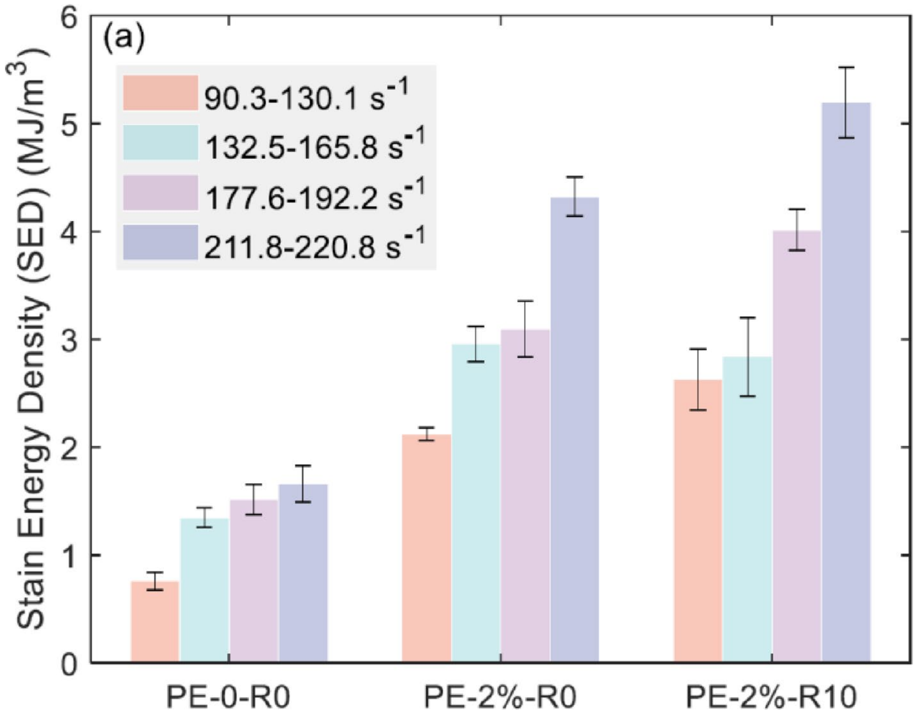


Fig. 18 Dynamic compressive energy absorption capacity of ECC with rubber contents (R) and polyethylene fiber (PE), showing an increased capacity when rubber particles are added [98]

response trends, it is also helpful to highlight the distinctive scientific contributions of representative studies in a compact format. Table 4 summarizes selected key works on rubberized ECC and related composites, indicating their primary focus, the mechanisms they clarified, and the application contexts they addressed. Rubber's role in ECC impact resistance, Table 5, presents both advantages and design considerations. While improved toughness and energy dissipation contribute to durability in impact-prone environments, mix proportioning must ensure that reductions in compressive and tensile strength do not compromise structural performance [24, 62, 104]. The combination of optimized rubber content, proper fiber reinforcement, and mix adjustments can support the development of ECC formulations tailored for impact-resistant applications.

5 Durability and long-term performance

Long-term performance, including resistance to chemical attack, freeze–thaw cycles, and temperature extremes, is a primary concern for any structural material [14, 63, 66]. ECC is already known for limiting crack widths and resisting ingress of harmful agents. Adding CR alters pore structure and microcrack development, which can either strengthen or compromise durability, depending on how effectively the mix design addresses porosity and interfacial bonding [37, 78].

5.1 Resistance to harsh environmental conditions

5.1.1 Chloride ingress and transport

Chloride penetration is a major problem for reinforced concrete in marine or deicing salt environments. ECC's fine crack network can provide an advantage by limiting direct channels for chloride transport, while the introduction of rubber can change the

Table 4 Representative scientific contributions on rubberized ECC and related cementitious composites

