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Review

Rubberized Geopolymer Concrete for Sustainable Construction: A Critical Review of Interface Engineering, Performance Trade-Offs, Durability, and Environmental Impacts

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Abstract

The use of Rubberized Geopolymer Concrete (RGC) represents a sustainable solution that can reduce reliance on Portland cement and make use of the potential uses of waste-tire rubber in construction. This review paper critically evaluates the constituent materials, design parameters, rubber pretreatment, fresh and hardened properties, durability, microstructure, and performance-enhancement measures of RGC. It is found that higher content of rubber usually lowers the workability, density, compressive strength, and elastic modulus owing to the flexible nature of the rubber and poor interface bonding between rubber and geopolymer matrix. However, a suitable content of rubber can improve the deformability, toughness, shock-absorption capacity, vibration damping, and thermo-acoustic properties. Surface treatment and matrix modifications can improve the interface transition zone and partially minimize mechanical strength loss but the efficiency of the technique varies based on rubber content, precursor mixture, activator chemistry, and curing conditions. Some of the major future research gaps are a standardization of design and testing procedures, durability and structural scale validation, and life-cycle and techno-economic analysis. In future research, it should be considered to use multi-criteria optimization for improving the strength, ductility, durability, environmental impact, cost, and constructability of RGC.

Keywords: rubberized geopolymer concrete; RGC; crumb rubber; alkali-activated binder; interfacial transition zone; mechanical properties; durability; microstructure; sustainability

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1. Introduction

In recent years, growing worries about climate change, exhaustion of resources, and waste generation have led to a paradigm shift in the construction sector towards sustainable materials and manufacturing techniques [1]. Traditional construction is based on the

use of primary raw materials and high-energy manufacturing, imposing significant pressure on the environment [2]. This has called for resource-efficient solutions. Therefore, modern infrastructure requires the incorporation of low-carbon binders, waste valorization, and circular-economy approaches while retaining the mechanical strength, durability, and serviceability characteristics required for structural applications [3]. Sustainable construction materials can contribute to reducing the impact of buildings and infrastructure on the environment and improving their resource efficiency during their life cycle [4]. Geopolymer concrete, among other solutions, has been widely investigated owing to the potential of low-carbon emissions, industrial-waste utilization, and good mechanical and durability properties [5]. The incorporation of such technologies into construction is thus a key pathway to resilience, resource efficiency, and environmental responsibility in infrastructure [6]. In this regard, one of the most significant environmental issues is ordinary Portland cement (OPC) production and the growing pile-up of discarded tires [7]. Production of OPC is characterized by great CO_2 emissions, high energy consumption, and the excessive use of limestone and other natural sources [8]. However, the constant creation of waste tires is also an important issue in terms of waste management and disposal since tires take much space and cannot be disposed of easily due to their long-term biodegradation period [9]. As a result, it stimulates the development of construction materials that will not only decrease the reliance on cementitious materials but will also valorize waste-tire products. The most studied way to do that is the incorporation of rubber particles from waste tires as a partial substitute for natural aggregates in cementitious systems [10]. In general, rubber incorporation leads to reduced stiffness and compressive strength at increasing replacement rates; however, at appropriate proportions, it may bring additional advantages such as toughness, deformability, energy dissipation and impact resistance [11]. Hence, the usage of waste-tire rubber as part of construction materials can become a solution to transform a waste stream into an engineering material [12].

Alongside waste-tire utilization, geopolymer and alkali-activated binder systems offer an alternative way to mitigate the environmental impacts of OPC [13]. Geopolymer cements are made from aluminosilicate materials such as fly ash, ground granulated blast-furnace slag (GGBS), and other industrial by-products that react under alkaline conditions to create a bound matrix. Depending on the source material, activator, curing process, and boundaries set for the system, these binders may result in reduced dependence on Portland cement and possibly decreased embodied energy and greenhouse-gas emissions [4,13]. In addition, the use of these materials offers the opportunity of converting the industrial waste products into useful building materials. Aside from the environmental benefits of these binders, appropriately designed geopolymer concretes may have good mechanical properties and excellent resistance to chemical attack and other aggressive environments [14]. These properties have raised interest in geopolymer binders as a low-carbon alternative to ordinary Portland cement [15–17]. Another environmental benefit is that geopolymer binders avoid the clinker formation process needed for OPC, which is an energy-intensive, high-temperature calcination process [18]. However, it must be understood that the overall environmental performance of the geopolymer cement is highly dependent on many factors, including precursor preparation, production of alkaline activators, transport distances, curing needs, and composition [19]. More importantly, the preparation of alkaline activators like sodium silicate and NaOH may result in significant energy use and greenhouse-gas emissions. Thus, their type and amount should be taken into consideration in evaluating the environmental advantages of geopolymer composites.

In other words, the geopolymer system cannot be considered environmentally friendly under any circumstances, and it is important to evaluate its environmental impacts over the full life cycle of materials [20]. On the other hand, the use of industrial waste as precursors can help to decrease the amount of raw-material consumption and prevent

the disposal of valuable materials [21]. The ongoing improvement of the combination of precursors, activators, curing procedures, technical performance, and environmental impacts can help in introducing these new binder systems into wide practical application [22].

The integration of two sustainable approaches, geopolymer binders and waste-tire rubber valorization, has led to the development of rubberized geopolymer concrete (RGC). In RGC, waste-tire rubber is generally incorporated as a partial replacement for natural fine or coarse aggregates. This method provides two-fold environmental advantages of decreased use of Portland cement due to geopolymer binding materials and the diversion of scrap tires from landfills as well as reduced use of natural aggregates. From the engineering point of view, rubber can increase flexibility, resilience, energy dissipation, damping, and impact resistance. Nevertheless, increased amounts of rubber lead to the decrease of compressive strength, elastic modulus, and bond between rubber and geopolymer, due to low rigidity and hydrophobicity of rubber. Therefore, RGC represents a multifunctional composite in which environmental benefits and engineering performance must be balanced through appropriate mixture design, rubber content, and interface engineering [23]

The novelty of the present review lies in extending the earlier property-oriented understanding of RGC toward an integrated, mechanism-based and application-oriented critical assessment. First, the review incorporates the substantial body of experimental evidence published after the earlier comprehensive review of Elzeadani et al. [24], with particular emphasis on studies published during 2022–2026. Second, greater attention is given to interface engineering by systematically relating rubber pretreatment and surface modification to rubber–matrix adhesion, ITZ morphology and porosity, microstructural development, and the resulting mechanical and durability performance. Third, the review considers the heterogeneity of RGC formulations by distinguishing among different precursor and binder systems, activation approaches, rubber replacement bases, particle sizes, curing conditions, test ages, and testing methods rather than treating all reported RGC results as directly comparable. Fourth, the available data is analyzed with performance trade-offs, especially the decrease in strength and stiffness due to the inclusion of rubber against possible enhancement in deformability, toughness, impact and energy dissipation, vibration attenuation, and thermal-acoustic properties. Moreover, the latest data concerning durability, high-temperature performance, material characterization, and state-of-the-art modification methods of rubber and matrix are incorporated to identify the underlying trade-off mechanisms. At the same time, sustainability is critically assessed by taking into account the dependence of the environmental benefits from the mixture design, production of alkaline activator, curing, transportation, system boundaries, life-cycle assumptions, as well as techno-economic evaluation. Finally, research-to-practice barriers such as inconsistent mixture and testing protocols, lack of durability data, insufficient validation at both structural and field scale, as well as absence of consistent life-cycle and techno-economic frameworks are identified. Based on that, multi-criteria optimization of mechanical performance, durability, environmental impact, cost, and constructability is recommended for practical development of RGC.

This paper is structured as follows. Following the Introduction, Section 2 describes the review methodology, including the scope and research questions, literature-search strategy, study selection, data extraction, comparability assessment, and evidence-synthesis framework. Section 3 addresses RQ1 by examining the influence of RGC constituents, mixture-design parameters, rubber pretreatment, alkaline-activator characteristics, and production and curing conditions on RGC performance. Section 4 addresses RQ2 by critically evaluating the physical, mechanical, durability, thermal, and microstructural performance of RGC, with particular attention to performance trade-offs and strategies for improving the rubber–geopolymer interface and matrix. Section 5 addresses RQ3 by

identifying the principal research gaps and future research priorities for advancing RGC toward practical, sustainable, and structurally reliable construction applications. Finally, Section 6 presents the main conclusions of the review and summarizes the findings in relation to RQ1–RQ3.

2. Review Methodology

2.1. Scope and Questions

This literature review critically synthesizes knowledge regarding the advanced technology of Rubberized geopolymer concrete (RGC) in relation to the constituent materials, mix design, production techniques, properties both fresh and mechanical, durability, microstructure, interface engineering between rubber and geopolymer, and applications.

The performance of RGC is controlled by a number of interacting factors, which include precursor composition, nature of the alkaline activator, ratio of liquid to binder, cure conditions, and nature, size, shape, dosage, substitution base, and surface condition of crumb rubber. As the rubber content increases, the density, compressive strength, splitting-tensile strength, and elastic modulus of RGC generally decrease. On the other hand, the deformability, toughness, impact energy absorption, and vibration absorption rise. However, the magnitude of these influences is dependent on the rubber replacement method, particle gradation, pretreatment, precursor properties, activator mixture, curing, and testing method. Hence, it is impossible to specify a general optimum level of rubber independently of these interrelated factors. This review addresses three principal Research Questions (RQs):

- RQ1. The influence of constituent materials, mixture-design parameters, and production conditions, including precursor composition, alkaline-activator characteristics, crumb-rubber content and replacement basis, pretreatment, and curing, on the performance of RGC.
- RQ2. The principal trade-offs associated with crumb-rubber incorporation in terms of fresh properties, mechanical behavior, durability, microstructure, and the rubber–geopolymer interfacial transition zone (ITZ), together with strategies for mitigating these trade-offs through interface and matrix engineering.
- RQ3. The main research gaps and future priorities for advancing RGC toward practical, sustainable, and structurally reliable construction applications.

The review employs an approach based on the study of mechanisms and applications rather than a straightforward comparison of individual studies. Consideration is mainly given to the relationship between material composition, rubber content and treatment, ITZ and microstructure, engineering and durability properties, sustainability, and application. The quantitative comparison is conducted with caution since the replacement base, precursor system, activator system, curing process, sample geometry, testing age, and methodological issues may considerably affect the results of the research.

2.2. Data Extraction and Methodology

The systematic literature-search/review and data-extraction process was employed to make the review more transparent and consistent. The sources used in the review were found in Scopus, Web of Science, and Google Scholar databases, mainly RGC literature from 2016 to 2026, with the latest literature search conducted in September 2026. The search combined geopolymer/alkali-activated concrete terminology with different forms of rubber and their commonly used abbreviations, including “rubberized/rubberised geopolymer concrete” (RGC), “rubberized/rubberised alkali-activated concrete”, “crumb rubber” (CR), “crumb-rubber concrete” (CRC), “waste tire/tyre rubber” (WTR), “waste

tire/tyre rubber aggregate" (WTRA), "waste rubber fiber/fiber" (WRF), "rubber aggregate" (RA), "rubber granules" (RG), "rubber chips", and "rubber powder" (RP).

These terms were combined with "geopolymer concrete", "alkali-activated concrete", and "geopolymer" as appropriate. The principal Boolean search structure can be represented as follows: ("rubberized geopolymer concrete" OR "rubberised geopolymer concrete" OR "rubberized alkali-activated concrete" OR "rubberised alkali-activated concrete" OR "crumb rubber" OR "waste-tire rubber" OR "waste-tyre rubber" OR "waste-tire rubber aggregate" OR "waste-tyre rubber aggregate" OR "waste-rubber fiber" OR "waste-rubber fibre" OR "rubber aggregate" OR "rubber granules" OR "rubber chips" OR "rubber powder") AND ("geopolymer concrete" OR "alkali-activated concrete" OR "geopolymer" OR "alkali-activated material"). Reference lists of relevant studies were also examined to identify additional publications.

Studies investigating rubber-containing geopolymer or alkali-activated concrete, and providing results for their experiments or analyses, have been considered. However, studies involving conventional concrete using OPC and containing rubber as the material of study have been considered merely to support the manuscript. Other studies not considering rubber, duplicate studies, out-of-scope studies, and studies not providing sufficient technical information have been excluded.

For the purpose of this review, RGC is used as a broad descriptive term for rubber-containing geopolymer and alkali-activated systems; however, these binder systems are not considered chemically equivalent. Low-cement mixtures were eligible when the primary binder system was geopolymer or alkali-activated, whereas conventional OPC-based rubber concrete was considered only as indirect supporting evidence. Accordingly, the reviewed studies were distinguished according to binder type, including FA-based, slag-rich, FA/GGBS, MK-based, one-part, two-part, and cement-containing hybrid systems. Therefore, these factors were considered when interpreting mechanical, durability, and microstructural results.

Data were comprehensively extracted on the precursor and activator systems, mixture design, source of rubber and its form (e.g., CR, WTR, WTRA, WRF, granules, chips, and powder), particle size, rubber content and replacement basis, pretreatment, curing procedure, test age and test method, as well as performance results. The rubber contents were kept with the same replacement basis (vol.% or wt.%) as in the original study, without converting unless sufficient data could be found in the source study. Differences in precursor and activator systems, replacement basis, curing, specimen properties, test age, and test method were taken into account when comparing across studies. The terminology and notation were standardized across the entire review process wherever possible. The CR content was expressed on the replacement basis stated in the original study (mass/volume) without any conversions unless adequate data are provided. The NaOH concentration used for alkaline activation is given in Molarity (M), and the NaOH used for rubber surface treatment is specified to differentiate it from the activator. Units and test ages were given wherever available. RGC is designated for rubberized geopolymer concrete, while RGM is designated for rubberized geopolymer mortar.

With consideration of the heterogeneity in the various studies, the quantitative data were interpreted with consideration of the rubber replacement rate, particle size, binder systems, curing process, testing age, and testing techniques. Quality of evidence was also taken into account with respect to control mixes, replication, testing techniques, statistical analysis, and full mix design. Studies with limited methodological details were interpreted with caution. These criteria were applied qualitatively to support the critical interpretation of the available evidence rather than as a formal scoring or ranking system for individual studies.

Figure 1 summarizes the overall search, screening, data-extraction, comparability assessment, and evidence-synthesis procedure. The methodological completeness of the studies that have been reviewed was qualitatively evaluated, which included reporting control mixtures, mixture preparation, curing conditions, testing conditions, standard tests, replicates and statistics, if possible. Studies with an incomplete methodology were taken into consideration with more caution. This study was carried out using a critical narrative review approach aided by a structured literature search and data extraction process. Since no numerical data on identified, screened, excluded, and included studies were recorded prospectively, such retrospective counts of screened studies are not provided. Figure 1 provides an overview of the study selection, data extraction, and evidence-synthesis methodology used in the current review.

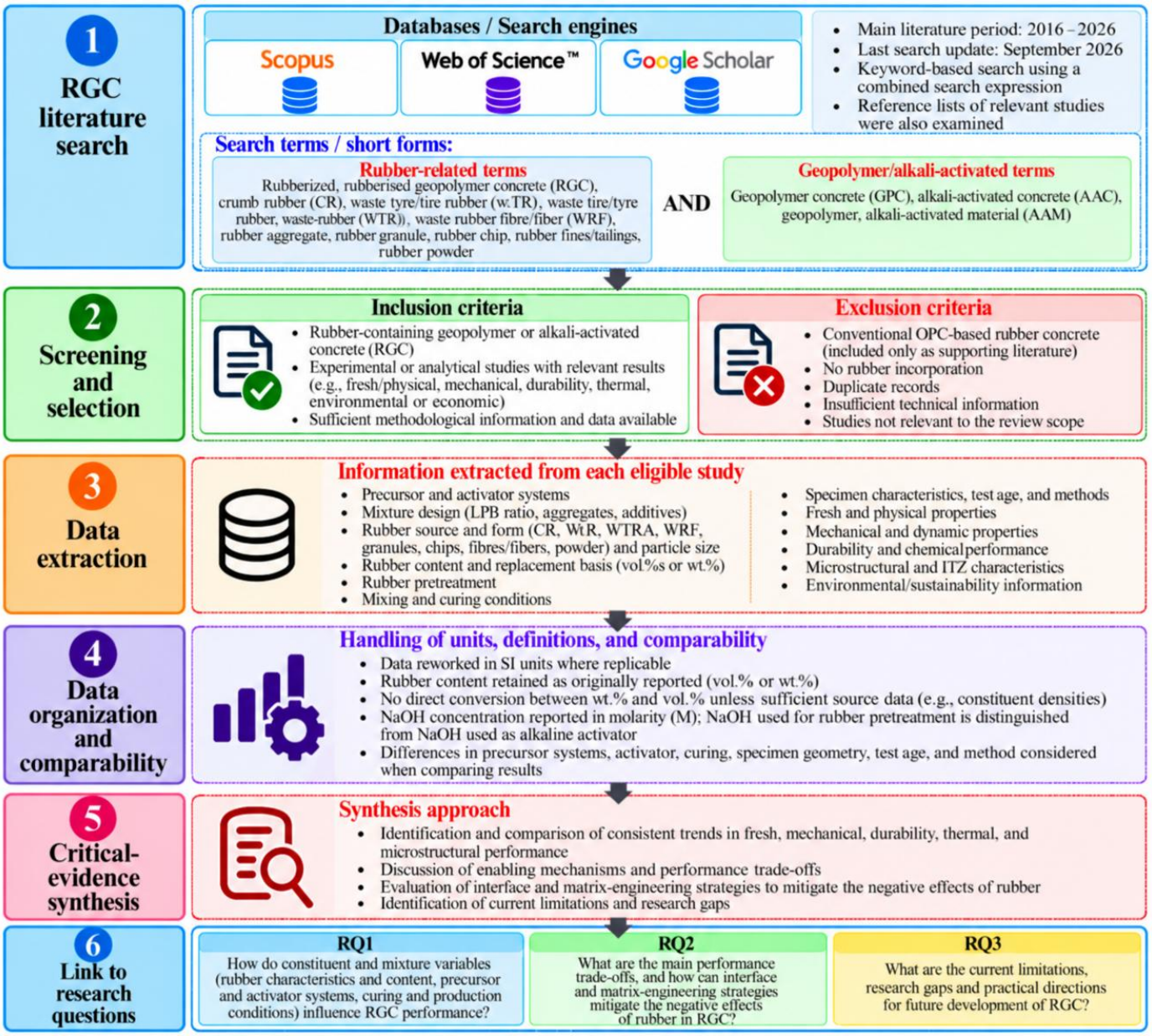


Figure 1. Review methodology and data-extraction framework for RGC.

