Review Article

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Recent trends in rubberized and non-rubberized ultra-high performance geopolymer concrete for sustainable construction: A review

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Abstract: The construction sector faces significant sustainability and environmental challenges due to the extensive use of conventional concrete. In this regard, ultra-high-performance geopolymer concrete (UHPGC) offers a promising alternative, featuring both rubberized and non-rubberized formulations with unique benefits. Rubberized UHPGC enhances ductility and resilience by incorporating recycled materials, while non-rubberized variants provide superior strength and durability. A comprehensive review is essential to enhance the understanding of UHPGC, evaluate its role in sustainable development, and guide future research and policy in the construction industry. This review article provides an innovative analysis of UHPGC, emphasizing its novel integration of geopolymer binders and the incorporation of recycled rubber particles to enhance mechanical and environmental performance. It examines the evolution, properties, and applications of both materials, highlighting their rapid setting times, improved workability, and reduced shrinkage. Moreover, it underscores their superior compressive, tensile, and flexural strengths, as well as enhanced energy absorption, ductility, fracture energy, and crack resistance, making them suitable for high-stress environments. This review suggests that using crumb rubber as a fine aggregate replacement in geopolymer concrete generally reduces compressive strength at higher levels. However, small additions, around 2%, may improve strength, highlighting the need for careful optimization to balance the performance and strength. The addition of steel and polypropylene fibers to UHPGC enhances flexural toughness and fracture energy. The integration of rubber particles into ultra-high-performance rubberized geopolymer concrete (UHPRGC) significantly enhances its ductility, toughness, and energy absorption, allowing the material to withstand higher strains and preventing brittle failure, making it ideal for high-performance applications. However, the inclusion of rubber compromises compressive strength because of inadequate interfacial adhesion, enhancements in surface treatment and the optimization of composite formulations can effectively overcome these challenges, and merging customized rubber proportions with advanced polymeric or fiber reinforcements maintains mechanical integrity while capitalizing on rubber's elasticity, suggesting the necessity for ongoing investigation into microstructural optimization and long-term performance to thoroughly harness the sustainability and functionality of UHPRGC.

Keywords: geopolymer concrete, rubber particles, strength, microstructure, fracture, sustainability

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1 Introduction

Ultra-high performance concrete (UHPC) has gained significant attention in the field of concrete research due to its remarkable strength, durability, and toughness characteristics [1]. Nevertheless, the conventional construction method for UHPC frequently depends on large quantities of cement and usually integrates steel fibers – regardless of the increasing availability of substitute reinforcement materials, all of which might exacerbate both environmental and economic worries [2]. Producing cement is particularly carbon-intensive, with each ton resulting in approximately 0.87 tons of CO_2 emissions [3]. Also, the high cost of steel fibers significantly raises the overall expenses involved in producing UHPC [2,4]. The factors, such as high costs and carbon emissions, are restricting the broader adoption and development of UHPC [5] (Figure 1). To mitigate these issues, integrating recycled materials has shown great promise in reducing both the environmental impact and production costs of concrete. An example of such materials comes from the recycling of waste tires, which are growing in volume annually, projected to hit 5 billion units by 2030 [6]. The accumulation of waste tires not only consumes valuable land but also poses significant fire hazards, contributing to environmental pollution and health risks due to the potential release of toxic substances during combustion [7]. Moreover, incinerating these tires generates substantial CO_2 emissions and other harmful gases, exacerbating environmental pollution [8]. Fortunately, waste tires can be processed into rubber particles or powder and recycled steel fibers, providing alternative raw materials for concrete production [9]. This innovation is particularly useful, as conventional concrete is known for its inherent brittleness [10]. The use of rubber in concrete could enhance its toughness [11], yet this modification can lead to a reduction in both the flowability and the elastic modulus of the concrete [12]. The compressive strength of concrete modified with rubber is influenced by the rubber content and the particle size [13]. Finer rubber particles tend to create fewer voids and minimize the volume of weak points at the rubber–matrix interfaces compared to coarser rubber particles [14]. Moreover, the impact of rubber on compressive strength is less detrimental when using rubber powder instead of crumb rubber (CR) [15]. Optimal results in concrete strength can be achieved by carefully selecting the appropriate rubber content and particle size [16].

The influence of rubber on concrete's compressive strength also depends on the inherent strength of the concrete [17]. Research indicates that small-sized rubber particles (0.15–1.9 mm) used in amounts up to 20% replacement have negligible effects on the compressive strength of normal concrete (NC), whereas they significantly reduce the strength of UHPC [18]. A greater decline in compressive strength is observed in UHPC than in NC when coarse rubber particles replace coarse aggregates [19]. Nonetheless, the synergistic reaction of silica fume (SF) with volcanic ash and the dense accumulation of particles in UHPC enhance the rubber–matrix interaction, thereby mitigating the strength loss associated with rubber incorporation in these types of concrete [17]. Currently, one of the most effective strategies to lower carbon emissions from concrete production involves substituting cement with new low-carbon gels [20]. Geopolymers, a type of innovative low-carbon gel rich in Si–Al minerals, are created when these precursors undergo hydration and polymerization through alkaline activators, forming a 3D network of Si, Al, and O [21]. This substitution can potentially cut the

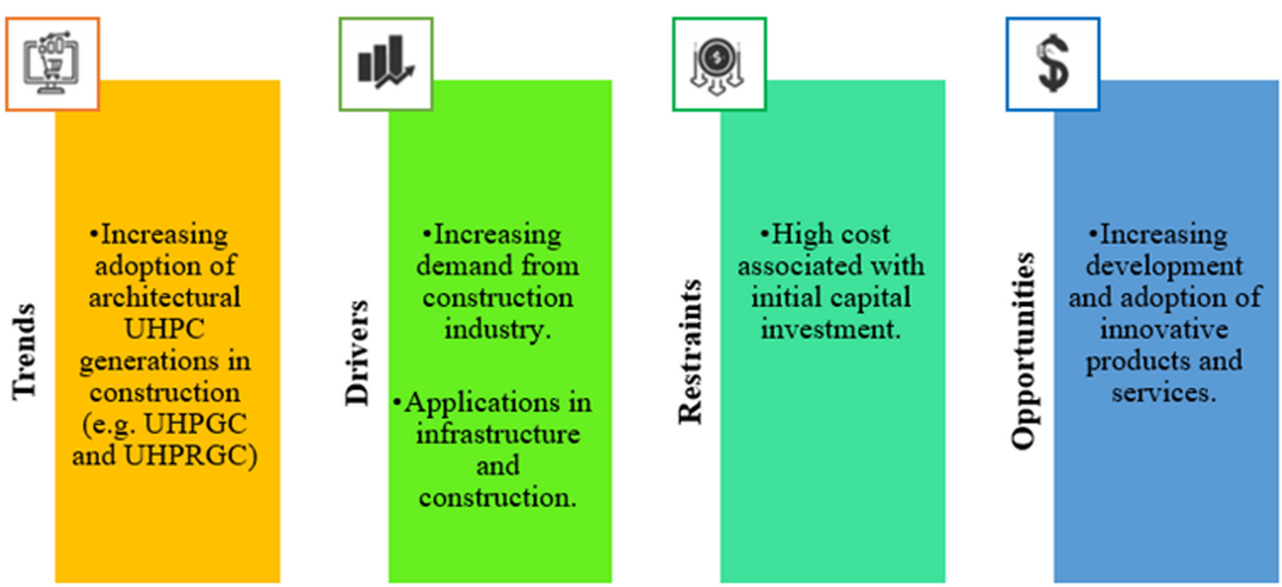

Figure 1: Global UHPC market, including upcoming generations such as UHPGC and UHPRGC.

concrete's carbon footprint by up to 80% [22]. There is optimism that innovative GPCs could serve as a viable solution, significantly reducing greenhouse gas emissions compared to ordinary concrete [23] due to cement reduction (Figure 2) [24].

Studies have shown that the addition of calcium in fly ash (FA) affects the ultimate properties and compressive strength of alkali-activated materials [25–28]. In particular, calcium oxide (CaO) can facilitate the formation of calcium–silicate–hydrate alongside Na–Al–silicate (N–A–S–H) gels, impacting the properties of hybrid OPC and alkali-activated Al–Si compounds [29]. These two gels can coexist and enhance the material properties significantly [30]. Previous research also indicates that high pH environments can influence the formation of these gels, with aqueous aluminate notably affecting C–S–H gel production, while aqueous calcium modifies N–A–S–H gels by substituting some sodium (Na) with calcium to form (N,C)–A–S–H gels [31,32]. The design of geopolymers occurs at low temperatures under alkaline conditions, akin to the natural geosynthesis of rocks, where aluminum and silicate-rich precursors react exothermically with alkali activators [33,34]. This method is considered eco-friendly and is gaining interest among modern researchers [26]. Previously, CR has been used as a partial substitute for fine aggregates in GPCs, producing materials such as rubberized ultra-high performance geopolymer concrete (UHPGC) interlocking bricks [28,35].

GPC demonstrates excellent mechanical attributes, enduring qualities, and superior performance at elevated temperatures [36]. A new variant, termed UHPGC, has been developed. This material, particularly when enhanced with steel fibers, exhibits compressive strengths exceeding 120 MPa under standard curing conditions and 175 MPa with the fibers incorporated [37]. Efforts have been made to combine steel fibers with geopolymer binders to further enhance UHPGC, resulting in a material with performance levels akin to UHPC [38]. Moreover, the inclusion of metakaolin (MK) and SF in slag-based GPC has shown potential to elevate its compressive strength to 180 MPa by improving the pore structure [38].

Another innovative formulation, ultra-high performance rubberized geopolymer concrete (UHPRGC), integrates technologies from both UHPC [39,40] and GPC [22,41] with the addition of rubber particles, offering unique properties ideal for constructing robust and durable structures [42]. UHPRGC is an advanced composite material designed to combine the exceptional properties of UHPC with the sustainability and environmental benefits of geopolymers and recycled rubber aggregates [43]. UHPRGC typically utilizes industrial by-products like slag or FA as the primary binder to reduce the use of cement (Figure 3) [44], activated by alkaline solutions, to form a geopolymeric matrix [45]. This matrix exhibits superior mechanical properties and durability performance compared to conventional cement-based concretes [46]. The inclusion of rubber particles, derived from recycled tires, not only enhances the material's flexibility and impact resistance but also addresses waste management issues by diverting rubber waste from landfills [15]. UHPRGC is increasingly studied for its potential to reduce the carbon footprint of construction materials, offering a more sustainable alternative for modern infrastructure projects.

UHPRGC combines the environmental benefits attributed to geopolymers with the improved mechanical characteristics of UHPC, thereby establishing its role as a material of significant potential for forthcoming building

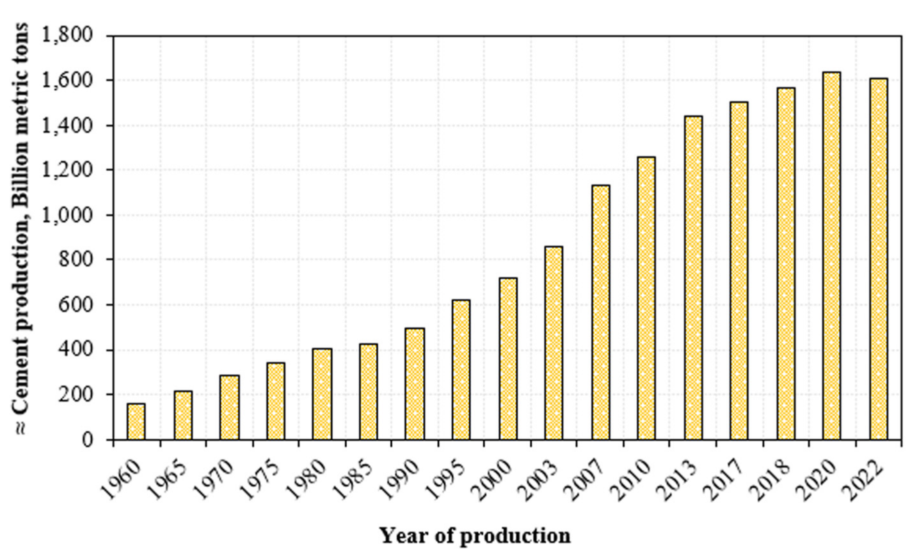

Figure 2: Global carbon dioxide emissions linked to cement production from 1960 to 2022, revealing a consistent upward trend and emphasizing the critical importance of integrating alternative low-carbon materials in the construction industry (Data from [24]).

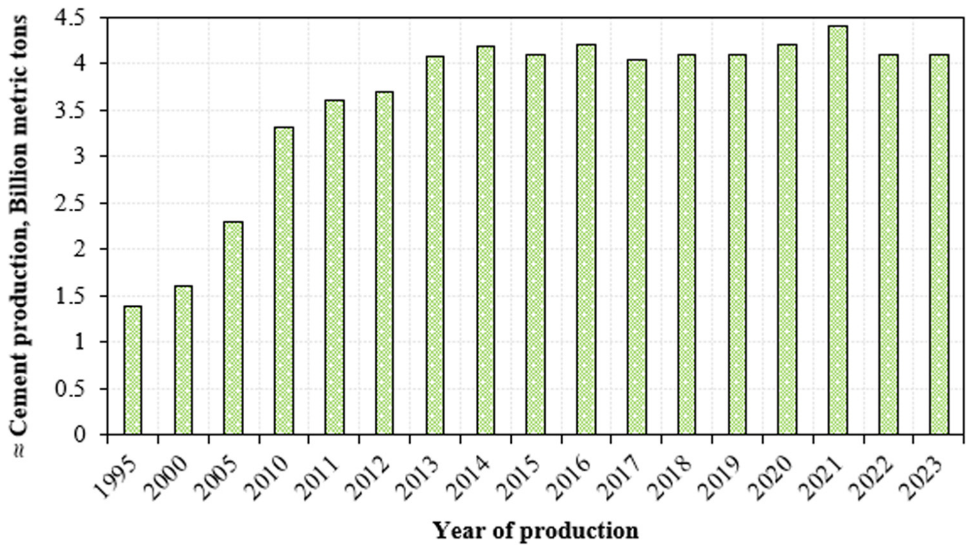

Figure 3: Schematic of ultra-high performance rubberized geopolymer concrete (UHPRGC) mix design, illustrating the use of industrial by-products (e.g., slag, fly ash) as the primary binder to reduce cement consumption (Adapted from [44]).

projects. However, it is important to note that geopolymers come with several challenges, including notable brittleness [43], susceptibility to cracking [45], and significant shrinkage [47,48]. UHPC, on the other hand, finds applications in the creation of long-span bridges, structures resistant to explosions, and constructions in highly corrosive settings [49]. Issues such as mortar porosity, discrepancies in the elasticity of aggregates and the matrix, along a fragile interface between aggregates and mortar, contribute to the emergence and widening of microcracks in UHPRGC structures [50]. Micro-cracks in concrete significantly influence its mechanical properties under stress, particularly affecting its fracture mechanics, which views concrete as a quasi-brittle material [39]. Utilizing fracture mechanics can therefore be a strategic approach to structural design [51]. It has been observed that increasing the volume fraction of fibers within the UHPRGC extends the effective fracture process zone and characteristic length, thereby enhancing the material's ductility. High-strength geopolymer binders, although noted for their brittleness leading to brittle failure, have shown improvement in the mechanical integrity of UHPRGC when reinforced with steel fibers [51,52]. The performance of steel fibers in enhancing the concrete depends on various factors, including their dosage, size, shape, distribution, and casting direction [46]. Studies on UHPRGC have indicated that its compressive, flexural, and tensile strengths improve with increased steel fiber content and length [53]. Moreover, the shape of steel fibers significantly influences the bond properties and pullout behavior in UHPGC/UHPRGC, with deformed fibers noted to enhance pullout strength, especially the geometric configuration of steel fibers exerts a significant impact on both the resistance to pullout and the capacity for crack bridging; fibers that are hooked-end or crimped generally exhibit superior performance compared to their straight counterparts, effectively retarding crack propagation and enhancing post-cracking strength. Consequently, the morphology of fibers emerges as an essential factor in optimizing flexural toughness and the overall mechanical performance of the composite material [54,55].

Furthermore, research has found that steel fibers enhance the compressive strength of slag-based UHPRGC mortars and that the length of the fibers affects flexural performance more significantly than the dosage [54,56]. However, it is also noted that while steel fibers can enhance post-hardening behavior, they may reduce compressive strength due to decreased workability of the geopolymer mix [57]. Comparatively, there is extensive research on the impact of steel fibers on UHPRGC's mechanical properties, but investigations into their effect on UHPGC are still limited [46,53]. Recognizing the high cost of steel fibers in UHPRGC, it becomes imperative to understand the similarities and differences in their roles between UHPC and UHPGC to optimize use and cost-effectiveness [53]. With significant strides in improving the mechanical characteristics of GPC with CRs, there are still few studies focusing on the development of UHPRGC, which is essential to meet modern construction demands for high-performance, cost-effective, and eco-friendly materials [38,46,53,58]. Figure 4 shows the global market for UHPC between 2022 and 2029 [59].

However, this review presents a pioneering exploration of both UHPRGC and UHPGC, emphasizing their novel integration of geopolymer binders and, in the case of UHPRGC, recycled rubber particles to enhance both mechanical and environmental performance. Unlike conventional studies, it offers a comprehensive analysis of the evolution, properties, and applications of UHPRGC and UHPGC, highlighting rapid setting times, improved workability, and reduced shrinkage. This study underscores the superior compressive, tensile, and flexural strengths of both UHPRGC and UHPGC, alongside their enhanced energy absorption, ductility, fracture energy, and crack resistance, making it ideal for high-stress environments. UHPGC, without the addition of rubber, still demonstrates exceptional compressive strength and durability resistance, making it suitable for a wide range of applications. By focusing on the sustainability aspects, such as waste material utilization and carbon emission reduction, this review aligns with global sustainability goals, positioning both UHPRGC and UHPGC as transformative materials in eco-efficient construction. This review differentiates itself by focusing on the synergistic interplay between fibrous reinforcements and elastomeric aggregates in UHPGC, particularly under heightened stress conditions. While antecedent investigations address rubberized or fiber-reinforced geopolymer systems, this study singularly explores fiber–rubber interactions and sophisticated mix designs that can mitigate conventional durability–ductility trade-offs, thereby enhancing the applicability of these materials in exigent structural settings.

2 Historical background

2.1 NC and ultra-high-strength concrete

Around 1300 BC, the discovery of concrete was made when builders in the Middle East realized that by applying a moist layer of burned limestone to the exteriors of their clay-based structures, a chemical reaction occurred with the air, creating a strong, protective coating. Concrete's development continued through the ages, notably with the advent of Portland cement by Joseph Aspdin in 1824, a key milestone in modern concrete production [60] (Figure 5). The term "concrete" today describes a composite material consisting of a calculated mixture of cement, water, sand, gravel, and various minerals [5,40,61]. In 1849, the innovation of reinforced concrete (RC) was pioneered by Joseph Monier [62] (Figure 5), a French gardener who incorporated steel wire mesh into mortar to craft more durable flowerpots, laying the groundwork for RC structures [63]. The incorporation of steel not only significantly improves the structural strength but also the flexibility of concrete [64–66]. Concrete's major limitations are its low tensile strength and rigidity. High-performance concrete (HPC) came into existence in the 1930s, engineered to enhance both the strength and durability of standard concrete under load [67]. Eugene Freyssinet revealed that enhancing the density of the cementitious matrix could bolster the compressive strength of concrete elements [68]. Interest in HPC spiked during the 1970s [61], with its development centered on reducing the water-to-cement (w/c) ratio to between 0.2 and 0.3 [69]. Throughout the 1980s, research efforts intensified to refine this innovative concrete, exploring the effectiveness of various additives for the first time [70,71]. The integration of steel fibers led to the development of various specialized concretes, such as macro-defect-free concrete, reactive powder concrete, dense silica particle concrete, and clay-modified concrete [72–76].

As the building industry's requirements intensified, the limitations of traditional concrete became more evident. Issues such as matrix instability, disproportionate compressive-to-tensile strength ratios, excessive weight relative to strength, and reduced durability were identified [61]. In

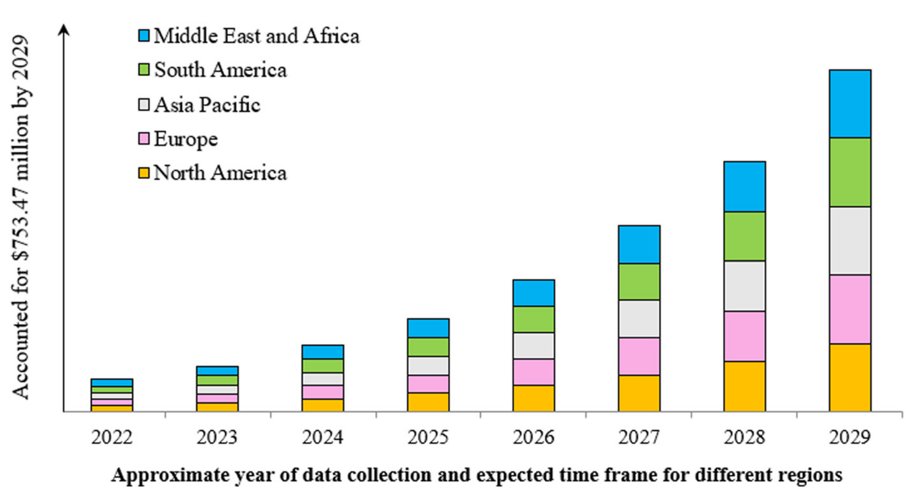

Figure 4: Global market for UHPC - Industry forecast and trends to 2029 (Raw data obtained from [59]).