References	Main focus area	Key mechanistic contribution	Application or design implication
Raghavan et al. [73], Raghavan [72] and Nehdi and Khan [64]	Early rubber-cement composites	Identified strength reduction due to weak rubber-matrix interface and lower stiffness, alongside gains in toughness and energy dissipation	Established feasibility of using tire rubber in cementitious systems and highlighted the fundamental strength-ductility trade-off
Bonnet et al. [22] and Turatsinze et al. [87, 88]	Rubber aggregates with steel fibers	Demonstrated synergistic crack-resistance when rubber is combined with fibers, reducing restrained shrinkage cracking	Motivated use of rubber-fiber systems for crack control in repair and overlay applications
Huang et al. [47], Zhang and Qian [101, 102] and Zhang et al. [103, 104]	Rubber-modified ECC	Showed that small rubber dosages preserve strain-hardening while refining crack patterns and reducing shrinkage cracking	Provided the basis for using low-modulus ECC in durable repair applications with improved crack management
Ismail et al. [49, 50] and Siad et al. [78]	Self-consolidating ECC with crumb and powder rubber	Clarified how particle size and form (crumb vs powder) affect workability, strength, and transport properties, including chloride permeability	Guided selection of fine rubber fractions and supplementary materials for structural ECC with acceptable transport performance
Mohammed et al. [60], Adamu et al. [8] and Labbani et al. [55]	High-temperature behavior	Linked the absence of explosive spalling to vapor venting through voids left by melted rubber and to gradual strength degradation of the matrix	Supported the use of rubberized ECC in fire-resistant elements where integrity is more critical than maximum strength
Abdulkadir et al. [1, 3, 4, 5, 7]	Graphene oxide-treated crumb rubber	Showed that GO pretreatment can strengthen the rubber-matrix interface, reduce shrinkage, and improve sulfate and acid resistance while partly recovering strength	Demonstrated a tunable route for enhancing durability of rubberized ECC using nanomaterial-based surface treatments
Helal et al. [45]	Physically treated rubber and waste quarry dust	Demonstrated that physical pretreatment and mineral fillers can recover part of the lost strength and improve workability without complex chemistry	Pointed to low-cost treatment strategies suitable for large-scale ECC production
Hou et al. [46], Jiangtao et al. [51] and Teng et al. [82]	Crack control and self-healing in rubberized ECC	Explained how rubber particles and ionic-cluster treatments refine crack width distributions and promote self-healing under wet–dry cycles	Suggested that properly designed rubberized ECC can achieve high ductility together with improved long-term tightness and self-healing
Chen et al. [28], Zhu et al. [109], Ye et al. [98, 99] and He et al. [44]	Impact and dynamic loading	Quantified strain-rate-sensitive ductility and energy absorption, showing that rubber functions as a compliant flaw that delays catastrophic cracking	Encouraged the use of rubberized ECC for impact- and blast-resistant components in cold and moderate climates
Valente et al. [90, 91] and Sambucci et al. [76, 77]	Rubberized cores and alkali-activated matrices	Explored rubberized cores in sandwich panels and alkali-activated matrices to reduce environmental footprint and enhance acoustic performance	Illustrated how rubberized ECC concepts can be integrated into low-carbon, multifunctional structural systems

permeability if interfacial gaps form [5, 53, 65]. Figure 19 shows that CR and powder rubber sand (PRS) exert different effects on rapid chloride permeability [78]. PRS-ECC generally yields lower chloride permeability than conventional crumb rubber, as smaller rubber particles can fill some void space and lead to a more refined pore structure [66, 87].

Kumar et al. [54] observed that a 30% crumb rubber inclusion significantly reduced chloride diffusion, suggesting that the highly distributed cracking and the presence of rubber might offset some negative effects of porosity [14, 81]. However, large rubber