As the studies under review vary in terms of their replacement basis, rubber properties, binder system, curing regime, test age, and test procedures, the values reported in this review should not be interpreted as direct performance rankings across studies. The

comparative tables are intended primarily to reveal trends within individual studies and comparable material systems.

3. RQ1: Influence of Constituents, Mixture Design, and Production Conditions on RGC Performance

3.1. RGC Constituents

RGC is a cement-free or low-cement composite in which an alkali-activated aluminosilicate binder surrounds conventional aggregates and waste-rubber particles [25]. Common precursor systems include fly ash and GGBS, while metakaolin has also been successfully employed in rubberized geopolymer concrete [26]. Metakaolin-based RGC containing crumb rubber as a volumetric replacement of fine aggregate has also demonstrated the feasibility of producing low- to moderate-strength lightweight composites [27]. Modified metakaolin systems incorporating silica fume have further been investigated to improve matrix characteristics [28]. Alkaline activation is commonly achieved using hydroxide and silicate solutions, while the resulting performance depends strongly on precursor and activator composition [29]. Crumb rubber generally replaces a proportion of natural aggregate, preferably reported on a volumetric basis because of the substantial density difference between rubber and mineral aggregates [30].

RGC performance is strongly influenced by the physical, chemical, and morphological characteristics of its constituents. In particular, rubber-particle size, gradation, replacement level, and whether fine or coarse aggregate is replaced can significantly affect fresh and hardened properties [26]. Rubber-surface condition is another important variable, and recent alkali-activated mortar research has examined NaOH pretreatment alongside different rubber replacement levels [31]. Matrix engineering can also be used to compensate for some rubber-induced performance losses; for example, ultra-fine slag and fly ash have been investigated for enhancing rubberized alkali-activated concrete [29]. The fibers can contribute to changing the mechanical and thermal behavior of the rubberized geopolymer matrix [32]. Some more advanced formulations of the mixtures have been developed that include rubber particle size distribution and rheological optimization for printing of alkali-activated composites [33], whereas optimized rubberized alkali-activated mortars have shown possibilities for high-performance repairs [34].

Rubber used in geopolymer composite materials is generally obtained from discarded passenger tires as crumb rubber, granules, powder, shreds, and fibers as a replacement for aggregates; see Table 1. Other forms like natural rubber latex are rarely used. Because rubber source and preparation method may influence rubber particle properties and matrix–rubber interactions, they must be considered when comparing RGC research.

Table 1. Classification of rubber sources.

Rubber Source	Processed Form
Post-consumer automotive tires	Crumb rubber (CR)
Post-consumer automotive tires	Rubber granules/chips
Post-consumer automotive tires	Rubber powder
Post-consumer automotive tires	Rubber fibers/shreds
Natural rubber source	Natural rubber latex (NRL)

3.2. RGC Mixture Design

The formulation of RGC mixture design entails the control of various parameters in order to create an appropriate balance of fresh, mechanical, durability, and environmental properties. Some of the most important aspects are:

- Rubber replacement: Rubber content should be clearly reported as a percentage of fine or coarse-aggregate replacement by mass or volume. Because of the substantial density difference between rubber and mineral aggregates, volume-based replacement generally provides a more consistent basis for comparison.
- Precursor composition is important as the type and proportions of aluminosilicate precursors influence binder formation and overall matrix performance.
- Activator characteristics, mainly depending on activator dosage, concentration, and silicate modulus, affect precursor activation and binder development.
- Liquid-to-binder ratio is an important factor and this parameter influences workability, porosity, and mechanical performance.
- Aggregate characteristics, particularly the aggregate type, grading, and proportions affect packing, workability, and load transfer.
- Admixtures may be used to improve workability and mixture stability without excessive water addition.
- Curing conditions like temperature, humidity, drying period, and environment influence the resulting material properties.

Increasing rubber content generally reduces density, stiffness, and strength and may increase entrapped air. Therefore, the optimum rubber dosage should not be selected based on strength alone, but should consider workability, mechanical and durability performance, density reduction, and environmental benefits together.

Effect of Crumb-Rubber Replacement Percentage and Sizes: The crumb-rubber content is an important factor, but its impact will depend on whether the concept of replacement is based on mass or volume, as well as whether it is based on fine aggregates or overall aggregates. A high content of rubber will result in low density, tensile and compressive strength, as well as elasticity, but high flexibility, shock and vibration resistance, and toughness. Lower amounts of rubber (about 5%) tend to yield better ductility at lower strength loss, while 10% can be viewed as a trade-off point. Higher amounts (15–20%) generally lead to greater reductions in strength and rigidity, although toughness may increase. For higher amounts (greater than 20%), rubberized geopolymer concrete is preferable in cases when density, vibration damping, insulation, and shock resistance are more important than strength. It depends on rubber pretreatment, its particle size, precursors, activators, compaction, and curing.

Park et al. [35] investigated crumb rubber (0.075–4.75 mm) at 5–20% volumetric replacement of fine aggregate in fly-ash-based geopolymer concrete, reporting reduced compressive strength with increasing rubber content. Similarly, Elzeadani et al. [24] investigated 0–60% volumetric replacement of natural aggregates with crumb rubber in one-part alkali-activated concrete, reporting reduced mechanical properties but increased deformation capacity at higher rubber contents**.** Figure 2 illustrates the Class-F fly ash and crumb rubber commonly used as constituent materials in RGC mixtures.

Hassan et al. [23] studied the mechanical properties of crumb-rubber geopolymer concrete using 5%, 15%, and 25% crumb rubber (Figure 3) as a partial replacement of natural fine aggregate. Untreated and NaOH-treated crumb rubber were used to study the effect of surface treatment on the material's performance. As shown in Figure 3, with increasing replacement ratio (25% as can be seen in Figure 3a, 15% in Figure 3b, and 5% as in Figure 3c), more crumb-rubber particles were found in the geopolymer matrix. Table 2 represents crumb-rubber replacement levels and associated mechanical responses reported in selected rubberized geopolymer concrete studies.



(**a**) (**b**)

Figure 2. (**a**) Class-F fly ash and (**b**) crumb rubber for RGC (adapted from Giri et al. [36]).

Whereas the CR particle size significantly affects both the mechanical performance and workability of RGC. Kuang et al. [37] performed tests with 5% replacement of fine aggregates with CR particles having sizes of 4, 1.7, 0.83, and 0.25 mm. Compressive strength decreased at 28 days by 38.6%, 28.1%, 22.2%, and 11.3%, respectively; flexural strength decreased by 25.6%, 14.7%, 7.4%, and 3.7%. Workability demonstrated inverse results, showing a fluidity drop from larger to smaller CR, caused by the larger surface area and higher friction of finer rubber particles.



(**a**) (**b**) (**c**)

Figure 3. Cylindrical samples with different rubber content (**a**) 25%, (**b**) 15%, and (**c**) 5% (Hassan et al. (2024) [23]).

Table 2. Crumb-rubber replacement levels and associated observed properties of RGC.

CR Replacement (%)	Replacement Basis	Main Reported Mechanical Response	Ref.
0, 5, 10, 15, 20	Fine aggregate, by volume	Increasing CR generally reduced compressive strength; the study examined 38 mixtures with CR content among the main variables	Park et al. (2016) [35]
0, 15, 30	Primarily coarse aggregate replacement	At 28 d, compressive-strength reductions of 67.0% and 89.3% were reported for 15% and 30% CR, respectively; ductility increased	Dong et al. (2021) [38]
0, 5, 10, 15	Fine aggregate, by volume	CR content was studied together with binder content and NaOH molarity; increasing CR generally lowered compressive strength	Gill & Parveen (2022) [39]
0, 5, 15, 25	Fine aggregate, by volume	Compressive strength and elastic modulus decreased with increasing CR; at 25% CR, compressive strength decreased by about 33%; pretreatment reduced the loss	Hassan et al. (2024) [23]
0, 5, 10, 15, 20	Fine aggregate	28-d compressive strengths were 65.0, 48.0, 30.0, 20.6, and 15.8 MPa, respectively	Azmi et al. (2016) [40]

0, 15, 30, 45	WTRA replacing pumice aggregate, by volume	Rubber content, silica fume, and curing temperature influenced mechanical and thermal behavior; TGA-DTG showed mixture-dependent mass loss at elevated temperatures	Mabrouk et al. (2024) [41]
10, 20, 30, 40, 50	Natural sand, by volume	Increasing CR generally reduced mechanical strength; SEM revealed distinct gaps at the CR–geopolymer paste interface, indicating weak ITZ bonding	Ipek and Mermerdaş (2022) [42]

Hassan et al. (2024) [23] used waste tire CR of sizes < 1 mm (Figure 4a), 1–3 mm (Figure 4b), and 2–4 mm Figure 4c) as 5–25% volume substitution of natural fine aggregate in the geopolymer concrete mixtures. Untreated and 16 M NaOH-treated CRs were used, and surface treatment increased rubber–matrix adhesion; thus, the strength was preserved. Table 2 summarizes the crumb-rubber replacement levels and corresponding mechanical responses reported in various RGC studies.

Effect of pre-treatment of crumb rubber: Higher addition of crumb rubber (CR) leads to a reduction in the mechanical strength of rubberized geopolymer concrete (RGC) due to the lower modulus of elasticity of rubber than mineral aggregates, the hydrophobic nature of the rubber surface, increased interfacial porosity, and poor bonding at the rubber-geopolymer ITZ [43]. Surface pretreatment helps to enhance the interaction between CR and geopolymer paste [23]. Namely, NaOH pretreatment helps to clean and modify the surface of rubber particles and increase their surface roughness, which contributes to improved mechanical interaction between the rubber and geopolymer matrix [23]. Thus, NaOH pretreatment may partially compensate for the decrease in compressive, splitting-tensile, and flexural strengths caused by higher CR content compared with untreated rubber at the same replacement level [43]. However, improved rubber–matrix bonding does not necessarily lead to increased deformability or energy absorption, since NaOH pretreatment can modify the stiffness and deformation mechanisms of RGC [44]. Moreover, the efficiency of surface modification depends on the CR content, particle size, pretreatment parameters, precursor composition, alkaline-activator characteristics, and curing conditions [43]. Thus, the optimum CR content cannot be regarded as universal and needs to be determined for a specific mixture system [23].



(**a**) (**b**) (**c**)

Figure 4. Crumb-rubber particle size on RGM: (**a**) <1 mm, (**b**) 1–3 mm, and (**c**) 2–4 mm (Hassan et al. (2024) [23]).

For example, Saloni et al. [43] investigated different crumb-rubber pretreatment methods, including water, 5% NaOH solution, cement slurry, and ultrafine slag (UFS) slurry, to improve the interaction between CR and the geopolymer matrix. As mentioned by the authors, these treatments modify or coat the rubber surface, with NaOH treatment intended to improve interfacial adhesion, while cement and UFS treatments form a coating around the CR particles that may enhance bonding with the matrix.

Similarly, the method used by Aown et al. [44] in order to alter the surface properties of crumb rubber was NaOH pre-treatment. This procedure comprised water-washing

(Figure 5a) initially, soaking in a 16 M NaOH solution for 2 h (Figure 5b), pressurized-water washing (Figure 5c) and then air-drying for a week (Figure 5d).

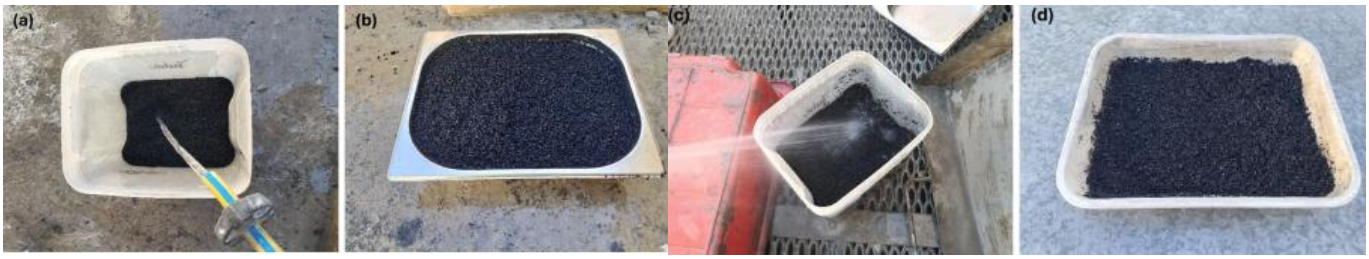


Figure 5. NaOH pre-treatment procedure for crumb rubber: (**a**) washing with water, (**b**) soaking in NaOH solution, (**c**) rinsing with pressurized water, and (**d**) air-drying (adapted from Aown et al. (2025) [44]).

Table 3 summarizes the influence of NaOH-pretreated crumb-rubber content on the mechanical and deformation responses of RGC.

Effect of NaOH Molarity of the Geopolymer Alkaline Activator: The molarity of NaOH used in the alkaline activator is an important mixture-design parameter governing the dissolution of reactive aluminosilicate species, geopolymerization kinetics, gel formation, pore structure, and mechanical performance of RGC [45].

Increasing NaOH concentration might increase the dissolution of Si and Al reactive elements and help the formation of the binding agents up to a certain maximum level [46]. However, it does not mean that increasing alkalinity would yield any further improvement and may negatively impact workability and reaction kinetics [47].

Therefore, NaOH concentrations ranging from 8 to 16 M (M8–M16) can be considered as an experimental range for evaluating the selected FA–GGBS–silica-fume-based RGC system rather than as a universally optimum range [36,39,48]. The optimum NaOH molarity should be established experimentally because its influence depends on precursor composition, Na_2SiO_3/NaOH ratio, liquid-to-binder ratio, CR content, curing conditions, and other mixture-design parameters [47]. Table 4 summarizes the influence of NaOH molarity in the alkaline activator on geopolymer matrix development and the mechanical performance of RGC.

Table 3. Influence of NaOH-pretreated crumb-rubber content on the mechanical performance of RGC.

CR Content (%)	Rubber Condition	Strength Response	Deformation Response	Overall Interpretation	References
5	NaOH-treated CR	Strength and elastic-modulus reductions are mitigated compared with untreated CR	Rubber incorporation promotes a more compliant response	Low CR dosage limits strength deterioration while retaining rubber-induced deformability	Hassan et al. (2024) [23]
10	Untreated CR; NaOH used as alkaline activator	Higher strength than mixtures containing greater CR contents; best investigated combination obtained with 10% CR and 14 M NaOH activator	Increasing CR generally lowers stiffness and modifies deformation behavior	Low CR content combined with higher activator molarity provides a favorable mechanical response	Giri et al. (2023) [36]
10	NaOH-pretreated CR	Pretreatment improves interfacial adhesion and partially mitigates CR-induced strength reduction	Improved interface restricts excessive interfacial deformation	Low CR dosage combined with pretreatment provides improved rubber–matrix interaction	Saloni et al. (2021) [43]
15	NaOH-pretreated CR	Strength and elastic modulus decrease with CR incorporation, but pretreatment mitigates the deterioration	Increasing rubber contribution produces a more compliant response	Intermediate CR dosage provides a compromise between mechanical-property retention and rubber-induced deformation	Hassan et al. (2024) [23]
20	NaOH-pretreated CR	Further strength reduction occurs with increasing CR, although pretreatment improves interfacial bonding	Deformation becomes increasingly influenced by rubber and ITZ characteristics	Pretreatment improves the interface but cannot completely compensate for increased CR content	Saloni et al. (2021) [43]
20	Untreated CR; NaOH used as alkaline activator	Strength decreases as CR content increases at comparable activator conditions	Higher rubber content contributes to reduced stiffness and increased compliance	CR dosage increasingly governs the mechanical response despite changes in activator molarity	Giri et al. (2023) [36]
25	16 M NaOH-pretreated CR	Pretreatment increased compressive strength by 15.2–15.4% and peak static force by 20.3–20.5% compared with untreated CR	Pretreatment reduced normalized energy absorption because improved bonding increased stiffness and reduced rubber-related deformation	Stronger rubber–matrix bonding improves strength but introduces a trade-off with energy-absorption capacity	Aown et al. (2025) [44]
25	NaOH-pretreated CR	Substantial strength and elastic-modulus reductions occur at high CR content; pretreatment mitigates these losses	Greater rubber content produces a more compliant mechanical response	Pretreatment partially recovers mechanical performance at relatively high CR dosage	Hassan et al. (2024) [23]

30	Untreated CR; NaOH used as alkaline activator	Pronounced strength reduction; the 30% CR–10 M mixture exhibited the lowest compressive strength (11.5 MPa)	High CR content results in a softer, more compliant composite response	At high CR dosage, the detrimental effect of rubber on strength becomes dominant	Giri et al. (2023) [36]
30	NaOH-pretreated CR	Pronounced strength reduction at high CR content; pretreatment improves bonding but cannot fully recover the lost strength	Rubber increasingly governs deformation as its content increases	High CR dosage limits mechanical performance despite improved interfacial characteristics	Saloni et al. (2021) [43]

Table 4. Influence of NaOH molarity of the alkaline activator on RGC-matrix development and mechanical performance.