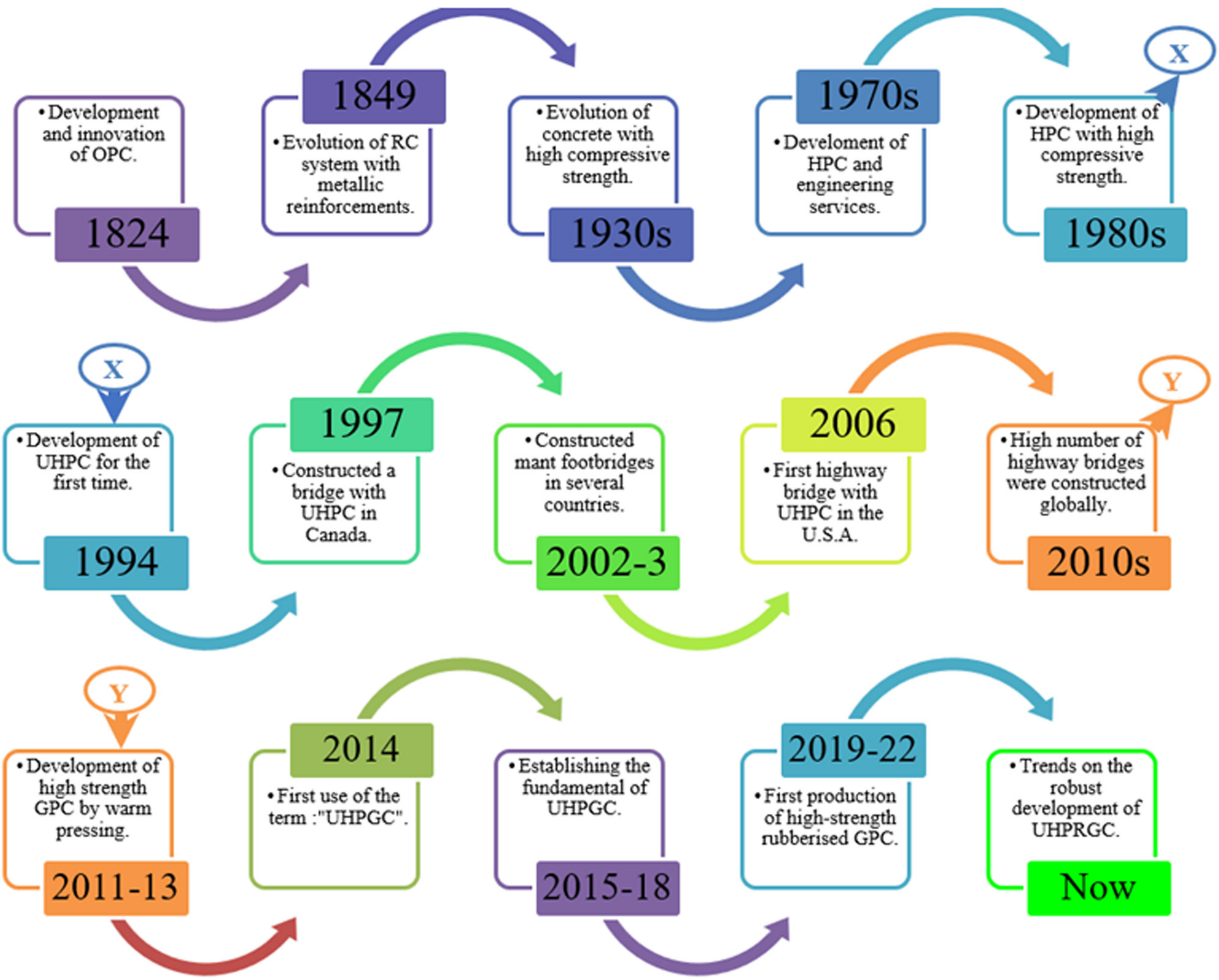

Figure 5: Historical development trends of NC, UHPC, UHPGC and UHPRGC.

response, the 1970s saw the development of HPC, characterized by low water-to-cement (w/c) ratios, meticulously selected and graded aggregates, and the integration of water-reducing admixtures, achieving compressive strengths between 50 and 120 MPa and enhanced durability [61,77,78]. However, HPC was prone to brittleness, leading to the invention of fiber-reinforced concrete (FRC) in the early 1980s. FRC, by incorporating fibers into the concrete mix, significantly improved its tensile strength, toughness, ductility, and fracture resistance [71]. UHPC represents further evolution, offering unprecedented strength, durability, and toughness [1]. The dominant formulation of UHPC utilizes Portland cement and quartz sand [79]. Yet, the extensive use of Portland cement raises concerns about resource depletion and environmental impact [80]. This has spurred interest in developing a sustainable UHPC (Figure 5), which is low in resource use and environmental impact [81]. Recent advancements have included using slag and SF as precursors and micro silica sand as the fine aggregate in the production of UHPC [82]. Research shows that SF enhances the reactivity of slag, leading to improved compressive strength.

Particularly, a strain-hardening UHPC was developed, achieving a compressive strength of 222 MPa by optimizing the FA to slag ratio and adjusting the steel fiber content [83]. Current research on fiber-reinforced UHPC primarily focuses on cementitious elements and less on fine aggregates. Some studies have considered the potential of demolition wastes as recycled aggregates in cementitious materials [84], although their application in UHPC and their freeze–thaw resistance remain underexplored. Alternatively, waste glass has been used as a fine aggregate replacement in UHPC, with studies examining its resistance to acidic and sulfate environments. It was found that UHPC with waste glass aggregate displayed less degradation after exposure to sulfuric and magnesium sulfate solutions, attributed to an improved bonding at the aggregate–paste interface [85]. In general, this research underscores the promising advancements in UHPC technology, particularly the development of strain-hardening composites with optimized FA-to-slag ratios and the innovative use of recycled materials like waste glass, highlighting their potential to enhance environmental sustainability and durability in aggressive environments. Figure 6 illustrates a comparative technical review of NC, UHPC, UHPGC, and UHPRGC, detailing trends in their compressive strengths and other critical characteristics (*e.g.*, ductility, durability, and environmental consequences). The figure demonstrates that UHPGC typically exceeds UHPRGC in compressive strength, predominantly due to the incorporation of rubber particles, which engenders relatively frail interfacial zones within the concrete matrix. These zones may function as stress concentrators under load, resulting in microcracking and reduced load-carrying capability. Conversely, UHPGC – devoid of rubber aggregates – preserves a more uniformly resilient matrix and can attain superior strengths. Nevertheless, the figure concurrently suggests that, notwithstanding this compressive strength reduction, including rubber aggregates confers several benefits, encompassing augmented ductility, enhanced energy absorption, and improved impact resistance. Methodologies such as rubber surface modifications, the utilization of smaller rubber particle dimensions, or the integration of fibers can facilitate the narrowing of strength disparity by ameliorating the bonding interface between rubber and binder, corresponding with the ascending trends depicted in the figure for optimized UHPRGC. Accordingly, Figure 6 highlights the performance trade-offs: UHPGC can attain remarkable compressive strengths, while UHPRGC capitalizes on rubber's elasticity and resilience for applications necessitating higher toughness and sustainability – both of which are imperative considerations when reconciling material performance with environmental and structural exigencies.

2.2 Rubberized geopolymer concrete (RGPC)

The development of rubberized concrete (RuC) was primarily aimed at addressing the accumulation of waste tires

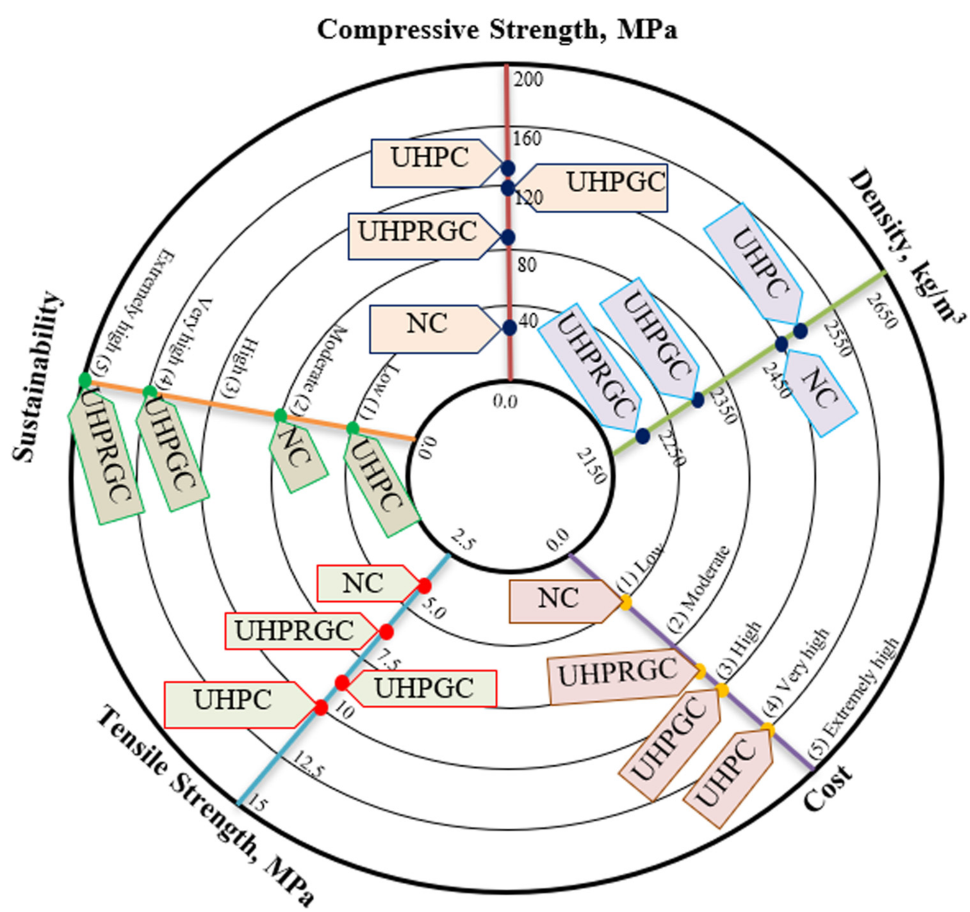

Figure 6: Technical comparison between NC, UHPC, UHPGC, and UHPRCG based on reported average values.

in landfills annually [86] (Figure 5). During tire recycling, materials such as steel fiber and rubber are extracted [87]. This rubber is transformed into crumb or chip form and is incorporated into various applications, one of which is substituting natural aggregates in concrete [88]. Compared to natural aggregates, rubber exhibits a much lower compressive strength and elastic modulus, recorded at 1 MPa, but has a considerably higher Poisson's ratio of around 0.3 [89]. Such characteristics lead to an increase in lateral expansion under load, which in turn induces microcracking within the concrete. Moreover, the smooth, slippery surface of tire rubber, coupled with residues of zinc stearate, impedes effective adhesion to the concrete matrix, forming gaps in the interfacial transition zone (ITZ) [90]. These gaps are exacerbated by zinc stearate's tendency to form a water-repellent soapy layer. Consequently, replacing natural aggregates with rubber can diminish the compressive strength of concrete significantly. For example, a 30% volumetric replacement of aggregates with rubber can decrease the compressive strength by as much as 77% relative to standard concrete [91]. To mitigate these effects, rubber particles are often treated with sodium hydroxide to enhance surface roughness and eliminate the zinc stearate layer [90]. Despite these challenges, RuC demonstrates superior impact resistance, ductility, energy absorption, fire resistance, and acoustic absorption compared to traditional concrete [86,92–94]. Moreover, rubber's lower specific gravity, ranging from 0.5 to 0.9, makes RuC lighter, thus reducing structural dead loads and enhancing ease of handling at construction sites [89]. It is reported that the increasing CR in RGPC, despite NaOH treatment, leads to smoother, weaker rubber particles that bond poorly with the matrix, causing early failure and reduced strength. The sodium hydroxide pre-treated RGPC utilizes geopolymer as an activating agent. The inherent lower elastic modulus of the geopolymer enhances compatibility with rubber particles. Furthermore, the primary binder in RGPC, FA, has a specific gravity of 2.25, considerably lower than that of OPC, which is 3.15 [95].

This lower density could help in preventing the rubber particles from floating, potentially improving the uniformity of the mix. The silicate-based GPC also tends to be more adhesive during the mixing process, facilitating better integration between the rubber and the geopolymer matrix [26]. RGPC offers several advantages, such as increased fire resistance, lower weight, and the promotion of recycling efforts. It addresses environmental concerns like CO_2 emissions and the depletion of natural resources [86]. While the inclusion of rubber in RGPC typically diminishes mechanical properties, RGPC is noted for its enhanced durability, particularly in terms of abrasion resistance and impact strength compared to conventional concrete [92]. Chemical treatment of the rubber particles with substances like sodium hydroxide or potassium permanganate can mitigate some of the mechanical weaknesses [96]. RGPC, made with CR as a partial substitute for natural aggregates, exhibits significant impact resistance and energy absorption capabilities, whereas geopolymer paste and natural aggregates by themselves are less effective under impact loads [97]. Research on RGPC remains relatively scarce. For instance, the effects of substituting 5–20% of sand by volume with fine CR with up to 4.75 mm size in FA-based GPC were studied [28]. A reduction in compressive strength of up to 30% was observed at the highest replacement level of 20%. This reduction rate was consistent across different mixtures, suggesting that even with optimized binders and activators, the inclusion of rubber affects the strength. Moreover, a significant reduction in 28-day compressive strength of 49.2 MPa (76%) was reported from an original strength of 65.0 MPa when 20% of the fine aggregates were substituted with fine CR (0.073–0.375 mm) [98].

Research on the acoustic insulation properties of MK-based GPC has shown that up to 14% fine CR (by weight of total aggregates) was incorporated, with particle sizes under 1 mm [94]. Initial findings showed a 6% increase in compressive strength with a minimal rubber content of 2%; however, this strength decreased by 78% when the rubber content was increased to 14%. It was noted that fully encapsulating the rubber particles in the paste is crucial to maintain the compressive strength. In another study, rubber fibers measuring 2–4 mm in width and up to 22 mm in length were used to replace up to 30% of the fine aggregates in an FA-based geopolymer mix, although this replacement reduced the mix's compressive strength by 55% after 28 days and enhanced the material's abrasion resistance. Moreover, both fine and coarse aggregates were substituted with CR (with a median diameter of less than 1 mm) up to a 30% volume [92]. This substitution led to a 7% increase in strength at a 10% replacement level at 28 days, but a 34% decrease at a 30% replacement level, while significantly boosting impact resistance [86]. Figure 7 in the referenced study showed that the control GPC mix achieved the highest compressive strengths at both 7 and 28 days, with an impressive strength increase of 28.3% at the latter stage, underscoring the effectiveness of geopolymerization reactions [99]. Conversely, mixes that incorporated BST and CR aggregates displayed smaller gains in strength, ranging from 1.2 to 16.7%, regardless of the level of aggregate replacement. This suggests that these materials may interfere with the geopolymerization process, a theory that should be explored further through microstructural studies [99]. Moreover, the variation in strength gain was also influenced by the concrete grade, with higher-grade GC6 showing more substantial differences in strength development between 7 and 28 days compared to lower grades. In brief, RGPC presents a sustainable and innovative solution by integrating recycled rubber particles, demonstrating significant potential in improving mechanical properties, enhancing durability, and contributing to the circular economy of construction materials.

In summary, the incorporation of recycled tire rubber as a substitute for natural aggregates in the development of RuC and RGPC presents both advantages and limitations. Notably, a 30% replacement of aggregates with rubber results in a significant reduction in compressive strength, with conventional concrete experiencing a decrease of 77%, while RGPC exhibits a reduction of 49.2 MPa, corresponding to a 76% loss. Nevertheless, RGPC demonstrates improved impact resistance, energy absorption capacity, and enhanced fire resistance. Experimental investigations have revealed a 78% decline in strength when the rubber content is increased from 2 to 14%. Despite these reductions in mechanical performance, RGPC offers notable durability advantages and environmental benefits, including the promotion of tire recycling and a reduction in CO_2 emissions (Table 1).

- Rubber particles, particularly those treated with sodium hydroxide, may hinder geopolymerization, reducing the strength development. However, the microstructural effects of rubber on this process are not well understood, highlighting the need for detailed analyses to clarify interactions between rubber, activators, and the geopolymer matrix.
- Treatments involving sodium hydroxide and potassium permanganate have been shown to improve the bonding between rubber and concrete. However, further investigation is required to assess the long-term durability and effectiveness of these treatments in enhancing mechanical properties. Additionally, exploring alternative chemical or physical treatments for rubber particles may yield more effective strategies for overcoming bonding issues and mitigating reductions in strength.
- RGPC exhibits enhanced durability, particularly in terms of abrasion resistance and impact strength. However, these benefits are often accompanied by a reduction in compressive strength. Further research is needed to explore strategies for optimizing the balance between mechanical strength and durability, potentially using hybrid materials or the inclusion of supplementary additives.

2.3 Ultra-high performance RGPC

UHPRGC is composed of OPC, a high level of activators, CR, steel fibers, and fine quartz sand, maintaining a low liquid-to-binder ratio [107,108]. This material is particularly advantageous for constructing structures that require blast resistance, long-span bridges, and those in highly corrosive environments [109–111]. Despite its superior mechanical properties and durability, UHPGC has raised environmental concerns due to its significant use of OPC, which leads to substantial CO_2 emissions [2]. The content of OPC in UHPGC ranges from 750 to 1,200 kg·m^{-3}, which is two to three times higher than in traditional concrete, necessitating considerable natural resources and energy, thereby producing large amounts of CO_2 [112]. The production of 1 ton of clinker, for

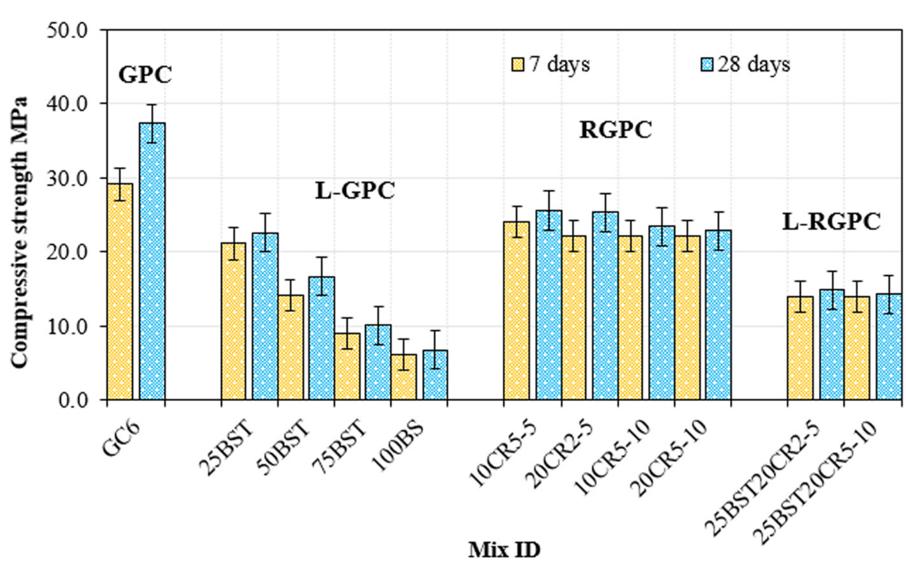

Figure 7: Compressive strength of developed L-GPC, RGPC, and L-RGPC mixes at 7 and 28 days (Adopted from [99]).

Table 1: Summary of key findings of previous studies on rubberized and non-rubberized GPCs [26,34,92,94,97,99–104]

Type of GPCs	Cementing materials	Alkali type	a/b ratio	Duration and type of curing	Type of aggregate	Rubber particles		Compressive strength (MPa)	Ref.
						Repl. rate (%)	Size (mm)		
FA-based RGPC	Class F FA	Na_2SO_4-NR, NaOH, 14M, NaOH-2.5, Na_2SO_4	0.4	Oven 90°C 4 days	FA-River sand (35%), crushed basalt – 10, 20 mm	10% FA	2–4	47.33–22.52 MPa at room temperature, 200, 400, 600, and 800°C	[34]
LWGC, RGPC, and LWRGC	Class F FA GGBS	Na_2SO_4-NR, NaOH, 14M, NaOH-2.5, Na_2SO_4	0.4–0.6	Ambient 23°C 7–28 days	FA-silica sand of <4 mm (45%(. CA-crushed of 7–10 mm	10 and 20% of FA and 20% CA	2–5, 5–10	17.1 MPa	[99]
Slag-based RGPC	GGBS	Na_2SO_4, NaOH-nr, 3.39 MS, NaOH-0.39, Na_2SO_4	0.54	Room conditions	Natural sand-FA of <0.5 mm (35%), crushed of 12 mm	10, 20, and 30% FA	—	24.8–40 MPa at 28 days and from 38.3 to 55.4 MPa at 60 days	[92]
FA-based RGPC	Class F FA	Na_2SO_4- NR, NaOH-14 M, NaOH-2.5, Na_2SO_4	0.4	Oven 90°C 4 days	CA: 10–20 mm	10, 20, and 30% FA	2–4 mm	30–54 MPa	[26]
L-FA-based GPC	Class C FA	15M, 20M NaOH- 10M, Na_2SO_4/NaOH, Na_2SO_4-2.41, MS	0.85	Oven 60–90°C, 4 days	River sand-FA	—	487 $kg{\cdot}m^{-3}$	2.07–3.29 MPa	[105]
Slag-based GPC	GGBS	Na_2SO_4-3.39, NaOH-NR, MS, NaOH, Na_2SO_4	0.3	Oven 45°C, 28 days	NR	1–15% slag	—	58.09 MPa at 7 days and 65.53 MPa at 28 days at 1% to 17.23 and 36.67 MPa at 15%, respectively	[104]
FA-based GPC	Class F FA	Na_2SO_4-NR, NaOH-12 M, NaOH-2.5, Na_2SO_4	0.5	Seawater condition	River sand-FA <4.75 mm. CA: rushed stone of 20 mm	5, 10, and 15%	50–100	39.6 MPa at 28 days and 31.5 MPa at 60 days	[106]
FA-slag-based RGPC	Class FA GGBS	NaOH-10M, Na_2SO_4-2 MS, Na_2SO_4, NaOH-2	0.4	Room conditions	River sand-FA	10, 40, 50% by sand	2–6	The compressive strength ranged from 15.0 to 21.3 MPa at 7 days and 22.6 to 35.8 MPa at 28 days	[103]
FA-based GPC	Class C FA	Na_2SO_4-2.41, NaOH-10 M, NaOH-1, MS Na_2SO_4	0.75	Oven 60°C 4 days	River sand	25–75%, and 100%	487 $kg{\cdot}m^{-3}$	2.7–12.3 MPa and 2.6–21.8 MPa, respectively	[102]
FA-based RGPC	Class F FA	Na_2SO_4-NR, NaOH-10 M, NaOH-2, Na_2SO_4	0.4	Room conditions	River sand zone – FA	5% by sand	75–4.75 μm	47.33–22.52 MPa at room temperature, 200, 400, 600, and 800°C	[100]
FA-based GPC	FA GGBS	Na_2SO_4-NR, NaOH-12 M, NaOH, Na_2SO_4	—	Room conditions	FA: Dune sand, CA of 4–7 mm	15 and 30% by CA	2–7	(3.71–19.77 MPa) at 7 days (4.32–37.68) at 14 days (12–67 MPa) at 28 days	[100]
MK-RGPC	MK-Kaolin	Na_2SO_4-NR, NaOH-15M, NaOH-2.9, Na_2SO_4	0.84	Oven 65°C, 4 days	Natural sand, crushed to 4.75–12.5 mm	5, 10, 15% by FA	Less than 1	40.68 MPa	[94]
FA-based GPC	Class F FA	NaOH-10 M, Na_2SO_4-NR	0.45	In 60°C hot water	River sand of 10 mm crushed gravel –FA	10, 20, and 30%	2–4	11.2–15.3 MPa with 2 mm and from 9.4 to 15.3 MPa with 4 mm	[101]

Annotations: alkali/binder ratio = (a/b) ratio, coarse aggregates (CA), fly ash (FA), ground granulated blast-furnace slag (GGBS), lightweight geopolymer concrete (LWGC), rubberized geopolymer concrete (RGPC), lightweight rubberized geopolymer concrete (LWRGC), and metakaolin (MK).

instance, is estimated to consume 6.65 MJ of energy and generate about 0.83 tons of CO_2 [113]. Efforts have been made to reduce the quantity of binder and replace some of the cement-based materials with alternatives to OPC. In recent years, the scientific community has shifted focus toward developing low or non-clinker cementitious materials. GPC is recognized as a low-carbon, clinker-free alternative, and is one such option [114]. It is produced by activating alumino-silicate materials such as FA, GBFS, and MK [41,47,115,116] with alkaline solutions like silicates, carbonates, alkali hydroxides, and/or sulfates. GPC can achieve mechanical properties comparable to those of traditional OPC concrete [117]. Recent innovations aimed at enhancing sustainability have led to attempts to utilize GPC as the binder in UHPGC [83]. According to Figure 8, an increase in fiber dosage from 2 to 3% and then to 4% in the concrete mix significantly boosts the compressive strength by 11.2 and 22.8 MPa, respectively. This increase is likely due to the robust modulus of the steel fibers included in the mix [83].

GPC has gained significant attention due to its role in substantially reducing carbon dioxide emissions and its use of natural resources [118]. Unlike Portland cement, the production of GPC's raw materials does not require a calcination process, which significantly reduces energy usage [119]. Research indicates that GPC emits 5–6 times less CO_2 compared to traditional concrete. Recent advancements in this field have led to the development of UHPGC, which uses geopolymers as a binder [41]. Studies have shown that UHPGC containing 3% fibers can achieve maximum flexural and compressive strengths of up to 181 MPa, respectively, after 28 days of curing with a chemical mixture of sodium hydroxide and sodium silicate [120]. Figure 9a–d shows the SEM images that reveal the incorporation of 10–30% basalt fibers into RHA paste results in a denser, homogeneous structure, indicating an enhancement in the hybrid paste's structure. This enhancement is further supported by an increase in Ca content [120]. In addition, basalt fibers partially react, as observed in the SEM images, performing a microaggregate function that leads to an increase in compressive strength.