Table 5 Impact resistance and energy absorption of ECC with crumb rubber

Study	Crumb rubber content (%)	Testing methodology	Impact resistance	Energy absorption	Key observations
Zhu et al. [109]	0–15	Low-velocity impact tests at – 196 to 25 °C	Improved resilience at lower temperatures	Matrix cracking, fiber pull-out, and rupture enhanced absorption	Rubberized UHP-ECC sustained steady-state energy absorption at room temperature and absorbed peak forces more efficiently at lower temperatures
Chen et al. [28]	0–40	Drop height tests (100–500 mm) at – 50 °C to 150 °C	Higher energy dissipation at cold temperatures	Rubberized ECC dissipated more impact energy	Rubber-ECC displayed superior impact resistance across varied temperatures, particularly in colder environments
Zhang et al. [104]	10–30	Rate-dependent tensile and drop weight tests	Retained integrity after multiple impacts	Stress redistribution via rubber-induced microcracking improved toughness	CR-ECC significantly outperformed normal ECC under repeated impact loading
He et al. [44]	0.2–0.9 mm rubber	Split Hopkinson pressure bar tests	Retained impact ductility despite stiffness reduction	Ultimate tensile strain reached 4.6% with strain hardening	CR-ECC showed toughness and flexibility improvements under both static and dynamic loads
Ye et al. [99]	0–5	Dynamic splitting tensile tests	Higher deformation capacity	Superior toughness under high strain rates	CR acted as pseudo-pores, enhancing strain capacity and energy dissipation
Saad et al. [75]	Varying	Review of over 130 studies	Improved impact resistance in rubberized ECC	Enhanced ductility	CR increased energy absorption and reduced damage potential across multiple applications
Teng et al. [82]	0–30	Tensile, compressive, and cracking tests	67% ductility increase at 28 days	Refined crack development with improved fiber bridging	CR-RHA ECC exhibited enhanced long-term toughness and ductility
Hou et al. [46]	Varying	Crack propagation via micro-CT scans	CR bridging controlled crack width	Maintained multiple cracking behavior	Smaller rubber particles improved crack control and impact response
Aziz et al. [19]	Varying	Surface modification and compressive strength tests	Increased energy absorption with 10% NaOH-treated rubber	Stronger matrix bonding improved load dissipation	NaOH-treated CR enhanced strength retention and impact toughness
Valente et al. [91]	100% rubberized core	Static and dynamic flexural tests	Enhanced energy absorption in sandwich panels	Rubberized cores provided superior ductility and noise damping	Cement-based sandwich composites with rubberized cores optimized for impact resistance
Hassan [42]	0–30	Load–deflection and cracking pattern tests on large-scale beams	10% CR improved ductility and energy absorption, but excessive CR degraded performance	Cushioning effect of rubber and fiber bridging enhanced crack resistance	Rubberized SCECC beams showed better performance than conventional SCC beams under impact
Rahman et al. [74]	10–30	Thermal conductivity and mechanical tests	Lower stiffness but better deformation response under loads	Reduced thermal conductivity aided energy absorption	CR inclusion improved energy dissipation while maintaining moderate mechanical strength

Table 5 (continued)

Study	Crumb rubber content (%)	Testing methodology	Impact resistance	Energy absorption	Key observations
Abdulkadir et al. [6]	Comprehensive review	Literature review on mechanical and dynamic properties	Impact resistance increased with moderate CR content	Enhanced toughness, but high CR content reduced compressive strength	CR acts as artificial flaws that improve ductility while maintaining acceptable structural integrity
Huang et al. [47]	Varying	Tensile, flexural, and cracking behavior tests	Improved ductility and deformation capacity	Rubber lowered stiffness but reduced cracking tendency	Rubber inclusion mitigated restrained shrinkage cracking and enhanced repair material durability
Ismail et al. [49, 50]	0–50	Compressive, tensile, and deflection tests	Up to 30% CR replacement achieved > 40 MPa strength while improving deformation	PR-ECC showed superior impact resistance over standard ECC	Powder rubber improved energy dissipation and toughness more than CR
Mohammed et al. [60]	0–5	Elevated temperature and fire resistance tests	No explosive spalling at 1000 °C	Rubber melting provided pathways for pressure relief, improving thermal shock absorption	CR-ECC demonstrated superior resistance to catastrophic failure under high-temperature impact loads

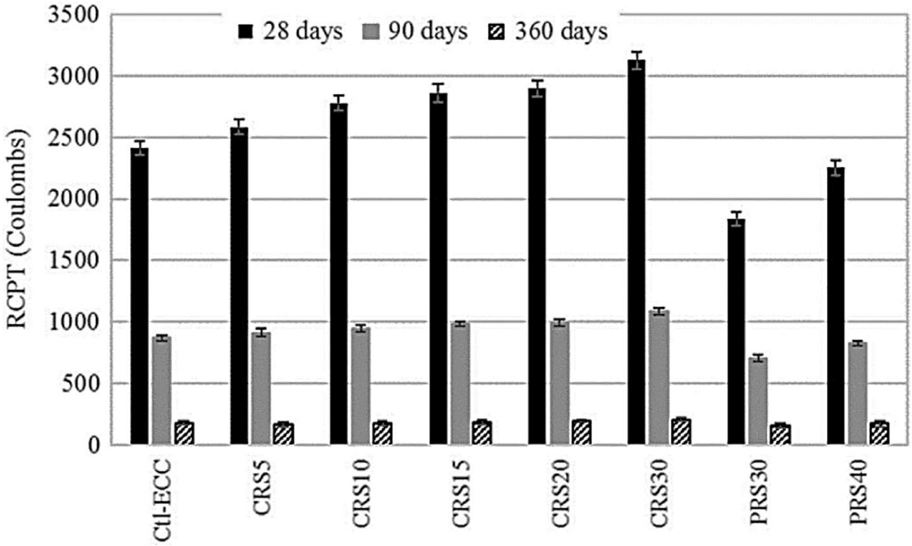


Fig. 19 Effect of crumb rubber (CRS) and powder rubber (PRS) contents on the rapid chloride permeability of ECC [78]

