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*Original Article*

# From Waste to Resilience: A State-of-the-Art Review on Fly Ash-Based Rubberized Geopolymer Concrete

Manjula Karmakar[1], Hasim Ali Khan[1], T. Senthil Vadivel[2]*, Sayandip Ganguly[2]

[1]*Department of Civil Engineering, Adamas University, Barasat, India.*
[2]*Department of Civil Engineering, Manav Rachna International Institute of Research and Studies, Faridabad, Haryana, India.*

*Corresponding Author : senthil.set@mriu.edu.in*

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***Abstract*** *- The construction sector remains heavily dependent on Ordinary Portland Cement (OPC) and natural aggregates worldwide, making it one of the largest contributors to carbon emissions and resource depletion. At the same time, industries still have challenges in properly disposing of fly ash and tires with a minimum useful life, both of which are produced in enormous quantities annually. Fly Ash-Based Rubberized Geopolymer Concrete (FRGC) presents a suitable alternative to replace cement, natural aggregates used in conventional concrete, and reduce carbon footprint by utilizing waste products. A geopolymer binder made from low-calcium fly ash is used in place of OPC in FRGC, and rubber fragments recovered from used tires are used in place of some of the natural aggregates. An extensive review is therefore performed in this study to highlight the research gaps to be addressed in the future and potential challenges in achieving the goal. The present study also examines the effects of rubber size/content, curing regime, silicate-to-hydroxide ratio, and alkaline activator molarity on the mechanical, fresh, and durability characteristics of FRGC. Results from previous studies show that adding rubber by 6% can lower compressive strength by 10–25%. However, it significantly improves ductility, impact resistance, and energy absorption by more than 50%. However, the geopolymer binder lowers the carbon footprint of concrete by 60–80% as compared to OPC and offers great early strength and exceptional durability in harsh settings. This consolidated literature reveals that while the alkaline chemistry of geopolymer binders and the toughness benefits of rubber are individually well studied, their combined influence under elevated curing and fire exposure remains critically underexplored. Furthermore, long-term durability and corrosion studies of FRGC are scarce, and no comprehensive datasets exist for machine learning-based prediction. Addressing these gaps will define the trajectory for future research and standardization.*

***Keywords*** *- Geopolymer Concrete, Rubberized Concrete, Fly Ash, Sustainable Construction, Lifecycle Assessment.*

## 1. Introduction

Climate change and unsustainable resource consumption are the two crises that define the twenty-first century. As the biggest user of natural resources and a major generator of greenhouse gas emissions, particularly from the manufacture of Ordinary Portland Cement (OPC), the building industry is at the center of both [1]. With over one tonne of $CO_2$ generated for every tonne of cement produced, the production of cement is responsible for around 8% of anthropogenic $CO_2$ emissions worldwide [2, 3]. At the same time, solid waste production keeps increasing.

With an estimated 1.2 billion units produced each year globally, tires from end-of-life vehicles represent a particularly hazardous waste stream. Due to their longevity and lack of biodegradability, disposing of them in landfills is both environmentally and financially unsound and frequently results in hoarding and illegal dumping, which increases the risk of fire and spreads disease [4, 5].

The core of sustainable construction is founded on two issues- utilization of waste products and mitigation of environmental impact. Rubberized Concrete (RuC) and Geopolymer Concrete (GPC) have been separately studied by many researchers in the past as a solution to sustainable construction. Davidovits [6] investigated the performance of GPC and compared it with OPC-based concrete [7, 8]. Utilizing the chemical reaction between aluminosilicate sourced from fly-ash or slag and high-alkali solution, an inorganic polymer binder is formed. It is estimated that using industrial waste in GPC can reduce $CO_2$ emissions by up to 80% [9, 10]. RuC, on the other hand, uses granulated tire rubber to make the material more resistant to impact, more flexible, and better at controlling fractures by partially replacing natural aggregates. It also serves as a repository for discarded rubber [11-13]. However, RuC, due to the weak bond between the cement paste and hydrophobic rubber in the Interfacial Transition Zone (ITZ), results in the reduction of compressive strength [14, 15].