The development of UHPGC was enhanced by the use of nano-silica and slag, achieving a compressive strength exceeding 145 MPa [121]. Research indicates that using only slag in geopolymers can cause issues such as decreased workability, increased shrinkage, rapid setting, and diminished strength during carbonation [122]. However, combining slag with SF is more effective in improving durability, strength, and the development of new properties in GPC [123]. There is considerable potential for further improvements in these areas of UHPGC [37]. Nano-silica and polypropylene fibers (PPFs) are key components in the composition of UHPGC [107]. The addition of PPFs notably improves the impact resistance of the material. Studies show that adding fibers at 4% by weight of the binder does not significantly affect the strength and ductility of the GPC [124]. PPFs are known to improve the toughness, ductility, and behavior after cracking in concrete [47,125]. Besides, the design and optimization process for achieving optimal performance in UHPGC with fibers is largely dependent on the fibers' properties [107]. The relatively high cost of fibers and the need for precise control during their integration into the GPC matrix are crucial for the practical application and commercialization of UHPGC [2]. Nano-silica plays an essential role in HSC due to its densifying effect [126]. Moreover, including 10–15% NS in UHPC has been shown to improve the material's freshness. Incorporating NS into GPC enhances strength but may decrease the slump value [127]. Appropriate proportions

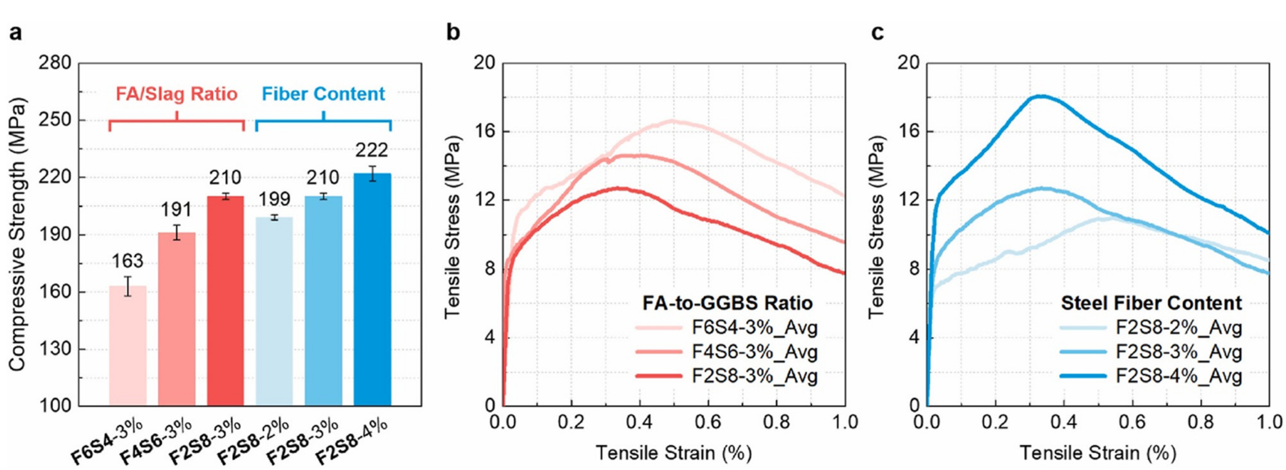

Figure 8: (a) Compressive strengths and tensile performance of UHPRGC with (b) different FA-to-GGBS ratios and (c) steel fiber contents (Adopted from [83]).

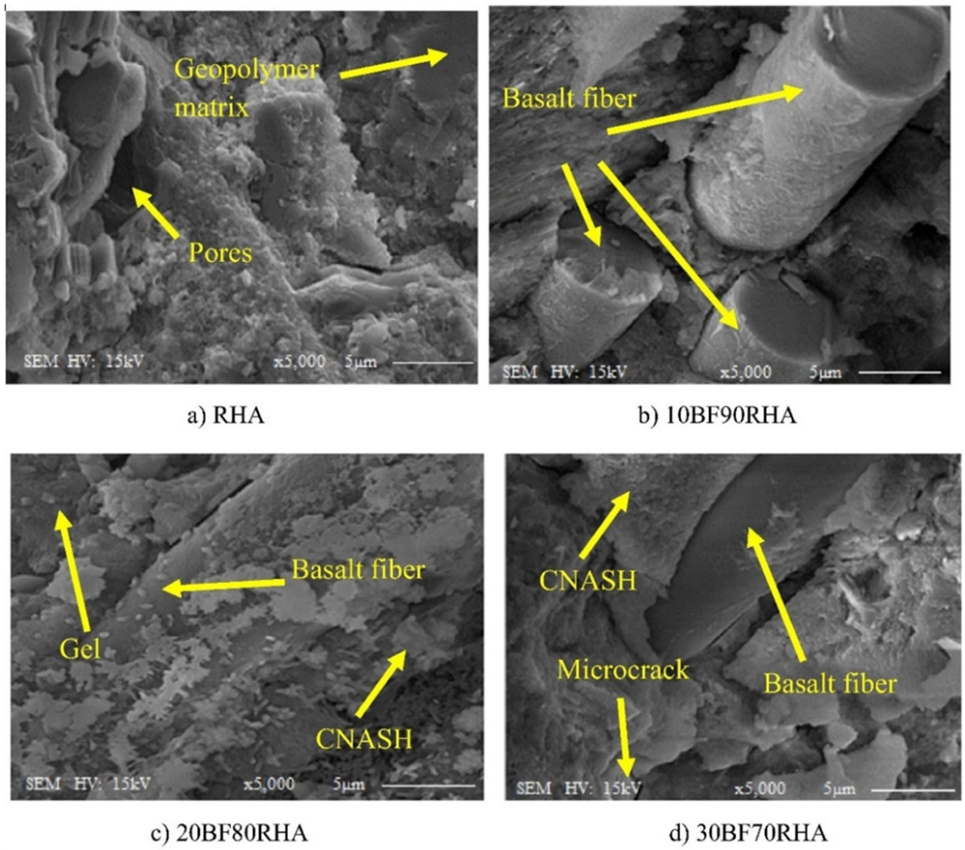

Figure 9: SEM images of the specimens with 0%, 10–100% basalt fiber content (Adopted from [120]). (a) RHA, (b) 10BF90RHA, (c) 20BF80RHA, and (d) 30BF70RHA.

of NS are shown to increase both the fresh and strength properties of UHPGC [128].

Figure 10 presents a detailed graphical representation of the compressive strength of a material, likely a type of concrete or composite, as a function of Na_2O percentage and the W/B ratio [129]. The vertical axis represents the Na_2O content, ranging from 4 to 9%, while the horizontal axis shows the W/B ratio, varying from 0.300 to 0.525. The figure uses a color gradient to denote different compressive strength ranges, with darker colors representing higher strengths. Notably, the highest compressive strengths (>120 MPa) are achieved with a high Na_2O content (8–9%) and a low W/B ratio (0.300–0.325). As the Na_2O content decreases and the W/B ratio increases, the strength diminishes, with the lowest strengths (<40 MPa) observed at low Na_2O levels (4–5%) and higher W/B ratios (0.425–0.525) [129]. This visual data emphasizes the significant impact of Na_2O content and W/B ratio on the material's performance, highlighting the optimal range for achieving high compressive strength. It underscores the importance of balancing these parameters to enhance the material properties [129]. In brief, these findings serve as a valuable tool for optimizing the composition of alkali-activated binders/geopolymer concretes, guiding researchers and engineers in developing high-performance, durable construction

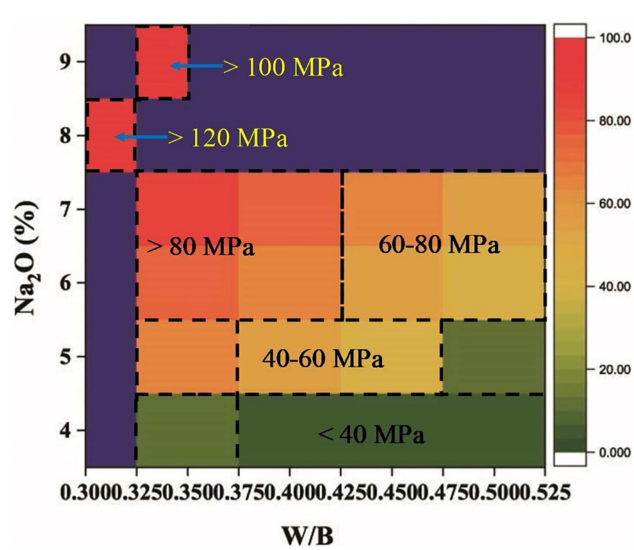

Figure 10: Range of the compressive strength of GPC/AAS with respect to the Na2O/binder and water/binder ratios (Adapted from [129]).

materials. Future research could further explore the microstructural effects and long-term durability of these compositions to support sustainable construction practices.

Nano-silica's role in improving the strength and long-term properties of UHPC is primarily attributed to its nanoscale size and its ability to densify the material [130]. Research indicates that while nano-silica contributes to increased strength, it can adversely affect the rheological properties [131]. Studies have also shown that an optimal amount of nano-silica can boost both the strength and the initial properties of GPC [132]. Conversely, replacing FA with nano-silica in GPC formulations has been found to diminish its fresh properties [27]. Although there has been some investigation into the use of nano-silica in fly-ash-based UHPCRGC, the broader application and incorporation into building codes are hindered by insufficient research on its impact on strength, ductility, and fracture behaviors when combined with slag/SF and PPFs [133] (Figure 11). Furthermore, the phenomenon of drying shrinkage significantly affects concrete's durability, with water loss through capillary action leading to cracking and shrinkage [134]. As concrete dries, it releases water by capillary action, resulting in cracks and shrinkage. [135]. The introduction of PPFs or steel fibers has been shown to markedly reduce these shrinkage issues [136].

Practically, UHPGC is increasingly recognized as a sustainable alternative to traditional UHPC [38]. The primary methods for producing standard UHPGC include (a) utilizing pressurized or thermal curing environments, as depicted in Figure 2 [133]; (b) combining GGBS and SF to enhance flowability and reactivate alkalis at lower precursor-to-water ratios [137]; (c) increasing the specific surface area and decreasing precursor particle sizes [138]; and (d) employing a potassium-based alkaline solution as an activator [37]. The alkali activation process significantly improves UHPGC's strength, potentially positioning it as a competitive material for civil engineering projects due to its durability and sustainability [112]. In conclusion, UHPRGC marks a significant advancement in sustainable construction materials by synergizing the high mechanical performance and durability of UHPC with the eco-friendly and waste-reducing attributes of geopolymer binders and recycled rubber. This composite material not only addresses the pressing need for reducing the carbon footprint and landfill waste but also improves the structural integrity and longevity of concrete structures. The integration of recycled rubber enhances the material's flexibility and impact resistance, making UHPRGC an ideal candidate for applications requiring both strength and resilience, while promoting circular economy practices in the construction industry.

Generally, UHPGC is gaining attention for its blast resistance and durability in long-span bridges and corrosive environments. While traditional UHPGC relies heavily on OPC, contributing to significant CO_2 emissions, GPC

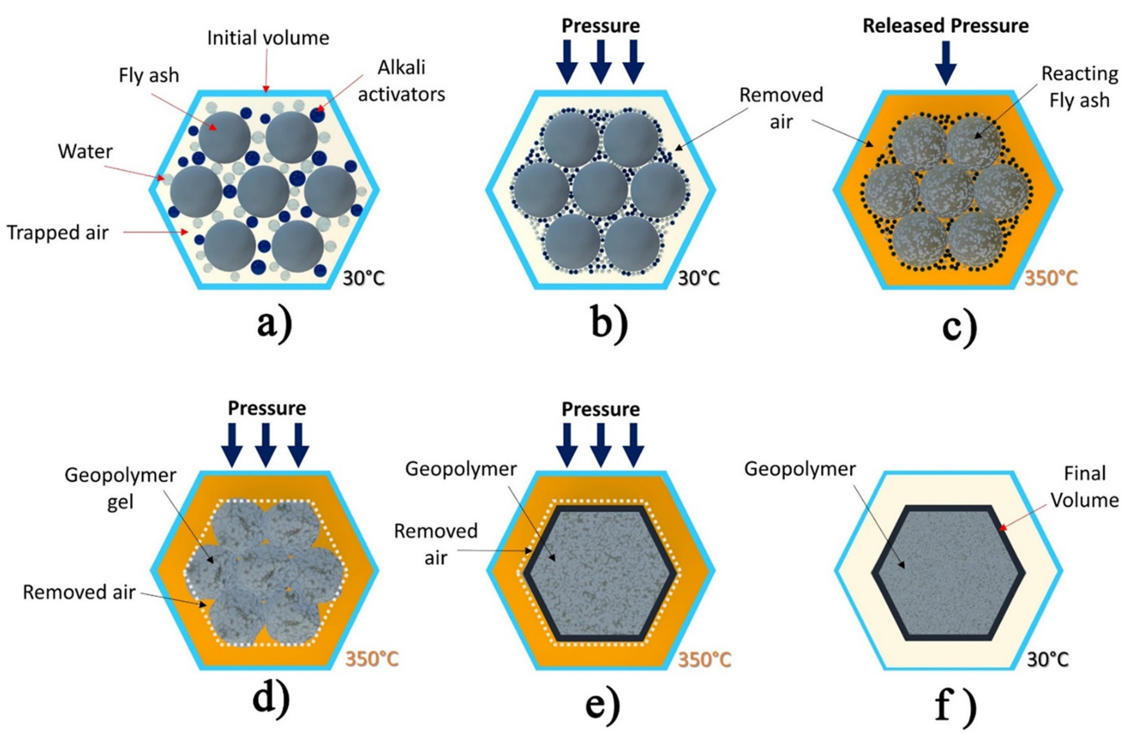

Figure 11: Schematic mechanism of geopolymerization under hot pressing (Adapted from [133]). (a) Initial mixture, (b) applying pressure, (c) heat treatment, (d) geopolymer gel production, (e) stabilization of reaction, and (f) cooling.

offers a low-carbon, clinker-free alternative that reduces binder usage and emits 5–6 times less CO_2. UHPGC utilizes geopolymers as binders, achieving compressive strengths up to 181 MPa after 28 days with sodium hydroxide and sodium silicate. The inclusion of nano-silica and PPFs enhances impact resistance, toughness, and ductility. Nano-silica, comprising 10–15% of the mix, improves the material's strength while maintaining fresh properties, although it may negatively affect the rheological behavior. A graphical representation illustrates that optimal compressive strength occurs with high Na_2O content (8–9%) and low water-to-binder (W/B) ratios (0.300–0.325). UHPCRGC combines the mechanical advantages of UHPC with the eco-friendly characteristics of geopolymer binders and recycled rubber, promoting the structural integrity and longevity of concrete structures. Various methods, including pressurized curing and the use of GGBS and SF, further enhance UHPGC's performance. Most research on geopolymer binders focuses on mechanical properties and energy efficiency, with limited studies examining the effects of different proportions of nano-silica, basalt fibers, and PPFs on the fracture behavior, workability, and shrinkage of UHPRGC. Furthermore, there is insufficient evidence on the environmental implications of commercializing these minerals.

3 Rapid setting and enhanced workability

Rapid setting of UHPGC is largely due to its unique composition, enabling swift setting and strength development that potentially accelerates building activities [42]. The inclusion of specialized admixtures and chemical enhancements in UHPRGC improves the ease of mixing and placement. Research has explored using CR as a substitute for natural sand in alkali-activated concrete, with findings resembling those from standard concrete that incorporates CR [139]. It was found that using finer rubber particles in GPC caused a minor reduction in compressive strength paralleled to coarser particles [92], indicating that the impact on compressive strength is lesser with fine rubber aggregate replacements than with coarse ones. Investigations have shown that using CR to replace up to 20% of sand by volume in FA-based UHPRGC results in a 35% reduction in compressive strength [28]. Available data suggest that rubberized geopolymers generally exhibit lower compressive strength and weaker structural integrity [105]. Consequently, recent developments focus on modifying the geopolymer mix and adding various physical and mineral additives to mitigate strength loss in rubberized GPC [139]. Studies on the effects of pre-treating rubber and adding fibers to improve the strength properties of OPC-based RuC have been conducted [140]. These studies confirm that water pre-treatment of rubber enhances RuC's workability more effectively than other chemicals, and incorporating 1.5% steel fibers significantly boosts its flexural strength. Research indicates that immersing rubber particles in water replaces adsorbed air with water molecules, thus improving the adherence of rubber particles within the cement matrix and enhancing the compressive strength of rubber concrete [140]. Figure 12 depicts how replacing CR affects the fluidity and setting time of UHPRGC [141]. Observational and flow measurement studies indicate that all mixtures were consistent, showing no signs of segregation or bleeding. Specifically, maintaining a constant alkali-activated slag (AAS)/binder ratio of 0.35, a constant SF content of

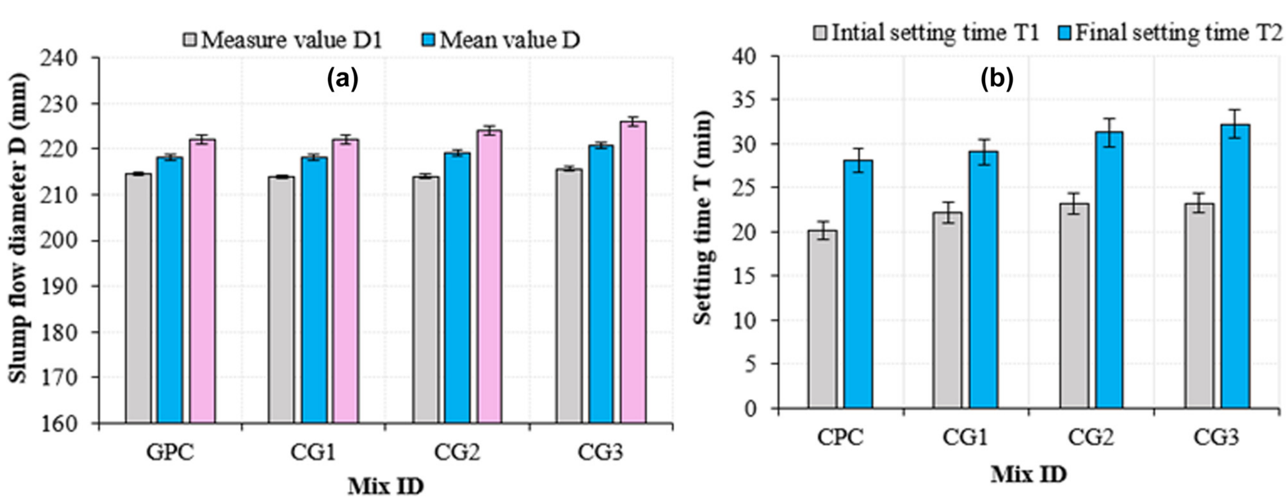

Figure 12: (a) The flowability and (b) setting times of fresh UHPRGC (Adopted from [141]).

25% for slag replacement, and a steel fiber dosage of 3% were critical for optimizing the flowability and setting time of the UHPRGC [141].

Briefly, UHPGC sets and strengthens rapidly, enabling faster construction. Its unique formulation facilitates efficient mixing and placement, especially when used with specialized admixtures. Research shows that alkali-activated concrete with CR as a replacement for natural sand exhibits reduced compressive strength, while rubberized geopolymer composites suffer from diminished strength and structural integrity. Additionally, studies indicate that water pre-treatment of rubber and steel fibers can improve the strength of OPC-based RuC. Observational and flow measurement experiments indicated that segregation and bleeding were absent in all mixes. For optimal flowability and setting time of UHPRGC, it was determined that a constant AAS to binder ratio of 0.35, a 25% replacement of slag with SF, and a 3% dosage of steel fiber are essential.

4 Rubber particles and fiber reinforcement

It is well-known that concrete exhibits varied mechanical properties when subjected to different loading rates, and the integration of rubber particles notably modifies its internal structure and dynamic mechanical attributes. Studies on RuC subjected to high loading rates indicate that an increase in rubber content mitigates brittle damage [142]. Further investigations reveal that the compressive strength of RuC under impact improves with higher strain rates, aligning with known strain rate effects on similar materials [143]. It is also found that the energy absorption capacity of RuC significantly enhances with increases in rubber content and particle size, though the primary failure often occurs at the rubber–cement interface due to inadequate bonding [144]. Research into the dynamic properties of lightweight rubberized GPC shows that its energy absorption, relative to its compressive strength, surpasses that of standard GPC under high-strain conditions [145].

The length of steel fibers is crucial in determining the effectiveness of fibers on the flexural behavior of concrete [146,147]. This performance is also dependent on the fiber orientation and distribution, which vary with the fiber's length and aspect ratio [148]. Previous studies have suggested that longer steel fibers generally improve flexural performance [46]. However, additional research indicates that when the length of steel fibers exceeds 13 mm, it can lead to reduced flexural performance due to increased spacing between fibers [149]. Steel fibers measuring 13 mm are commonly used in UHPC to fulfill requirements for tensile ductility and toughness, and have been extensively examined in previous studies [150]. Figure 13 illustrates normalized flexural load–deflection curves for UHPGC and UHPC, indicating that although the descending phase of the UHPGC curve shows lower loads for equivalent deflections compared to UHPC, the curve configurations are similar, featuring ascending and descending phases. This similarity suggests the possibility of developing a flexural behavior model for UHPGC based on existing models for UHPC [151].

Fiber reinforcement is widely applied to enhance both the static and dynamic properties of concrete [17]. Research on the impact resistance of UHPC is approximately twice as strong and dissipates 3–4 times more energy than conventional RC under similar conditions [152]. Further studies on UHPC with steel fiber reinforcement reveal that its compressive strength improves with increased fiber content, and the damage initiation factor increases with strain rate. These studies concluded that higher strain rates correlate with enhanced compressive strength at a fixed fiber content [153]. Investigations into UHPC using a combination of short and long steel fibers indicate significant enhancements in both compressive and flexural strengths under quasi-static and dynamic loads due to the dual fiber system [154]. The hybrid fibers function such that short fibers initially prevent microcrack formation while long fibers continue to carry the load as cracks develop and short fibers are dislodged [155]. Another study on UHPC examined the impact of different steel fiber shapes and content on mechanical properties,

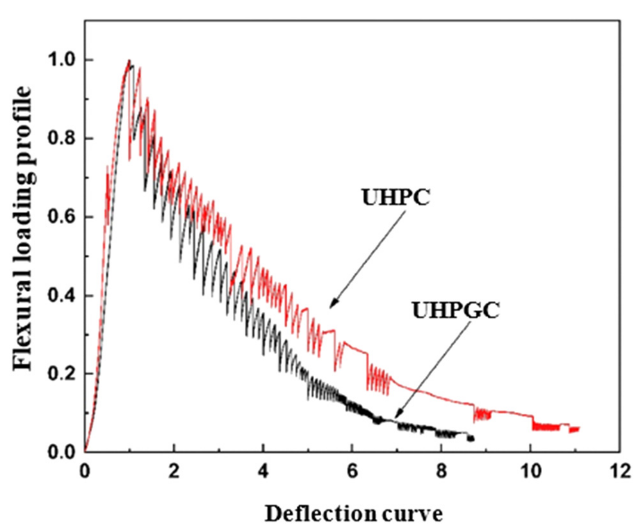

Figure 13: Normalized flexural load-deflection curves of UHPGC and UHPC with 2% straight steel fibers (Adopted from [151]).

showing marked progress in static compressive and flexural strengths with increased fiber content, particularly using hooked-end fibers over straight or corrugated types [151]. The effect of fiber aspect ratio was also explored, revealing that shorter fibers (lower aspect ratio) improve compressive strength more effectively than longer fibers due to easier vibration and consolidation, resulting in less porous concrete [156,157]. Comparative research on concrete reinforced with steel, polyvinyl alcohol (PVA), and PPFs under chemical erosion found that steel FRC performed best, followed by PVA and PP fibers [158]. Recent studies on PVA fiber-reinforced RuC showed that incorporating 0.5% PVA fibers slightly reduced compressive strength, which decreased further with the addition of rubber aggregates as sand substitutes. An examination of steel FRC with rubber waste indicated an improvement in fracture energy, especially when both rubber and steel fibers were incorporated [159]. Overall, increasing fiber length tends to boost flexural strength under various curing conditions, as illustrated in Figure 14a and b [46]. However, steam curing may negatively affect the toughening efficiency of fibers, possibly due to increased porosity in the geopolymer matrix and decreased bond strength at the fiber–matrix interface, necessitating further study [52].