inclusions must be accompanied by supplementary cementitious materials or mineral admixtures to avoid macro-void formation [21, 45, 49, 50]. The mechanisms controlling chloride transport in rubberized ECC involve a balance between increased local porosity around rubber particles and refined crack networks. On one hand, weak ITZ regions around rubber can create preferential micro-paths for ingress,on the other, the ability of ECC to keep cracks narrow and well distributed limits continuous channels reaching the reinforcement [66, 78]. Powders or very fine rubber fractions tend to fill microvoids and disrupt percolation pathways, which explains the reduced charge passed in rapid chloride permeability tests for PRS-ECC compared with mixtures using coarser crumb rubber [54, 78].

5.1.2 Acid and sulfate attack

Rubber's hydrophobicity can theoretically reduce water penetration, yet if poor adhesion exists at the rubber-cement interface, micro-gaps can form pathways for acid or sulfate solutions [7, 96, 100]. Figure 20 illustrates the influence of GO-pretreated crumb rubber on sulfate-induced mass loss in ECC, showing that untreated rubber often increases mass loss under sulfate attack, but GO-treated CR exhibits a more stable matrix [7, 10]. Several studies confirm that CR usage in ECC can yield adequate resistance to sulfuric or sulfate environments if the mixture is carefully proportioned [14, 24, 60]. In acidic and sulfate environments, rubber itself is relatively inert, so the critical factor is the microstructure of the surrounding cementitious matrix. Where untreated rubber leads to porous ITZs, aggressive ions can accumulate and accelerate decalcification of calcium-silicate-hydrate and the formation of expansive ettringite or gypsum. When GO-treated rubber or supplementary cementitious materials such as slag and fly ash are used, the refined matrix and denser ITZ limit these reactions, which explains the lower mass loss and reduced expansion observed in several studies [7, 65, 81].

5.1.3 Freeze–thaw cycles and shrinkage-related effects

ECC typically performs well under freeze–thaw cycles, owing to microcrack control and ductility [65, 78, 88]. Rubber's low stiffness can supply additional resistance to freeze–thaw by cushioning internal stresses. However, if the matrix is too porous or if the mixture experiences microcracking at interfacial zones, that might encourage water ingress, ultimately reducing freeze–thaw durability [21, 64].

The lower modulus of elasticity contributed by rubber can lessen internal restraint, potentially limiting large shrinkage cracks [47, 87]. Conversely, rubber can introduce micro-voids that might store extra free water, raising concerns about shrinkage if not well managed [5, 17, 47]. Some studies show that physically or chemically modifying CR can reduce early-age cracking and shrinkage, although the net effect depends on other mixture components [9, 19, 66].

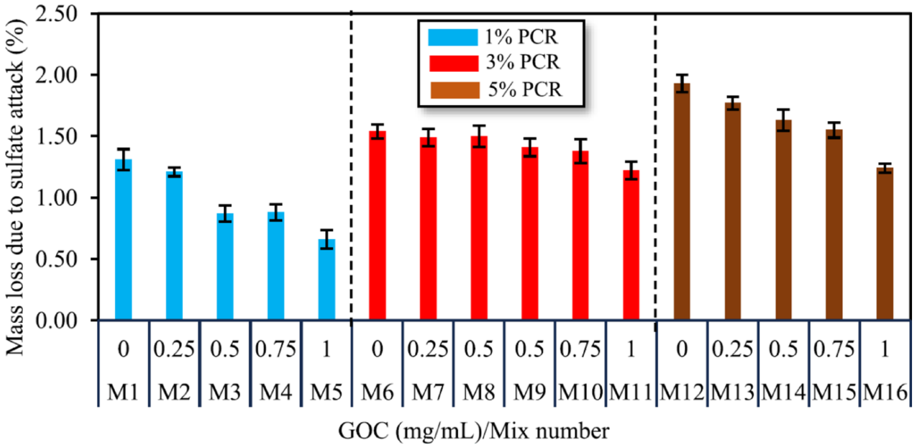


Fig. 20 Effect of graphene oxide (GOC) pretreated crumb rubber (PCR) content on the sulfate attack-induced mass loss of ECC, showing that despite the higher mass loss as rubber particles are added GOC there is a controlled mass loss with respect to the GOC treatment dosage [3, 7]

Experimental data generally show that, for rubber contents up to roughly 15–20% by volume, the relative dynamic modulus of rubberized ECC after repeated freeze–thaw cycles remains comparable to, or only slightly lower than, that of reference ECC, whereas higher rubber dosages can lead to more pronounced reductions in residual strength and stiffness [65, 78]. This behavior indicates that the stress-relief effect of the low-modulus rubber and the crack-width control supplied by fibers can compensate for a moderate increase in matrix porosity, provided that the mix design prevents interconnected void networks.