The next logical and innovative step is to combine these two technologies to create Fly Ash-Based Rubberized Geopolymer Concrete (FRGC). The aim of developing this composite material is to incorporate advanced properties of both systems, utilizing more waste products. Properties of rubber, such as toughness, damping, and strength, improve concrete resilience, energy dissipation capacity, and impact resistance of concrete when used as an aggregate in geopolymer concrete. On the other hand, the Use of fly-ash-based binder minimizes CO2 emissions by avoiding the Use of cement and makes it durable and environmentally friendly. This study presents an extensive review of the advancements of FRGC to highlight its possible impact on the environment, existing research gaps, and future scopes. For this purpose, a detailed review is also provided on the constituent materials of FRGC, focusing on their origin, physical, mechanical, and chemical properties, and their possible uses. This shows that FRGC is a new material that can be used to build infrastructure that lasts longer and is better for the environment.

It is noted from all literature that the specific problem based on geopolymer concrete and rubberized concrete has been investigated individually as sustainable alternatives. However, the performance of concrete integrating both fly-ash-based geopolymer concrete and rubber is not extensively studied.

Past research has mostly analysed either the performance of geopolymer concrete and its chemical reactions, or the addition of rubber in concrete. Also, evaluation of both of these is mostly limited to small-scale experiments, without addressing their combined effects under critical service conditions. Thus, a significant research gap exists in the following areas:

- Limited knowledge on the interaction mechanism between the alkaline activator and rubber content in FRGC.
- Insufficient number of studies on the FRGC to evaluate its durability under adverse environmental conditions, bond strength with embedded steel reinforcement, and performance under high temperature curing or direct or indirect exposure to fire.
- Small-scale practical implementation to date or real-scale investigations on different structural members, such as beams, columns, pavements, etc., and a lack of standardized mix-design guidelines.
- Minimal Use of advanced tools such as machine learning to optimize FRGC properties and predict long-term performance.

This review addresses these gaps by highlighting existing knowledge on the constituent materials, geopolymerization mechanism, and engineering performance of FRGC. It systematically evaluates the effects of rubber size/content, curing regimes, and activator chemistry, while highlighting unexplored areas such as fire resistance, long-term durability, and structural applications. Furthermore, it identifies opportunities for machine learning-based modelling and optimization, offering a roadmap for future research and codification.

Thus, this paper contributes a state-of-the-art review that summarizes the current trend of research and also clarifies the challenges that need to be solved for FRGC to shift from laboratory research to practical application in sustainable and resilient infrastructure.

## 2. Constituent Materials and Geopolymerization Mechanism

### *2.1. Aluminosilicate Source: Low-Calcium Fly Ash*

For FRGC, the most common raw material is low-calcium (ASTM Class F) fly ash, a byproduct of coal-fired power plants. It consists of a lot of silica (50–60%) and alumina (20–30%) with a small amount of calcium (<10%), which makes it perfect for geopolymerization [8, 16-19].

In an alkaline environment, the amorphous glassy phase of fly ash dissolves, releasing silica and alumina species. After restructuring, it creates a bond to form a dense three-dimensional aluminosilicate network [6, 20]. The fineness of the ash and the proportion of reactive silica directly influence the reaction rate and final strength. In general, finer and more reactive ashes produce better-performing binders [21, 22].

### *2.2. Alkaline Activators*

Strong alkaline solutions are necessary for geopolymerization in order to dissolve and activate the fly ash. For this reason, Sodium Hydroxide (NaOH) or Potassium Hydroxide (KOH) is usually combined with either Potassium Silicate ($K_2SiO_3$) or Sodium Silicate ($Na_2SiO_3$) [23]. The significance of these chemicals is explained as follows:

- The molarity of the NaOH concentration: In geopolymer concrete, the hydroxide ion concentration is a crucial component. The majority of research employs 8–14M NaOH, with 12M being considered as the ideal concentration [24, 25]. It is observed that up to a certain extent, with the increase in molarity, dissolution accelerates and increases strength. However, an excessively high rate of reaction can cause microcracking and rapid setting.
- Alkaline ratio ($Na_2SiO_3$/NaOH): The ratio of hydroxide to silicate is also a significant factor in changing the characteristics. Strength and workability are typically optimized at ratios between 2.0 and 2.5 [26]. Sodium silicate enhances mix flow and supplies more reactive silica for polymerization. To allow for stabilization and prevent overheating during the reaction, NaOH solutions should be made ahead of time, usually 24 hours before mixing [27].