Various pre-treatment methods for rubber particles are employed to reduce their negative impact when incorporated into concrete [159]. Table 2 summarizes the pre-treatment approaches for different RGPC formulations, with a primary focus on NaOH and water treatments. These methods typically involve submerging the rubber particles in the respective medium, stirring for around 60 s, and then sealing them for 24 h at room temperature [86]. Following NaOH treatment, the solution is discarded, and the particles are thoroughly rinsed until the pH nears neutrality, after which they are dried to a saturated surface dry (SSD) state. In contrast, for water-soaked particles, they are simply drained and left to dry on the SSD before mixing [99]. Both methods effectively clean the CR particle surfaces and yield a similar texture, but the NaOH treatment tends to produce more needle-like crystals on the rubber surfaces compared to water soaking [145]. NaOH treatment also removes the zinc stearate layer, which otherwise forms a barrier between the rubber and the concrete [160], while water soaking is noted to decrease trapped air, enhancing the concrete's compressive strength [161]. A study exploring four different CR pre-treatment techniques on FA-based RGPC found that each method improved the compressive strength of the final product [96]. The techniques involved submerging CR in a NaOH solution, soaking it in water, applying a cement paste coating to the particles, and covering them with ultra-fine slag (UFS) [87]. Among these, NaOH treatment and UFS coating were particularly effective, with UFS acting as a microstructural filler to form calcium silicate hydrates that enhance the concrete's integrity, more so than cement paste coating. The use of UFS also slightly enhanced other mechanical properties, such as splitting and flexural strengths, and the elastic modulus [96]. Regarding durability, NaOH pre-treatment provided superior resistance to acid degradation, maintaining the highest residual strength after 90 days of exposure to hydrochloric and sulfuric acids [96]. Rubber particles, typically sourced from recycled tires, confer distinctive benefits on concrete, enhancing its energy absorption and toughness, which is advantageous for resisting impacts and vibrations. Furthermore, rubber incorporation lightens the concrete, making it advantageous for applications requiring lightweight structures. In brief, this study revealed that the integration of rubber particles and fiber reinforcement in the

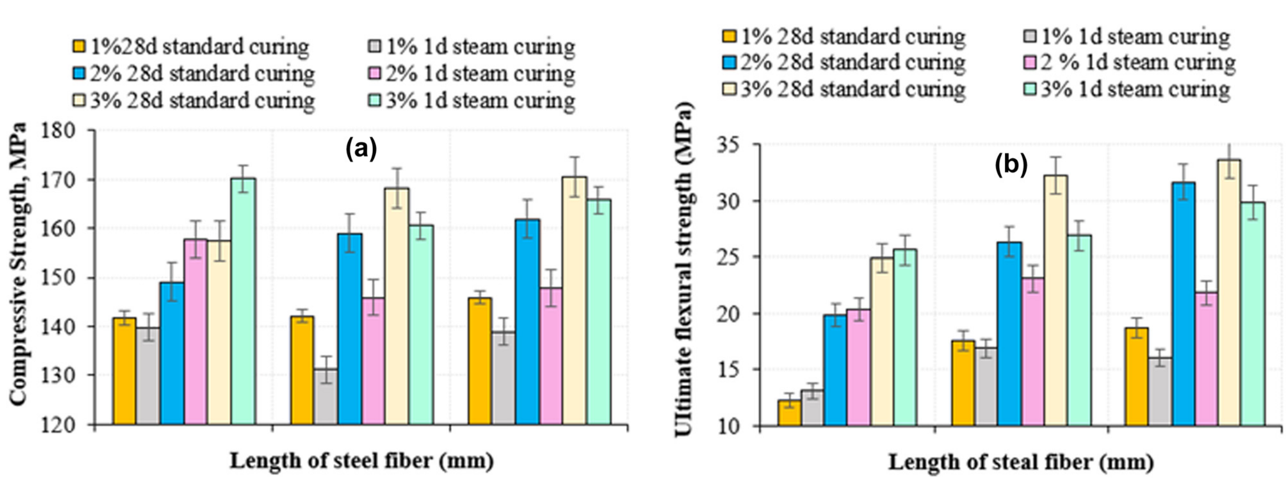

Figure 14: Effect of straight steel fibre length on (a) compressive and (b) flexural strengths of UHPGC (Adopted from [46]).

Table 2: Summary of major findings based on raw materials used to develop rubberized and non-rubberized GPC [26,28,34,86,92,94,96,98–103,105,106,145,159,162–167]

Type of GPCs	Fine natural aggregates				Coarse natural aggregates				CR				Compressive strength (MPa)	Ref.
	Type	Rate (%)	Specific gravity	Size (mm)	Sort	Rate (%)	Specific gravity	Size (mm)	Sort	Specific gravity	Size (mm)	Replacement rate (%)		
FA-based RGPC	Sand	20–25	—	—	CA	75–80	—	9.5–16	CR	—	0.075–4.75	5, 10, 15, 20% by vol. of FNA	≈42.5 MPa	[28]
RGPC	Sand	100	—	—	—	—	—	—	CR	—	0.073–0.375	5, 10, 15, 20% by vol. of FNA	48.0 MPa at 28 days	[98]
L-RGPC	River sand	100	2.63	0.075–4.75	—	—	—	—	CR	1.16	0–4	100% of FNA	2.07–3.29 MPa	[105]
RGPC	River sand	35	2.61	—	Crushed basalt	65	2.59	10–20	Fibers	1.09	*W* = 2–4 <22	10% by wt. of FNA	21.85–47.33 MPa	[34]
RGPC	River sand	35	2.61	—	CA	65	—	—	Fibers	1.09	*W* = 2–4 <22	10, 20, 30% by wt. of FNA	30–54 MPa	[26]
RGPC	Natural sand	35	2.65	<0.5	Crushed dolomite	65	2.96	<12	CR	0.45	Mesh 40 (0.42), 1–4	10, 20, 30% by vol. of FNA and CNA	24.8–40 MPa at 28 days and 38.3–55.4 MPa	[92]
RGPC	River sand	47	2.56	—	CA	53	2.59	10–20	Fibers	1.07	—	10% by wt. of FNA	2.7–20.8 MPa	[165]
L-based RGPC	Silica sand	45	—	<4	CrA	55	—	7–10	CR	1.15	2–5, 5–10	10, 20% of FNA and 10, 20% of CNA	≈40.68 MPa	[99]
FA-based RGPC	River sand	—	2.63	0.15–4.75	—	—	—	—	CR	1.16	0.073–4.75	25, 50, 75, 100% by vol. of FNA	31.5–39.6 MPa at 5% for both exposure durations	[102]
FA-based RGPC	Quartz-sand	40	—	0.15–4.75	Crushed gravel	60	—	10	CR	0.62	2, 4	10, 20, 30% by vol. of FNA	At 0–30% CR = 9.4–17.1 MPa	[101]
UHPGC	Sand	—	2.63	0.15–4.75	—	—	—	—	CR	1.22	0.15–4.75	20, 40, 60% by vol. of FNA.	At 0–10% CR = 30.5–55.6 MPa	[163]
RGPC	Natural sand	—	2.26	0.075–4.75	Crushed gravel		2.58	4.75–12.5	CR	0.38	<1	2, 6, 10, 14% by wt. of FNA and CNA	22.6–35.8 MPa	[94]
FA-based GPC	River sand	40	—	<4.75	Crushed stone	60	—	<20	CR	—	5–10	5, 10, 15, 20% by vol. of CNA	At 10% CR 17 MPa for 2 mm and 15.7 MPa for 4 mm	[106]
FA-based RGPC	CA	33	2.65	4.75	CA	67	2.7	<20	CR	1.28	4.2	5–15% of FNA and CNA	15–33.5 MPa	[168]
GPC	Dune sand	31	—	0.24	CA	69	—	4–7	CR	—	2–5, 5–7	15, 30% of CNA	≈ 58 MPa	[86]
L-based RGPC	Silica sand	36	—	—	CA	64	—	<10	CR	0.54	1–3, 5–7	15, 30% by vol. of FNA and CAN	At 2–5 mm, CR = 17.1 MPa	[145]

(*Continued*)

Table 2: *Continued*

Type of GPCs	Fine natural aggregates				Coarse natural aggregates				CR				Compressive strength (MPa)	Ref.
	Type	Rate (%)	Specific gravity	Size (mm)	Sort	Rate (%)	Specific gravity	Size (mm)	Sort	Specific gravity	Size (mm)	Replacement rate (%)		
FA-based GPC	River sands	—	—	0.125–4.75	—	—	—	—	CR	—	2–6	5, 10, 15% of FNA	10.23–20.21 MPa	[103]
FA-based RGPC	Sand	—	—	—	—	—	—	—	CR	—	—	5, 10, 15, 20% by wt. of FNA	At 0, 15, and 30%, CR = 54.06, 26.41, and 12.19 MPa, respectively	[100]
GPC	River sand	—	2.65	—	—	—	—	—	CR	—	0.075–4.75	5% of FNA	At 0, 15, and 30%, CR = 54.0, 26.2, and 11.7 MPa, respectively	[166]
GPC	River sand	—	2.62	—	—	—	—	—	Natural rubber latex	—	—	1, 2, 3, 5, 10% by wt. of FA	30.5–55.6 MPa	[164]
Slag-based RGPC	Copper slag	—	3.79	—	—	—	—	—	CR	0.93	0–4.75	5, 10, 15% by vol. of copper slag	At 5–20%, CR = 33.28 and 11.52 MPa	[167]
FA-based GPC	Sand	—	—	—	Gravel		—	—	CR	—	0–4.75	10% by vol. of FNA	≈35 MPa	[162]
RGPC	Fine aggregate	30	2.6	<4.75	CA	70	2.7	<14	CR	1.1	0.15–0.60	10, 20, 30% by vol. of FNA.	At 20–60%, CR = 3.0–13.2 MPa	[96]

Annotations: Geopolymer concrete (GPC), fly ash (FA), ground granulated blast-furnace slag (GGBS), crushed aggregates (CrA), coarse aggregate (CA), rubberized geopolymer concrete (RGPC), crumb rubber (CR), fine natural aggregate (FNA), and coarse natural aggregate (CNA).

development of UHPRGC and UHPGC marks a pivotal advancement in sustainable construction materials.

In brief, loading rates significantly affect the mechanical properties of concrete, and the addition of rubber particles modifies its internal structure and behavior. Increasing rubber content and particle size enhances the impact of compressive strength and energy absorption of RuC, although inadequate bonding often leads to failures at the rubber–cement interface. The effect of steel fibers on concrete's flexural behavior is influenced by their length; longer fibers generally improve performance, while fibers longer than 13 mm may diminish it. UHPC utilizes 13 mm steel fibers to enhance tensile ductility and toughness. Fiber reinforcement enhances both the static and dynamic characteristics of concrete. UHPC exhibits twice the strength of standard RC and dissipates three to four times more energy under similar conditions. Increased fiber concentration correlates with improved compressive strength, and strain rates affect damage initiation. The use of a dual fiber system in UHPC, combining short and long steel fibers, significantly enhances compressive and flexural strengths under quasi-static and dynamic loads. Shorter fibers improve compressive strength by facilitating better vibration and consolidation, resulting in reduced porosity. Additionally, steel FRC outperforms PVA and PPFs in resistance to chemical erosion.

- Despite improvements in energy absorption and dynamic properties with higher rubber content, the primary failure occurs at the rubber–cement interface due to inadequate adhesion. This highlights the need for further research to enhance bonding processes between rubber particles and the cement matrix to mitigate failures at this contact.
- While fiber length and aspect ratio affect flexural performance, optimal combinations for different applications are not well defined. Additional research is needed to explore how fiber orientation, distribution, and aspect ratio influence the static and dynamic properties of concrete under diverse loading conditions.
- Studies on dual fiber systems combining short and long steel fibers indicate potential improvements in compressive and flexural strengths of UHPRGC. However, further research is necessary to clarify the mechanics of hybrid fibers under dynamic loads and to investigate the synergistic benefits of using different fiber types.

5 High compressive strength

It is well-known that UHPRGC without fibers tends to become more brittle as its compressive strength increases. To address this, adding various types of fiber can improve the material's ductility. A notable difference in brittleness is observed when GPC is compared with NC. It is indicated that GPC has lower fracture energy than NC, which further decreases as compressive strength increases [169]. This makes the integration of rubber into GPC a worthwhile endeavor. Studies have used CR as a substitute for fine aggregates in GPC, resulting in an enhancement of 31.5–53.3% in energy dissipation capacity with rubber substitution ratios ranging from 5 to 20% [170]. Moreover, investigations into slag-FA-based low-strength RGPC show that a rubber replacement ratio of 0–10% slightly enhances compressive performance. However, exceeding a 10% replacement ratio adversely impacts this performance [171]. When rubber was substituted for fine aggregates in UHPGC at various levels, tests on its mechanical properties and microstructure revealed an increase in porosity and pore size, which in turn reduced its mechanical strength with higher rubber content [141]. Figure 14 shows the correlation between steel fiber volume and UHPC strengths [79].

In UHPGC, different water-to-binder ratios result in varying compressive strengths. A ratio of 0.4 achieves a compressive strength of 70 MPa, whereas a lower ratio of 0.25 reaches up to 200 MPa after 56 days [38]. This elevated strength permits the creation of thinner, more efficient structural components. Varying the types of pozzolans incorporated into the UHPGC matrix influences these strength outcomes [42]. For instance, using MK, which has a lower calcium content than slag, results in decreased compressive strength in comparison to samples that contain slag [172]. The higher calcium levels found in other aluminosilicates facilitate the formation of Ca–Al–Si hydrates in the microstructure, enhancing the concrete's mechanical properties [173]. Incorporating SF into UHPGC enhances the geopolymerization process and improves the microstructural integrity, thus strengthening the concrete [42]. Optimal results were observed when 15–30% of SF was substituted with slag, with the peak compressive strength occurring at 30% substitution [25]. This strength gain is primarily due to the slag filling voids between cement particles, which minimizes water requirements during hydration [174]. Moreover, increasing the SF content up to 30% not only augments compressive strength but also reduces permeability due to an increase in cement hydration products [175]. However, substituting more than 30% of slag with SF leads to an excessive amount of hydrated silica fume particles, compromising the microstructure and diminishing the compressive strength [176]. Excessive water in UHPGC mixtures also undermines the compressive strength by disrupting the polymerization process [177]. The existence of interfacial voids encircling

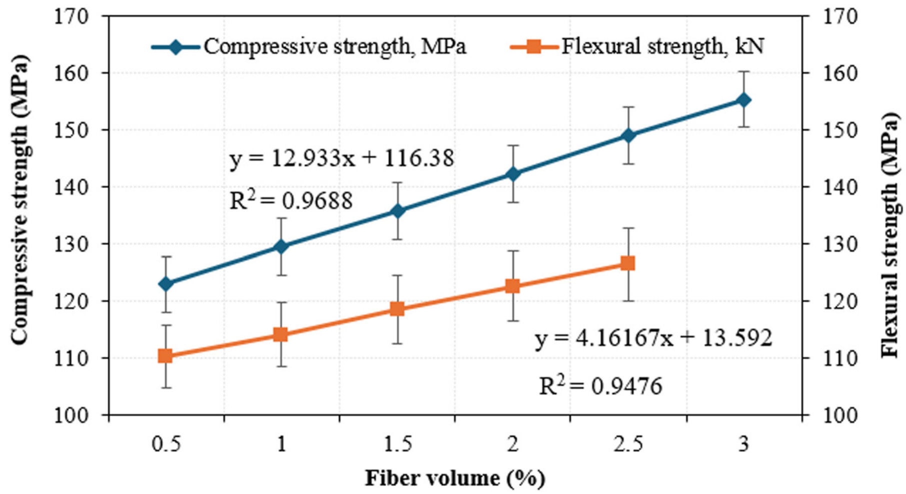

Figure 15: Correlation between steel fiber volume and compressive and flexural strengths of UHPC (Adopted from [79]).

elastomeric particles and phase alterations at the rubber–matrix interface are pivotal determinants of mechanical functionality in rubber-toughened polymers. These voids frequently emerge from discrepancies in mechanical attributes, engendering stress concentrations that may culminate in debonding [178]. In styrene polymers, cavitation within the elastomeric particles can diminish stress without fracturing, influenced by parameters such as particle dimension and cross-linking extent [179]. Elevated filler concentration and prolonged curing durations can amplify the quantity of voids, although void dimensions typically remain invariant [180]. In core–shell rubber particles, heterogeneous deformation beyond the yield threshold propels debonding and cavitation bands [181]. Simultaneously, chemical interactions at the interface, encompassing Fe–C and Fe–S bonding in magnetite-filled rubber composites, indicate robust stress-transfer mechanisms that can modify phase behavior [182]. X-ray diffraction (XRD) affords further elucidations, unveiling alterations in crystallinity and sharper peaks with increased filler concentration, as observed in silica nanoparticle-reinforced systems [183]. Furthermore, discrepancies in thermal expansion between rubber and the polymer matrix can induce thermal stresses and facilitate phase transitions at reduced temperatures [179] (Figure 15).

The relationship between fiber length and the mechanical properties of UHPGC is depicted in Figure 16 [46]. Contrary to what might be expected, reducing fiber length does not necessarily detract from compressive strength. In fact, for specimens cured for 28 days under standard conditions, both compressive and ultimate flexural strengths tend to increase with longer fibers. However, these strengths

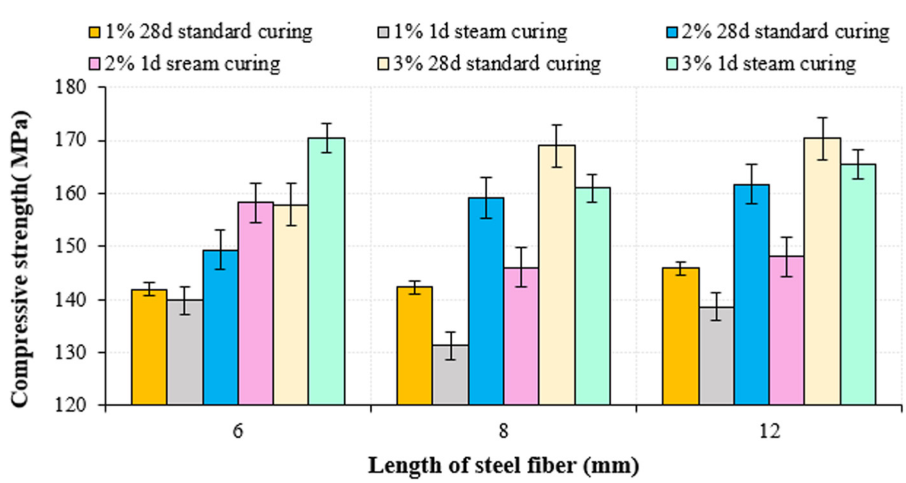

Figure 16: Effect of straight steel fibre length on compressive strength of UHPGC (Adopted from [46]).

exhibit variability when the fiber length is altered during steam curing [46]. Researchers have developed UHPGC utilizing GGBS and SF, activated with alkaline substances, achieving compressive and flexural strengths of 175 and 13.5 MPa, respectively [37]. A study explored the impact of substituting a portion of GGBS with SF in the UHPGC production process [38]. This substitution enhanced the UHPGC's compressive strength to approximately 178.0 MPa at a 12.5% replacement level, though further replacement to 15% led to a reduction in strength. In small proportions (2%), elastomeric materials effectively bridge microcracks and improve toughness while not leading to substantial declines in compressive strength [184–186]. Nevertheless, when the elastomer content exceeds a critical limit, the consequent stagnation in porosity and interfacial irregularities between elastomer particles and the surrounding matrix significantly reduces compressive strength [186]. Furthermore, the morphology and large-strain mechanical characteristics of the elastomer itself determine the efficacy with which it disperses stress, highlighting the significance of regulating strain-stiffening behavior [187]. To alleviate these drawbacks, additives such as SF can refine the microstructure, enhance particle densification, and fortify interfacial adhesion, thereby mitigating the detrimental effects on compressive strength while capitalizing on the toughness enhancements conferred by elastomers [186,188]. Sophisticated design methodologies, including multi-scale dynamic physical networks, can further optimize fracture resistance and facilitate rapid self-healing [189]. Achieving a balance between elastomer-derived toughness and sufficient compressive strength relies on meticulous mixed design, prudent material selection, and alignment with specific application requirements to ensure dependable, long-term performance.

Moreover, there is scant research on the behavior of UHPGC under high-temperature conditions, specifically its mechanical degradation, physicochemical alterations, and susceptibility to spalling. The reduction in strength of UHPGC at temperatures below 600°C is attributed to the breakdown of the calcium–aluminum–silicate–hydrate (C–A–S–H) phase, resulting in thermal cracking that increases porosity and leads to a coarser pore structure [190]. The challenges of recycling solid waste materials have also been reported, as recycling firms struggle with the diverse melting points and high costs associated with processing various wastes [191]. Consequently, much of these materials end up in landfills, posing environmental risks due to their non-biodegradable nature [192]. Recent studies have concentrated on producing GPC that cures at room temperature to reduce the energy required for the curing process [193]. Despite the advancement in geopolymer technology, limited focus has been given to UHPGC production. Elzeadani *et al.* developed UHPGC using SF and GGBS, noting that the material's compressive strength reached 124 MPa without steel fibers and increased to 175 MPa with the inclusion of steel fibers [159]. Wetzel and Middendorf [38] examined the influence of SF on UHPGC, highlighting its significant compressive strength and low capillary porosity, comparable to traditional UHPC. It is also confirmed that the optimal strength of 178.6 MPa was achieved with a 12.5% volume substitution of GGBS with SF, though this strength decreased when the substitution level reached 15% [141].