5.1.4 Combined and long-term durability

Research indicates, Table 6, that rubber addition combined with mineral admixtures can produce stable, crack-resistant systems in acid and sulfate exposures [7, 24, 60]. Others highlight that high-temperature exposure does not trigger explosive spalling, in part due to CR melting channels [8, 45]. The ability of ECC to keep cracks small is crucial for restricting the intrusion of harmful substances [81, 105].

5.2 Performance under high-temperature conditions

Rubber's melting range typically falls below 300–400 °C, so at temperatures beyond that, rubber begins to degrade or volatilize, leaving voids that vent steam [24, 55, 60, 93, 94]. Figure 21 shows the effect of temperature on compressive strength of ECC with various rubber contents [60]. It shows that there is a decrease in residual compressive strength for all composites at higher temperatures, yet above ~ 500 °C, differences among rubber dosages become less pronounced as the matrix itself experiences significant microstructural damage.

Microstructural observations from SEM and XRD support these macroscopic trends. At intermediate temperatures, dehydration of calcium-silicate-hydrate and decomposition of portlandite lead to microcracking and a gradual coarsening of the pore structure in both reference and rubberized ECC [55, 60, 96]. In rubber-modified mixtures, SEM images show elongated voids and channels where rubber particles have softened or volatilized, together with microcracks emanating from former rubber–matrix interfaces. These features reduce load-bearing cross-section and stiffness, explaining the observed strength losses. At the same time, the newly formed voids provide pathways for vapor escape, which reduces pore pressure and mitigates explosive spalling. XRD patterns confirm the progressive disappearance of portlandite peaks and the transformation of C–S–H to more amorphous phases as temperature increases, while no new crystalline phases directly associated with rubber degradation are detected, indicating that the primary effect of rubber at high temperature is physical rather than chemical.

A visual demonstration of compression failure at 900 °C is presented in Fig. 22 [60]. Mixtures incorporating CR sustain more diffuse cracking, and no explosive spalling is observed [8, 45]. This behavior is favorable for fire resistance compared to conventional high-strength concrete, where spalling can be catastrophic [58, 63].

Rubberized ECC exhibits a gradual loss in compressive strength rather than a sudden collapse at temperatures between 800 and 1000 °C [8, 60]. The matrix experiences microcracking, and the CR is largely destroyed, yet the leftover network may still carry load due to fiber reinforcement and partial matrix continuity [3, 61]. The escape of vapor through melted rubber channels reduces internal pressure, lowering spalling risk [9, 80].