NaOH Molarity	Effect on Geopolymer Matrix	Mechanical Response	References
8 M	Provides precursor activation, although relatively lower alkalinity may result in less extensive aluminosilicate dissolution and geopolymerization than at higher molarities	Relatively lower strength development within the investigated molarity ranges; increasing NaOH molarity can improve strength under otherwise suitable mixture conditions	Park et al. (2016) [35]; Gill and Parveen (2022) [39]; Nair and Meena (2025) [49]
10 M	Increased OH^- availability promotes dissolution of reactive Si and Al species and subsequent geopolymerization	Improved mechanical performance compared with lower molarity under comparable conditions; the magnitude of improvement depends on CR content, precursor composition, and curing	Gill and Parveen (2022) [39]; Giri et al. (2023) [36]; Nair and Meena (2025) [49]
12 M	Enhanced precursor dissolution and geopolymerization can promote formation of a denser and more cohesive reaction matrix	Generally enhanced compressive, tensile, and flexural performance within the investigated 8–12 M range	Gill and Parveen (2022) [39]; Giri et al. (2023) [36]; Nair and Meena (2025) [49]
14 M	Higher alkalinity promotes extensive precursor dissolution, polymerization, and development of the geopolymer network	High mechanical performance can be achieved under suitable mixture conditions; 14 M with 10% CR was identified as the optimum investigated combination by Giri et al.	Park et al. (2016) [35]; Giri et al. (2023) [36]
16 M	High alkalinity supports extensive aluminosilicate dissolution and geopolymerization, facilitating development of the geopolymer matrix under appropriate activator and curing conditions	High mechanical performance can be achieved at 16 M; Karmakar et al. identified 16 M with 6% CR and Na_2SiO_3/NaOH = 2.5 as the optimum investigated combination	Abd-Elaty et al. (2022) [32]; Azunna et al. (2025) [50]); Karmakar et al. (2026) [51]

Effect of Na_2SiO_3/NaOH Ratio of the Alkaline Activator: The Na_2SiO_3/NaOH ratio is yet another critical parameter for the alkaline activator that governs precursor dissolution, availability of soluble silicates, geopolymerization reactions, gel formation, activator viscosity, workability, and development of mechanical strength [45]. With a relatively low Na_2SiO_3/NaOH ratio, the availability of soluble silicates may not be sufficient to develop the geopolymer network, while higher values facilitate gel formation and densification of the matrix [45,52]. However, excess content of Na_2SiO_3 increases the viscosity of the activator, which has an adverse effect on the workability, compaction, and dispersal of lightweight CR particles [45]. While in the RGC experiments, various values in the range of approximately 0.33 to 2.90 [45,52] have been used as Na_2SiO_3/NaOH ratios, ratios of 1.5–2.5 are more often tested [45]. The optimal ratio depends on the combined analysis of workability, mechanical properties, and microstructure, since the response is mixture-dependent [24,45,52]. Table 5 summarizes the influence of the Na_2SiO_3/NaOH ratio of the alkaline activator on the matrix development and mechanical performance of RGC.

Table 5. Reported Na_2SiO_3/NaOH ratios and their influence on the performance of rubberized geopolymer concrete (RGC).

Na_2SiO_3/NaOH Ratio	Influence on RGC	Refs.
0.33–0.44	Represents the lower end of the Na_2SiO_3/NaOH ratios reported in RGC studies	[45]
0.50	Relatively low ratio; lower compressive strength than at higher ratios was reported in some RGC systems	[45,52]
1.00	Intermediate ratio investigated in RGC systems; the strength response was dependent on curing age and mixture characteristics	[45,52]
1.50	Commonly investigated ratio; strength improvement compared with lower ratios has been reported in some RGC systems	[45,52]
2.00	Favorable strength development was reported; an optimum ratio of 2.0 was identified in some RGC studies	[45]
2.50	Commonly investigated higher ratio; favorable performance has been reported, although the response is mixture-dependent	[24,45]
>2.50–2.90	Represents the upper end of the range reported in RGC literature; comparatively less commonly investigated	[45]

Production, Casting, and Curing Procedures: The preparation of the alkaline activator is usually done prior to the process and left to cool before it is used [24,45]. The dried precursors, aggregates, and crumb rubber are usually mixed prior to the alkaline activator and further water [45]. The freshly mixed RGC is then cast into molds and consolidated by vibration or tamping. However, too much vibration should not be done as the low density of the rubber might cause particle segregation [24,45,52]. Curing affects geopolymerization; various ambient and thermal curing methods have been well documented, especially the latter for fly ash systems [45].

Hassan et al. (2024) [23] developed RGC through the addition of untreated and NaOH-treated crumb rubber as partial replacements for fine aggregate (at 5%, 15%, and 25%). The samples were then kept at room temperature for 24 h, followed by oven curing at 80 °C for 48 h, and further storage at room temperature until testing.

While Luhar et al. (2021) [52] produced rubberized geopolymer concrete using Class-F fly ash and rubber-tire fibers as partial replacements for river sand (10%, 20%, and 30%). The mixtures used 14 M NaOH, an Na_2SiO_3/NaOH ratio of 2.5, and an alkaline-liquid-to-fly-ash ratio of 0.4; specimens were subjected to a 1-day rest period followed by curing at 90 °C for 48 h.

Karmakar et al. (2026) [51] prepared rubberized fly-ash geopolymer concrete by dry mixing fly ash, natural sand, crumb rubber, and coarse aggregates for 3 min, thereafter adding the pre-mixed alkali solution and superplasticizer and mixing for another 5 min. The concrete was cast into pre-lubricated steel molds and compacted by a vibrating table. Post-casting, the specimens were wrapped in polyethylene sheets for 1 h at 27 ± 2 °C before being subjected to oven curing at 100 °C for 24 h, followed by removal from molds and kept in a laboratory environment for 7, 14, or 28 days before testing.

Therefore, curing temperature, duration, moisture condition, demolding age, and test age should be clearly reported to enable meaningful comparison among RGC studies.

Testing and Performance Assessment Methods: Performance assessment of RGC generally includes fresh-state, mechanical, physical, and durability characterization [24,45]. Fresh-state assessment commonly includes workability and density, whereas hardened-state testing includes compressive, splitting-tensile, and flexural strength, elastic modulus, stress–strain behavior, and toughness [23,45]. Durability investigations may include water absorption, permeability, and resistance to aggressive environments [24,43]. Test standard, specimen geometry, conditioning, curing regime, loading or exposure conditions, and test age should be clearly reported to enable reliable comparison among RGC studies [24,45].

4. RQ2—Performance Trade-Offs and Strategies for Mitigating Them Through Interface/Matrix Engineering

4.1. Physical Properties

Workability: Workability of RGC is influenced by crumb-rubber content, crumb-rubber particle size, crumb-rubber surface condition, and properties of the alkaline activator [53,54]. The higher the content of crumb rubber, the lower the workability because of the irregular structure and hydrophobicity of crumb rubber, which causes friction and air-bubble formation [54]. Smaller crumb rubber can cause lower workability because of its larger surface area. Surface pretreatment may change the wettability of rubber and rubber-paste interactions, thus modifying fresh properties [54]. In addition, NaOH concentration and the ratio between Na_2SiO_3 and NaOH affect activator viscosity and thus workability [55]. These phenomena are dependent on the mixture and should therefore be considered as a whole and not only CR content (Zhong et al., 2019 [53]). Workability showed the opposite trend, with fluidity dropping as CR particle size decreased (Figure 6), due to the larger surface area and higher friction of finer rubber particles.

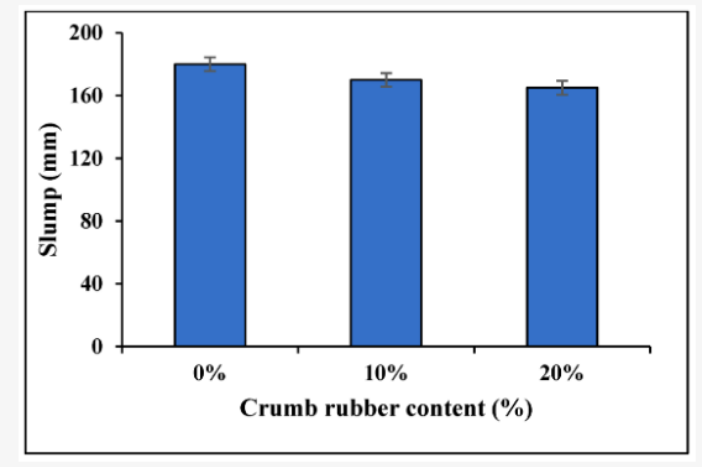


Figure 6. Workability of RGC containing different crumb-rubber particle sizes (adapted from Azunna et al. (2025) [50]).

Gill and Parveen (2022) [39] incorporated CR at 0–15 vol.% as fine-aggregate replacement in low-calcium fly-ash/OPC geopolymer concrete and simultaneously varied binder content and NaOH molarity. Their mix-design methodology targeted compressive strengths of 30–60 MPa and slump values of 75–140 mm, demonstrating that CR dosage, binder content, and activator molarity should be considered jointly when designing RGC for specified fresh-state consistency and mechanical performance.

Setting Time: The setting time of rubberized geopolymer composites depends on the effect of the chemistry of binders-activators and the type and quantity of rubbers added. Typically, higher amounts of rubber lead to higher setting times, both initial and final, but it depends on specific mixtures.

Arunkumar et al. (2021) [56] have developed rubberized low-calcium waste wood ash-based geopolymer concrete with 0–2 vol.% of waste-rubber fibers and found that the inclusion of rubber fibers led to an increase in the initial and final setting times, which was more in the case of higher addition of fibers. The binder used here comprised fly ash and low-calcium-waste wood ash in 70:30 proportions, whereas the concentrations of NaOH and activator ratio were maintained at 10 M and 1:2.5, respectively.

Chindaprasirt and Ridtirud (2020) [57] studied high-calcium fly-ash geopolymer mortar containing 0–10% natural-rubber latex (NRL) by weight of fly ash and found a progressive increase in setting time with NRL content. The initial/final setting times increased from 60/105 min for the control to 87/135 min at 10% NRL; the authors primarily related this increase to the additional water introduced by the latex.

Recently, Shao et al. (2025) [58] examined CR aggregate in geopolymer-based UHPC and reported that an increase in the level of CR led to a delay in the setting time of the mixes, especially at higher percentages of CR. In comparison to the control (~46/58 min initial/final), 10–20% CR delayed the setting time by about 2–7/3–9 min, whereas 30% CR resulted in a setting time of 57–59/70–71 min. Medium-sized CR showed more retardation effect than the coarse-size CR for the same percentage of replacement. These researchers have attributed the retardation effect to the dual action of dilution of the alkali activator and the hydrophobic character of CR, delaying the dissolution and polycondensation reaction.

Density and Unit Weight: The density of rubberized geopolymer composite materials tends to reduce when dense mineral aggregates are substituted with lighter crumb rubber (CR). This is because the degree of reduction varies depending on several factors such as rubber content, particle size and gradation, replacement method, and entrained air.

Wongsa et al. (2018) [55] completely replaced river sand with CR in high-calcium fly-ash geopolymer mortar. The CR had a specific density of 1.16, compared with 2.63 for river sand, and the resulting CR geopolymer mortars exhibited densities that were, on average, approximately 42% lower than the control mortar.

Pham et al. (2020) [59] investigated geopolymer concrete in which both fine and coarse natural aggregates were replaced by CR at 0, 15, and 30 vol.%. The rubber particles were divided into 1–3 mm and 5–7 mm fractions for replacing fine and coarse aggregates, respectively. The reported density decreased from approximately 2340 kg/m^3 for the control to 1980 kg/m^3 at 30% CR, corresponding to a reduction of about 15%, confirming the lightweighting effect of increasing rubber replacement.

Also, Shao et al. (2025) [58] noticed that there is a continuous reduction in the hardened unit weight of the geopolymer-based UHPC, when the natural sand is replaced by 10–30% CR. Here, the CR has a low bulk density of 662 kg/m^3, whereas the quartz sand has a specific gravity of 2.65. The highest reduction rate is about 5.9%, where the control has 2298.4 kg/m^3 and the Ru30M has 2162.0 kg/m^3. This is due to the lower density of CR, air entrapment because of the rough surface, and low packing efficiency, especially for coarser rubber particles; hybrid gradation helps compensate for this reduction to some extent.

In general, these studies prove that adding crumb rubber lowers the density of geopolymer composites and hence can be used to decrease the weight of structures; however, the degree of such reduction significantly varies depending on the dosage and characteristics of rubber and the replacement technique.

Air Content: The available studies indicate that crumb rubber (CR) generally promotes air entrapment and pore formation in rubberized geopolymer composites, although direct measurement of fresh-air content is rarely reported.

Notably, there is a higher amount of entrapped air present in rubberized systems compared to those that do not contain rubber due to the rough or irregular geometrical shape of particles, hydrophobic surface, and interference of rubber in the compaction process [60]. This may decrease the density and compressive strength of materials, although controlled air voids are sometimes used to improve the thermal insulation and freeze–thaw resistance of concrete [61,62]. Air voids affect the packing of cement and increase the heterogeneity of microstructure [62].

Incorporation of 5–15 vol.% CR in alkali-activated slag mortar by Ameri et al. (2020) [54] showed reduced matrix compactness due to CR incorporation, and NaOH surface treatment was helpful in improving the interface between rubber and binder.

Replacement of 15 and 30 vol.% CR for both fine and coarse aggregate, along with pre-soaking of CR in water to minimize hydrophobic behavior, has been used by Pham et al. (2020) [59]. It is worth noting that water-soaked CR has been linked to reduced entrapped air in their previous study, thus underlining the significance of the surface of rubber particles in affecting entrapped air.

IIqbal et al. (2023) [63] found increasing porosity and decreasing matrix compactness with increasing CR content (10–30%) and improved microstructure and CR-matrix interface with the addition of graphene nanoplatelets (GNP); the mean microhardness of the mixture with 30% CR was enhanced by 34% due to 0.3% GNP addition.

The decrease in unit weight of rubberized geopolymer-based ultra-high-performance concrete due to air entrapment related to the rough surface of the CR and decreased packing efficiency was noted by Shao et al. (2025) [58], especially for coarse rubber; improved packing and aggregate skeleton continuity due to hybrid gradations were also mentioned.

Overall, results show that higher contents of CR favor air trapping and porosity, while pre-rubber treatment, smaller or well-graded particles, better matrix consolidation, and proper compaction will offset the negative influence. However, since in most of the studies on RGCs porosity is determined instead of fresh air content, these two variables cannot be seen as equivalent.

4.2. Mechanical and Hardened Properties

The mechanical response of RGC depends not only on the percentage of rubber, but also on the nature of replacement, particle size and shape, composition of the raw material, curing process, surface treatment, and additional reinforcement, thus creating a typical strength/deformability balance. Although several studies report a reduction in static strength with increasing CR content, this relationship is not universal and depends on factors such as rubber dosage, replacement basis, particle characteristics, surface treatment, binder composition, and curing conditions. For example, the studies compiled in the present review show a reduction in 28-day compressive strength (CS) from 65.0 to 15.8 MPa at 20% CR in the mixtures of Azmi et al. (2016) [40], while Pham et al. reported a decrease from 54.0 to 11.7 MPa at 30% CR [59]. Pham et al. further noted that complete replacement of river sand with rubber in an earlier fly-ash geopolymer system produced reductions of approximately 93% in CS and 78% in flexural strength (FS), demonstrating the severe strength penalty associated with very high rubber contents. Similarly, Dong et al. (2021) [38] found a high correlation between CS and STS, EM, density, ductility, and

water absorption, showing that the increase in rubber percentage changes not only the strength but also the stiffness and deformation properties of concrete. On the other hand, Hassan et al. (2024) [23] focused on CS, EM, and the full compressive stress–strain relationship and observed around a 33% decrease in CS when 25% natural fine aggregate was substituted with CR; yet, pre-treatment of the rubber helped to minimize the loss of strength and stiffness.

Zhang et al. (2021) [64] reported an increase in 28-day compressive strength from 39.4 MPa for the control mixture to 46.9 MPa at 10% CR. The authors attributed this improvement to the NaOH pretreatment of CR, which increased surface roughness and adhesion and thereby improved the rubber–geopolymer interfacial interaction. They further suggested that the alkalinity retained by the pretreated CR could favor the geopolymerization process. However, when the CR replacement increased beyond 10%, the adverse effect of the higher rubber content became dominant, resulting in a progressive reduction in compressive strength.