Figure 17 displays SEM micrographs of samples after 28 days of curing, illustrating the microstructure's impact

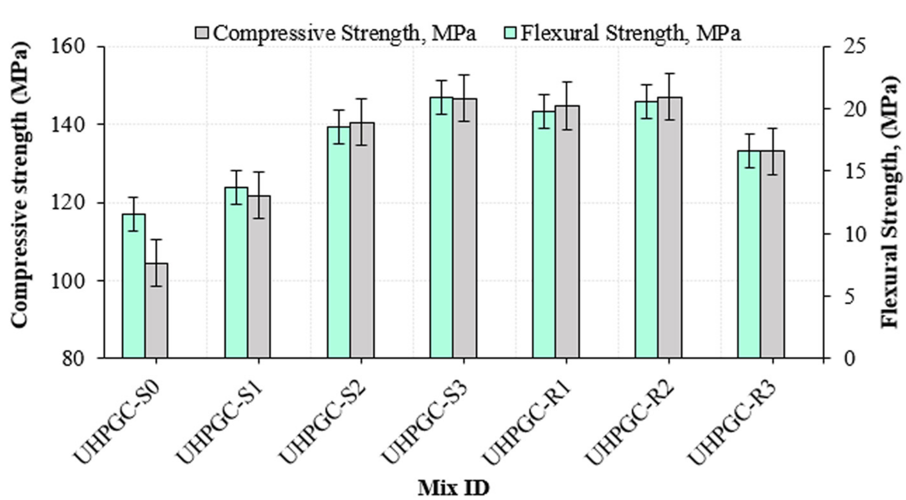

Figure 17: A comparative analysis explaining the flexural and compressive strengths of various Ultra-High Performance Grout Concrete (UHPGC) formulations following a curing period of 28 days, underscoring the significant impact that modifications in the mix design and curing conditions exert on the overall mechanical performance (Adapted from [196]).

on UHPGC's mechanical properties [141]. The control mix (Figure 17a) shows a uniform, dense microstructure with a continuous geopolymer gel phase of calcium–aluminum–silicate hydrates (C–A–S–H), enhanced by high slag content. A mixture with 22.5% CG (CG3) substitution for fine aggregate (Figure 17b–d) improves the microstructure by strengthening the particle–geopolymer gel bond, unlike the CC3 and CR3 mixtures [141]. Meanwhile, the incorporation of SF at levels ranging from 20 to 30% was found to reduce the flowability of GPC, despite significantly impacting its rheological and mechanical properties when used at higher substitution rates. In addition, it has been observed that in polymer concrete (PC)-based UHPC systems, fibers with hooked ends and corrugations display enhanced bonding strength compared to straight fibers [194,195]. The flexural and compressive strengths of the UHPGC at 28-day curing age are shown in Figure 7 [196]. It is reported that the UHPGC-S3 specimen demonstrates superior compressive and flexural strengths of 146.3 and 20.8 MPa, respectively, which are 40.4 and 80.9% greater than those of the UHPGC-S0 specimen [196]. This increase in compressive strength is due to the delayed formation and growth of cracks in fiber-reinforced UHPGC [46]. Furthermore, a higher steel fiber content reduces the average spacing between fibers, enhancing their load-bearing capacity and overall mechanical properties [197]. The fibers' bridging effect on the matrix plays a crucial role in significantly boosting the ultimate flexural strength of UHPGC [46]. However, from an economic perspective, the extensive use of steel fiber will inevitably raise the cost of UHPGC.

In contrast, UHPGC systems exhibit different behaviors. The use of C fibers, characterized by a higher deformation ratio, leads to increased bonding strength through chemical bonds, mechanical interlocks, and friction. However, the brittle nature of the geopolymer matrix in UHPGC systems is less capable of handling increased localized stress, often leading to premature failure [198]. Similar mechanisms have been observed in PC-based composites [199]. Moreover, hooked-end steel fibers have been shown to be more effective in enhancing flexural strength compared to corrugated fibers in UHPGC systems, mirroring findings in previous research on PC-based UPHC. This is attributed to the superior mechanical interlock provided by hooked-end fibers and their optimal deformation ratio [200]. In general, the development of UHPRGC achieves exceptional compressive strength, making it ideal for high-stress construction applications. This strength results from the synergistic effects of GPC and advanced reinforcement techniques, enhancing structural integrity and load-bearing capacity. By integrating rubber particles and fibers, UHPRGC surpasses performance criteria for demanding engineering projects, providing a durable and sustainable alternative to traditional concrete.

In general, UHPRGC without fiber reinforcement tends to exhibit brittleness as compressive strength increases, making the incorporation of various fibers essential for enhancing ductility. Rubber replacement ratios of 5–20% can increase energy dissipation by 31.5–53.3%, but ratios exceeding 10% may negatively impact performance. The compressive strength of UHPRGC is influenced by water-to-binder ratios, with MK demonstrating lower compressive strength compared to slag due to its reduced calcium content. The addition of SF promotes geopolymerization and enhances microstructural integrity, with optimal compressive strength achieved by replacing 15–30% of SF with slag. Research on thermal cracking and spalling in UHPRGC is limited, although recent studies have investigated room-temperature geopolymer concrete to decrease curing energy requirements. Some studies have reported compressive strengths of up to 175 MPa with steel fibers and 178.6 MPa with a 12.5% volume substitution of GGBS with SF. An investigation into the microstructure after 28 days of curing revealed a continuous sodium hydroaluminosilicate geopolymer gel phase in the control mix, while replacing 22.5% of fine aggregate with coarse aggregate improved the particle–geopolymer gel bond. Although the inclusion of SF can reduce flowability, it significantly enhances the material's rheological and mechanical properties. Increased steel fiber content improves the load-bearing capacity and mechanical performance of UHPRGC-S3 specimens; however, excessive fiber use may raise overall costs. Due to its high compressive strength, UHPRGC is particularly suitable for high-stress construction applications.

- GPC demonstrates unique fracture energy characteristics compared to NC. However, the microstructural changes affecting fracture toughness in UHPRGC with rubber inclusions are not well understood. Further empirical research is needed to clarify how varying rubber content influences the fracture energy of GPC relative to NC, especially at higher substitution ratios.
- The mechanical degradation of UHPGC at elevated temperatures is insufficiently studied, with limited research on the thermal stability of the C–A–S–H phase and the mechanisms responsible for spalling.
- Further research is necessary to develop environmentally sustainable curing methods and formulations for UHPRGC, specifically focusing on room-temperature curing techniques that minimize energy consumption.

6 Flexural and tensile strengths

The material demonstrates notable flexural strength, making it well-suited for scenarios that demand high

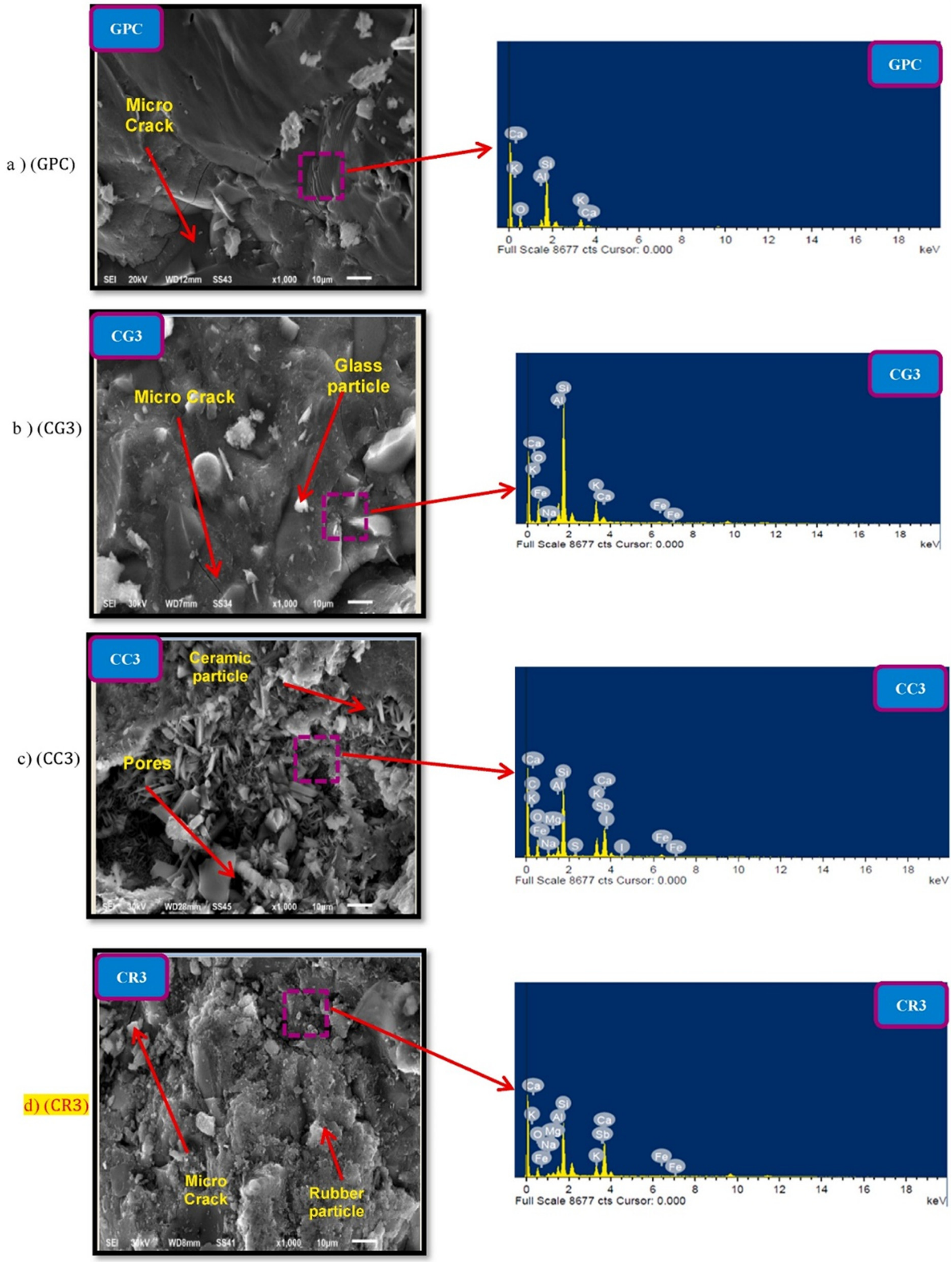

Figure 18: SEM images and EDX characterization of UHPGC (Adopted from [141]). (a) GPC, (b) CG3, (c) CC3, and (d) CR3.

resistance to bending or tensile forces. Research has shown that increasing the amount of GGBS replaced by SF in GPC leads to longer initial and final setting times as well as improved flowability [201]. Studies have found that incorporating up to 0.5% PPF by volume enhances the mechanical properties of traditional concrete [47,124,125]. Moreover, it has been observed that an increase in SF content in UHPRGC markedly boosts both its compressive and flexural strength [37]. However, despite similar compressive strengths, the ultimate flexural strengths of UHPGC are reported to be lower than those of UHPC. Specifically, when UHPGC reaches a compressive strength of about 170 MPa, its ultimate flexural strength ranges between 25 and 30 MPa, which is 25–37.5% less than that of UHPC [46]. Studies have indicated that while PPF does not significantly boost the compressive strength of concrete used in water tunnel linings when compared to SF, it considerably enhances tensile strength, flexural strength, stiffness, and energy absorption capacity [202]. Concrete samples with lower fiber volumetric percentages demonstrate higher tensile and flexural strengths than those without fibers, underscoring the role of fibers in strengthening the concrete's resistance to harsh conditions. When comparing the effects of SF, PPF, and glass fibers in concrete, it has been observed that adding fibers increases both air content and porosity, with SF-containing mixtures showing the smallest increase in air volume [203]. Figure 18 depicts the SEM micrographs and EDX analysis of UHPGC [141].

The electrical resistivity (ER) of concrete is also lowered by fiber addition, with the greatest reduction occurring with SF due to its conductive properties. The durability of GPC is enhanced by increasing SF content, which also reduces permeability and water absorption [204,205]. Studies have also highlighted that PPF controls crack propagation by mitigating plastic and drying shrinkage, which in turn decreases permeability. It is concluded that a low percentage of PPF can minimize moisture loss and early age shrinkage in concrete [206]. However, it has been found that increasing the consumption of PPF or SF can diminish the durability of high-strength concrete, particularly in SF-rich mixes [207]. The integration of either polypropylene or steel fibers into UHPC is known to improve many of its properties [149]. Typically, steel fibers are used to boost physical and chemical properties, especially tensile and flexural strengths [208]. PPF offers additional benefits such as thermal stability, chemical inertness, and resistance to corrosion, making it well-suited for the alkaline environment of concrete. Furthermore, the hydrophobic surface properties of polypropylene do not interfere with the concrete hydration process [209].

Figure 19 offers an in-depth examination of the relationship between various CR replacement ratios and changes in the tensile performance of UHPRGC [210]. Notably, the peak tensile strength of the R-50 group is 2.79 MPa, the highest recorded, exceeding that of the R-0 by 3.20%. The R-20 group exhibited a peak tensile strength comparable to that of the R-0. Conversely, the R-50 group demonstrated the lowest tensile strength at 2.16 MPa, indicating a decrease of 22.6 and 25.0% compared to those of the R-0 and R-5, respectively [211]. Generally, CR replacement of up to 20% can enhance the peak tensile strength, which contradicts some existing studies [212]. This discrepancy may arise from the distinct hydration behavior of the slag-FA UHPRGC binder material used, differing from conventional concrete [213]. Moreover, the CR particles, being smaller than 1 mm, possess a favorable particle size distribution with other materials, optimizing the

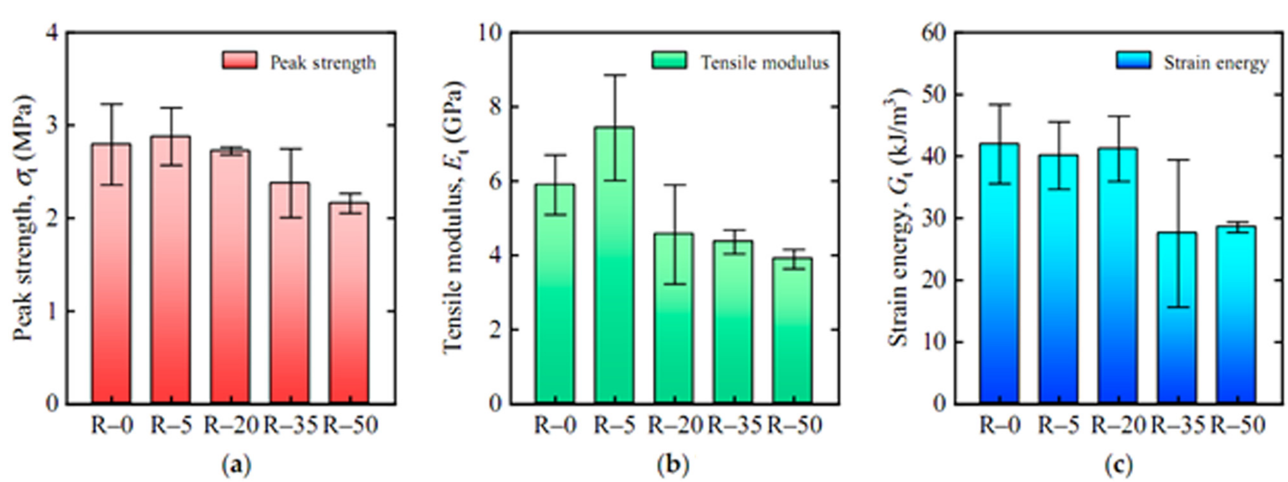

Figure 19: The consequence of replacing ratios of crumb rubber on tensile mechanical property index of UHPRGP: (a) peak strength; (b) tensile modulus; and (c) strain energy (Adopted from [210]).

internal structure when the CR replacement ratio is below 20% [210]. It is important to note that the strain energy in the R-20 and R-35 groups significantly declined compared to the other groups. This reduction may be due to the increased CR content weakening the interfacial density of UHPRGC, thereby affecting its bonding performance [213].

In summary, UHPRGC exhibits exceptional flexural strength, making it suitable for high-strength applications. Its mechanical properties can be improved by adding PPF up to 0.5%, by volume. While increasing SF content enhances compressive and flexural strengths, the ultimate flexural strength of UHPRGC remains lower than that of UHPC. PPF significantly enhances the tensile strength, flexural strength, stiffness, and energy absorption capacity, although it does not notably improve the compressive strength. The inclusion of fibers increases air content and porosity, with SF mixtures showing the least increase in air volume. Moreover, fiber addition reduces ER, particularly in SF-containing mixtures, which also improves durability by decreasing permeability and water absorption. PPF aids in controlling crack propagation by reducing plastic and drying shrinkage, further decreasing the permeability. The incorporation of polypropylene or steel fibers in UHPC enhances thermal stability, chemical inertness, and corrosion resistance.

- The relationship between GGBS and SF replacement in GPC is not well understood, particularly regarding how different ratios affect setting times, durability, and strength. Future research could identify optimal blend proportions for enhanced performance.
- Peak tensile strength in slag-FA UHPRGC varies with CR replacement ratios, indicating a need for further study on the hydration behavior. Future research should investigate the interactions between CR particles and other components during hydration and their effects on concrete properties.
- Higher CR concentration correlates with reduced strain energy in some groups, suggesting potential weakening of interfacial bonding. Future studies should explore how variations in interfacial density affect the structural integrity and performance of the material under different loading conditions.

7 Reduced shrinkage

Fiber integration generally mitigates drying shrinkage by enhancing the bond between the matrix and fibers or by managing crack development [214]. The efficacy of this control is notably higher in hybrid fiber-reinforced cementitious composites compared to single-fiber composites, owing to the diverse properties of the mixed fibers, which address cracks at varying scales more effectively. Specifically, longer fibers are efficient at bridging and controlling the expansion of larger cracks, while shorter fibers are adept at managing smaller crack growth [215]. This dual action significantly reduces drying shrinkage in the composites, a primary factor observed in certain samples that showed optimal shrinkage reduction in high-strength concrete [215]. Nonetheless, the inherent porosity of FRRC can diminish its resistance to shrinkage. Higher porosity levels facilitate easier moisture migration to the surface through the pores, consequently increasing the shrinkage strain [214].

UHPRGC typically exhibits lower shrinkage rates than traditional concrete, enhancing both its crack resistance and long-term durability. Despite UHPRGC's reduced porosity, its geopolymer binder system – particularly with high calcium content – can heighten susceptibility to freeze–thaw cycles due to autogenous shrinkage, leading to potential cracking [216]. Studies on high-strength GPC have shown increased polymerization and strength during the initial 56 freeze–thaw cycles, which diminish after 300 cycles. At this stage, compressive strength-related cracks, aligned with the load direction and induced by perpendicular flexural stress, become evident [217]. The influence of freeze–thaw conditions has thus been identified to impact flexural strength more severely than compressive strength due to early internal cracking [107]. Another research indicates significant strength reductions after undergoing various numbers of freeze–thaw cycles – specifically 225, 100, and 120 [218]. In contrast, conventional UHPC generally shows little strength variation even after 300–800 cycles. The more pronounced degradation in geopolymer binders is linked to their inherent shrinkage stresses and greater porosity [72]. Figure 16 highlights that despite the slow formation of microcracks, geopolymer samples maintain stability and exhibit strong resistance to 300 freeze–thaw cycles [217].

Studies have demonstrated that RTS fibers significantly impact the reduction of drying shrinkage in FRRC [215]. Specifically, FRRC mixes incorporating 1% RTS fiber showed marked improvement in shrinkage control over time compared to other mixes, supporting the effectiveness of the fiber bridging mechanism [219]. However, the mix designated as R10S1.5P0.5 was less effective at reducing shrinkage compared to R10S1.0P0.5, likely due to poorer compaction caused by a higher fiber content of 2% [220]. Conversely, increased doses of RTP fibers consistently improved shrinkage control, with the most significant reduction being 22.3% compared to mixes devoid of RTP fibers. This enhanced performance is attributed to the RTP fibers' ability to distribute shrinkage stresses across cracks [221]. Interestingly, all FRRC compositions outperformed plain mortar in terms of shrinkage resistance, with improvements ranging from 7.9 to 41.6%. This indicates the substantial potential of utilizing a combination of CRs, RTS fibers, and RTP fibers to decrease the drying shrinkage in plain mortar [215]. Furthermore, this reduction in shrinkage not only helps prevent cracking but also contributes to the enhanced durability of the concrete. Figure 20a shows that at day 7, the UHPGC microstructure is generally dense but contains some unreacted material [222]. As source materials dissolve more slowly, more C(N)–A–S–H gel forms, enhancing mechanical properties by day 28 (Figure 20c) [223]. The alkaline activator partially dissolves GGBS particles, creating the C(N)–A–S–H gel (Figure 20a). At day 7, rapid reactions cause minor microcracks, but by day 28, more GGBS dissolves, leading to an increase in the C(N)–A–S–H gel in UHPGC (Figure 20d). The microstructure of geopolymer concrete is closely related to its mechanical properties [36]. At day 7, UHPC exhibits a loose structure with microcavities and unreacted particles (Figure 20b) due to incomplete hydration. By day 28, the number of unreacted particles significantly decreases (Figure 20d) [222]. In summary, UHPGC production presents an environmentally friendly solution for managing industrial waste. From a sustainability perspective, UHPGC emerges as a cost-effective and eco-conscious alternative to traditional UHPC. The development of UHPGC represents a major advancement in sustainable construction materials. The integration of rubber aggregates into geopolymer matrices reduces shrinkage, enhancing the durability and lifespan of concrete structures. This shrinkage reduction is due to the flexibility of rubber particles, which alleviate internal stresses that typically lead to cracking. Moreover, the use of geopolymer binders not only improves mechanical performance but also promotes environmental sustainability by incorporating industrial by-products like FA and slag. Overall, the innovative combination of UHPRGC and UHPGC offers a promising approach for building eco-friendly, high-performance structures with enhanced dimensional stability and lower maintenance costs.

Overall, the integration of fibers in hybrid FRRC effectively mitigates drying shrinkage by enhancing the bond between the matrix and fibers and regulating crack

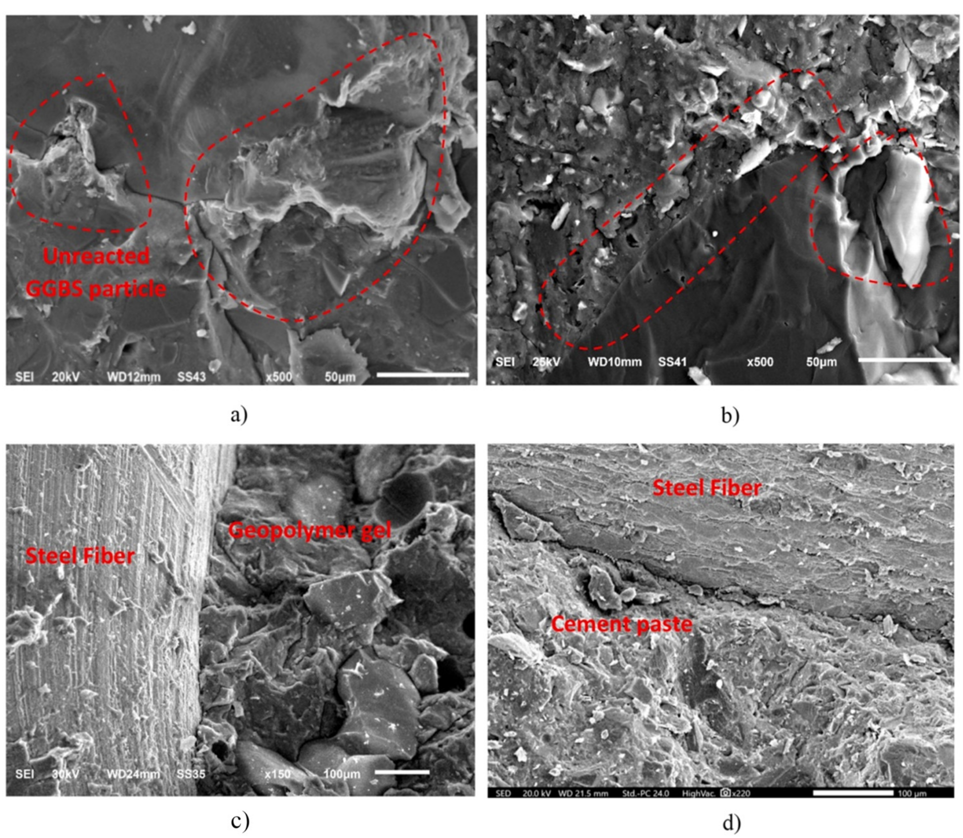

Figure 20: SEM images of UHPGC and UHPC mixtures (Adopted from [222]). (a) UHPGC at 7 days (G6SF24F3), (b) UHPC at 7 days (UHPC2F3), (c) UHPGC at 28 days (G6SF24F3), and (d) UHPC at 28 days (UHPC2F3).

development. Longer fibers bridge larger cracks, while shorter fibers manage smaller crack growth, significantly reducing drying shrinkage, especially in high-strength concrete. Although UHPRGC generally exhibits lower shrinkage rates due to reduced porosity, its geopolymer binder, particularly with high calcium content, can increase susceptibility to freeze–thaw cycles from autogenous shrinkage, potentially leading to cracking. RTS fibers notably improve shrinkage control in FRRC, with mixtures containing 1% RTS fiber showing significant enhancements over time. The combination of CR, RTS fibers, and RTP fibers further decreases drying shrinkage in plain mortar, enhancing the concrete's durability. Additionally, the production of UHPGC offers an environmentally sustainable solution for managing industrial waste, serving as a cost-effective and eco-friendly alternative to traditional UHPC.