### *2.3. Rubber Aggregates*

Waste tire rubber can be incorporated in various sizes:

- Crumb Rubber: Fine aggregates that are of size 4.75 mm or lower are produced by ambient or cryogenic grinding.
- Chip Rubber: Coarse aggregates of size in the range of 5-20 mm are produced by shredding or chiseling. Incorporating rubber transforms the material characteristics from a brittle composite to a ductile one. However, the weak bond between the rubber and the geopolymer matrix and the low stiffness of rubber particles are the primary reasons for the reduction in compressive strength [27]. An important finding that has emerged from a number of studies is the identification of an optimal rubber replacement level of approximately 6% by weight of aggregate [4, 5, 19, 35]. At this percentage, the detrimental effect on strength with a maximum reduction of as much as 15% is manageable, as the improvements in ductility, impact resistance, and energy absorption are also maximized. Pre-treatment methods with NaOH solution, cement slurry, or silane coupling agents to improve the rubber-matrix bond are also an area of research evolving rapidly nowadays [28, 29].

### *2.4. Natural Aggregates and Additives*

The primary structural skeleton still needs to be provided by traditional fine and coarse materials like sand and gravel, in addition to rubber. To guarantee appropriate particle packing, its grading must adhere to standard specifications (such as IS 383 [31]). The rough texture of aggregates and the viscosity of alkaline solutions frequently make workability difficult [32, 33]. Superplasticizers based on Polycarboxylate Ether (PCE) are commonly used to encounter this problem by improving flow without loss of strength at dosages of roughly 1% to 2.5% of the fly ash mass.

### *2.5. Geopolymerization Process*

The transformation of fly-ash-based aluminosilicate binder to a hard matrix in the presence of alkaline activators in a geopolymer concrete is referred to as the geopolymerization process. In conventional concrete, cement powder reacts with water to form C-S-H gel as a binder at ambient temperature. On the other hand, the geopolymerization process occurs at high temperature, and thus it is considered to be a highly temperature-dependent process. The geopolymerization occurs through three interconnected stages [6-8, 23, 24]:

- Dissolution: In this stage, Si–O–Si and Al–O–Si bonds in the amorphous phase of fly ash are attacked by the Hydroxide Ions ($OH^-$) from the alkaline solution. It releases reactive Silicate ($SiO_4^{4-}$) and Aluminate ($AlO_4^{5-}$) ions into the liquid phase of the geopolymer matrix. The rate of reaction depends on the molarity of alkaline NaOH/KOH solution, percentage of calcium content present in the mix, and fineness and content of fly-ash.
- Gelation / Reorientation: The dissolved silicate and aluminate units formed in the previous stage of dissolution undergo condensation reactions in the presence of alkali cations ($Na^+$, $K^+$). As a result, oligomers are generated, which gradually reorganize to develop a colloidal gel. The extent of gel formation is dependent on the availability of silica in the mix. The presence of silica is again governed by the silicate-to-hydroxide ratio of the activator.
- Polycondensation / Hardening: The oligomeric gel particles progressively link through –Si–O–Al–O– bonds to form a three-dimensional aluminosilicate framework, also referred to as N–A–S–H (sodium aluminosilicate hydrate) or K–A–S–H gel, depending on the cation. With elevated curing (60–90 °C), polycondensation accelerates, producing a dense, cross-linked matrix with early high strength.

### *2.6. Microstructural Evolution*

During this process, crystalline byproducts such as zeolites may form depending on curing temperature and calcium availability. In low-calcium fly ash systems (Class F), the binder is dominated by N–A–S–H gel, while partial substitution with GGBS introduces C–A–S–H type gels that improve ambient curing. Rubber aggregates do not directly participate in geopolymerization but influence the microstructure through their weak Interfacial Transition Zone (ITZ), which is often improved by surface treatments.

Figure 1 presents FESEM images that provide magnified views of the morphology of various RGC mixtures (Giri et al. [30]). In line with the mechanical strength results, the microstructure of the different Rubberized Geopolymer Concrete (RGC) mixes indicated a reduction in the ITZ between the Crumb Rubber (CR) and the geopolymer matrix with an increase in the NaOH concentration. For better comparison, samples having the same CR content of 10% but different NaOH concentrations were considered (M1, M4, and M7).

In the topmost figure of Figure 1, the mix has 10 M NaOH (M1), and it is evident that the ITZ is very wide, with the CR appearing to have a low amount of the geopolymer paste adhering to its surface. The size of the ITZ is measured to be 6.10 μm. On the other hand, as the molarity of the NaOH increased to 14 M (M7), there is a noticeable decrease in the size of the ITZ, as shown in the middle one of Figure 1.