However, this loss in mechanical properties is not absolute at low levels of rubber content. According to Park et al. [35], about 5% CR can be included without a significant statistical decrease in CS under the given set of conditions, while proper matrix design has even led to positive effects. Arunkumar et al. [56], through the use of waste rubber fibers instead of regular granular CR, determined 1 vol.% as the optimal content of rubber, where at 90 days, CS, STS, FS, and EM increased by 4.36%, 6.25%, 3.64%, and 10.62% from the control, respectively, while increasing the fiber content further led to a deterioration of these properties. Particle size is another important parameter.

Surface and matrix modification can further mitigate rubber-induced strength losses. Lazorenko et al. (2021) [65] compared several physical and chemical CR pretreatments and found $KMnO_4$ treatment particularly effective: the amount of adsorbed water vapor increased from 1.5 to 3.3 wt.%, indicating more than a twofold increase in rubber hydrophilicity, while CS increased from 12.8 MPa for untreated CR to 15.5 MPa for the composite containing treated CR.

The reduction in static strength and stiffness should also be considered together with the accompanying increase in deformability, toughness, and resistance to dynamic loading. High-performance formulations illustrate this trade-off particularly clearly. Chen et al. (2023) [66] examined rubber-modified high-performance geopolymer concrete containing 0, 5, 20, 35, and 50% rubber and developed corresponding compressive stress–strain relationships. Even though the mechanical performance was reduced by adding more rubber, due to the deformability becoming greater and stiffness becoming lower, ultra-high-performance strength (greater than or equal to 120 MPa) was still achieved with 5% rubber, and high-performance strength (greater than or equal to 55 MPa) with 35% rubber. More recently, Wan et al. (2025) [67] developed engineered geopolymer composites containing 0, 30, 60, and 100% replacement of fine silica sand by waste rubber. While the addition of rubber decreases CS, the fully rubberized composite was able to produce a CS value of around 47 MPa, along with 7.7% tensile strain, indicating remarkable ductility. The results obtained using the X-CT and BSE analyses indicated increased porosity and a wider ITZ due to the inclusion of the rubber phase, which facilitated premature cracking, with the stress being transferred via fiber-matrix bridging.

Energy dissipation improvements become much clearer in the case of impact loading. For example, according to Pham et al. (2020) [59], when 0, 15, and 30 vol.% CR were used as a replacement for coarse and fine aggregates using Split Hopkinson Pressure Bar tests at strain rates of up to 136 s^{-1}, RGC showed better impact properties, reduced brittleness and brittle crack propagation, as well as greater normalized energy absorption; moreover, the increase in strain-rate sensitivity of dynamic compressive strength became greater with an increase in CR content. Aly et al. (2019) [68] also proved the effectiveness of CR in

impact-loading cases; thus, for instance, the flexural impact energy of concrete increased from about 4.9 J (control group) to 14.7 J (30% CR). As a result, it increased about three times compared to the control one.

The new results further confirm the hypothesis that the moderate CR dose leads to particularly advantageous dynamic properties. Zhang et al. (2025) [69] showed that at a strain rate of about 90 s^{-1}, there was an 18.43% increase in dynamic CS when the content of CR varied from 0% to 10%, while its further increase to 20% led to a 1.96% decrease due to increasing cracks and porosity, which cannot be neutralized by energy dissipation from rubber anymore. Meanwhile, the dynamic strength of the material for 10% CR composition increased by 108.91% with increasing strain rate from approximately 25 to 90 s^{-1}. The authors explain the improved impact behavior at appropriate CR content by energy dissipation from rubber and optimum pore structure. The same difference between static and dynamic behavior exists in lightweight RGC. Çelik et al. (2025) [70] noted that static mechanical properties were increasingly lower with an increase in WTR content, i.e., when WTR was increased from 0 to 15%, then the FS decreased by about 20–26%. Furthermore, Azunna et al. (2025) [71] claimed that when 10 and 20% CR were added to RGC columns, impact-energy absorption increased by 42.91% and 52.38%, respectively.

The use of pumice along with WTR had an effect on decreasing CS and STS. At the material level, Shao et al. (2025) [58] showed that rubberized geopolymer-based ultra-high-performance concrete can retain high compressive and flexural strengths while providing sustainability benefits.

It follows from the above that the mechanical behavior of RGC should be explained as a balance between strength, stiffness, and ductility/energy dissipation rather than a degradation caused by rubber. An increase in conventional CR content in GR generally results in reduced CS, STS, FS, and EM values due to replacing a stiff mineral aggregate with compliant rubber, which may cause increased porosity and a weakened rubber–matrix interface. But low to moderate CR content, small CR particles, fiber-like shape of CR, proper curing, surface chemical modification, nanoparticle addition, and fiber reinforcement allow considerable compensation of such a loss and even improvement in some cases. On the other hand, decreased stiffness and higher deformability of CR are beneficial for RGC under impact and high strain-rate loading through delay of crack growth and reduction of brittleness with increasing energy dissipation. Therefore, only compressive strength cannot be taken into account when determining optimum RGC composition.

4.3. Dynamic Mechanical Properties

Rubber incorporation can improve the dynamic response of geopolymer composites despite the associated reduction in static strength [44,59,68–71].

Pham et al. [61], employing Split Hopkinson Pressure Bar experiments conducted at strain rates of 50–136 s^{-1}, found higher strain-rate sensitivity and energy absorption as a function of CR; at 130 s^{-1}, normalized energy absorption values rose from 15.9 kJ/m^3/MPa in the control to 29.7 kJ/m^3/MPa in the case of 30% CR. Similarly, Aly et al. [70] found a rise in flexural impact energy from 4.9 to 14.7 J at 30% CR.

Aown et al. [44] found that untreated CR increased normalized dynamic energy absorption by 41–59%, whereas NaOH pretreatment reduced this benefit by 15–25% because of the increased stiffness and reduced ductility associated with stronger rubber–matrix bonding. Zhang et al. [69] further showed that, at ~90 s^{-1}, dynamic CS increased by 18.43% from 0 to 10% CR, but decreased slightly when CR was increased to 20%. At the structural scale, Azunna et al. (2025) [71] reported 42.91% and 52.38% increases in impact-energy absorption at 10% and 20% CR, respectively. Overall, the available results indicate that low-to-moderate CR contents can enhance strain-rate response, deformability, and

impact-energy absorption, although excessive CR may reduce dynamic strength because of increased porosity and weaker interfacial bonding.

4.4. Durability Performance

Water absorption and sorptivity: Water absorption and sorptivity can serve as useful indicators of the moisture penetration rate and capillary behavior in rubberized geopolymer concrete (RGC). In turn, these parameters are significantly dependent on the following factors: rubber concentration, porosity interconnectivity, compactness of the matrix, and quality of the rubber-geopolymer interfacial transition zone (ITZ).

Luhar et al. (2021) [52] investigated the sorptivity of rubberized geopolymer concrete and its OPC counterpart. At 28 days, the geopolymer concrete exhibited lower sorptivity values (0.09–0.164 mm/min$^{0.5}$) than the corresponding OPC concrete (0.113–0.203 mm/min$^{0.5}$), indicating comparatively lower capillary water transport. Sorptivity increased with increasing rubber-fiber content in both geopolymer and OPC concrete. As shown in Figure 7, sorptivity also increased with age from 28 to 365 days for all investigated mixtures.

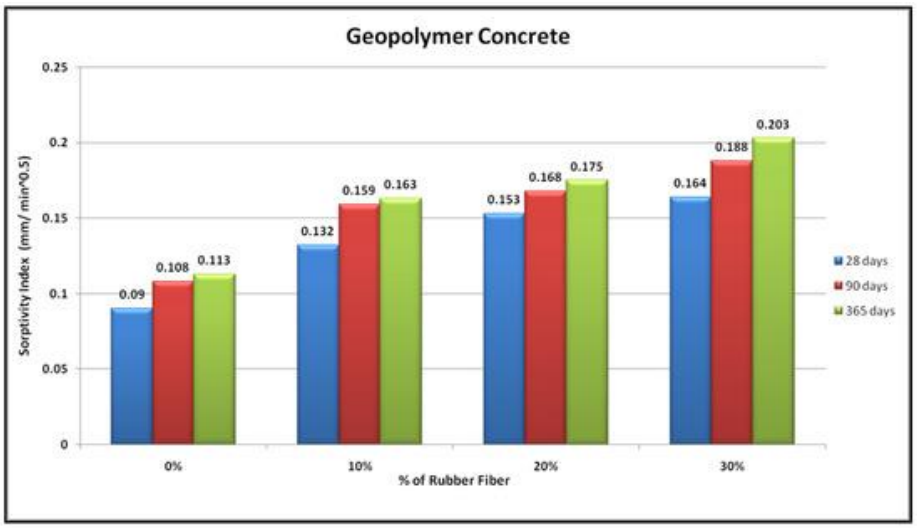


Figure 7. Sorptivity of RGC (Adapted from Luhar et al. (2021) [52]).

In the study conducted by Saloni et al. (2021) [43], where CR was used in amounts of 10, 20, and 30 vol.% as a fine-aggregate substitute, it was found that the water absorption of the geopolymer increased with CR addition, as opposed to the reference GPC. Meanwhile, the NaOH and UFS treatments decreased the water absorption due to better adhesion between CR and the matrix, along with the creation of a denser geopolymer matrix.

Raut et al. (2024) [72] found similar results with increased water permeability in steel slag-based geopolymer blocks that contained CR. The velocity of water absorption (VWA) was raised from 10.74 × 10^{-6} m/s$^{0.5}$ in the control sample to 15.52–18.41 × 10^{-6} m/s$^{0.5}$ in the samples that contained CR. The coefficient of water absorption (CWA) increased from 2.35 × 10^{-10} m/s in the control sample to 4.44–5.84 × 10^{-10} m/s in samples that contained CR. The reason for the above behavior may be due to higher porosity and voids formed by CR addition.

Permeability/Water Transport: Permeability refers to the capacity of fluids to flow through the pore structure that is interconnected in RGC. While geopolymer matrices tend to be less permeable, increased amounts of rubber may cause more pores and interfacial defects which means that permeability is highly dependent on rubber dosage (as well as rubber content, particle size [73]), matrix composition, compaction, and interfacial conditions. A well-reacted geopolymer binder can provide low permeability; however,

untreated or excessive rubber may create voids and weak interfacial regions that increase fluid ingress [74,75].

Luhar et al. (2021) [52] reported relatively low water penetration for rubberized geopolymer concrete, with values ranging from 31.2 to 35.7 mm, compared with 38.03–42.8 mm for corresponding rubberized OPC concrete. Nevertheless, water penetration increased with rubber-fiber replacement because of increased concrete porosity. The lower overall permeability of the geopolymer mixtures was attributed to the denser aluminosilicate matrix.

The research conducted by Saloni et al. (2021) [43] showed that the transport properties of RGC were considerably influenced by the surface of CR. The untreated CR increased water uptake; NaOH treatment of CR led to better adhesion of the rubber to the geopolymer matrix, while UFS treatment of CR caused higher density of the matrix due to fillers and calcium–silicate interactions. Thus, these treatments resulted in reduced water uptake compared to untreated CR, emphasizing the significance of ITZ modification in reducing permeability.

Obeidy and Khalil (2024) [28] studied metakaolin-based GPC reinforced with 10, 20, and 25 vol.% CRWA as coarse-aggregate replacement. The increase in crumbed rubber waste aggregate (CRWA) caused a decrease in the density of the concrete and resulted in more air trapping and interfacial voids due to the lower specific gravity and non-polarity of rubber, which suggests a more open transport structure with increasing rubber content.

Khan et al. (2026) [76] found that water absorption had shown very little variability, with values being in the range of 1.63% to 1.73% when the content of rubber increased from 0% to 15%, which indicates that the presence of rubber powder does not influence the moisture permeability of the mortar and may have a positive effect on impermeability in higher amounts, while the void content decreased from 3.73% to 3.38%, which might be due to the micro-filling properties of the fine rubber particles.

Chloride Penetration: Chloride resistance is crucial for reinforced materials that operate under marine conditions or de-icing salts [77]. Densified geopolymer gels and refined pore structures can reduce chloride penetration [27], while interfacial air pockets associated with rubber may increase diffusion when the amount of rubber is high and compaction is poor [78]. The amount of slag, activator types, curing conditions, electrical conductivity, and test method influence measured chloride parameters. Test results from quick electrical tests should not be considered as diffusion coefficients unless they are calibrated due to different pore solution chemistry.

Alsaif et al. (2022) [27] conducted an examination on the rapid chloride permeability of RGC mixes based on metakaolin incorporating 10–50% crumb rubber, replacing fine aggregates with respect to volume. At 28 days, the mixes with 10–40% crumb rubber had similar amounts of charge passed at 2887–3038 C with a moderate chloride permeability level, while the 50% crumb rubber mix had 1702 C with a low permeability level. Deng et al. (2023) [78] studied the rapid chloride permeability of FA-GGBFS geopolymer mortar mixes using recycled crumb rubber (RCR) and recycled glass cullet (glass). The mix with a high content of RCR had the least chloride permeability, and higher glass content usually had higher amounts of charge passed. This is mainly due to differences in pore structure and the nature of rubber particles.

Similarly, Luhar et al. (2021) [52] studied the diffusion of chloride ions in rubberized geopolymer concrete (Figure 8). It was observed that the increase in the amount of rubber fiber led to higher values of the chloride diffusion coefficient, which indicates increased porosity and the presence of interfaces between the rubber and matrix, allowing for better transport of chlorides. The geopolymer mixtures had relatively lower values of chloride diffusion coefficients ($1.0–1.2 \times 10^{-12}$ m²/s) compared to the OPC mixtures ($1.5–1.7 \times 10^{-12}$ m²/s).

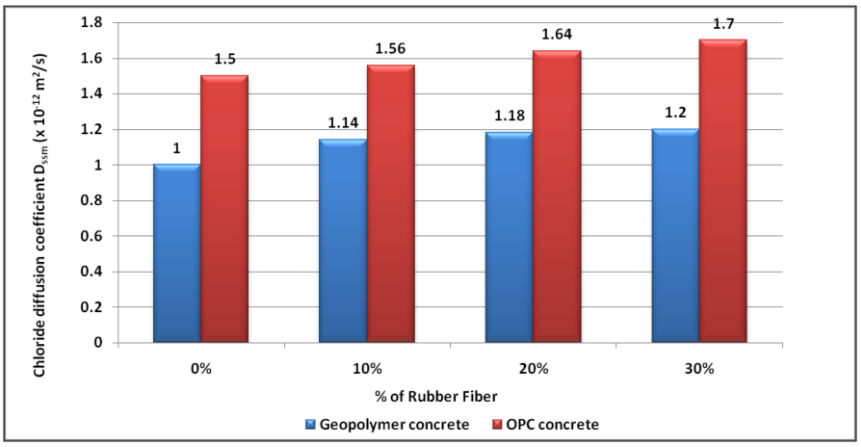


Figure 8. Effect of rubber tire-fiber content on the chloride diffusion coefficient of geopolymer and OPC concrete. Adapted from Luhar et al. (2021) [52].

Sulphate Resistance: The alkali-activated binding system is typically associated with reduced portlandite compared to the Portland cement system and less formation of expansive sulfate reaction products. Sulphate resistance is nevertheless influenced by the chemical nature of the precursors, calcium content, permeability, exposure solution, and duration of the test. Rubber can allow for local deformation; however, too much rubber would make the material more porous and thus enable the entrance of aggressive substances.

Luhar et al. (2021) [52] assessed the performance of rubberized geopolymer concrete with respect to its sulphate resistance properties by exposing it to 5% Na_2SO_4 solution up to 365 days. As can be seen from Figure 9 below, there was no appreciable deterioration observed in the geopolymer concrete specimens over the period of 365 days, while the OPC concrete specimens were subjected to cracking and expansion (see Figure 9).



Figure 9. Visual comparison of rubberized geopolymer and OPC concrete after prolonged sulphate exposure (adapted from Luhar et al. (2021) [52]).

Acid Resistance: Geopolymers and alkali-activated binders may have higher resistance to acid than Portland cement-based materials due to differences in the reaction products and reduced amounts of portlandite formed. However, geopolymer and alkali-activated materials are susceptible to acids that can lead to leaching of alkali and calcium and deterioration of the aluminosilicate network. Increased interfacial porosity in RGC owing to the inclusion of rubber may enable acid entry into the system. Hence, acid resistance comparisons must clearly define the type of acid, concentration, time of exposure, pH, and performance criteria used [79].

Acid resistance was also studied by Luhar et al. (2021) [52] employing H_2SO_4 solutions of 3%, 5%, and 10% concentration for 365 days. As seen in Figure 10**,** with an increase in concentration, the erosion of the surface becomes pronounced, being much more pronounced for OPC concrete than geopolymer samples.



Figure 10. Surface deterioration of rubberized geopolymer and OPC concrete following sulphuric-acid exposure (adapted from Luhar et al. (2021) [52]).

Freeze–Thaw Resistance: Rubber particles and voids can help in reducing hydrostatic and crystallization stresses developed during freezing; however, there are limitations depending on the degree of saturation, porosity, air voids, and interface quality. The densely cured material minimizes water absorption, while voids generated due to excess rubber can lead to saturation and damage. Freeze–thaw damage cases need validation using standardized tests based on mass loss, dynamic modulus, strength loss, and surface scaling.