- Recent studies have shown that the strength of high-strength GPC decreases after repeated freeze–thaw cycles. Evaluating the long-term performance of different GPC formulations, especially beyond 300 cycles, may offer valuable insights for optimizing mixtures in areas vulnerable to severe weather conditions.
- While rubber aggregates show promise in reducing shrinkage, further investigation is needed to understand the mechanisms by which they alleviate internal stresses.
- While the effectiveness of hybrid FRRC in mitigating drying shrinkage is well established, further research is needed to explore the synergistic interactions among different fiber types, investigating the optimal combinations of longer and shorter fibers for various applications, and fracture sizes could improve the performance across a range of environmental conditions.

8 Microstructural properties

The microstructural properties of UHPRGC are fundamental to its enhanced performance, influencing its strength, durability, and ductility. Understanding these microstructural features requires an in-depth exploration of the interactions between the geopolymer matrix, rubber particles, and the overall composite structure [46]. The geopolymer binder in UHPRGC is synthesized from aluminosilicate materials such as MK, slag, or FA, activated by alkaline solutions like potassium or sodium hydroxide and silicate [25]. The geopolymerization process results in a three-dimensional aluminosilicate network that forms a dense, amorphous structure. This structure is highly resistant to chemical attacks and thermal degradation, providing a robust matrix that binds the other components of the concrete. The dense nature of the geopolymer matrix is crucial in minimizing voids and porosity, which are common pathways for water and chemicals to infiltrate and damage conventional concrete [176].

Rubber particles, typically derived from recycled tires, are integrated into the geopolymer matrix, contributing significantly to the microstructure [224]. These particles vary in size and shape, creating a heterogeneous composite. The rubber particles introduce a degree of flexibility and energy absorption that is not present in traditional concrete. Microscopically, the rubber particles are dispersed within the geopolymer binder, forming a complex network [225]. The contact between the geopolymer matrix and rubber particles is critical; a strong bond at this interface ensures effective stress transfer, enhancing the mechanical performance of UHPRGC [42]. One of the notable microstructural benefits of UHPGC is its ability to resist and control microcracking [172]. Under loading conditions, micro-cracks can initiate within the concrete matrix. However, the presence of rubber particles acts as a bridging mechanism, absorbing energy and preventing the cracks from propagating rapidly [208]. This crack-bridging capability enhances the material's toughness and allows it to sustain larger deformations without significant damage. The delayed crack propagation contributes to the overall durability and longevity of the material, making it suitable for demanding applications [209].

Figure 21 shows the deconvoluted spectrum of UHPGC paste specimens cured for 28 days, focusing on the range of 1,300–800 cm^{-1} [196]. It is reported that the deconvoluted spectra reveal bands around 1,144 and 1,080 cm^{-1}, which originate from the typical Si–O stretching vibrations at Q4 and Q3 sites [226]. It is generally accepted that the Si single bond O stretching vibration at the Q2 site produces the band near 990 cm^{-1} [227]. The band at 870 cm^{-1} is commonly attributed to Si–O terminal vibrations [226]. In sodium-based geopolymer systems, the Si–O stretching vibration in Si–O–Na structures is responsible for the band at 933–954 cm^{-1} [226]. Sodium ions, acting as common network modifiers, directly influence the non-bridging oxygen atoms in the first coordination sphere of silicon atoms, which is closely linked to the distribution of structural units (SiQn, where n = 0–4) in sodium silicate gels [228]. This interaction might explain the variation in the bands occurring between 1,031 and 1,038 cm^{-1} [229].

The porosity and density of UHPGC are key microstructural characteristics that influence its performance. The geopolymer binder's dense nature, combined with the optimized mix design of UHPC, results in a composite with minimal voids [209]. This reduced porosity plays a crucial role in improving the mechanical properties and durability of the concrete. Lower porosity restricts the penetration of water and harmful chemicals, which are key contributors to the deterioration of traditional concrete [230]. As a result, UHPRGC demonstrates excellent resistance to freeze–thaw cycles, sulfate attacks, and other environmental challenges. Additionally, the ITZ between the rubber particles and the geopolymer matrix is a vital aspect of its microstructure. In conventional concrete, the ITZ is often considered the weakest area due to the presence of micro-cracks and voids [231]. In UHPRGC, the geopolymer binder and rubber particles form a more cohesive ITZ, reducing the likelihood of defects. A strong ITZ ensures effective load transfer between the matrix and the rubber particles, contributing to the composite's overall strength and ductility [231]. This robust interfacial bonding is essential for the material's high-performance characteristics.

At the nanoscale, the geopolymer matrix of UHPRGC contains a network of aluminosilicate gel phases, primarily composed of N–A–S–H. This gel phase is accountable for the high compressive strength and durability of the geopolymer binder [232]. The presence of rubber particles does not significantly disrupt the formation of this gel phase but instead complements it by introducing energy-dissipating features. Advanced analytical methods, including SEM and transmission electron microscopy, show a uniformly distributed gel phase with few micro-cracks and a compact network structure [190]. This nanoscale organization is

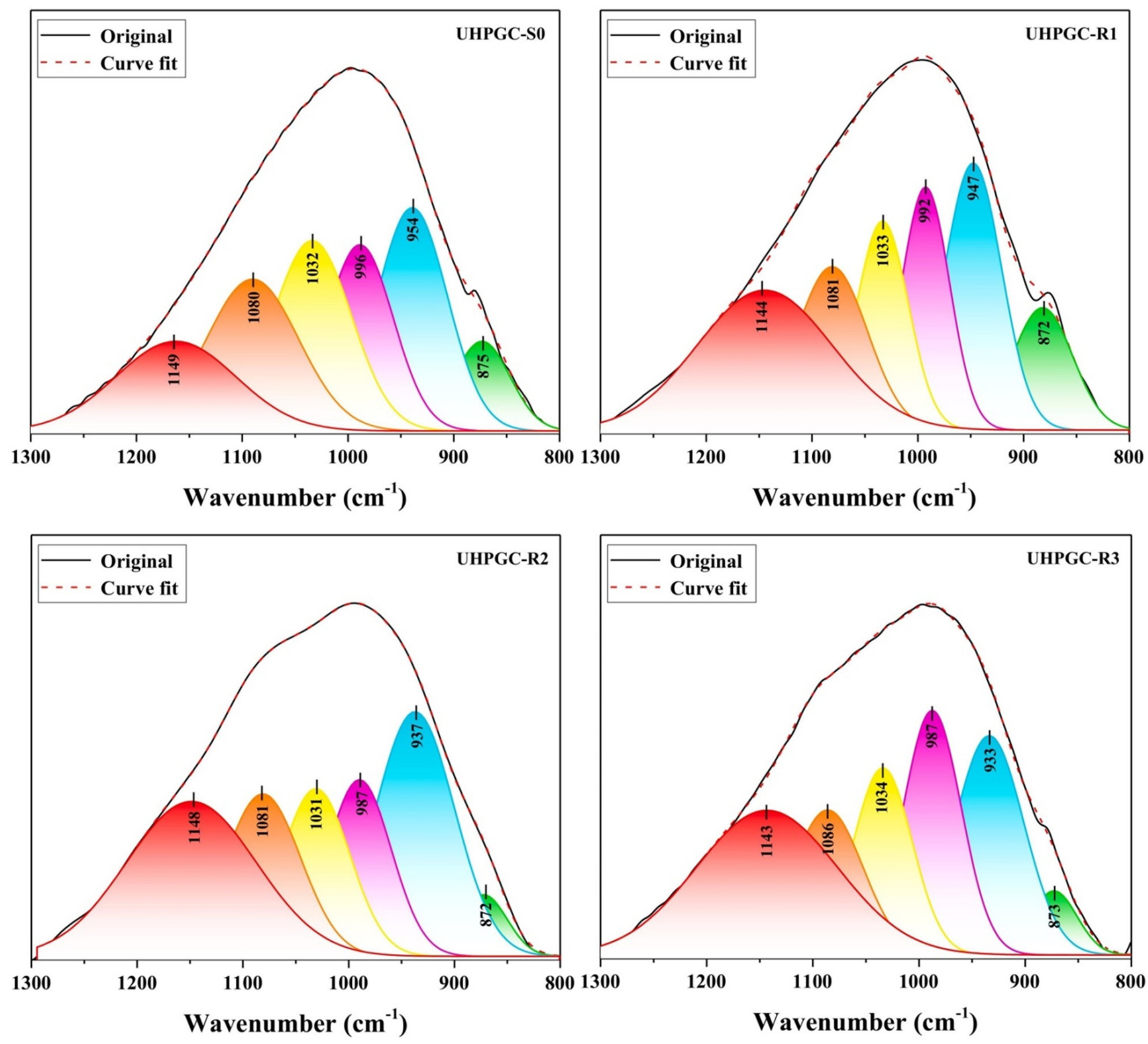

Figure 21: Deconvolution spectra of 28-day cured UHPGC paste specimens over 1,300–800 cm^{-1} (Adopted from [196]).

pivotal for the composite's superior performance [209]. Also, mechanical reinforcement provided by the microstructural arrangement of rubber particles within the geopolymer matrix is another critical aspect [208]. As illustrated in Figure 22a, a high slag dosage resulted in a denser microstructure with fewer internal defects like pores and micro-cracks.

At a slag dosage of 0.193, incompletely reacted FA indicates incomplete polymerization. However, increasing the slag dosage to 0.731 achieved a significantly denser microstructure. The ITZ between the binding phase and aggregate also became denser and less distinct, improving bonding with aggregates [233]. Figure 22b shows the effect of the Si/Al ratio on G-UHPC's microstructure at a CaO dosage of 0.3. A Si/Al ratio of 3 produced a denser microstructure than a ratio of 4.5. At a Si/Al ratio of 3, the ITZ between the matrix and aggregate was less distinct, with fewer pores and unreacted materials. Increasing the Si/Al ratio to 4.5 led to more silicates, aluminates, and unreacted slag, resulting in a less dense microstructure. Figure 22c and d illustrates that the ITZ between G-UHPC and the steel fiber was nearly flawless, similar to UHPC, indicating

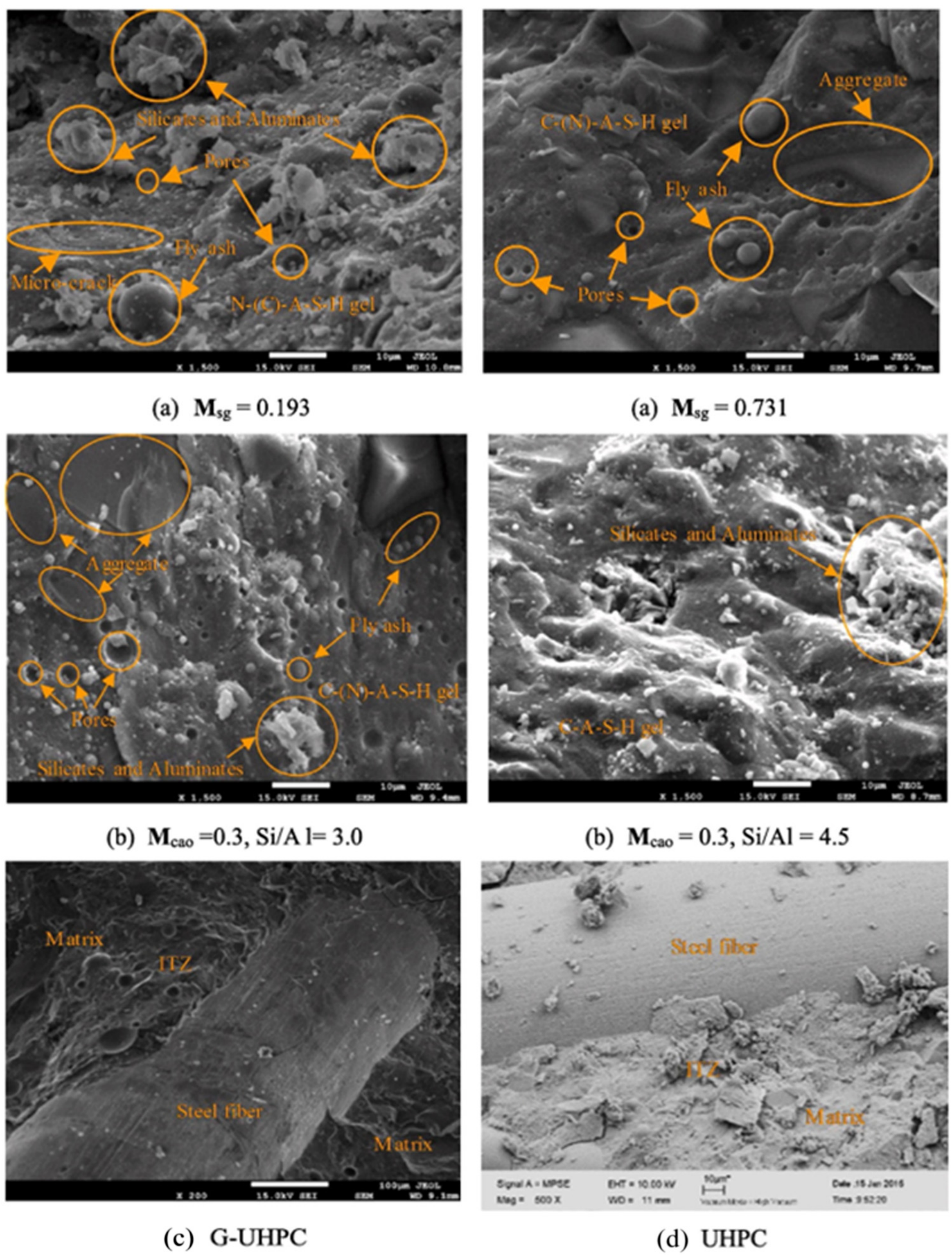

Figure 22: The effect of (a) slag and (b) Si/Al ratio microstructures of UHPGC, and (c) the interaction zone among the steel fiber of UHPGC and (d) UHPC (Adopted from [129]).

excellent bonding. This flawless ITZ improved the mechanical behavior of G-UHPC by ensuring synergy between the concrete matrix and the steel fibers. The inherent elasticity and toughness of rubber particles enhance UHPGC's ability to withstand dynamic loads and impact forces. This mechanical reinforcement at the microstructural level translates to improved macro-scale properties, such as increased impact resistance and extended fatigue life. Structures made from UHPRGC can better absorb and dissipate energy, making them ideal for applications in seismic regions or where blast resistance is required [111,159].

From an environmental perspective, the microstructural properties of UHPRGC contribute to its sustainability. The use of recycled rubber particles addresses waste management issues and reduces the carbon footprint associated with concrete production [172]. The dense, durable geopolymer matrix requires less maintenance and repair over its lifespan, further reducing environmental impact [158]. Moreover, the production of geopolymer binders generates significantly lower CO_2 emissions compared to traditional Portland cement, making UHPRGC an environmentally friendly alternative [177]. In brief, the microstructural properties of UHPRGC are characterized by a dense geopolymer binder matrix, well-integrated rubber particles, and a strong ITZ. These microstructural features contribute to the material's enhanced mechanical properties, durability, and sustainability. The rubber particles provide energy absorption and crack-bridging capabilities, while the geopolymer binder ensures a dense, chemically resistant matrix. Together, these properties make UHPRGC a promising material for various advanced construction applications, offering both performance and environmental benefits.

Ultimately, the UHPRGC is formulated using a geopolymer binder derived from MK, slag, or FA, activated by potassium or sodium hydroxide and silicate. This composition creates a dense, amorphous matrix that exhibits high resistance to chemical and thermal degradation. The incorporation of recycled tire rubber particles enhances the microstructure, resulting in a heterogeneous composite that promotes flexibility and energy absorption. A strong bond between the rubber particles and the geopolymer matrix facilitates effective stress transfer, thereby improving the mechanical properties of UHPRGC. The performance of UHPRGC is influenced by its porosity and density, with an optimal mix design minimizing voids and enhancing durability against water and chemical intrusion. The ITZ between the rubber particles and the geopolymer matrix is crucial for mitigating flaws and enhancing strength and ductility. Due to the elasticity and hardness of the rubber particles, UHPRGC demonstrates superior performance in seismic and blast resistance applications. Moreover, the utilization of recycled rubber significantly contributes to environmental sustainability by reducing waste and lowering the carbon footprint associated with concrete production, as geopolymer binders emit less CO_2 compared to traditional Portland cement.

- While the qualitative benefits of the interactions between the geopolymer matrix and rubber particles are recognized, there is a lack of quantitative data regarding their effects on the mechanical properties of UHPRGC. Future research should systematically investigate how variations in the rubber particle size, shape, and distribution affect key properties such as strength, ductility, and energy absorption.
- The importance of the ITZ between rubber particles and the geopolymer matrix is highlighted; however, further research is essential to fully elucidate its microstructural properties and mechanics. Future studies should focus on the evolution of the ITZ under different environmental conditions and loading scenarios, as well as how modifications to the ITZ can enhance the overall performance of UHPRGC.

9 Fracture behavior

It is reported that various factors affect the fracture behavior of FRC, including the characteristics of the aggregate/matrix, the strength of bonding between aggregate–matrix and fiber–matrix, and the properties of the fibers themselves [54,234]. Previous research has explored the fracture properties of GPC, focusing on how different elements impact these properties [235]. It has been observed that GPC generally exhibits higher fracture energy compared to OPC [236]. However, studies examining the detailed fracture behavior of steel–PPF-reinforced UHPRGC are still emerging and limited in scope [205]. Research has modeled the combined impact of fibers and the matrix in UHPC, suggesting that an optimal fiber content should be determined for mixes with substantial fiber volumes [237]. Investigations into the effects of monofilament and fibrillated PPFs, as well as monofilament polyolefin fibers on GPC, have shown significant enhancements in flexural toughness. In particular, 19 and 51 mm fibrillated PPF fibers improved flexural toughness by 1.5 and 2.5 times, respectively, while the inclusion of 48 and 55 mm polyolefin fibers increased it by 5.6 and 6.3 times compared to plain GPC [238]. These mixtures also exhibited increased fracture energy. Further studies indicate that increasing the volume of steel fibers in slag-based UHPGC boosts both fracture energy and toughness [235]. Maximum fracture energy was observed with a 1.5% fiber volume fraction, and fracture toughness of the mortar quadrupled with a 2% volume fraction. According to Figure 23, increasing the modulus of the alkali activator in the concrete leads to greater shrinkage, which in turn causes more initial micro-cracks [235]. These initial defects can negatively impact strength gains but result in a more ductile matrix that absorbs more energy during crack propagation, enhancing overall toughness. Research comparing GPC and conventional concrete, both with a specified compressive strength of 30 MPa, reveals that increases in the volume percentage of steel fibers enhance both fracture energy and toughness across concrete types [54]. The most significant enhancement was recorded in a mix containing a 0.75% volume fraction of fiber, with GPC consistently exhibiting superior fracture energy and toughness compared to conventional concrete.

Moreover, AAS steel FRC demonstrated a fracture toughness three times higher than that of steel fiber-reinforced ordinary Portland cement concrete [205]. Further findings indicate that adding up to a 0.5% volume fraction of PPFs and SF to FA-based GPC significantly boosts its flexural toughness, especially in heat-cured specimens compared to those cured under ambient conditions [52]. Studies also show that end-deformed (hooked) SF enhances flexural toughness more effectively than straight or length-deformed fibers. When SF and PPF volumes are increased in sodium carbonate-activated slag mortar, the fracture parameters improve, with SF-enriched mixes displaying superior properties such as crack resistance and ductility over those containing only PPF [239]. Expanding the research to UHPGC, increases in SF volume from 1 to 3% led to increases in fracture energy by 56.5 and 45%, respectively [49] (Figure 4). Similarly, increasing the PPF volume from 1 to 3% also increased the fracture energy, with SF notably enhancing the tensile strength, flexural toughness, and resistance to shrinkage and cracking [240]. PPF is distinguished by its high melting point, chemical inertness, hydrophobic nature, and stability in alkaline environments, which contribute to controlling shrinkage cracking [191]. It is also among the most affordable and readily available fibers [241] (Figure 24).

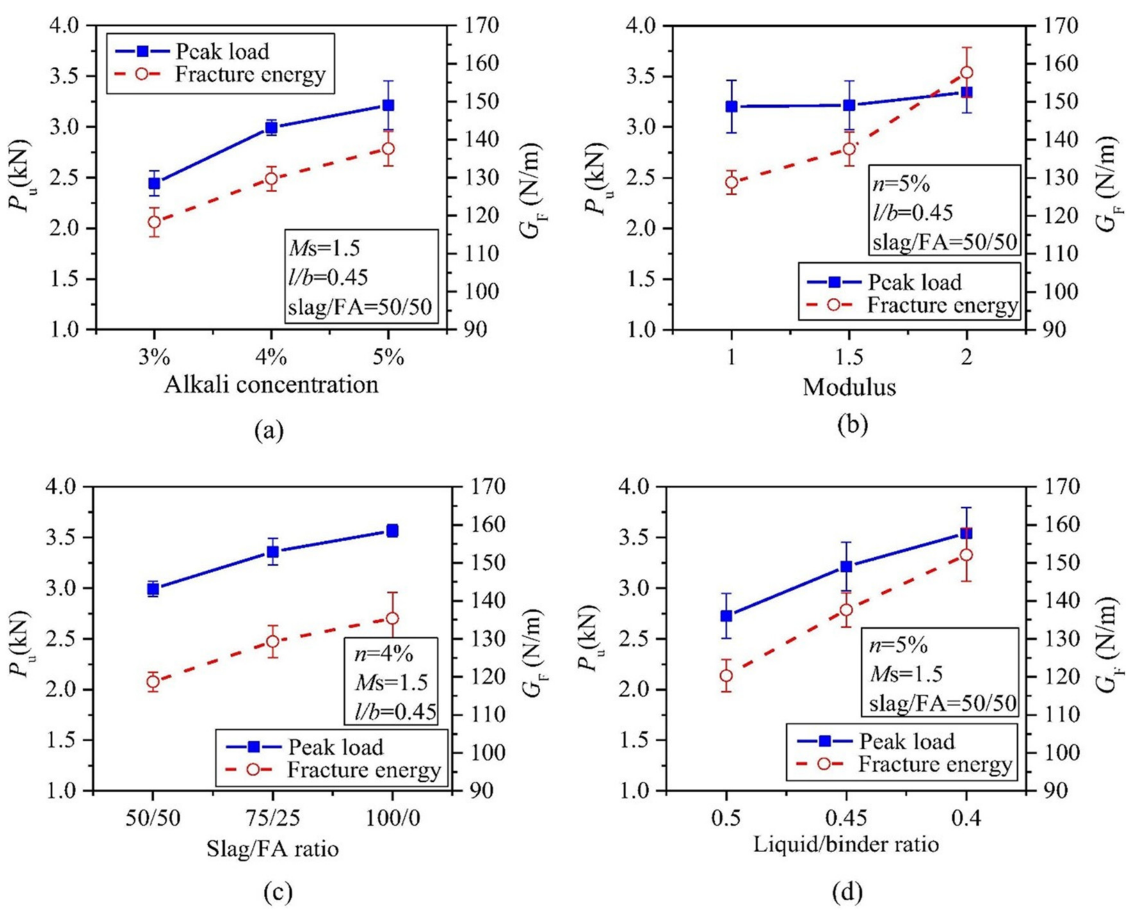

Figure 23: Parametric effects on fracture energy and peak load of the samples (Adopted from [235]). (a) Alkali concentration, (b) modulus, (slag/FA ratio, and liquid/binder ratio.