Furthermore, when the molarity of NAOH increased to 14 (M4), the ITZ size decreased significantly to 764.32 nm at some point and 347.91 nm at another point. From these figures, it is also observed that the CR surface is enveloped with the paste, indicating a better reactivity of the CR owing to the NaOH reactivity-inducing effect. This led to the improved mechanical strengths of the mixes owing to the better stress transfer at the ITZ.

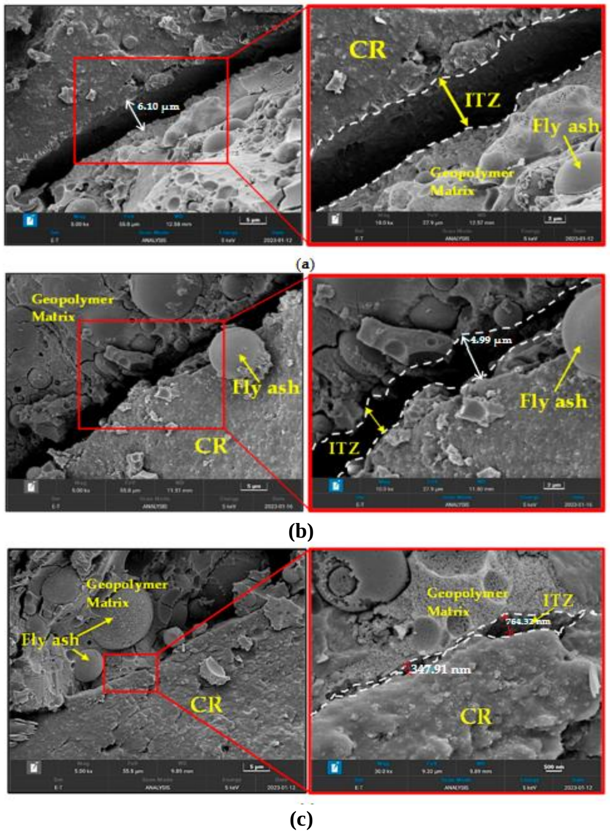


**Fig. 1 FESEM micrographs (a) M1 (NaOH: 10 M, CR: 10%), (b) M7 (NaOH: 10 M, CR: 10%), and (c) M4(NaOH: 10 M, CR: 10%) (Giri et al. [30])**

The process of geopolymerization is different from the fundamental process of cement hydration in the following way:

- The geopolymerization mechanism is alkali-activated, unlike the water-activated cement hydration process
- Reaction kinetics are highly temperature-sensitive rather than moisture-sensitive.
- Final products are Si–O–Al networks where cement hydration forms a Ca–Si–H phase matrix
- The binder offers superior chemical stability and resistance to sulphates and acids compared to OPC.

Although the dissolution and gelation mechanisms are well established, the kinetics of geopolymerization in the presence of rubber particles and admixtures remain underexplored. Advanced microstructural tools such as SEM–EDS, NMR, and FTIR are still required to clarify ITZ behavior, reaction degree, and long-term stability under variable curing and environmental exposures.

## 3. Performance based on Engineering Properties of FRGC

The performance of FRGC is governed by the characteristics of its individual constituents and the compounds formed through their chemical reactions. Therefore, to ensure attainment of the intended properties of FRGC, it is important to investigate the underlying properties and mechanisms in detail. A review of different properties of FRGC is presented as follows.

### *3.1. Fresh Properties: Workability and Rheology*

The intricate relationship between the non-polar rubber particles and the extremely viscous alkaline solution determines how FRGC behaves in its fresh form. The chemical description of alkaline solutions and the possible difficulties in their interaction with rubber particles are given below:

- Alkaline Chemistry and Rheology: The Sodium Silicate Solution ($Na_2SiO_3$), which is also called "water glass," is inherently viscous. When combined with a high-molarity NaOH solution, it creates a sticky, cohesive gel that coats the aggregates. The dissolution of silica and alumina from the fly ash surface initiates immediately, which further increases the mixture's viscosity, leading to an instant loss of workability over time [32, 36].
- Rubber Integration Challenge: Crumb rubber particles are hydrophobic and have a non-polar surface, creating a weak Interfacial Transition Zone (ITZ) with the polar geopolymer gel. This poor adhesion can cause segregation and bleeding if not properly addressed. Furthermore, the irregular shape and high surface area of rubber crumbs increase the internal friction within the mix [34, 46, 63].
- Mitigation Strategies: The Use of advanced superplasticizers, for example, Polycarboxylate Ethers (PCE), is critical. It works by imparting steric hindrance between particles, dispersing the geopolymer gel, and allowing for better lubrication. A target slump of 75-100 mm usually requires a dosage of 1-3% by mass of fly ash [32-36]. Rubber crumbs' surface can also be gently etched by pre-treating them with a 1-5% NaOH solution for 24 hours, which increases their hydrophilia and strengthens their bond with the matrix [28, 32].

### *3.2. Mechanical Properties: Trade-off between Strength and Ductility*

The mechanical performance of FRGC is defined by the synergy and trade-off between the strong but brittle geopolymer matrix and the soft but ductile rubber aggregates.

- Compressive Strength: Mechanisms of Reduction
  The reduction in compressive strength with increasing rubber content is well-established [37] in various research. The primary mechanism that leads to this reduction in strength is
- The bond between the rubber and the geopolymer binder is very weak in nature. During compression testing, with the application of load, this bond breaks very easily and forms several microcracks. These cracks further lead to

the collapse of the test cubes at lower compressive strength [48, 54].

- The slope of the stress-strain curve of FRGC is smaller than that of conventional concrete. The range of elastic modulus of FRGC is found to be approximately 1-10 MP, whereas the value of modulus of elasticity of geopolymer paste is 10-20 GPa. This greater margin of difference in elastic properties within the geopolymer matrix creates differential strain, and consequently, significant stress concentration occurs around the rubber particles. With the increase in load, the induced stress results in debonding of materials or the formation of cracks [52-58].
- Lower Compactness: The specific gravity of rubber being much lower, an additional amount of cement paste with equivalent weight is required. It may increase the number of pores and weaken the concrete. An optimized amount of alkaline activator and alkali-silica ratio is studied in many studies to avoid this weakening effect. In most of the fly-ash-based geopolymer concrete, 12M NaOH and $Na_2SiO_3$/NaOH of 2.5 at a curing temperature of 90°C for 24 hours is obtained as the optimized amount. It forms a highly dense and high-strength microstructure. Strength decreases at 6% replacement can be kept to 10-15% while maintaining 30–35 MPa, which is appropriate for a variety of structural applications [66].

- Tensile and Flexural Strength: The "Pin-Effect"

Compared to compression, the loss of split tensile and flexural strength is frequently less pronounced. Some studies even demonstrate gains in flexural strength at modest replacement amounts (2-4%). The "pin effect" or crack-arresting mechanism is responsible for this. Microcracks come into contact with rubber particles as they develop and spread under tension. Energy is absorbed by the soft rubber particles, blunting the crack tip and requiring more energy for the crack to move around them. This causes a longer failure time and a more convoluted fracture route [38].

- Ductility and Impact Resistance:This is the most significant benefit of FRGC. The incorporation of rubber transforms the failure mode from a sudden, brittle explosion to a gradual, ductile crumbling.

Energy Absorption: The ability to absorb energy, calculated as the area under the stress-strain curve or from impact tests (Energy = m·g·h·N, where N is the number of blows), increases dramatically with the Use of rubber as aggregate. It is also concluded in many studies that the increase in pact energy even attains 50-100% more compared to plain geopolymer concrete [39, 40]. The rubber particles act like miniature springs, storing and dissipating energy through large elastic deformations.

Ductility Index: The ratio of energy at failure to energy at first crack can be 3-4 times higher than that of conventional concrete, indicating a massive improvement in post-crack performance and structural resilience [14, 55].

### *3.3. Durability Properties: Inherited Resilience*

The durability of FRGC is a function of the excellent inherent properties of the geopolymer matrix, which can be slightly modified by the rubber.