Zhang et al. (2021) [64] have analyzed the freeze–thaw resistance of the rubberized geopolymer concrete (RGC). Mass loss, dynamic elastic modulus, and cracks in the concrete were determined for specimens, which were tested periodically for 25 freeze–thaw cycles, while 5% of mass loss and 60% reduction in relative dynamic elastic modulus were used as stopping criteria. Zhang et al. found that the number and size of internal cracks in RGC with 10% CR content was reduced compared to others.

As indirect mechanistic supporting evidence from conventional OPC-based rubberized concrete, Sun et al. (2023) [80] investigated strength retention after 0, 25, 50, 75, and 100 freeze–thaw cycles (see Figure 11a for R2-4C1-25, Figure 11b for R2-4C1-25, and Figure 11c R2-4C1-25**)**. Relative compressive strength was used to evaluate the progressive deterioration, and the results indicated that rubber particles restrained the reduction in strength. However, because this study employed an OPC-based binder rather than a geopolymer/alkali-activated system, these findings are considered only as supporting evidence for possible freeze–thaw mechanisms and not as direct evidence of RGC performance.



(**a**) (**b**) (**c**)

Figure 11. Evolution of compressive failure in conventional OPC-based rubberized concrete under freeze–thaw cycling: (**a**) R2-4C1-25, (**b**) R2-4C1-25, and (**c**) R2-4C1-25, presented as indirect mechanistic supporting evidence for RGC (adapted from Sun et al. (2023) [80]).

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Similarly, Richardson et al. [81] provide indirect mechanistic supporting evidence from conventional cement-based rubberized concrete. The study investigated the freeze–thaw behavior of concrete containing crumb rubber and reported improved freeze–thaw resistance compared with plain concrete. These observations provide useful mechanistic support for the potential role of crumb rubber in relieving freeze–thaw deterioration; however, they should not be directly extrapolated to RGC because the binder chemistry differs from geopolymer/alkali-activated systems.

Carbonation: Carbonation in alkali-activated systems is different from that in Portland cement concretes and depends on calcium, alkalinity, curing, humidity, and exposure to CO_2. Rubber-based porosity at the interface may promote CO_2 penetration. Since accelerated carbonation in a CO_2 atmosphere may not represent natural carbonation, the extent of carbonation can be evaluated based on depth, loss of alkalinity, phase changes, and corrosion of steel.

Dong et al. (2021) [38] conducted an experimental study on the carbonation resistance of RGC by using both carbonation depth and compressive strength after carbonation. The carbonation depth of the specimens under 1% CO_2 exposure for 28 days was measured using the phenolphthalein test. The researchers pointed out that carbonation depth could not be sufficient to represent RGC due to its complicated pore solution chemistry of geopolymer binders; thus, complementary compressive strength tests were advised.

Luhar et al. (2021) [52] investigated accelerated carbonation of fly-ash-based rubberized geopolymer concrete containing 10–30% rubber tire fibers as partial replacement of river sand. Carbonation was evaluated after 14–90 days of exposure to 5% CO_2 using phenolphthalein to determine carbonation depth, providing direct evidence of the carbonation behavior of RGC at different rubber contents (see Figure 12).

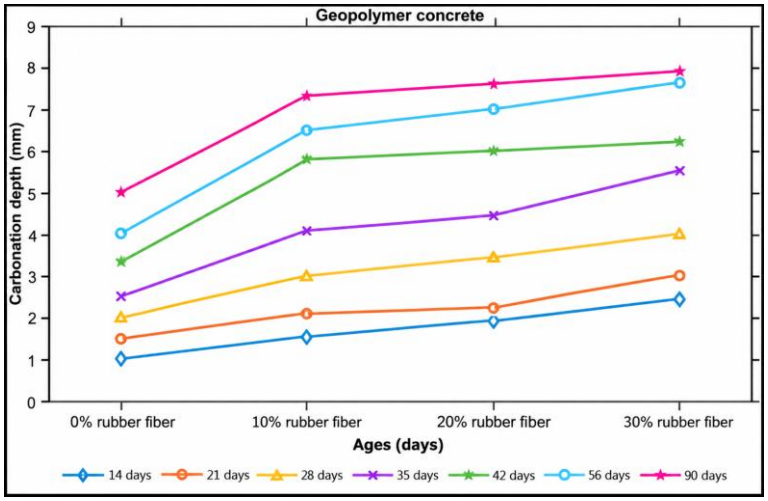


Figure 12. Carbonation depth of rubberized geopolymer concrete and rubberized OPC concrete at different rubber-fiber replacement levels (re-adapted from Luhar et al. (2021) [52]).

High-Temperature Performance: Crumb rubber tends to undergo decomposition at high temperatures and consequently form extra voids, which tend to decrease the strength remaining for RGC. Nevertheless, formation of voids could aid in the release of vapor and reduction of pressure and thermal cracking. Evaluation of high-temperature performance therefore should include mass loss, strength loss, cracking and spalling, and microstructure changes.

Notably, Azmi et al. (2022) [82] studied the crumb-rubber geopolymer mortar made from fly ash with 0 to 20% rubber at 200 to 800 °C and found that both the increase in temperature and amount of rubber caused a rise in the mass loss and reduction in compressive strength. Decomposition of the rubber resulted in the formation of additional

voids from around 200 to 600 °C, while cracking and surface deterioration were noted at higher amounts of rubber at 800 °C (see Figure 13).

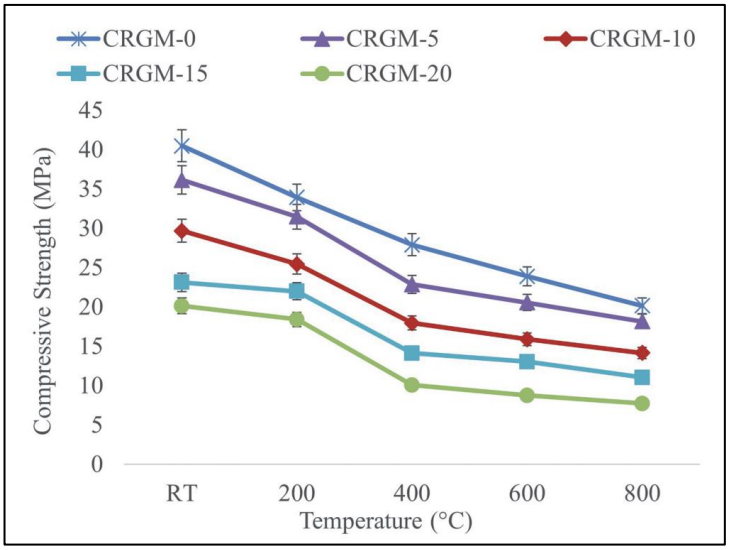


Figure 13. Effect of elevated-temperature exposure on RGC (adapted from Azmi et. al. (2022) [82]).

Most recently, Arjun Raj et al. (2026) [83] studied GGBS-dolomite and GGBS-fly ash-dolomite RGC reinforced by 0–20% crumb rubber under 700 °C. Higher temperatures and higher contents of rubber tended to lower the residual compressive and splitting tensile strength and UPV values, whereas the addition of fly ash to the GGBS-dolomite matrix increased its thermal resistance. In other words, the results presented prove that the behavior of RGC at elevated temperatures is highly dependent not only on the amount of rubber but also on the composition of the geopolymer precursor. Figure 13 shows increasing thermal damage with temperature, while the rubberized mixture exhibits fewer visible cracks at intermediate temperatures, possibly because rubber-induced voids facilitate vapor release.

However, the pressure relief effect may not necessarily lead to any improvement in the residual mechanical properties. Generally, it can be noted that, at high temperatures and larger rubber amounts, the negative impact of degradation of rubber, higher porosity, and damage of the matrix outweighs, leading to low residual strength. Hence, the pressure relief is a secondary property, primarily related to the reduction of cracking/spalling.

4.5. Microstructure and Rubber–Geopolymer Interface

Scanning Electron Microscopy (SEM): SEM is used to evaluate matrix continuity, unreacted particles, porosities, cracks, and the rubber–binder interface.

Notably, SEM analysis reveals that CR in the raw state has a smoother surface with poor interface bonding, while NaOH treatment provides a rougher surface with enhanced mechanical interlocking with the geopolymer matrix [23].

In turn, Shao et al. (2025) [58] revealed that the shape of CR impacts interfacial interactions, where medium-sized CR with a serrated surface allows mechanical interlocking, while coarse CR shows weak bonding and fiber debonding at the interface.

Abd-Elaty et al. (2023) [84] reveal a distinct void gap surrounding the CR particles, indicating poor adhesion between the hydrophobic rubber surface and the geopolymer matrix. This weak ITZ limits effective stress transfer and helps explain the reduction in mechanical strength observed after CR incorporation.

In more recent research, Mohabbi and Bulsu (2026) [85] have noted that microstructure formation in rubberized geopolymer mortar depended largely on the composition of

binders. According to SEM results (see Figure 14a for 50× view, and Figure 14b for 200× view), poor bonding at the interface between waste tire rubber and geopolymer was found due to the hydrophobicity of rubber, while optimal slag-based matrices featured a denser and more homogeneous structure of the gel network. Addition of small amounts of cement contributed to matrix densification.

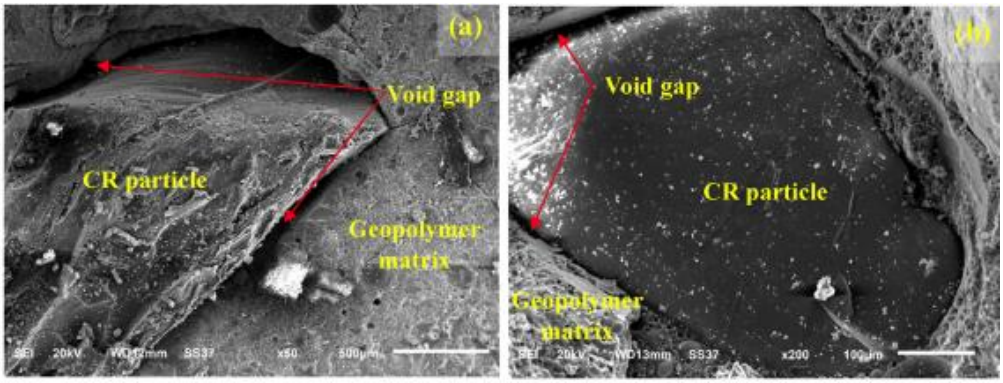


Figure 14. SEM micrographs of rubberized geopolymer mortar: (**a**) 50×, and (**b**) 200× (adapted from Abd-Elaty et al. (2023) [84]).

Interfacial Transition Zone (ITZ): The ITZ between the crumb rubber particles and the geopolymer matrix is an important parameter that significantly affects the mechanical and durability properties of RGC. The inherent hydrophobicity of unmodified rubber and the poor compatibility of the organic compound with the inorganic geopolymer matrix result in interfacial cracks and weak bond formation, hence ineffective load transfer. Surface modification techniques such as NaOH, silane coupling agents, and mineral/geopolymer coatings improve the roughness and wetting of the rubber surfaces for effective bonding, hence dense ITZ formation. However, microstructural examination needs to be complemented by mechanical and transport studies.

From the standpoint of interface engineering, the results from this research can be organized into a mechanistic sequence in which the surface modification of rubber leads to macroscopic properties of RGC. In surface treatments, the physical and chemical properties of the rubber surfaces are changed through increased wettability and surface roughness, among other factors. These changes aid in the adherence of the rubber to the geopolymer matrix, resulting in fewer interfacial voids, micro-cracks, and porosity, which creates a denser ITZ. This helps in the transfer of stress and prevents premature interfacial debonding, which can help prevent strength reduction due to the use of rubber. Another reason is that increased density and reduced connectivity of the ITZ can reduce the pathways of water and ion transport and therefore increase its durability properties. In general, surface treatment affects wettability, surface chemistry, and roughness, which, in turn, control ITZ structure, porosity, stress transfer, and transport properties and the performance of RGC. Nevertheless, the effectiveness of interface engineering depends on the treatment method and intensity, rubber content, geopolymer chemistry, and curing conditions, and further systematic studies are required to establish these relationships quantitatively.

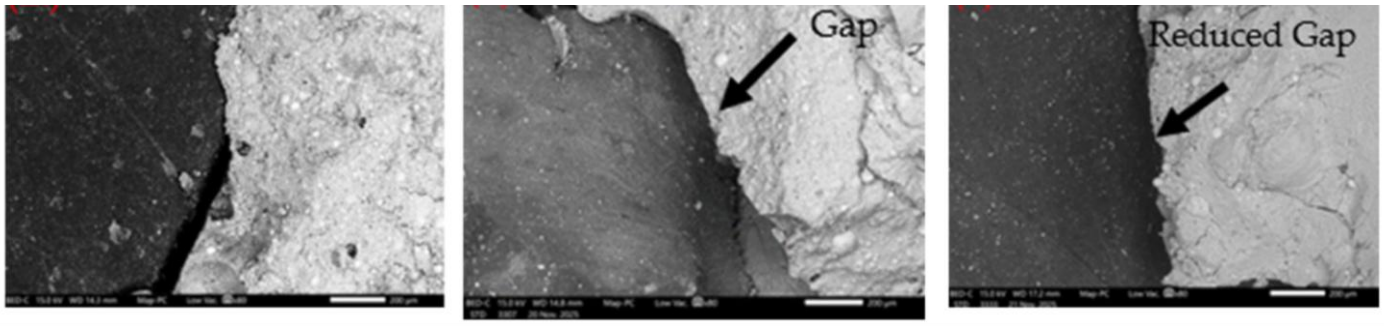
Table 6 compares the main interface-engineering approaches reported for RGC. NaOH treatment generally improves rubber–matrix adhesion through surface modification [23,44,64], while UFS treatment can further enhance matrix interaction [43]. $KMnO_4$ treatment also improved rubber hydrophilicity and interfacial bonding [66]. However, the effectiveness of these treatments depends on treatment conditions and mixture characteristics, and improved bonding may involve trade-offs such as reduced energy absorption [44].

Table 6. Comparative assessment of interface-engineering approaches for crumb rubber in rubberized geopolymer composites.

Study	Treatment	Treatment Conditions	Interface Mechanism	Main Reported Benefit	Limitation/Trade-Off
Hassan et al. (2024) [23]	NaOH	16 M NaOH; soaked 24 h; air-dried	Increases surface roughness and improves CR–matrix bonding	Pretreatment minimized losses in compressive strength and elastic modulus	Strength and modulus still decrease as CR content increases
Saloni et al. (2021) [43]	Water, NaOH, cement paste and UFS	CR = 10, 20, and 30 vol.%; NaOH treatment and UFS treatment among investigated pretreatments	NaOH enhances CR–matrix adhesion and promotes a denser matrix; UFS treatment promotes calcium-silicate products	NaOH and UFS treatments improved GPC properties; pretreatment reduced water absorption relative to untreated CR mixtures	Increasing CR generally reduced slump, density and strengths; CR mixtures showed poorer HCl/H_2SO_4 resistance
Aown et al. (2025) [44]	NaOH	16 M NaOH; immersion 2 h; pressurized-water rinse; air-dried 1 week	Removes surface contaminants and increases roughness, porosity, and hydrophilicity, improving adhesion	At 25% CR, pretreatment increased CS by 15.2–15.4% and peak static force by 20.3–20.5% versus untreated CR	Normalized dynamic energy absorption decreased by approximately 15–25% because of increased stiffness/reduced ductility
Zhang et al. (2021) [64]	NaOH	1% NaOH solution; immersion 1 h; subsequently washed	Dissolves zinc stearate and coarsens the CR surface, improving interfacial adhesion	Strength increased up to 10% CR; the study identified 10% CR as the optimum investigated replacement for combined strength and freeze–thaw performance	Strength decreased when CR replacement increased beyond 10%
Lazorenko et al. (2021) [65]	$KMnO_4$ oxidation	5 wt.% $KMnO_4$; CR subsequently rinsed six times with deionized water and dried 72 h at room temperature	Oxidation forms surface-active functional groups and substantially increases CR hydrophilicity	Adsorbed water increased 1.5 → 3.3 wt.%; CS increased 12.8 → 15.5 MPa with 10 wt.% treated CR	Further optimization of geopolymer composition and curing was identified as necessary

İpek and Mermerdaş (2022) [42] utilized SEM to analyze the ITZ formation for geopolymer mortars prepared from fly ash with 10–50% CR as a volume fraction of natural sand. The samples showed a clear distinction in the ITZ formation compared to the natural sand and geopolymer mortar due to clear gaps between the CR particles, which indicate poor interfacial bonding that resulted in poor mechanical performance.

According to Islam et al. (2026) [86]), the CR geopolymer concrete displays a relatively porous and weakly bonded rubber–matrix ITZ. The normal condition in Figure 15a indicates weak interface bonding, while the saline condition in Figure 15b indicates more interfacial debonding and voids, which correlates with a decrease in compressive strength by approximately 13%. The hygrothermal condition in Figure 15c, on the other hand, facilitates the occurrence of secondary geopolymerization and local densification of the matrix that minimizes the interfacial space.