Table 6 Durability and chemical resistance of ECC with crumb rubber

Study	Crumb rubber content (%)	Durability factors	Testing conditions	Key findings
Adamu et al. [8]	0–5	Fire resistance	Heated to 1000 °C	No explosive spalling; rubber melting prevented internal pressure buildup. Gradual strength loss observed
Mohammed et al. [60]	0–5	High-temperature durability, acid/sulfate resistance	Heated to 1000 °C; exposed to acid and sulfate solutions	Maintained structural integrity with reduced permeability; resisted sulfate attack effectively
Alaloul et al. [14]	0–30	Acid and sulfate resistance	Sulfuric acid and sulfate exposure	15% CR minimized strength loss from 38 to 15%. Crack propagation was mitigated
Abdulkadir et al. [7]	1–5	Sulfate expansion, acid resistance	Water absorption, sulfate expansion, acid attack	Graphene oxide (GO)-treated CR reduced sulfate expansion and porosity. Optimal mix: 0.73 mg/mL GO and 2.5% CR
Rahman et al. [74]	10–30	Thermal insulation	Thermal conductivity tests	30% CR reduced thermal conductivity to 0.66 W/mK while maintaining structural stability
Zhao et al. [105]	Varying	Water permeability	Crack permeability tests	CR reduced water penetration by refining crack distribution; synergy with fly ash improved waterproofing
Helal et al. [45]	10–30	Chemical durability & sorptivity	Acid exposure, water absorption	Physically treated CR improved strength retention. Waste quarry dust (WQD) reduced cement consumption
Abdulkadir et al. [1]	1–5	Drying shrinkage	Three-month shrinkage tests	GO reduced shrinkage by up to 38.8%; CR increased shrinkage unless offset by GO
Siad et al. [78]	0–40	Long-term durability	Tested over 360 days	PRS-ECC (powder rubber sand) exhibited improved resistance to chloride permeability and microstructural refinement
Kumar et al. [54]	10–30	Chloride penetration resistance	Rapid chloride ion penetration test	30% rubber significantly reduced chloride transport, improving durability of pavement overlays
Ye et al. [98]	10	High-strain-rate durability	Dynamic compressive strength, stress–strain tests	10% CR improved structural resilience under dynamic loading and increased strain energy density
Hassan [42]	0–30	Shear and structural durability	Beam load–deflection tests	10% CR increased ductility and energy absorption, though higher CR reduced strength
Jiangtao et al. [51]	Full replacement	Self-healing potential	Wet–dry cycles after 0.5%, 1%, 2% strain loading	CR-induced microcracks facilitated self-healing through continued binder hydration
Hou et al. [46]	Varying	Crack width control	Crack propagation mapping via micro-CT scans	CR weakened matrix but improved multiple cracking and reduced crack width
Teng et al. [82]	0–30	Long-term ductility & durability	7-day and 28-day tests	30% CR at 28 days increased ductility by 67% and reduced crack width
Valente et al. [91]	100% Rubberized core	Noise insulation & durability	Static and dynamic flexural tests	Rubberized sandwich panels had enhanced acoustic insulation and load capacity
Huang et al. [47]	Varying	Shrinkage and crack resistance	Restrained drying shrinkage tests	Free shrinkage increased, but reduced modulus alleviated cracking
Ismail et al. [49, 50]	0–50	Self-consolidating ECC durability	Fresh properties (slump flow), mechanical durability	Powder rubber at 40% achieved > 40 MPa while enhancing ductility

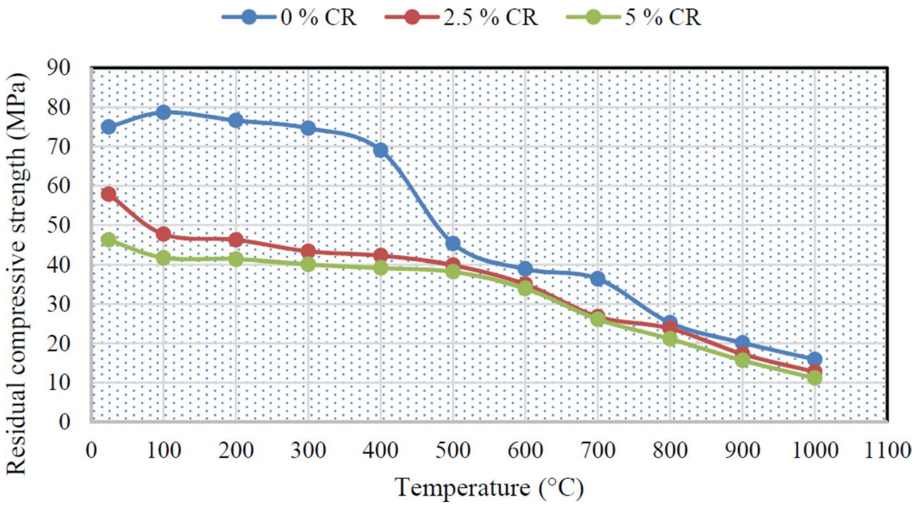


Fig. 21 Effect of temperature on the compressive strength of ECC with varying rubber contents, showing that beyond 500 °C there is not much impact of the rubber content on the residual compressive strength [60]

CR-ECC with 0% CR at 900 °C

CR-ECC with 5% CR at 900 °C

Fig. 22 Effect of temperature on the compression failure pattern of ECC at 900 °C with varying rubber contents, showing better failure pattern when rubber practices are used regardless of the high temperature sustained [60]