- Geopolymer Matrix Durability: The low calcium content (<5% in Class F fly ash) prevents the formation of Portlandite ($Ca(OH)_2$) and secondary ettringite, which are responsible for sulphate attack in OPC concrete. The highly cross-linked Si-O-Al network is also more resistant to acid attack, as it lacks the vulnerable calcium-based phases [42-45, 55]. Chloride ion diffusion coefficients are typically an order of magnitude lower than in OPC concrete, offering superior protection to embedded reinforcement [45, 53].
- Influence of Rubber: Rubber is a hydrophobic material. Thus, its inclusion in concrete has an effect in reducing the retention of water in the capillary pores of concrete and consequently the water absorption of concrete. This, in turn, enhances the resistance of concrete to chloride attack and rust formation in steel embedded within the concrete [53]. However, degradation of rubber with age may adversely affect the long-term performance of concrete. Also, geopolymer concrete is generally subjected to high-temperature curing. At this elevated temperature, the properties of rubber may be modified, which can affect the vulnerability of FRGC to crack formation. A sufficient number of research studies are therefore necessary to determine the rubber-geopolymer interface's long-term stability during wet-dry cycles and UV exposure.

## 4. Applications in Construction

The incorporation of alkaline activators and crumb rubber particles alters the properties of Fly Ash-Based Rubberized Geopolymer Concrete (FRGC). These modified properties offer a wide range of benefits compared to conventional concrete. Some of the advanced properties related to applications in construction are summarized to highlight their essential aspects.

- Precast and Prestressed Elements with Rapid Turnaround: The requirement of high temperature (60-90°C) for curing is sometimes considered as one of the limitations of geopolymer concrete. However, it also possesses a technical advantage. Curing at high temperature results in accelerated gain in early strength, even greater than 30 MPa within 24-48 hours. Consequently, it significantly brings down the time for attaining the strength that is equivalent to a 28-day curing period strength for OPC-based concrete. This property makes it suitable for rapid construction [50].

- Prestressed Electric Poles: An extensive review of past research [76] led to the observation that prestressed members built with geopolymer concrete can attain 12% higher transverse strength than OPC-based concrete. The serviceability performance also improves with 30% less deflection than conventional concrete sections. It demonstrates a significant advantage of the FRGC with a dense, high-strength geopolymer matrix formed under optimized alkaline chemistry.
- FRGC can also be advantageously used for railway sleepers, architectural cladding, and noise barriers. Properties such as early setting and accelerated gain in strength, increased durability against chemical attack, and the enhanced damping capacity imparted by crumb rubber as aggregate, make FRGC a suitable candidate for these applications. The rubber particles dissipate vibrational energy from passing trains or traffic, reducing noise pollution and improving longevity [55, 61, 81].
- Sustainable Pavements and Overlays: The enhanced performance of FRGC in terms of abrasion resistance and skid is influenced by its geopolymer binder and the elastic rubber aggregates. It asserts that FRGC can qualify as an alternative solution to use as a sustainable material in paving. The elastic behaviour of crumb rubber and its integration into FRGC alters the rigid and brittle behavior of conventional concrete. This modification in the elastic property of concrete facilitates reducing the generation of cracks from thermal contraction and subgrade movement. Furthermore, industrial floors, aprons in airports, and different vehicle terminals demand high impact and abrasion-resistant properties of concrete. As many experimental investigations [49-52] in the past show that FRGC can improve the energy absorption by 50-100%, FRGC can be suitably used as a promising material.
- Structures that can withstand earthquakes and blasts: The seismic-resistant design of structures greatly depends on the damping and energy absorption capacity of the materials. The property of crumb rubber shows its ability to undergo large elastic deformations before failure. Therefore, it provides ductility to FRGC when used as a replacement for natural aggregates in concrete. Due to their high-energy dissipation capacity, beam-column joints and shear walls can dissipate seismic energy through large deformations, thereby reducing the risk of sudden collapse.
- Performance of FRGC-based beam and column: Due to the same reason as stated earlier, beams and columns of FRGC present wider hysteresis loops when structures are subjected to cyclic loading, fuller hysteresis loops. This wide hysteresis loop indicates significant energy dissipation by damping without any significant reduction of stiffness and strength in each cycle. This ductile behavior with large sway allows users of the structures to come out and save lives by delaying the collapse of the structure even at critical earthquake events or other disasters [54, 64, 68, 77]. It is also seen that the modulus of elasticity of FRGC is generally lower than that of conventional concrete. Now, since the modulus of elasticity is proportional to stiffness, it increases during the natural period of vibration. This change in natural period mitigates the risk of resonance of the building during seismic vibration [75].