(**a**) (**b**) (**c**)

Figure 15. SEM micrographs of RGPC under (**a**) normal, (**b**) saline, and (**c**) hygrothermal conditions (adapted from Islam et al. (2026) [86]).

As indirect supporting evidence from conventional rubberized concrete, Wang et al. (2020) [87] investigated the ITZ characteristics of crumb-rubber concrete using SEM and porosity analysis at different curing ages. Although the OPC-based matrix differs chemically from geopolymer and alkali-activated binders, the study provides useful mechanistic context for rubber–matrix interfacial behavior and is therefore considered here as supporting rather than direct evidence of RGC behavior. SEM observations revealed distinct microcracks and gaps around the rubber particles, indicating poor interfacial bonding between the rubber and mortar matrix. The interaction between the rubber and matrix was reported to be predominantly mechanical.

Energy-Dispersive X-Ray Spectroscopy (EDS): Energy-dispersive X-ray analysis is normally associated with SEM as a way of acquiring local elemental information about the geopolymer matrix and interfacial zones. The common elements may consist of Si, Al, O, Na, and Ca, while elemental ratios such as Si/Al or Ca/Si could aid in understanding the matrix composition. But EDS cannot determine bonding or crystalline phases directly and thus requires combination with other techniques like XRD and FTIR.

Valente et al. (2022) [88] used EDX analysis to study rubberized alkali-activated mortars and discovered that increasing replacement of sand by rubber from tires resulted in an increased Si/Al ratio but a decrease in the compressive strength. The authors linked this observation with the effect of changes in the availability of reactive species as a result of the mineral-aggregate substitution.

Çelik et al. (2025) [70] used EDX analysis on lightweight fly-ash geopolymer concrete incorporating pumice and scrap tire rubber. According to the authors, the EDX analysis revealed that oxygen, silicon, aluminum, and sodium were major elements in the geopolymer structure. The silicon and aluminum were attributed to the formation of the aluminosilicate gel, while the sodium was mostly derived from the activation process.

Figure 16 present SEM–EDS analysis of the crumb-rubber geopolymer concrete (CR mix) (Islam et al. (2026) [86]). The SEM image demonstrates that there is an evident void between the crumb rubber and geopolymer matrix, reflecting low interfacial bonding strength caused by the elasticity and non-polarity of rubber. The EDX spectrum highlights the contrast between the rubber-containing zone and the adjacent geopolymer matrix that has distinctive Si, Al, Na, Ca, and O elements corresponding to the aluminosilicate binder.

X-Ray Diffraction (XRD): X-ray Diffraction (XRD) analyzes crystal phases and any amorphous transformation that occurs during the process of geopolymer activation. Other residual phases include quartz and mullite. Calcium-rich systems can have other reaction phases formed because of geopolymerization reactions. Crumb Rubber is predominantly amorphous and acts on the matrix physically.

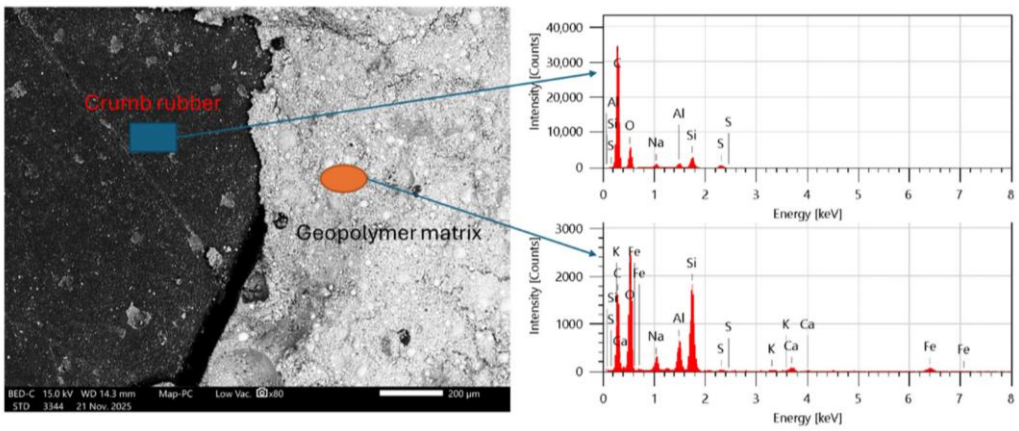


Figure 16. SEM-EDX spectrum showing the elemental composition of RGPC (adapted from Islam et al. (2026) [86]).

Zhang et al. (2021) [64] applied XRD analysis for identifying the mineral components of RGC before and after being exposed to the freeze–thaw condition; primary crystal phases included quartz, calcite, and mullite; meanwhile, the broad band moved to around 28° (2θ) after being alkali-activated. In addition, crumb rubber did not have any effects on the mineral phases of RGC. As far as the freeze–thaw cycle is concerned, no substantial change in mineral phase was observed except the increase in crystal peak intensity, suggesting the decline of the amorphous geopolymer phase.

According to Gill et al. (2023) [89] (Figure 17), crumb rubber enhanced the amorphous nature of the geopolymer matrix, while OPC addition formed some C-S-H/C-A-S-H-related phases. In terms of H_2SO_4 exposure, the formation of anhydrite ($CaSO_4$) and calcite ($CaCO_3$) showed acid-induced changes in the matrix structure.

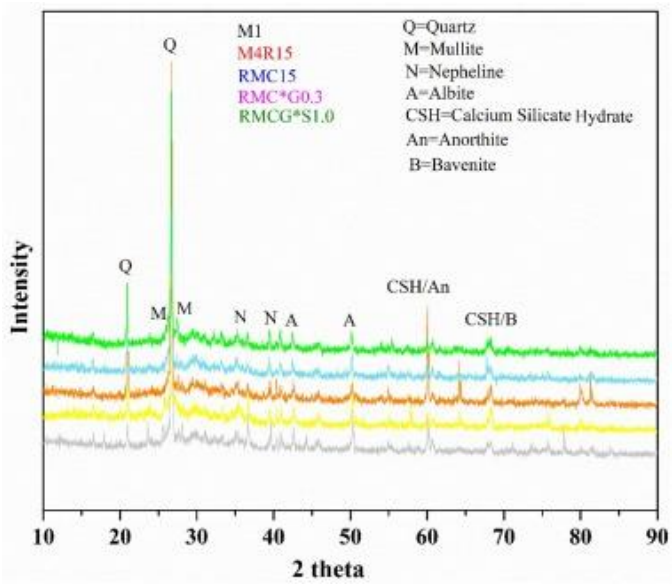


Figure 17. XRD of GPC specimens (Gill et al. (2023) [89]).

Fourier-Transform Infrared Spectroscopy (FTIR): FTIR is widely used to characterize functional groups and to assess structural modifications in the aluminosilicate network during geopolymerization. The asymmetric stretching band of Si–O–T (T = Si or Al) is usually observed in the range of 900–1100 cm^{-1}. The modification of its position indicates a change in the aluminosilicate framework after activation. Typical broad absorption bands at about 3400 cm^{-1} and 1650 cm^{-1} are assigned to O–H stretching and molecular water, respectively, and bands in the 1400–1500 cm^{-1} region may be indicative of carbonate species. The FTIR results should be considered together with other techniques, such as XRD and SEM–EDS, to obtain a more reliable evaluation of the phase and chemical evolution.

For example, Lazorenko et al. (2021) [65] used ATR–FTIR to study the chemical changes of crumb rubber after different surface treatments. The authors have highlighted that the treatment with NaOH, H_2SO_4, acetone, and UV resulted in relatively minor changes in the CR spectra, while treatment with $KMnO_4$ caused dramatic spectral changes, especially the prominent reduction of C–H stretching bands, indicative of the oxidative modification of the rubber surface. These changes were attributed to the formation of more polar functional groups, increasing the hydrophilicity of the rubber surface and its interaction with the geopolymer matrix.

Meanwhile, Raut et al. (2024) [72] used FTIR on steel-slag/GGBS-based geopolymer composites with crumb rubber. The spectra showed a carbonate-related band at approximately 870 cm^{-1}, an –OH-related band at about 1600 cm^{-1}, and typical vibrations of Si–O–Si and Si–O–Al in positions between 900 and 1200 cm^{-1}. These spectral features were

employed to interpret the evolution of geopolymer reaction products in the crumb-rubber-containing matrix.

In Gill et al. (2023) [89] (Figure 18), the FTIR spectra of the rubberized geopolymer composites showed the presence of Si–O–Si/Si–O–Al bonds at 1000 cm^{-1}, which proves the formation of geopolymer. An increase in the peak intensity of the OPC-modified rubberized composite (RM*C15) was observed for the C-A-S-H gel formation, but the introduction of CR, glass fiber, and steel fiber did not create any new FTIR peaks.

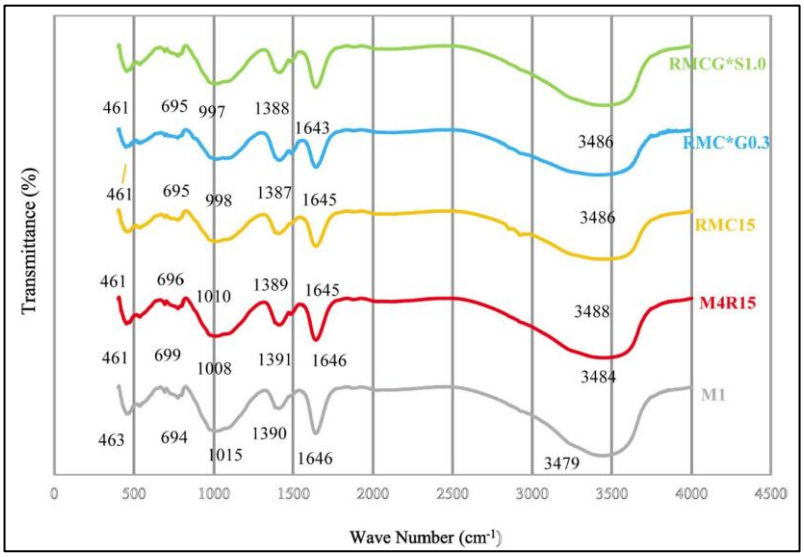


Figure 18. FTIR of GPC specimens (Gill et al. (2023) [89]).

TG/DTA: Thermogravimetric (TG) and Differential Thermal Analysis (DTA) techniques are employed for determining the thermal stability and decomposition patterns of RGC. The initial mass loss at temperatures below 150 °C is primarily due to the release of physically absorbed and capillary water, and further dehydration of chemically bonded water takes place from 150 to 350 °C. Thermal degradation of the crumb rubber occurs at 350 to 550 °C, and decomposition of carbonate phases occurs above 600 °C.

Luhar et al. (2018) [90] investigated the thermal behavior of fly-ash-based rubberized geopolymer concrete containing 10% waste-rubber tire fibers using TGA-DTA. The specimens were exposed to temperatures of 200, 400, 600, and 800 °C, while TGA was performed up to 900 °C under a nitrogen atmosphere. The thermal analysis, together with XRD and FTIR, was used to identify temperature-induced changes in the geopolymer matrix and to explain the thermal response of rubberized and control geopolymer concrete.

In addition to the above work, Luhar et al. (2019) [91] carried out an investigation on rubberized geopolymer concrete by applying thermal and microstructural studies such as TGA/DTA. This study was applied to assess the thermal stability and decomposition process of the geopolymer matrix with waste rubber tire fibers.

Mabrouk et al. (2024) [41] applied the TGA-DTG technique to analyze the thermal behavior of lightweight geopolymer composites based on GGBS material, which included 15–45 vol.% waste-tire rubber aggregate (WTRA) replacing pumice aggregate either with or without silica fume, under various curing temperatures. The LG-0-80 mixture had the minimum mass losses equal to 15.25% and 19.36% at 400 °C and 600 °C, respectively, while the maximum ones were observed for the LG-SF-45-100 mixture (22.22% and 24.53%).

4.6. Comparative Analysis, Findings, Observations, and Discussions

The data shown in Table 7 clearly illustrate the fact that the behavior of rubberized geopolymer concrete cannot be explained with a one-dimensional connection between the

amount of rubber and the properties of the material, since this behavior is largely governed by the rubber replacement ratio and basis, rubber particle size, precursor composition, activator type, curing procedure, surface treatment, and other additives used. However, there is still a major trend that can be noted—the increase in rubber content leads to the reduction of compressive strength and stiffness of the material. For instance, Azmi et al. found a decrease in 28-day compressive strength from 65.0 MPa for the control to 15.8 MPa with 20% CR, whereas Pham et al. observed a decrease in the same parameter from 54.0 to 11.7 MPa with 30% CR. At very high rubber replacement levels, the reduction in compressive strength becomes particularly pronounced; Wongsa et al. [55] reported compressive strengths of only 2.07–3.29 MPa when river sand was completely replaced with crumb rubber.

Nevertheless, this strength disadvantage is not always applicable, as Park et al. (2016) [35] discovered that 5% CR did not statistically differ from the control group, and Zhang et al. noted that 10% NaOH-treated CR increased the 28-day compressive strength from 39.4 MPa to 46.9 MPa. Thus, lower rubber contents coupled with proper matrix and interface designs can ensure the same or even better mechanical properties.

One of the advantages that comes with rubber inclusion is the shift towards a more lightweight and deformable material that is able to absorb energy. The density becomes smaller when the higher-density mineral aggregate is substituted with lower-density rubber. According to Wongsa et al. [55], the density range was between 1067 and 1275 kg/m^3, which is about 42% less than the control. Meanwhile, Pham et al. recorded a reduction in density from 2340 to 1980 kg/m^3 at 30% CR. However, the loss in static strength could be accompanied by increased toughness and impact resistance. For instance, Aly et al. observed that flexural impact energy increased from 4.9 J in the control sample to 14.7 J at 30% CR, while Pham et al. found higher normalized energy absorption at high strain rates for the 30% CR mixture. On a structural level, according to Azunna et al. (2025) [71], energy absorption was improved by 42.91% and 52.38% at 10 and 20% CR, respectively. This means that CR cannot be judged only on the basis of compressive strength.

Table 7. Comparative synthesis of experimental studies on rubberized geopolymer concrete, highlighting mixture variables, mechanical performance, physical and transport properties, durability, thermal behavior, and microstructural characteristics.

Refs.	Rubber Content/Main Variables	Mechanical Response	Physical/Transport Response	Durability/Thermal/Microstructural Response
Park et al. (2016) [35]	FA-based GPC; CR replaced sand at 5–20 vol.%; three FA types; 8/14 M NaOH; Na_2SiO_3/NaOH = 0.5/2.0; CR = 0.075–4.75 mm.	CS generally decreased with CR. For high-Ca FA/14 M NaOH, 7-d CS decreased from 42.5 to 32.3 MPa at 0–20% CR; 5% CR was statistically comparable to control.	Unit weight decreased due to low-density CR; transport tests NR.	Durability/thermal tests NR; CR sensitivity depended on FA and activator characteristics.
Azmi et al. (2016) [40]	Class-F FA; CR = 0–20% fine-aggregate replacement; 12 M NaOH; ambient curing.	28-d CS decreased from 65.0 to 15.8 MPa at 0–20% CR, showing substantial strength loss at high CR contents.	Unit weight decreased; absorption/transport tests NR.	Dedicated tests NR; strength loss was associated with increased porosity and weak CR–matrix bonding.
Mohammed et al. (2018) [92]	FA geopolymer bricks; CR used as 100% fine aggregate; optimized with 18 M NaOH and solution/FA = 0.8.	Optimized CS = 3.98 MPa and MOR = 0.258 MPa, indicating suitability mainly for non-load-bearing use.	WA = 25.23%; average brick weight = 3091 g.	Bricks were non-efflorescent; dedicated thermal/microstructural characterization NR.
Wongsa et al. (2018) [55]	High-Ca FA; 100% CR replacing river sand; CR = 0–4 mm; curing = 25–90 °C.	28-d CS = 2.07–3.29 MPa and FS = 0.98–1.89 MPa; failure became more ductile.	Density = 1067–1275 kg/m^3; porosity = 29.7–36.3%; WA = 7.8–17.1%.	Thermal conductivity = 0.237–0.298 W/m·K, ~79% below control (1.284 W/m·K).
Luhar et al. (2018) [90]	FA-based GPC containing waste-rubber tire fibers; exposure from RT to 800 °C.	CS decreased from 47.33 MPa at RT to 21.85 MPa at 600 °C, followed by slight recovery to 22.52 MPa at 800 °C.	Density decreased after elevated-temperature exposure.	Rubber decomposition generated additional pores/voids and contributed to thermal deterioration.
Luhar et al. (2019) [91]	Waste-rubber tire fibers partially replacing fine aggregate in GPC.	CS, STS, FS, EM, and pull-off strength were evaluated; rubber modified strength and deformation behavior.	NR.	Abrasion, thermal behavior, and microstructure were investigated and compared with rubberized OPC concrete.
Aly et al. (2019) [68]	Rubberized geopolymer composite with CR contents up to 30%.	Static strength decreased, but impact performance improved; flexural impact energy increased from ~4.9 J to 14.7 J at 30% CR.	—	CR substantially enhanced impact-energy absorption and reduced brittle behavior.
Aslani et al. (2020) [93]	Lightweight rubberized GPC with varying rubber contents and mixture proportions.	Increasing rubber generally reduced strength but enhanced deformation capacity.	Rubber reduced density, supporting lightweight composite development.	Results demonstrated the feasibility of lightweight rubberized geopolymer composites.
Pham et al. (2020) [59]	FA-based RuGPC; CR = 0, 15, and 30 vol.% replacing fine/coarse aggregates; pre-soaked CR.	Static CS decreased from 54.0 to 11.7 MPa at 30% CR, while ductility and high-strain-rate response improved.	Density decreased from 2340 to 1980 kg/m^3 at 0–30% CR.	At ~130 s^{-1}, normalized energy absorption reached 29.7 kJ/m^3/MPa at 30% CR versus 15.9 for control.