Table 7 Behavior of ECC containing crumb rubber under high temperature

Study	Crumb rubber content (%)	Temperature exposure (°C)	Residual compressive strength (%)	Spalling resistance	Thermal damage behavior	Key observations
Adamu et al. [8]	0–5	23–1000	Gradual reduction with increasing temperature	No explosive spalling observed	Crumb rubber created venting channels, reducing internal pressure	Even at 1000 °C, rubber-modified engineered cementitious composite retained moderate strength
Mohammed et al. [60]	0–5	100–1000	Strength declined, but remained intact at high temperatures	No explosive spalling occurred	Crumb rubber melting relieved internal pressure, preventing structural failure	Rubberized engineered cementitious composite showed superior fire resistance despite strength loss
Chen et al. [28]	0–40	− 50 to 150	Strength decreased at high temperatures	No spalling observed	Impact resistance improved at colder temperatures	Crumb rubber-engineered cementitious composite performed better under impact at sub-zero temperatures
Abdulkadir et al. [3]	0–5	200–1000	Higher residual strength when graphene oxide was included	Improved thermal stability	Graphene oxide-treated crumb rubber reduced thermal damage effects	Graphene oxide pretreatment improved rubber-matrix interfacial bonding, enhancing fire resistance
Helal et al. [45]	10–30	100–200	28.1% strength loss with untreated crumb rubber, 20.1% increase with treated crumb rubber	Improved with physically treated crumb rubber	Crumb rubber increased thermal resilience	Physically treated crumb rubber enhanced high-temperature performance

Moderately dosed CR content can thus be beneficial for structural elements where high-temperature performance is critical [41, 45, 104]. Table 7 summarizes previous research on the behavior of ECC containing crumb rubber under high temperature.

6 Discussion and future research trends

The incorporation of recycled crumb rubber into ECC has gained attention as a means to enhance sustainability while modifying mechanical and durability properties [15, 21, 65]. Existing research demonstrates both the benefits and challenges associated with this approach. Although CR improves ductility by promoting multiple microcracks and fiber bridging, it often results in a reduction in compressive strength, which can limit certain structural applications [45, 49, 50]. Studies have explored partial rubber replacement levels between 5 and 15% to balance toughness and strength retention [48, 58, 89, 104], but an optimal ratio ensuring performance and cost-effectiveness remains under investigation.

Maintaining adequate workability in rubberized ECC is complicated by the hydrophobicity and angularity of CR, especially when combined with high fiber volumes [17, 52, 68]. Methods to improve fresh behavior include increasing superplasticizer dosage, using physically or chemically treated rubber, and optimizing paste volume [1, 92]. While chemical pretreatments enhance bonding, they may add to material costs and require specialized equipment [33–35, 85]. Physical treatments are more economical yet potentially less effective. Moreover, ECC formulations often demand high binder content, fiber reinforcement, and specialized admixtures, raising costs compared to conventional concrete [15, 45, 89].

A feature of the current literature is the strong consistency of some trends and the variability of others. The reduction in compressive strength with increasing rubber content, the improvement in ductility, and the enhancement of impact resistance are all highly repeatable findings across different research groups and mixture designs. In contrast, reported transport and durability properties sometimes diverge: some studies observe reduced chloride permeability and improved sulfate resistance, whereas others report increased sorptivity or mass loss when rubber is used without adequate mineral admixtures or surface treatments. These discrepancies emphasize that rubberized ECC should be viewed as a design space rather than a single material, and that performance cannot be inferred from rubber content alone without accounting for particle size, pretreatment, binder composition, and curing conditions.

A primary concern is the weak bond between CR and cement, leading to interfacial zones that reduce mechanical integrity if rubber content is too high [45, 46]. Various surface modifications, such as acid etching, silica fume coatings, and GO pretreatment, have shown promise but remain to be standardized [3, 19, 66]. Another critical barrier to broader adoption is the lack of recognized design codes specifically addressing rubberized ECC [61, 101]. Addressing this limitation requires collaboration among researchers, regulatory agencies, and industry professionals to develop formalized guidelines.

Hybrid mixtures that combine crumb rubber with alternative aggregates, such as expanded clay, or with alkali-activated binders, are emerging as approaches to balance compressive strength with the ductility advantages of rubber [96, 106] (Yang et al. 2024). The potential for these materials to reduce CO_2 emissions and incorporate large volumes of industrial byproducts underscores their environmental benefits [15, 90, 91]. Furthermore, CR-ECC can improve thermal insulation and acoustic performance [17, 56, 93, 94], which broadens applications in energy-efficient building envelopes and noise-dampening systems.

To enhance rubber-cement bonding more cost-effectively, researchers have examined mild chemical solutions, short-duration mechanical milling, partial oxidation, or infiltration with nano-silica [5, 31, 85]. Some have also investigated 3D printing of rubberized ECC to produce lightweight, ductile components, though extrudability and buildability remain challenging [93, 94, 108]. In parallel, the use of high-volume supplementary cementitious materials can offset CR-induced porosity while reinforcing ECC's inherent crack-controlling properties [45, 74, 81].