Blast and Impact Mitigation: FRGC is an excellent material for protective structures like safety barriers, bunkers, and blast walls because it can absorb a lot of kinetic energy through the viscoelastic deformation of rubber. This makes it an excellent material for reducing the effects of collisions or explosions [41, 76].

## 5. Environmental and Economic Impact

The implementation of FRGC is also subject to verification of its environmental and economic benefits, as well as its technical performance, through a comprehensive lifecycle assessment.

### *5.1. Lifecycle Assessment (LCA) and Carbon Footprint*

A cradle-to-gate Life Cycle Assessment (LCA) of geopolymer concrete shows that $CO_2$-equivalent emissions are 60–80% lower than those of OPC concrete [9, 65]. The prevention of clinker production is the reason for this achievement. Utilization of waste end-of-life rubber further reduces the carbon footprint. At the same time, it eliminates the challenges of land management required for its dumping as a waste product. Replacing natural aggregates with rubber minimizes the depletion rate of natural resources. Estimation of the sustainability performance index with environmental impact as one of the pillars is essential for LCA. In the literature, it is demonstrated that geopolymer concrete requires a significant amount of energy for its production. Yet, it has a substantially lower environmental impact compared to Ordinary Portland Cement (OPC). This is especially true when potassium-based solutions or waste-derived silica are used to make sodium silicate [41].

### *5.2. Circular Economy and Waste Valorization*

The development of FRGC plays an important role in advancing the circular economy of the building industry. The inclusion of both fly ash and end-of-life tires in concrete production, which are abundantly produced worldwide, promotes FRGC as a sustainable material for the construction industry. FRGC also addresses challenges related to waste management by diverting waste from landfill dumping and minimizing the extraction of natural resources, such as gravel, sand, and limestone, by offering a waste product as a substitute [72-74, 79].

### *5.3. Economic Viability and Total Cost of Ownership*

The cost of alkaline activators, which can be more expensive than OPC, is now part of the direct material cost of

FRGC. However, a simple comparison is not accurate. A complete cost-benefit analysis must consider:

- Avoided waste disposal costs for tires and fly ash.
- Reduced lifecycle costs due to enhanced durability (lower maintenance and repair needs).
- Potential for lighter structures due to lower density, resulting in savings on foundations and transportation.
- Performance benefits in specific applications (e.g., longer lifespan of pavements, reduced damage in seismic events).

As production of activators scales up and technology optimizes, their cost is expected to decrease, making FRGC increasingly economically competitive [67, 78].

## 6. Research Gaps and Future Scope

To elevate the adoption of FRGC in the practical field from a laboratory innovation as an advanced and innovative construction material, several challenges need to be addressed. The present challenges are enumerated in the following,

- The lack of design guidelines and standards for rubberized concrete and geopolymer is the primary constraint to its broad adoption. To refer to the mix design of FRGC, structural engineers need to establish guidelines related to durability specifications, mix design, and structural design (such as bond-slip behavior with reinforcement and stress-strain models) separately for different projects [62, 69]. Therefore, a universal guideline for mix design of FRGC based on a large number of experimental investigations and their dataset is required for establishing its Use with a higher degree of reliability.
- The requirement for high-temperature heat curing (60-90°C) poses a challenge to the Use of FRGC, primarily to precast applications. Several research studies need to be conducted in the future to develop a robust ambient-cure geopolymer system. The scope of work may include:
  - ➢ Use of multiple precursors, such as a combination of fly ash with Ground Granulated Blast Furnace Slag (GGBS). The presence of calcium content in such precursors may facilitate initial setting at room temperature [59, 70].
  - ➢ Identifying suitable chemical accelerators or seed crystals to initiate the geopolymerization reaction at ambient conditions [59].
  - ➢ Investigation of thermal activation methods like microwave curing that are more energy-efficient than oven curing [80].
- Although promising, there are few long-term (>5 years) data on how well FRGC performs in actual settings. There are critical research needs, such as:
  - ➢ Long-term studies on carbonation, Alkali-Silica Reaction (ASR), and creep and shrinkage under load.
  - ➢ Corrosion behavior of steel reinforcement embedded in FRGC. The high alkalinity (pH >13) should be protective, but the long-term stability of this passivation layer needs verification [60].
  - ➢ Durability of the rubber-geopolymer interface under aggressive environments, freeze-thaw cycles, and UV exposure [47].