The integration of SF and PPF, and specifically the substitution of 0.25% of SF volume with PPF, not only reduced mechanical properties but also improved the durability of UHPGC, raising questions about how these fibers interact to influence fracture properties [242]. Figure 25 illustrates that fiber addition and increased volume fraction lead to greater mid-span deflection and a more ductile response post-peak load, enhancing fracture energy [240]. Analysis of load–displacement curves after the peak load reflects the concrete's enhanced resistance to crack growth and propagation [243]. Hooked-end steel fibers, when added at varying volumes, showed that greater fiber fractions directly correlate with higher fracture energies [244]. Orientation of fibers perpendicular to the crack was found to be most effective in inhibiting micro-crack growth, enhancing fracture energy [245]. In contrast, in high water-to-cement ratio concretes, SF tends to pull out of the matrix, whereas in low ratio settings, fibers with lower tensile strength are likely to break [246]. Figure 18 illustrates the results of optical microscopy observations on UHPGC samples containing varying amounts of SF [49]. The images reveal that hardened geopolymer pastes are present on the surface of steel fibers, but this phenomenon is not evident in specimens with 10% SF content. The findings from this study suggest that the mechanical properties of UHPGC are significantly influenced by the fiber–matrix bonding, which is related to the SF content, supporting conclusions from previous research [247].

Figure 26 demonstrates that adding 1, 1.5, and 2% fiber volumes significantly increases fracture energy, with declines observed after substituting PPF into the mixes [240]. The inclusion of rubber in RGPC as a replacement for fine aggregates led to increases in energy dissipation capacity by 31.5–53.3% for rubber replacement ratios between 5 and 20% [213]. However, exceeding a 10% rubber content in slag-FA-based low-strength rubber GPC adversely affected compressive performance [170]. Replacing fine aggregates with rubber in UHPGC increased porosity and pore size, which negatively impacted mechanical performance as rubber content increased [171]. The unexplored uniaxial compressive behavior of UHPRGC and the need to verify the environmental and economic benefits of incorporating rubber underscore ongoing research directions [171]. This displays that the efficacy of FRC hinges on the interaction between the matrix's resistance and the fibers' tensile strength. The fracture behavior of UHPRGC shows enhanced toughness and ductility due to the energy-absorbing rubber particles, reducing crack propagation. In contrast, UHPGC exhibits superior compressive strength but with more brittle fractures. The combination of rubberized and non-rubberized GPC offers a balanced solution, providing both high fracture toughness and rigidity

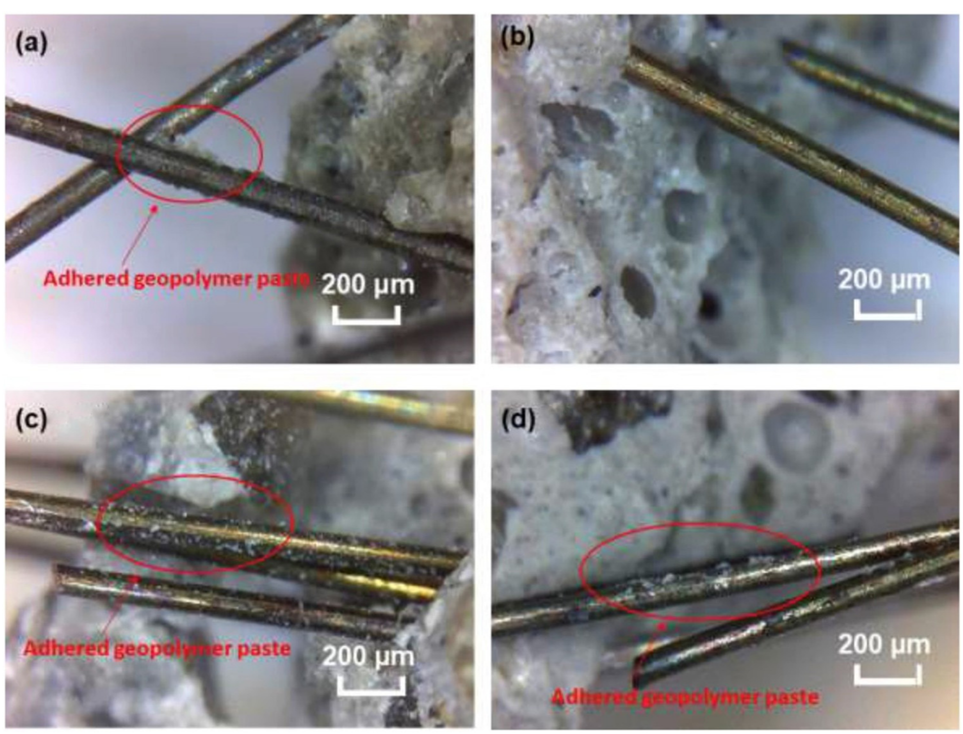

Figure 24: Observation of the crack zone of UHPGC with optical microscopy (Adopted from [49]). (a) 5%, (b) 10%, (c) 20%, and (d) 30%.

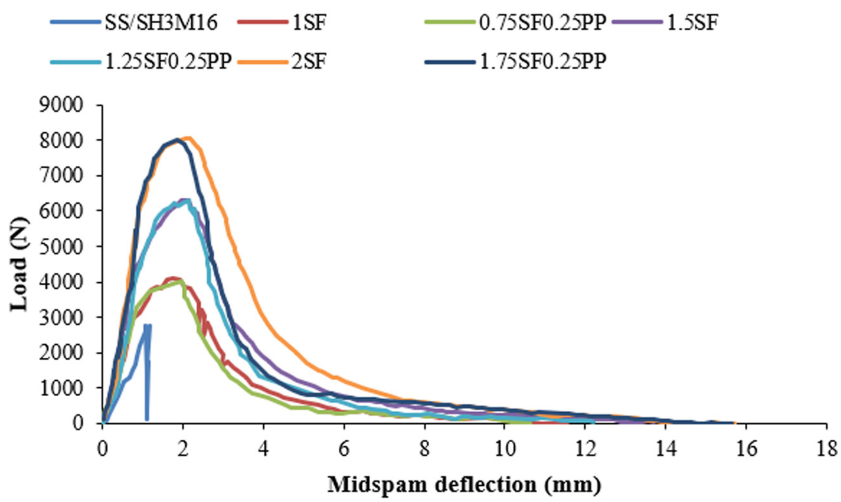

Figure 25: Load-mid-span deflection curves for different mixtures (Adopted from [240]).

for advanced, durable, and sustainable concrete structures. Ultimately, the enhanced fracture properties of these innovative materials pave the way for more resilient and durable concrete structures, contributing to the advancement of sustainable construction technologies.

In brief, GPC has demonstrated superior fracture energy compared to OPC. However, there is a scarcity of research focusing on the fracture characteristics of UHPRGC reinforced with steel and PPFs. Existing studies highlight the importance of identifying an optimal fiber content for mixtures with elevated fiber volumes. Particularly, the addition of steel fibers significantly enhances both fracture energy and toughness in slag-based UHPGC, with a 0.75% fiber volume fraction yielding the most substantial enhancements relative to traditional concrete. Moreover, AAS steel FRC exhibits fracture toughness that is three times greater than that of Portland cement concrete. The inclusion of 0.5% volume of polypropylene and steel fibers in FA-based GPC substantially improves flexural toughness, especially in heat-cured specimens. Conversely, substituting 0.25% of steel fiber volume with PPFs can lead to a decline in mechanical properties, although it enhances the durability of UHPRGC. Additionally, the mechanical performance of UHPGC is influenced by the bonding between the fibers and the matrix, which correlates with the SF content. Despite the limited research on the fracture behavior of steel and PPF-reinforced UHPRGC, further investigation is necessary to elucidate the mechanisms of fracture initiation and propagation. Employing advanced imaging techniques, such as SEM or digital image correlation, could provide valuable insights into the characterization of fracture surfaces and associated processes.

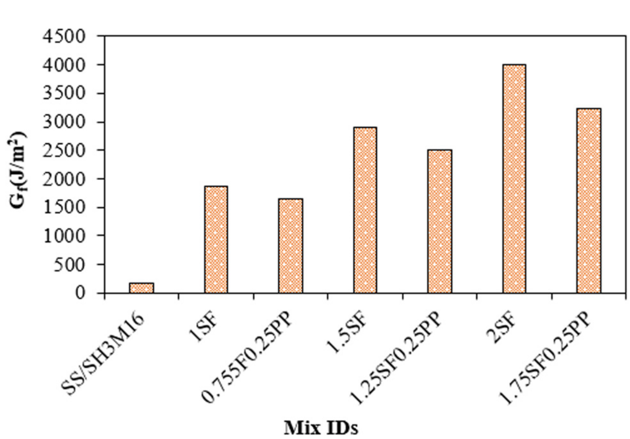

Figure 26: G_f variation versus mixtures (Adopted from [240]).

10 Ductility properties

Overall, the ductility of UHPGC and UHPRGC is notable for its contribution to structural resilience and safety. UHPRGC demonstrates increased ductility, resulting from the combined effects of rubber particles and the geopolymer matrix [248]. The incorporation of rubber particles within the concrete matrix greatly enhances its capacity to deform under stress without breaking [268]. The ductility of UHPRGC is significantly better than that of traditional concrete due to several critical factors [249]. First, the inclusion of rubber particles in the geopolymer matrix significantly enhances the ductility of the concrete. Rubber particles, typically sourced from recycled tires, are flexible and can absorb substantial energy during deformation. These rubber particles act as flexible inclusions that bridge micro-cracks, delaying their propagation and thus enhancing the material's toughness and energy absorption capacity [240].

Figure 27 presents the stress–strain curves of UHPRC with varying rubber contents and strain rates [17]. The data show that maximum compressive stress generally increases with strain rate across all UHPRC mixes, consistent with previous studies on the strain rate hardening effect of concrete [250]. At first, the stress–strain curves are linear, signifying elastic deformation, before gradually bending as they approach the peak stress. Post-peak, the compressive stress decreases, with UHPC exhibiting ductile behavior due to steel fiber bridging, unlike the brittle post-peak behavior of normal strength concrete [250]. Three scenarios were observed. Scenario 1: (i) stress decreases with an outward bowing curve, (ii) stress decreases linearly, and (iii) stress plateaus before dropping. Scenario 2: (i) occurred at lower strain rates, (ii) at higher strain rates, and (iii) with high strain rates and high rubber content (40%) [17]. Scenario 3: (i) involved a few major cracks, while (ii) and (iii) showed full-length cracks with uniform width expansion [17].

Similarly, UHPGC demonstrates excellent strain hardening behavior, allowing it to undergo substantial deformation before reaching failure [2]. This flexibility allows the concrete to withstand greater strains before failing, which is crucial in applications where the material is subjected to dynamic loads or impacts [61]. The rubber particles effectively act as energy dissipators, distributing stress more evenly throughout the matrix and reducing the likelihood of sudden brittle failure. Moreover, the rubber particles contribute to crack bridging within the concrete. It is reported that when micro-cracks develop under stress, the rubber particles help bridge these cracks, preventing them from propagating rapidly [85]. This crack-bridging mechanism delays the onset of significant damage and allows the concrete to maintain its integrity under higher strains. The delayed crack propagation and increased crack resistance are essential for enhancing the overall toughness and durability of the material [124].

The strain-hardening behavior observed in UHPGC is another critical aspect of its ductility, as strain hardening refers to the material's ability to withstand increasing loads even after initial yielding [251]. In the case of

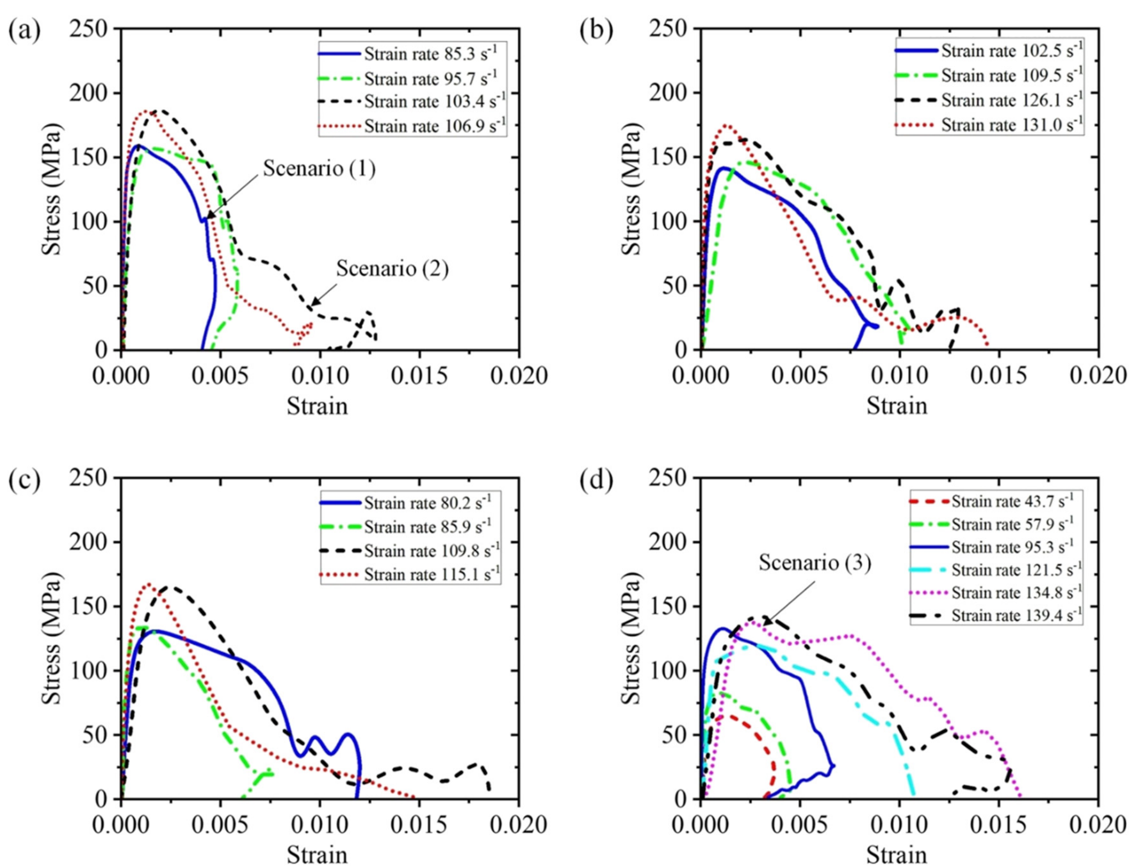

Figure 27: Comparison of stress-strain curves of UHPRC at different strain rates for different rubber contents: (a) 0%, (b) 10%, (c) 20%, and (d) 40% rubbers (Adopted from [17]).

UHPRGC, the rubber particles and the geopolymer matrix can work together to provide this property [252]. As the concrete deforms, the rubber particles stretch and absorb energy, while the geopolymer matrix undergoes plastic deformation. This combined effect allows UHPRGC to sustain higher loads and larger deformations, making it particularly suitable for structures subjected to extreme loading conditions [85].

Moreover, the geopolymer matrix itself contributes to the enhanced ductility of UHPRGC [252]. Geopolymer binders, synthesized from industrial byproducts such as slag and FA, provide superior long-term durability and chemical resistance compared to traditional Portland cement [252]. The amorphous structure of geopolymer binders allows for greater flexibility and deformation capacity, which complements the rubber particles' energy-absorbing properties [253]. This results in a composite material with a unique ability to resist cracking and withstand high strains without losing its structural integrity. The improved ductility of UHPRGC also has significant implications for its practical applications [254]. In earthquake-prone regions, it is revealed that structures made from UHPGC can better absorb and dissipate seismic energy, reducing the risk of catastrophic failure [255]. From Figure 28, it can be observed that increasing the rubber replacement ratio leads to the gradual formation of saturated cracks, thereby enhancing tensile ductility [186]. The incorporation of rubber lowers the matrix toughness, which further boosts the tensile ductility of UHPRC. On a microscopic level, results from the single-crack tensile test indicated that longer fibers substantially increase fiber-bridging strength, thereby enhancing the tensile ductility of UHPRC [186].

The addition of rubber slightly raises the fiber-bridging strength, possibly due to the bridging effect of PR particles or improved fiber dispersion, resulting from the increased viscosity of the mortar [256]. Longer fiber lengths and higher rubber replacement ratios notably elevate the PSH indices, signifying enhanced ductility. Conversely, very short fiber lengths do not achieve the desired

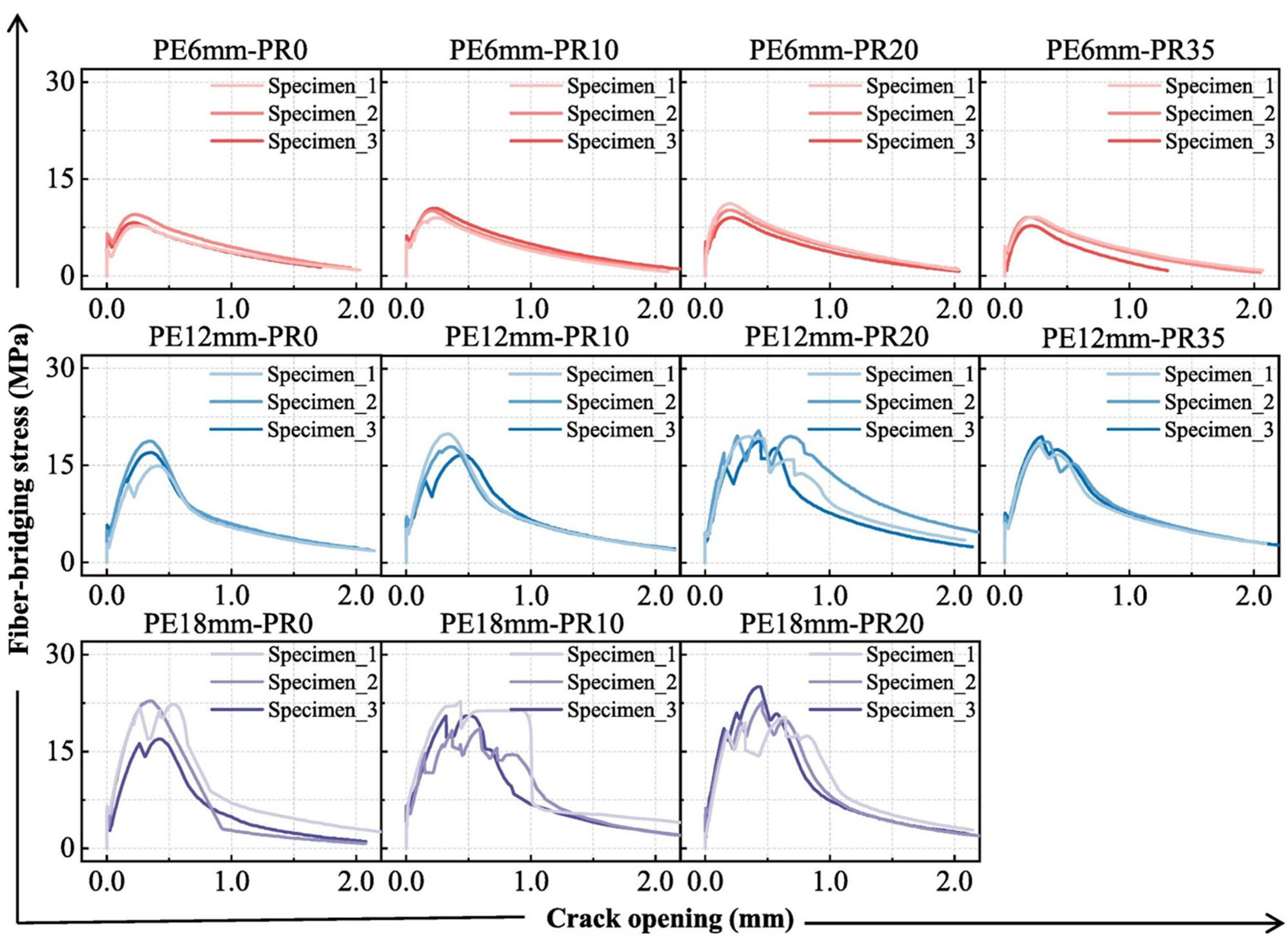

Figure 28: Pseudo-strain-hardening and fiber-bridging stress-crack opening indices of UHPRC (Adopted from [186]).

multiple cracking and steady-state cracking characteristics observed in ECC [252], likely due to inadequate fiber embedment length. An excessively high rubber replacement ratio detrimentally affects the tensile ductility of UHPRC [186].

Likewise, in applications requiring blast resistance, such as military or critical infrastructure, UHPRGC's ability to withstand high-impact forces and deformations makes it an ideal material choice [26,257,258]. The enhanced ductility also translates to improved fatigue resistance, extending the lifespan of structures exposed to cyclic loading [26]. This improved ductility makes UHPRGC particularly suitable for applications requiring high impact resistance and energy dissipation, such as in earthquake-prone regions or for blast-resistant structures [259]. In summary, the ductility characteristics of UHPGC stem from the combined effect of rubber particles and the geopolymer matrix [85]. The rubber particles contribute flexibility and energy absorption, while the geopolymer binder improves toughness and resistance to cracking. This combination leads to a material with exceptional strain-hardening behavior, crack-bridging capabilities, and overall durability. UHPRGC's enhanced ductility makes it a promising material for various advanced construction applications, offering both performance and sustainability benefits. Overall, the ductility properties of UHPGC and UHPRGC are notable for their contribution to structural resilience and safety. UHPGC exhibits exceptional ductility due to its dense microstructure and the strong bond between the aggregate and geopolymer matrix. The incorporation of rubber aggregates in UHPRGC further enhances ductility by introducing flexibility and energy absorption capabilities. This combination allows UHPRGC to withstand higher deformation under stress without significant loss of strength, making it particularly suitable for seismic-prone regions and applications requiring enhanced impact resistance, contributing to the development of safer and more resilient structures. Figure 29 shows the most potential benefits of UHPRGC products.

UHPGC combines the outstanding mechanical properties of UHPC with the ecological benefits of geopolymer technology, representing a practical and sustainable solution for contemporary construction challenges. In contrast to conventional UHPC, which depends significantly on cement clinker and emits considerable volumes of CO_2 during fabrication, UHPGC utilizes aluminosilicate-rich industrial byproducts (*e.g.*, FA or ground granulated blast furnace slag) activated by alkaline solutions. This culminates in a significantly diminished carbon footprint and reduced embodied energy [222]. Furthermore, UHPGC can incorporate recycled materials, enhancing its sustainability profile. A principal advantage resides in its capacity to achieve elevated compressive strength, frequently attaining up to 133 MPa at day 28, placing it on par with numerous cement-based UHPC formulations [222]. Although its flexural and tensile strengths may be slightly inferior, these characteristics are amenable to deliberate enhancement through meticulous optimization of mix design and strategic reinforcement, such as the inclusion of fibers or the adjustment of the binder-to-aggregate ratio [179]. This adaptability in mechanical performance optimization renders UHPGC advantageous for various construction applications that necessitate both strength and durability.