Arunkumar et al. (2021) [56]	FA–wood ash GPC (70:30); rubber fibers = 0–2 vol.%; ambient curing.	1% fiber was optimum; at 90 d, CS, STS, FS, and EM increased by 4.36%, 6.25%, 3.64%, and 10.62%, respectively.	Rubber fibers increased water demand and setting time.	Durability/thermal tests NR; SEM/EDX focused mainly on precursor materials.
Dong et al. (2021) [38]	High-volume CR with varying binder/treatment conditions.	Increasing CR reduced CS, STS, and EM but substantially increased ductility.	Bulk density decreased, whereas WA/sorptivity increased.	Carbonation was investigated, highlighting a strength–transport–durability trade-off.
Lazorenko et al. (2021) [65]	CR subjected to NaOH, H_2SO_4, acetone, $KMnO_4$ and UV treatments.	$KMnO_4$ treatment increased CS from 12.8 to 15.5 MPa (~21%).	Water-vapor adsorption increased from ~1.5 to 3.3 wt.% after treatment.	Increased hydrophilicity improved CR–geopolymer interaction; $KMnO_4$ was the most effective treatment.
Saloni et al. (2021) [43]	FA-GPC; 10–30 vol.% CR; untreated or water-, NaOH-, cement- or UFS-treated CR.	Untreated CR reduced 28-d CS from 62.61 MPa to 39.91 MPa at 30% CR; NaOH/UFS treatments mitigated the loss.	WA increased from 7.52% (control) to 9.36% at 30% untreated CR; pretreatment reduced WA.	CR reduced HCl/H_2SO_4 resistance, while NaOH and UFS treatments improved acid resistance and CR–matrix adhesion.
Zhang et al. (2021) [64]	FA/GGBS GPC; 0–20 vol.% CR; CR pretreated with 1% NaOH for 1 h.	28-d CS increased from 39.4 MPa (control) to 46.9 MPa at 10% CR, then decreased to 38.0 MPa at 20%.	Slump remained ~250–270 mm.	F–T performance improved: 25-cycle mass loss decreased from 4.6% to 1.3% at 20% CR; XRD showed no major phase change.
Luhar et al. (2021) [52]	Class-F FA GPC; 10–30% rubber tire fibers replacing sand; 14 M NaOH; 90 °C/48 h curing.	Residual CS decreased with H_2SO_4 concentration and exposure duration.	Water penetration increased with CR; sorptivity = 0.09–0.164 mm/min$^{0.5}$.	After 365 d in 5% Na_2SO_4, no cracking/spalling occurred; chloride diffusion = 1.0–1.2 × 10^{-12} m^2/s; 30% CR carbonation depth = 8 mm at 90 d.
İpek & Mermerdaş (2022) [42]	Class-F FA mortar; 10–50 vol.% CR replacing sand; 12 M NaOH; 60 °C/24 h curing.	CS decreased from ~35.5 to 11.2 MPa and FS from 5.41 to 2.42 MPa at 50% CR.	Unit weight and UPV decreased; flowability remained approximately unchanged.	SEM revealed gaps and weak bonding at the CR–geopolymer ITZ, explaining reduced performance.
Azmi et al. (2022) [82]	Class-F FA mortar; 0–20 wt.% CR; 12 M NaOH; exposure = 200–800 °C.	At RT, CS decreased from 40.48 to 20.13 MPa at 0–20% CR; at 800 °C, residual CS was 20.16–7.71 MPa.	—	CR decomposition at high temperature increased pores and cracking, especially at high CR contents.
Valente et al. (2022) [88]	Fine rubber powder/coarse rubber granules; NaOH and SF modification investigated.	Finer and treated rubber generally provided better mechanical performance than coarse untreated rubber.	—	SEM showed better integration of fine rubber; NaOH/SF treatment improved compatibility and surface condition.
Toufigh et al. (2022) [94]	Rubberized GPC with varying rubber contents/replacement ratios.	Increasing rubber generally reduced mechanical strength.	Rubber increased voids/porosity.	SEM indicated weak rubber–matrix ITZs; XRD showed no rubber-related crystalline phases.
Yolcu et al. (2022) [95]	GPC containing 0–15 vol.% waste-rubber fibers; 12 M NaOH.	Mechanical performance decreased as WRF increased.	—	At 15% WRF, CS losses reached 60.52% and 76.71% at 500 and 750 °C; SEM

				showed pores, microcracks and weakened ITZ.
Gill & Parveen (2022) [39]	FA/OPC GPC; 0–15 vol.% CR; NaOH = 8–12 M; 60 °C/24 h curing.	CR content, binder content and NaOH molarity governed CS; increasing CR generally reduced strength.	—	Dedicated durability, elevated-temperature and rubber–matrix ITZ investigations NR.
Gill et al. (2023) [89]	FA-based rubberized GPC incorporating glass fibers.	GF partially mitigated CR-induced strength deterioration.	Acid permeability was assessed.	At 15% CR, H_2SO_4-related CS loss reached ~43%; GF addition improved acid resistance; SEM/XRD/FTIR were performed.
Iqbal et al. (2023) [63]	High-Ca FA GPC; CR = 10–30%; GNP = 0.1–0.4%.	GNP addition improved the mechanical performance of CR-GPC.	Porosity increased with CR but decreased with suitable GNP addition.	At 30% CR, 0.3% GNP increased microhardness by 34% and produced a denser CR–matrix interface.
Zhong et al. (2023) [96]	Rubberized engineered geopolymer composite with varying CR contents.	CR promoted ductility and multiple-cracking behavior.	—	At CR40, average residual crack width was 38.92 μm, ~44% below control.
Chen et al. (2023) [66]	High-performance GPC containing 0–50% rubber.	≥120 MPa CS was retained at 5% rubber and ≥55 MPa at 35%; higher rubber increased deformability.	—	SEM showed increased ITZ cracking with CR, but higher rubber contents promoted less brittle failure.
Orhan et al. (2023) [97]	Slag GPC; 0–15 vol.% CR; 12 M KOH; ambient curing.	28-d CS decreased from 38.17 to 25.95 MPa at 0–15% CR.	WA decreased from 4.57 to 4.03%; sorptivity decreased ~33% at 15% CR.	CR reduced F–T deterioration/cracking and improved sulfate response; SEM showed fewer cracks at 15% CR.
Hassan et al. (2024) [23]	FA/GGBFS; 5–25 vol.% CR; untreated/16 M NaOH-treated; 80 °C/48 h curing.	At 25% CR, CS decreased ~33%; NaOH pretreatment mitigated strength/stiffness losses.	NR.	NaOH treatment produced a rougher/cleaner CR surface and improved CR–matrix bonding.
Mabrouk et al. (2024) [41]	GGBS lightweight GPC; WTRA = 15–45 vol.% replacing pumice aggregate; 0/20% SF; curing = 80/100 °C.	CS and FS generally decreased with WTRA; response depended on SF and curing temperature.	Density decreased and WA/porosity increased; density reached 1709 kg/m^3 in one 45% WTRA mixture.	F–T, thermal and microstructure assessed; maximum TGA-DTG mass loss = 22.22%/24.53% at 400/600 °C.
Raut et al. (2024) [72]	Steel slag/GGBS; 10–30 vol.% CR; three CR sizes; 12 M NaOH.	Control CS = 58.67 MPa; 30% finest CR caused ~34.3% reduction; finer CR performed better.	Density ↓; porosity/WA ↑ with CR.	Thermal conductivity = 0.48–0.63 W/m·K; coarser/higher CR improved insulation; XRD/FTIR confirmed gel formation.
Sarkaz et al. (2024) [98]	GGBS mortar; 5–15 vol.% CR; particle sizes < 1–4 mm.	CS/FS decreased with CR; finer CR provided better mechanical performance.	Density decreased, while WA/porosity generally increased.	Higher CR generally reduced F–T, carbonation and high-temperature (300–600 °C) resistance.

Abedato et al. (2024) [99]	FA/GGBS = 60:40; 5–15% CR; PEF = 0.25–0.75%; treated CR.	CR reduced strength but improved toughness; PEF improved both strength and toughness.	Density decreased due to low-density CR.	Microstructure showed improved bonding with PEF; excessive CR adversely affected matrix integrity.
Iqbal et al. (2024) [100]	High-Ca FA; CR = 10–30%; GNP = 0.1–0.4%	Optimized 10% CR + 0.3% GNP: CS = 49.43 MPa before fire and 13.94 MPa after 30 min.	Fire increased porosity/mass loss; GNP reduced deterioration.	GNP improved fire resistance; 10% CR + 0.3% GNP was identified as the optimized combination.
Aown et al. (2025) [44]	FA/GGBFS; 25% CR; untreated or 16 M NaOH-treated; static/impact loading.	CR reduced CS; NaOH treatment improved bonding and recovered strength/peak force.	NR.	Untreated CR increased normalized dynamic energy absorption by 41–59%; treatment reduced it by 15–25% due to higher stiffness.
Çelik et al. (2025) [70]	FA lightweight GPC; pumice and WTR = 0–15%; 13 M NaOH.	CS/STS/FS generally decreased; at 10% pumice, CS fell from 33.97 to 26.36 MPa at 0–15% WTR.	Slump decreased ~5–15% with WTR.	10% WTR provided the most favorable impact response; SEM/EDX/TGA were conducted.
Shao et al. (2025) [58]	Cement-free GUHPC; CR = 10–30%; medium, coarse, and hybrid gradations; 1.5% steel fiber.	Performance depended strongly on CR grading and interface quality.	Unit weight decreased by up to ~5.9%.	SEM showed better interlocking with medium CR; coarse CR produced weak ITZs, microcracking and fiber debonding.
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Zhang et al. (2025) [69]	FA/GGBS; 0–20% NaOH-treated CR; SHPB dynamic testing.	At ~90 s^{-1}, dynamic CS increased 18.43% from 0→10% CR, then slightly decreased toward 20%.	Moderate CR improved pore structure; excessive CR increased porosity.	XRD showed no major phase change; SEM/EDX/MIP characterized CR-related microstructural changes.
Azunna et al. (2025) [71]	0, 10, and 20% CR; lateral-impact testing.	Maximum deflection increased 44.02%; energy absorption increased 42.91%/52.38% at 10/20% CR.	NR.	Peak-impact force decreased by 18.68–26.61%, confirming a more flexible impact response.
Mohabbi & Bulsu (2025) [85]	Slag/FA mortars; GWTR = 1/4, 1/3 and 1/2 by volume; selected binders with 5–10% cement.	Increasing GWTR reduced CS/FS; 5–10% cement substantially mitigated the reduction.	UPV decreased markedly at 1/2 GWTR.	SEM showed that optimized hybrid binders reduced rubber-induced porosity and produced a denser matrix.

Abbreviations: CR = crumb rubber; WTR = waste-tire rubber; WTRA = waste-tire rubber aggregate; WRF = waste-rubber fiber; GWTR = granulated waste-tire rubber; GPC = geopolymer concrete; RGC = rubberized-geopolymer concrete; RGM = rubberized-geopolymer mortar; EGC = engineered-geopolymer composite; FA = fly ash; GGBS/GGBFS = ground-granulated blast-furnace slag; SF = silica fume; CS = compressive strength; STS = splitting tensile strength; FS = flexural strength; EM = elastic modulus; WA = water absorption; IRA = initial rate of absorption; UPV = ultrasonic pulse velocity; ITZ = interfacial transition zone; GNP = graphene nanoplatelets; PEF = polyethylene fiber; UFS = ultrafine slag; SEM = scanning electron microscopy; XRD = X-ray diffraction; FTIR = Fourier-transform infrared spectroscopy; TGA/DTG = thermogravimetric/derivative thermogravimetric analysis; MIP = mercury intrusion porosimetry; SHPB = split Hopkinson pressure bar; DIF = dynamic increase factor; LCA = life-cycle assessment; RT = room temperature; NR = not reported.

Regarding the physical and durability properties, however, the reaction is more complicated. Higher rubber content may lead to more pores and weaker interfacial zones, which can cause higher water absorption or lower UPV, as shown by many researchers. Yet, it does not mean that there would be worse results under any conditions of exposure. For instance, Zhang et al. (2021) [64] demonstrated better freeze–thaw resistance of mortars due to a decrease in mass loss at 25 cycles from 4.6% for control mortar to 1.3% at 20% CR. In contrast, Saloni et al. showed that increasing the content of untreated CR increased water absorption and reduced resistance to HCl and H_2SO_4; however, NaOH pretreatment and ultrafine slag mitigated these adverse effects by reducing water absorption and improving acid resistance [43].

Elevated-temperature studies further highlight this dual role. Rubber decomposition forms more pores and thereby lowers residual strength, especially at elevated temperatures and higher CR content. As an example, Azmi et al. (2022) [82] noted that the room temperature compressive strength dropped from 40.48 to 20.13 MPa as CR varied from 0% to 20%, with respective residual strengths of 20.16 and 7.71 MPa at 800 °C. On the other hand, rubber-formed channels may assist in relieving vapor pressure, which may help lower internal stresses and prevent explosions. Therefore, thermal effects of rubber involve a compromise between weakening due to decomposition and pressure relief due to pore formation.

Microstructural evidence in Table 7 provides a consistent explanation for many of these macroscopic trends. SEM observations frequently identify gaps, pores, microcracks and weak bonding at the untreated rubber–geopolymer ITZ, which restrict effective stress transfer and contribute to strength reduction.

Nevertheless, the table reveals that the interface between rubber and the alkali-activated matrix can be engineered. The positive effects of NaOH treatment and the UFS method were demonstrated by Saloni et al. (2021) [43]. While Lazorenko et al. (2021) [65] showed an increase in compressive strength of 12.8 and 15.5 MPa, and Valente et al. showed better integration of fine rubber particles in the alkali-activated matrix. The same can be said about the particle size.

The recent developments highlighted in Table 7 reveal a trend from mere replacement of rubber to performance optimization of RGC. Steel, polyethylene and glass fibers, graphene nanoplatelets, advanced hybrid binder systems, and rubber pre-treatments are some of the materials that have been employed in the attempt to offset the weakness caused by rubber.

The research efforts are also moving towards addressing the influence of dynamic loading, high temperatures, the environment, and the structural scale, rather than compressive strength only. In general, Table 7 summarizes the design criteria of RGC by stating that the increase in the amount of rubber is accompanied by a sacrifice of mechanical strength and stiffness to achieve lower density, more deformability, energy absorption, as well as possibly enhanced thermal or durability properties in certain cases; the efficiency of these trade-offs depends on interface engineering and matrix modification. Thus, the existing literature does not provide a universal optimal CR content, and material choice should be guided by the specific combination of desired properties. It is worth noting that the research presented in Table 7 includes chemically different binder systems, such as FA-based, high-calcium FA-based, slag-based, FA/GGBS, blended precursor, and cement-containing hybrids. This means that the systems can form different reaction products, pores, and ITZ; thus, it is inappropriate to consider the outcomes of the systems equal.

4.7. Sustainability and Life-Cycle Assessment

The available environmental assessments of RGC consistently demonstrate the potential of waste-rubber incorporation to reduce environmental burdens, although the

magnitude of the benefit depends strongly on mixture composition, rubber content, and the adopted assessment methodology. Sarkaz et al. (2024) [98] studied GGBS-based geopolymers with 5–15 vol.% CR as fine-aggregate replacement and found that CR inclusion led to a small increase in production cost of 3.99–11.97% and embodied energy of 0.08–0.24%, while resulting in a significant decrease in embodied CO_2. However, the embodied CO_2 showed a reduction in the values from 324.4 to 90.4, −143.6, and −377.6 kg CO_2-eq/m^3 for 5%, 10%, and 15% CR, respectively. The negative values at 10% and 15% CR were caused by the negative value of the embodied CO_2 of the recycled CR applied by the authors in the ecological assessment, and the negative values must be understood according to the assumptions made in the study. It should also be mentioned that the analysis did not account for the transport of raw materials and raw material manufacturing, such as NaOH and Na_2SiO_3, as well as the production of geopolymers. Thus, these data cannot be considered life-cycle carbon-footprint figures or compared with other results calculated with different system boundaries and assumptions. Increased CR content also negatively impacted the mechanical and durability properties of the mixture, and CR contents of 5–10 vol.% were considered adequate for the strength class under investigation.

However, higher CR contents adversely affected mechanical and durability properties, with 5–10 vol.% CR identified as providing satisfactory performance for the medium-strength applications considered.

Zhang et al. (2025) [69] extended the sustainability assessment to rubberized FA/GGBS geopolymer concrete by integrating life-cycle assessment with dynamic mechanical performance and production cost. Their analysis considered global-warming potential, energy consumption, and cost and showed that geopolymer-based rubberized concrete had lower construction-related environmental impacts than the corresponding OPC system. Considering dynamic performance, environmental impact, and production cost together, the mixture containing 10% CR provided the most favorable overall performance among the investigated RGC mixtures.