- Machine learning techniques can be implemented for predicting the behaviour of FRGC and the optimum replacement of rubber for its intended properties. The following areas of research can be performed in the future to develop a suitable data-driven model,
  - ➢ Developing large, open-access databases of FRGC experimental results for training ML models.
  - ➢ Application of different ML-algorithms such as ANN, SVR, and Gaussian Process Regression to accurately predict mechanical and durability properties from mix proportions [69, 79].
  - ➢ An alternative way of maximizing the rubber content, maintaining its strength and durability properties, can be achieved by combining a machine-learning model with multi-objective optimization techniques (e.g., Genetic Algorithms) [70, 71].
- Nano-Engineered Interfaces and Smart Functions: To strengthen the crucial rubber-geopolymer ITZ, future studies could investigate nano-modification (e.g., with nano-silica or graphene oxide) [67]. Additionally, the incorporation of self-sensing capabilities may advance the Use of FRGC for assessing the health monitoring of structures by estimating the composite's electrical resistivity change under strain [82]. For the comprehensiveness of the reader, research gaps identified through this extensive literature review are summarized with a heatmap in Figure 2.

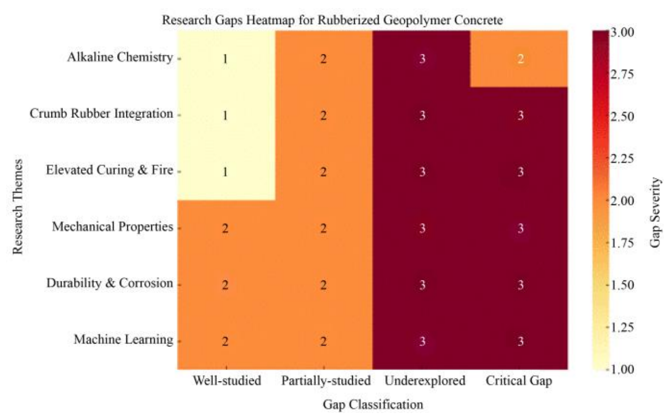


**Fig. 2 Heatmap of research gaps with their severity**

## 7. Conclusion

This extensive review identifies Fly Ash-Based Rubberized Geopolymer Concrete (FRGC) as a practically advantageous and sustainable alternative for conventional concrete. It efficiently addresses significant environmental issues and disposal issues associated with cement manufacturing industries and end-of-life tires. The observations derived from the current review are highlighted below with both quantitative and qualitative conclusions that describe its performance parameters:

1. The review summarizes the effect of alkaline activator, including a 12M NaOH concentration and a $Na_2SiO_3$/NaOH ratio of 2.5, high-temperature heat curing at 60–90°C, and replacement of aggregate with end-of-life tire rubber by weight of aggregate.
2. The compressive strength of FRGC and its durability attain an optimum value with the aggregate with 6% rubber. This optimum fraction of replacement results in a 10–25% decrease in compressive strength. Yet, FRGC achieves considerable strength greater than 30 MPa, which is adequate for usual structural applications. The Use of waste rubber aggregate significantly modifies the properties of concrete by increasing ductility and toughness. Some of the previous research results also indicate that the addition of rubber increases impact resistance and energy absorption of FRGC by 50-100% in comparison to standard geopolymer concrete.
3. It is observed that the geopolymer binder diminishes the carbon footprint by 60–80% in comparison to Ordinary Portland Cement (OPC). The valorization of waste rubber amplifies this advantage by redirecting resources from landfills and diminishing the need for fresh aggregates.
4. The quantitative benefits of FRGC in terms of early strength development, exceptional durability, and improved energy-dissipation capacity make it suitable for precast components such as electric poles, which exhibit 12% higher transverse strength; the development of pavements with sustainable materials; and seismic-resistant structures where energy dissipation plays a vital role.
5. Achieving widespread adoption necessitates the identification of explicit research priorities. Future research should concentrate on creating resilient ambient-cure formulations, producing long-term durability data (exceeding 5 years) on features such as carbonation and chloride diffusion, and, most importantly, formulating standardized design standards grounded in a substantial body of experimental data. The incorporation of machine learning for mixture optimization and forecasting will be a crucial catalyst in this process. In summary, FRGC signifies a transformative movement towards a circular economy in the building sector. This review on the evolution of FRGC shows its practical applicability as a high-performance construction material for developing a resilient, eco-friendly, and sustainable infrastructure in the future.

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