From a cost–benefit perspective, the main economic advantages of rubberized ECC are linked to diverting end-of-life tires from landfills and reducing consumption of natural aggregates, while potential drawbacks arise from higher binder and fiber contents and, in some cases, the added cost of chemical or nanomaterial pretreatments. Existing studies rarely quantify these trade-offs in a unified way; very few report cost per cubic meter or life-cycle cost alongside mechanical and durability data. There is therefore a clear need for comparative assessments where mixtures are optimized not only for performance but also for cost, constructability, and maintenance savings at the structural level.

Real-world implementation of rubberized ECC remains relatively limited. Field studies and large-scale demonstrations are needed to confirm performance under diverse climate conditions and long-term loading [16, 39]. Potential applications include bridge deck overlays, protective barriers, seismic dampers, and pavement systems where ductility and resilience can outweigh strength loss [97, 104]. Ultimately, to facilitate commercial acceptance, code provisions must evolve to incorporate CR-ECC's strain-hardening and crack distribution characteristics, which differ from those of conventional concrete [45, 90, 91].

While recycling waste tires into ECC is environmentally beneficial by reducing landfilling and reliance on virgin aggregates, comprehensive life-cycle assessments are necessary to confirm net reductions in carbon footprint [15, 76]. The synergy between crumb rubber and other industrial byproducts, such as fly ash, slag, and quarry dust, could further enhance sustainability and performance [14, 21, 45]. Future research should concentrate on standardizing and simplifying surface treatment methods for CR, evaluating the durability of rubberized ECC in extreme climates, and addressing logistic aspects of material production and transportation [18, 61, 83, 84]. Through continued innovations, rubberized ECC has the potential to be a viable, eco-friendly solution for advanced structural applications.

7 Conclusion

The purpose of this review was to consolidate and critically analyze the existing data on ECC incorporating recycled tire rubber, highlighting how crumb rubber influences fresh properties, mechanical performance, crack management, impact resistance, and durability under various environmental conditions. Previous studies have occasionally focused on standard rubberized concrete, creating a gap in knowledge about the specific behavior and challenges of rubberized ECC with its unique strain-hardening mechanism. This study addresses that gap by focusing on ECC formulations only.

- Introducing crumb rubber typically reduces compressive and tensile strengths but promotes higher ductility, crack refinement, and energy absorption.
- Rubber content significantly affects fresh property parameters such as slump flow and V-funnel time, though surface pretreatments can maintain self-consolidating behavior.
- ECC with crumb rubber shows improved impact resistance and less risk of explosive spalling under high temperatures, but the residual strength can drop if the rubber dosage is too high.
- Chemical or physical modification of rubber, alongside supplementary cementitious materials, limits detrimental porosity and preserves matrix cohesion, thereby improving both mechanical and durability characteristics.
- Cracking patterns are generally more dispersed with rubber, creating smaller crack widths and more potential for self-healing.
- For structural applications where compressive strength must remain above typical design thresholds, current evidence suggests that modest rubber contents (on the order of 5–15% replacement of fine aggregate by volume, with fine or pretreated particles and adequate supplementary cementitious materials) can achieve a workable compromise between strength, ductility, and durability. Higher replacement levels may be reserved for non-structural or impact-attenuating elements where ductility and energy absorption are prioritized over strength.

- In aggressive environments, rubberized ECC mixtures should be proportioned with matrix refinement in mind such as combinations of fine or powder rubber, fly ash or slag, and, where feasible, simple surface treatments (such as NaOH or silica-rich coatings) appear more promising than mixtures relying solely on coarse, untreated rubber. Reporting of durability results would benefit from standardized exposure conditions and complementary microstructural characterization.

A key limitation in current practice is the lack of universally accepted design guidelines for rubberized ECC, which hampers large-scale deployments in structural applications. Further field demonstrations are necessary to validate lab findings under realistic conditions, particularly involving pumping, placement, and long-term exposure to aggressive environments. Future investigations should concentrate on optimizing pretreatment approaches, exploring hybrid fiber systems to balance strength and ductility, and developing standardized test protocols that enable direct comparison across research groups. Economic studies are also required to evaluate the cost viability and life-cycle benefits of substituting natural aggregates with crumb rubber in ECC.

Author contributions

The authors confirm their contribution to the paper as follows: study conception and design: A. H., T. J., M. M., S. A., S. B., and M. H.; analysis and interpretation of results: A. H., T. J., M. M., S. A., S. B., and M. H.; draft manuscript preparation: A. H., T. J., and M. M.; manuscript review & editing: S. A., S. B., and M. H. All authors reviewed the results and approved the final version of the manuscript.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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