Capitalizing on UHPGC's essential strengths, adopting three-dimensional (3D) printing demonstrates the transformative potential for lightweight, modular construction methodologies. Robotic 3D printing, for example, facilitates precise layer-by-layer deposition that can encapsulate intricate geometries and complex architectural forms without a traditional framework [261,262]. This precision mitigates material waste since each component is fabricated to exact specifications, and promotes mass customization, a paradigm in which structural elements can be tailored to design and performance criteria. Additionally, the rapid setting characteristics of geopolymer binders are well-suited to automated printing processes, permitting the extruded layers to maintain their shape and bond effectively with

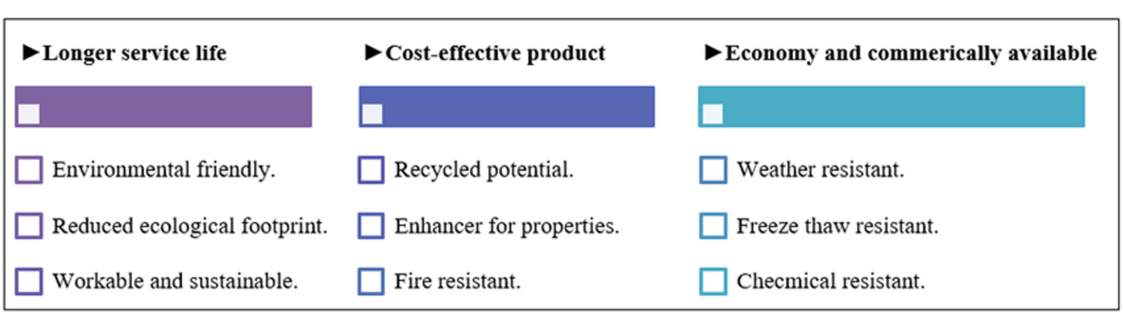

Figure 29: Most potential benefits of UHPRGC products (Adapted with improvements from [260]).

subsequent layers. When amalgamated with quaternary blended mixes (*e.g.*, FA, slag, SF, and other pozzolans), the printability and mechanical integrity of the finished structures can be substantially enhanced [263]. This customized approach guarantees that the rheology, setting behavior, and early age strength satisfy the rigorous demands of 3D printing, thus expanding the scope of applications for UHPGC in practical construction contexts.

To summarize, UHPRGC offers enhanced ductility due to the interaction between rubber particles and the geopolymer matrix. The rubber particles absorb energy, bridge micro-cracks, and delay crack propagation, improving toughness, strain hardening, and energy absorption. This prevents brittle failure and maintains structural integrity under higher loads. Moreover, UHPRGC's geopolymer matrix provides greater durability and chemical resistance than Portland cement, thanks to its amorphous structure and the energy-absorbing properties of rubber. Its high ductility, compact microstructure, and crack resistance make it ideal for seismic and impact-resistant applications, supporting safer and more sustainable construction practices.

11 Sustainability

UHPRGC exhibited superior performance compared to conventional concrete, including faster compressive strength development and improved bonding strength between the reinforcement and paste, as well as between the aggregate and paste [264]. However, UHPRPCs also have some limitations, such as high brittleness, vulnerability to cracking, and significant shrinkage [43,45,48]. These challenges can be addressed by incorporating fibers. While substantial research has been done on the mechanical properties of UHPRGC using ordinary Portland cement with various admixtures, the study of SF and PPF's effects on the strength and durability of UHPRGC, particularly in relation to chloride ion penetration resistance, is still in its early stages.

All concrete mortars typically involve a significant cement content, challenging the sustainability goals of modern construction due to cement's extensive carbon footprint [265]. Cement production is responsible for about 12–15% of global energy consumption and 5–8% of worldwide CO_2 emissions [104]. To mitigate these impacts, there is a growing trend toward substituting conventional aggregates in concrete with industrial waste products such as CR, which helps decrease emissions of CO_2 and SO_2 [266]. Recycled tire products include steel fibers, CR, rubber powder, and occasionally, rubber fibers, derived from components like carbon black, synthetic and natural rubbers, and textile or metal reinforcements found in tires [267]. Despite their potential, recycled rubbers are minimally used in construction, representing only 5% of their applications [268]. However, Figure 30 provides detailed quantitative data that can be used to estimate both the CO_2 emissions and embodied energy associated with the cementitious materials utilized in the composition of UHPGC [42,231,269,270].

It has been observed that using CR as a substitute for fine and coarse aggregates in concrete influences its

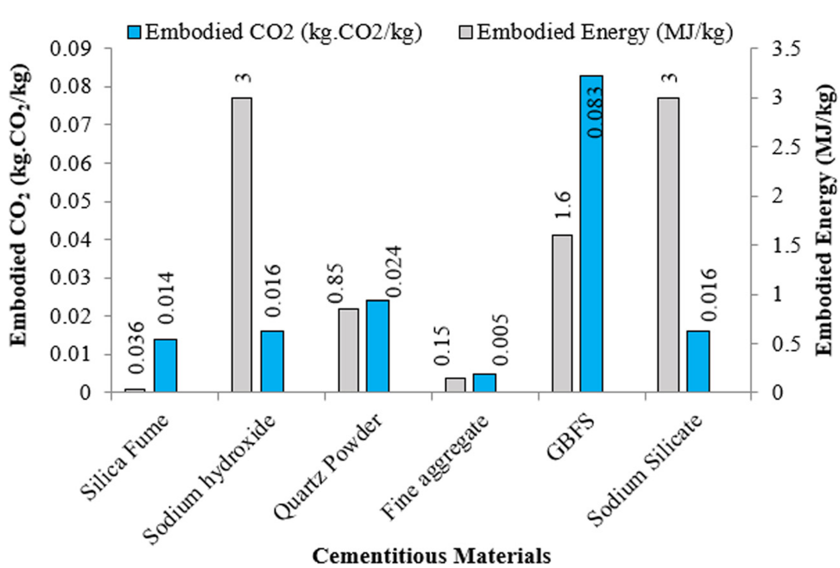

Figure 30: The CO_2 and energy emissions of cementitious materials used in the mix design of UHPGC (Raw data obtained from [42,231,269,270]).

properties [265]. Although it reduces certain mechanical properties, such as compressive, flexural, and tensile strength, as well as durability factors like moisture absorption and chloride ion permeability [104], it improves ductility, energy dissipation, and thermal and acoustic insulation [271]. Research has been directed toward optimizing the use of finer rubber particles, such as rubber fibers and powder, to enhance the durability of RuC. These additives have been shown to improve the concrete's fracture resistance and resistance to chloride ion penetration, while also increasing water permeability and carbonation depth. However, finding the ideal rubber replacement ratio involves balancing strength and durability to meet the needs of specific applications [272].

Despite considerable research, the adoption of GPCs and alkali-activated materials is limited by challenges associated with using highly corrosive liquid alkaline activators. This has led to increased use of solid activators like sodium metasilicate anhydrate, which can be mixed similarly to OPC. Ambient temperature curing of one-part GPC has been shown to attain compressive strengths up to 107 MPa at day 28 [273]. GPC and alkali-activated materials are recognized for their high thermal resistance, up to 1,350°C, and significantly enhanced acid resistance, offering a cost-effective alternative to traditional UHPC [274]. These materials are promising for high-temperature ceramics, precast applications, eco-friendly concrete binders, fire-resistant coatings, and hazardous waste encapsulation [275]. Figure 31 presents the advantages of advanced UHPRGC integrated with FA-GPC.

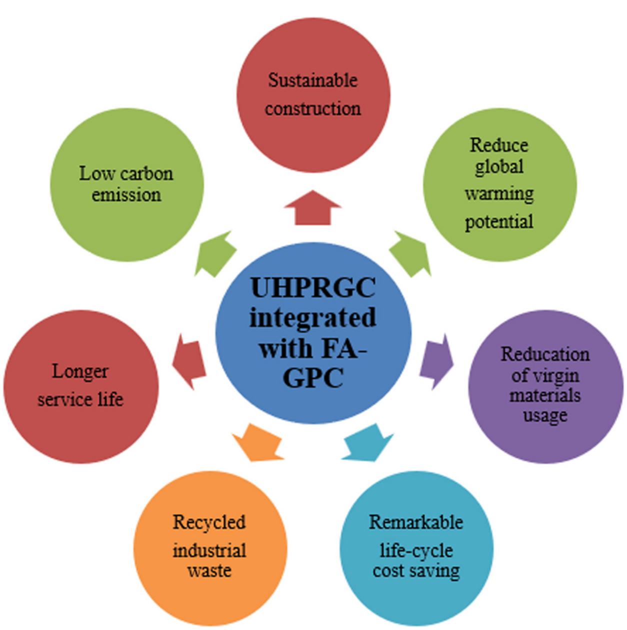

Figure 31: Advantages of advanced UHPRGC integrated with FA-GPC products (Adapted from [41]).

The transportation industry's growth has led to an increase in vehicle numbers and, consequently, a surge in waste tires, with about 100 million tires discarded annually worldwide [276]. Currently, nearly four billion waste tires populate landfills and stockpiles [277]. This has spurred extensive research into using processed waste products as partial or full substitutes in concrete, driven by the rapid production rate and mineral content of concrete [278]. As vehicle numbers increase, the environmental issues associated with discarded rubber become more pressing, leading to innovative RuCs created by replacing natural aggregates in OPC-based concretes with rubber particles [26]. Approximately 86% of the scrap tires are recycled through various methods like retreading, energy recovery through incineration, pyrolysis for gas and carbon black production, or shredding for use in asphalt, concrete, and polymers [279]. These recycling practices not only mitigate environmental harm but also stimulate economic growth across several industries.

The performance of RuCs is influenced by factors like rigidity, particle size, gradation, and surface characteristics of the rubber [280]. The rubber's hydrophobic nature can reduce the bond strength between rubber particles and the cement paste, but treating the rubber with sodium hydroxide or incorporating supplementary cementitious materials can help enhance this bonding [281]. Advanced uses of tire waste to enhance concrete quality have been thoroughly investigated, suggesting the inclusion of siliceous or limestone mineral fillers to bolster the mechanical properties of RuC [282]. Using SFs together with rubber and steel fibers can increase concrete's compressive strength by up to 20% when rubber content reaches 20%, resulting in more predictable tensile properties and improved bonding strength [283]. Figure 32a highlights how UHPGC with rubber and recycled steel fibers is more environmentally friendly than conventional UHPC, showing a notable reduction in CO_2 emissions, which further decreases with higher rubber content [213]. Similarly, Figure 32b shows significant cost savings with the use of recycled steel fibers, although the impact of CR on cost is relatively minimal [213] (Figure 33).

UHPRGC is acknowledged for its environmental advantages, largely due to its incorporation of industrial by-products like FA or slag, which substitute a portion of the cement content and thereby reduce carbon emissions from cement production. This material provides both economic and environmental benefits by allowing direct integration into concrete without necessitating additional industrial processing. The integration of waste lathe scraps into OPC and similar enhancements in GPC underline the ecological improvements achievable through such innovations. In addition to mechanical and durability factors, a

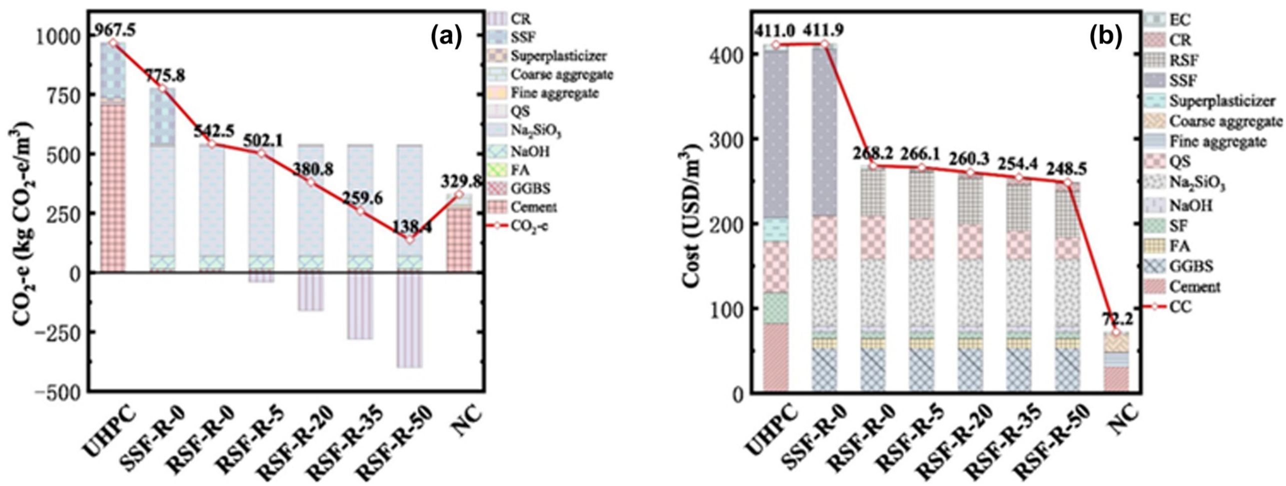

Figure 32: (a) Breakdown of carbon emissions and CO_2-e per cubic meter of concrete and (b) breakdown of cost and total cost per cubic meter of concrete (Adopted from [213]).

comprehensive life cycle assessment (LCA) can clarify the net ecological benefits of RGPC in comparison to traditional concrete. While geopolymer binders already demonstrate a diminished carbon footprint by replacing a substantial portion of the Portland cement content, integrating recycled rubber further reduces landfill waste. Nevertheless, the compromise in compressive strength introduced by rubber may necessitate overengineering or the application of supplementary binder, thereby counteracting some of these ecological advantages. For example, if thicker sections or more significant volumes of concrete are required to attain equivalent load-bearing capacity, the increased material consumption could undermine the overall carbon savings. Conversely, rubber incorporation may enhance durability and reduce long-term maintenance requirements, presenting a potential ecological "payback" over the structure's lifespan. Balancing these elements – diminished embodied carbon, waste diversion, potential structural overengineering, and maintenance considerations – demands a holistic LCA methodology, integrating performance criteria and ecological metrics to optimize the long-term sustainability of RGPCs.

Recent research highlights that adding fibers to the brittle geopolymer matrix not only controls shrinkage but also boosts mechanical strength by enhancing fracture

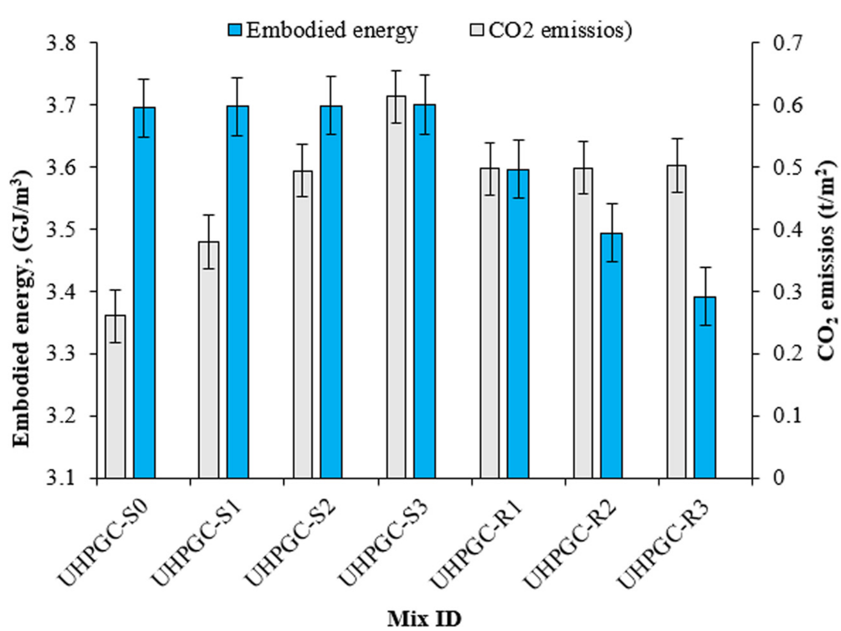

Figure 33: CO_2 emission and embodied energy of UHPGC samples (Adopted from [196]).

toughness. This improvement stems primarily from the fibers' ability to bridge across cracks, effectively managing crack propagation and thus delaying the onset of significant cracking, which in turn reduces the energy demand associated with crack management. The application of recycled rubber tires in concrete also contributes significantly to waste reduction and sustainability efforts [284].

Advances in geopolymer technology have revealed its superior binder qualities, offering substantial environmental benefits, with studies estimating that geopolymers have approximately 9% lower CO_2 emissions than traditional concrete made entirely from cement [285]. Further efforts to decrease CO_2 emissions involve the development of waste-based activators [286]. Moreover, the performance of GPC structures matches that of conventional concrete in key metrics such as compressive, flexural, and tensile strengths [287], making it a viable alternative for various construction applications. Besides, GPC has gained attention for its potential in reducing greenhouse gas emissions and is increasingly studied for applications in concrete mix enhancements, repair, retrofitting, fireproofing of structures, and more [288]. Notable successes include its use in pavement construction [289], masonry [290], reinforced geopolymer structures [29], and as a repair material [291], all of which underscore its versatility and environmental benefits. Figure 31 illustrates the CO_2 emissions and embodied energy for fiber-reinforced UHPGC specimens, highlighting the environmental advantages of green UHPGC [196]. Among these specimens, UHPGC-S0 has the lowest CO_2 emissions at $0.2598\ t{\cdot}m^{-3}$. Due to the high CO_2 emissions from steel fiber production [292], increasing steel fiber content raises CO_2 emissions, implying a trade-off between enhanced performance and higher carbon costs. At a fixed 2% steel fiber content, the precursor ratio results in only a slight increase in CO_2 emissions. The embodied energy analysis showed that adding steel fiber slightly raises the total energy consumption for UHPGC production due to the relatively low individual embodied energy of steel fibers ($0.0205\ GJ{\cdot}t^{-1}$) [196]. However, replacing GGBS and FA with RHA, a pozzolanic byproduct generated *via* the regulated incineration of rice husks, a widely prevalent agricultural waste. Owing to its elevated amorphous silica concentration, RHA functions as a highly efficient supplementary cementitious material, enhancing the mechanical properties and longevity of concrete and geopolymer matrices. As RHA has a negative individual embodied energy ($-0.354\ GJ{\cdot}t^{-1}$) due to its use as fuel [293], this substitution greatly lowers the total energy consumption. These findings suggest that partially replacing GGBS and FA with RHA enhances the "green potential" of UHPGC.

It is also reported that while CR composites offer certain beneficial properties and environmental advantages, their practical application in construction has been limited [294]. This limitation stems primarily from inadequate research on these properties and a prevalent misconception that compressive strength is the sole determinant of concrete's utility, irrespective of its intended use. To better integrate RuC into specific applications, a "design by function" approach is recommended, which tailors the concrete's properties to its intended purpose [295]. There are numerous potential uses for concrete that require characteristics not typically found in traditional mixes. For instance, applications such as resurfacing or lining sidewalks, certain types of slabs on soil, and specific repair scenarios may benefit from concrete with lower compressive strength [296]. RuC-based materials are proposed for a variety of specialized applications where their unique properties can be leveraged [295]. In brief, the sustainability of UHPRGC is crucial in promoting eco-efficient construction practices. Both UHPGC and UHPRGC utilize industrial by-products like FA and slag, significantly reducing the reliance on Portland cement and thereby lowering carbon emissions. The inclusion of recycled rubber aggregates in UHPRGC further enhances sustainability by diverting waste tires from landfills and contributing to circular economy principles. These materials exhibit superior mechanical properties and durability, ensuring a longer service life and reduced maintenance needs, collectively diminishing the overall environmental impact. Their high performance in infrastructure applications supports the transition to more sustainable and resilient built environments. By integrating advanced materials science with environmental stewardship, UHPGC and UHPRGC represent a significant step forward in sustainable construction.

12 Conclusions

This review article offers a novel evaluation of UHPGC, emphasizing the distinctive combination of geopolymer binders and recycled rubber particles to enhance both mechanical properties and environmental sustainability. Based on the review, several key conclusions can be drawn.

- The substitution of fine aggregates with fine CR in geopolymer concrete significantly reduces compressive strength, with notable reductions of 76% in FA-based mixes and 78% in MK-based mixes at higher rubber contents. However, a minimal 2% rubber content can lead to a slight increase in strength.

- The effects of CR replacement on compressive strength are complex, showing a 7% strength increase at a 10% replacement level of fine and coarse aggregates, but a substantial 34% decrease at the 30% level, demonstrating the need for careful optimization of rubber content in geopolymer concrete formulations.
- UHPRGC achieves remarkable compressive and flexural strengths with 3% fiber and optimal sodium oxide and water-to-binder ratios. However, its high OPC content (750–1,200 $kg \cdot m^{-3}$) contributes significantly to CO_2 emissions, estimated at 0.83 tons per ton of clinker produced. The best compressive strength exceeds 120 MPa with 8–9% Na_2O and a W/B ratio of 0.300–0.325, while lower strengths correlate with reduced Na_2O and higher W/B ratios.
- Research indicates that when steel fibers exceed 13 mm in length, the flexural performance of concrete diminishes due to increased spacing, highlighting the significance of fiber length and spacing for optimal performance. Additionally, RGPC demonstrated maximum residual strength after 90 days of exposure to hydrochloric and sulfuric acids, confirming that the NaOH pre-treatment method enhances its durability.
- Incorporating rubber into UHPRGC enhances energy dissipation by 31.5–53.3% at substitution ratios of 5–20%, though performance may decline above 10%. Optimal compressive strength is achieved with 15–30% SF replaced by slag, peaking at 30% substitution. UHPGC can reach compressive strengths of 175 MPa with steel fibers and 178.6 MPa with a 12.5% GGBS substitution. Furthermore, substituting 22.5% crushed glass for fine aggregate improves microstructural properties and mechanical performance.
- Incorporating up to 0.5% PPF by volume improves the mechanical properties of traditional concrete and helps reduce moisture loss and early-age shrinkage. For GPC, increasing SF content enhances durability by lowering permeability and water absorption. However, excessive amounts of PPF or SF can negatively impact the durability of high-strength concrete, especially in SF-rich mixes.
- Blends of FRRC with 1% RTS fiber effectively controlled shrinkage. High-strength GPC experienced polymerization and strengthening during the first 56 freeze–thaw cycles, but performance declined after 300 cycles, resulting in load-aligned cracks. In contrast, conventional UHPC exhibited no significant strength changes after 300–800 freeze–thaw cycles, while strength reductions occurred after 225, 100, and 120 cycles.
- At 7 days, UHPGC displayed a predominantly dense microstructure while still containing unreacted components. By 28 days, the degradation of GGBS particles enhanced the formation of (C(N)–A–S–H) gel, thereby improving the mechanical properties.
- Increasing the slag dosage from 0.193 to 0.731 enhances the density of the microstructure, leading to a reduction in internal flaws and an increase in aggregate density within the ITZ. This higher slag content significantly improves bond strength and, consequently, the mechanical performance of UHPRGC.
- Fiber reinforcement significantly enhances GPC and AAS concrete. Fibrillated PPFs and polyolefin fibers improved flexural toughness up to 6.3 times. Steel fibers increased fracture energy, with optimal performance at 1.5–3% volume, confirming a strong fiber-content correlation.

13 Recommendations for future work

- RGPC offers improved durability, including better abrasion resistance and impact strength, but often at the cost of reduced compressive strength. Further research is necessary to optimize the trade-off between strength and durability, possibly using hybrid materials or additives.
- Developing comprehensive guidelines and standards for the integration of UHPRGC in construction practices is essential. This includes providing recommendations on optimal combinations of fibers and binders to ensure consistent performance.
- Future research could concentrate on the development of novel bonding agents or treatments specifically aimed at enhancing the adhesion between rubber particles and the cement matrix. Such advancements may result in improved mechanical properties and increased durability of RuC.
- Developing predictive models to simulate the mechanical behavior of UHPRGC under diverse loading conditions and environmental factors could improve design methodologies and construction processes. Future research may investigate the integration of machine learning techniques to predict performance based on mix design parameters and material properties.
- Explore the development of hybrid concrete systems that incorporate various supplemental materials (*e.g.*, SF, GGBS, CR) and fibers to enhance performance characteristics, including flexural strength, ductility, and durability.
- Thorough analysis of the lifecycle environmental impacts associated with the production of UHPRGC is necessary to identify strategies for minimizing its carbon footprint and resource consumption, thereby promoting its adoption within sustainable construction frameworks.

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