Chen et al. (2023) [66] similarly emphasized that environmental assessment should be linked to engineering performance. For rubber-modified high-performance geopolymer concrete (R-HPGC), they introduced CO_2-emission and comprehensive-cost indices normalized by compressive strength. Although recycled steel fiber and CR reduced carbon emissions and cost, increasing rubber content also reduced mechanical performance; consequently, a rubber replacement level of ≤5% was recommended for balancing compressive, environmental, and economic performance.

More recent studies have examined substantially higher rubber contents. Wan et al. [67] conducted a cradle-to-gate LCA of engineered geopolymer composites containing 0–100% replacement of fine silica sand with recycled waste rubber. With an increase in rubber replacement ratio, the carbon embodied decreases from 253.69 to 221.16 kg CO_2-eq/m^3 (12.82%), the energy embodied decreases from 3524.41 to 3012.15 MJ/m^3 (14.53%), and the material cost decreases from 3084.99 to 2950.61 CNY/m^3 (4.36%). This was done in consideration of raw-material extraction, transportation, and specimen preparation but without consideration of the use phase and end-of-life. It is therefore necessary to understand the results within the cradle-to-gate system used in the assessment rather than the life-cycle environmental impact.

Shao et al. further demonstrated the environmental potential of CR in cement-free geopolymer UHPC. A substitution of 10–30% of sand with CR resulted in reducing CO_2 embodied in concrete by 26–79% and the cost of materials used in construction by around 10%. In the case of substitution with 30% CR, CO_2 was reduced from 443 to 94 kg/m^3, while compressive strength decreased from 164 to 114 MPa. On the basis of evaluation of all three properties—fresh, mechanical, and sustainable characteristics—the most favorable proportion found by the authors was 20% hybrid rubber [58].

Collectively, these RGC-specific studies indicate that increasing waste-rubber utilization can reduce embodied carbon and, in several formulations, material cost and embodied energy within the system boundaries considered; however, these reported benefits are largely based on material-production or cradle-to-gate assessments and therefore do not represent complete life-cycle environmental performance. However, the environmental benefit is accompanied by mixture-dependent reductions in strength and other engineering properties. Thus, the sustainability of the RGC cannot be assessed only based on the rubber replacement or the embodied CO_2. A better way to evaluate its sustainability is to consider the carbon footprint, embodied energy, cost, performance, and durability of the RGC system. The currently limited number of RGC-specific LCA studies also indicates a need for full life-cycle assessments incorporating transportation, service life, maintenance, and end-of-life scenarios, rather than relying predominantly on material-production or cradle-to-gate assessments.

However, direct comparison of the outcomes of life cycle assessment of RGC studies is not possible since the outcomes of the impact analysis depend greatly on the chosen functional unit and the system boundaries, as well as assumptions about allocation or avoided burdens related to waste rubber. The other significant factors include transportation distances, production of the alkaline activator, the curing energy, and whether the use phase and end-of-life phases are considered. This means that the embodied carbon or energy of RGC calculated under various approaches cannot be compared without taking into account these differences. Future LCAs of RGC should clearly indicate the functional unit, the system boundaries, allocation approach, transportation assumptions, curing needs, activator production, and the end-of-life phases.

In other words, although including waste rubber in RGC offers an avenue for waste diversion and material recovery, it should not be assumed to provide a proven environmental advantage across the entire life cycle.

5. RQ3—Research Gaps and Future Priorities for Practical and Sustainable RGC

5.1. Practical Applicability of RGC

The applicability of RGC is dependent on the trade-off between environmental and engineering considerations. Valorization of waste tires and industrial products by means of RGC helps to promote environmentally efficient constructions [23]. In addition, using recycled materials may help reduce the environmental impact of conventional building materials [56]. As far as engineering concerns are concerned, it is possible to find a trade-off between stiffness and deformation with moderate amounts of rubber [64]. Better impact resistance and higher energy dissipation ability of such materials may be helpful for applications subjected to dynamic loads [68]. But high amounts of rubber generally lead to significant stiffness reduction [38].

Durability is highly dependent on rubber content, particle size, surface characteristics, and exposure conditions. Proper rubber pretreatment may enhance the interface between rubber and the geopolymer matrix and partially mitigate the associated strength degradation [65]. Pretreatment may also reduce permeability and improve resistance to aggressive environments [43]. Furthermore, rubber incorporation has been investigated to develop lightweight rubberized geopolymer concrete in [93]. All of these factors have made RGC applicable in light construction and prefabricated elements [55] as well as in building blocks and applications where better thermal insulation properties are needed [58].

Deng et al. (2023) [78] proposed several potential non-structural applications for RCR–RGC geopolymer mortar, which include flat roof slopes, sole plates, and slab

packings. The non-structural use of the material is based on its light weight, flexibility, resistance to cracking, and transportation-resistant properties.

Figure 19 illustrates some of the wider implications of RGC, in the sense that its advantages in terms of the environment are tied to the structural performance, durability, design, and applicability of RGC. RGC can serve the purpose of waste-tire valorization and reduce dependence on traditional cement-based materials. It has better deformability, energy dissipation, and thermodynamic and acoustic properties. However, its implementation needs optimization of the amount of rubber, surface modification, precursor mixture, and curing process to avoid any strength reduction and increased porosity.

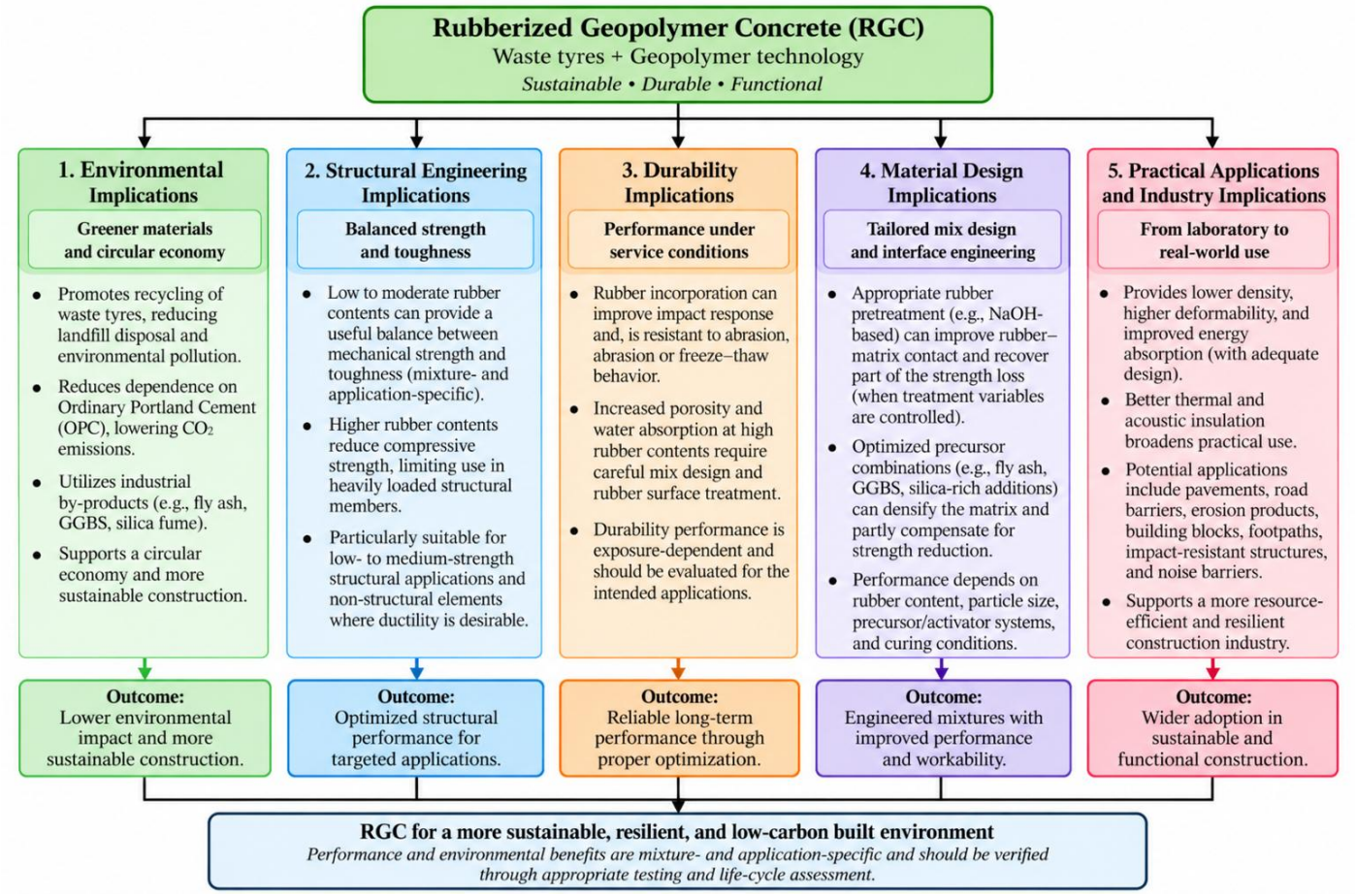


Figure 19. Key environmental, structural, durability, material-design, and practical implications of rubberized geopolymer concrete (RGC) for sustainable construction.

5.2. Research Gaps

Despite the development of extensive research in RGC, there still exist many gaps that should be addressed before further implementation of this concept. Present research works differ in their rubber base, particle size, precursors used, activation system used, curing, and testing methods used; thus, it is hard to find a universal optimal content of rubber. Data on creep, shrinkage, fatigue, chloride penetration, carbonation, freeze–thaw resistance, fire resistance, and reinforcing-steel corrosion remain limited. Although Xiao et al. (2026) [101] recently investigated the bond failure of corroded reinforcing bars embedded in RGC, the available evidence remains insufficient to establish the long-term corrosion and bond durability of reinforced RGC systems.

Apart from traditional construction uses, the diverse nature of the properties of RGC can be exploited in some unique areas, including support and backfilling of deep mines and geothermal systems. This material has low thermal conductivity, high deformability,

and energy-absorption properties. In light of emerging trends in geothermal power generation in mines [102], further research should explore the suitability of RGC for support and backfilling under the combined influence of thermal and mechanical loading.

5.3. Future Research Directions

Future research efforts should focus on developing standard procedures for RGC mixture design, rubber characterization, cure conditions, and testing so as to increase the comparability of RGC research findings. The research should be extended from material properties to full-scale structural testing and field exposure under realistic loading conditions. Attention must be paid to the issues of interface engineering, improved hybrid precursor system design, fibers, and other improvements while retaining the beneficial characteristic of rubber deformability. Finally, LCA, techno-economic analysis, and multi-objective optimization can be applied to find application-specific RGC mixtures balancing different objectives, as outlined in this review.

6. Conclusions

Rubberized geopolymer concrete (RGC) is one potential strategy to merge tire-waste recycling with geopolymer-based binders, which may provide some environmental benefit if suitable mixture design and manufacturing conditions are met. As the reviewed literature indicates, increasing the content of crumb rubber results in decreasing the density, compressive strength, stiffness, and workability due to the reduced rigidity of the rubber, increased porosity, and poor interaction between rubber and geopolymer phases. Nevertheless, rubberizing could lead to improved deformability, toughness, impact resistance, energy absorption, vibration damping, and thermal-acoustic properties.

The performance of RGC is highly mixture-dependent and depends on rubber content and particle size, precursor composition, activator composition, curing process, and especially the quality of the interfacial transition zone. Pretreatment of the surface, densification of the matrix, optimized particle gradation, and proper precursor and activator combinations may partially offset the reduction in strength and durability caused by the rubber. Hence, no optimum rubber content can be determined independently of its use.

Nevertheless, the quality of the evidence for the various reported performance trends of RGC is uneven. In terms of the effects on density, compressive strength, stiffness, and workability of an increase in the amount of untreated rubber, a relatively consistent trend emerges from the analyzed literature, although the extent to which the parameters change will vary significantly according to the mixture proportions used, the type of rubber, the nature of the precursor and activator systems, the curing process, and the method used for testing. There are many references in the literature to improvements in the deformability, energy absorption, and certain other thermal and acoustic properties; yet, evidence about the long-term durability and structural-level performance, as well as life-cycle environmental advantages of RGC, is far less plentiful and is dependent on the conditions considered in specific studies.

Notably, from a sustainability standpoint, RGC could decrease the consumption of natural resources, utilize waste tires and industrial by-products, and minimize environmental impacts in suitably designed systems. However, environmental impacts need to be considered alongside mechanical properties, durability, cost, and lifespan rather than merely based on rubber use and carbon footprint. Further research needs to focus on the standardization of mix design and testing procedures, durability, large-scale structural and field tests, life cycle, and techno-economic assessment. On the whole, multi-criteria optimization that will consider strength, deformability, durability, environmental impact, cost, and constructability is necessary for the successful implementation of RGC in sustainable building. Therefore, the main observations can be summarized as:

- RQ1: RGC performance is mainly governed by rubber content and characteristics, precursor and activator composition, surface treatment, and curing conditions; therefore, no universal optimum rubber content can be defined.
- RQ2: Rubber generally reduces strength and stiffness but can improve deformability, toughness, energy absorption, and impact resistance. Interface treatment and matrix optimization can partially mitigate these adverse effects.
- RQ3: Major research needs include standardized mix-design and testing procedures, long-term durability assessment, structural- and field-scale validation, and consistent life-cycle and techno-economic evaluation.

Future research should concentrate on developing RGC from laboratory to application in structures through standardizing the mixture design and testing procedures, optimizing rubber content and surface treatment, and evaluating the long-term effects of durability, creep, fatigue, and dynamic response. Structural tests are also needed to determine the design parameters of RGC, which could be used to test the material's performance in more realistic environments. In addition to that, comprehensive life-cycle and techno-economic assessment is necessary to measure if the positive environmental effects of utilizing rubber wastes and geopolymer binders could be realized without any financial and performance losses.

Further, the combination of thermal insulation, deformability, and energy-absorbing characteristics can be expected to give RGC possibilities in addition to those in conventional construction, such as backfilling in deep mining and geothermal energy exploitation. Additional experiments should be performed in the future to confirm the performance of the material under realistic conditions.

The review also has some limitations. While the literature searching and data extraction methods were structured, the current study is carried out as a critical review and not a PRISMA systematic review, lacking retrospective numerical screening results. Additionally, direct quantitative analysis between the studies is restricted due to variations in the rubber replacement (in terms of mass or volume, fine or total aggregates), the precursor and activator system, curing process, specimen features, testing age, and method. As such, the rubber content was kept based on the original studies' reports since conversion to a quantifiable form was not possible for some studies.

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Abbreviations

The following abbreviations are used in this manuscript:

AAM	Alkali-Activated Material
BSE	Backscattered Electron Imaging
CR	Crumb Rubber
CRG	Crumb-Rubber Geopolymer
CR-GPC	Crumb-Rubber Geopolymer Concrete
CRGM	Crumb-Rubber Geopolymer Mortar
CRWA	Crumb-Rubber Waste Aggregate
CS	Compressive Strength
CWA	Coefficient of Water Absorption
DIF	Dynamic Increase Factor
DTA	Differential Thermal Analysis
DTG	Derivative Thermogravimetry
EDS	Energy-Dispersive X-ray Spectroscopy
EDX	Energy-Dispersive X-ray Spectroscopy
EGC	Engineered Geopolymer Composite
EM	Elastic Modulus
FA	Fly Ash
FS	Flexural Strength
FTIR	Fourier-Transform Infrared Spectroscopy
F–T	Freeze–Thaw
GDR-GPC	GGBS–Dolomite-Rich Geopolymer Concrete
GF	Glass Fiber
GGBFS	Ground-Granulated Blast-Furnace Slag
GGBS	Ground-Granulated Blast-Furnace Slag
GNP	Graphene Nanoplatelets
GPC	Geopolymer Concrete
GWTR	Granulated-Waste Tire Rubber
IRA	Initial Rate of Absorption
ITZ	Interfacial Transition Zone
LCA	Life-Cycle Assessment
MIP	Mercury Intrusion Porosimetry
MOR	Modulus of Rupture
NR	Not Reported
NRL	Natural Rubber Latex
OPC	Ordinary Portland Cement
PEF	Polyethylene Fiber
PPF	Polypropylene Fiber
RCR	Recycled Crumb Rubber
RGC	Rubberized Geopolymer Concrete
RGM	Rubberized Geopolymer Mortar
RQ	Research Question
RSM	Response Surface Methodology
RSF	Recycled Steel Fiber
RT	Room Temperature
SEM	Scanning Electron Microscopy
SF	Silica Fume
SHPB	Split Hopkinson Pressure Bar
STS	Splitting Tensile Strength
TG	Thermogravimetry
TGA	Thermogravimetric Analysis
TGA-DTG	Thermogravimetric Analysis–Derivative Thermogravimetry
UFS	Ultrafine Slag
UHPC	Ultra-High-Performance Concrete
UPV	Ultrasonic Pulse Velocity
VWA	Velocity of Water Absorption

https://doi.org/10.3390/su182010699

W/C	Water-to-Cement Ratio
WA	Water Absorption
WRF	Waste-Rubber Fiber
WTR	Waste-Tire Rubber
WTRA	Waste-Tire-Rubber Aggregate
X-CT	X-ray Computed Tomography
XRD	X-ray Diffraction

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