High Strength Geo-ploymer Concrete with Crumb Rubber Tyre Aggregates Performances and Sustainability

Nafisa D Shaikh[1*], Niraj D Shah[2]

[1] Assistant Professor, P P Savani University, India
[2] Dean, P P Savani University, India

Abstract. Given the increasing worries regarding climate change, waste management, and carbon emissions [1–3], geopolymer concrete (GPC), which is produced from alkali-activated aluminosilicate sources such as fly ash is becoming a promising substitute for traditional Portland cement concrete (PCC) because of its lower environmental impact and similar strength. [4,5]. At the same time, researchers are investigating the incorporation of crumb rubber aggregates into concrete to minimize waste in landfills and improve energy absorption characteristics [6–9]. While the inclusion of crumb rubber enhances flexibility, shock resistance, and sustainability, it usually leads to decreases in compressive, tensile, and bending strength because of weak interfaces among the rubber and binder, as well as increased porosity [10–12]. This study explores the performance of high-strength GPC with different proportions of crumb rubber, evaluating its mechanical and durability characteristics under standard testing conditions [13,14]. The findings indicate a compromise between strength and sustainability, suggesting that the optimal rubber content in geopolymer mixes can yield eco-friendly, cost-effective, and functional concrete suitable for non-structural or low-load applications, such as paving blocks and pathways [15].

.**Keywords:** high-strength geopolymer concrete, crumb rubber tire aggregates, sustainability, environmental impact.

1. Introduction

Around 8% of global CO_2 emissions are linked to the widespread utilization of Portland cement concrete (PCC) in onstruction sector [1,2]. This concerning figure has spurred the search for sustainable alternatives to traditional concrete, in line with worldwide initiatives to mitigate environmental damage and enhance eco-friendly infrastructure. In response to this issue, recent research has concentrated on sustainable building practices that encourage waste recycling and circular economy principles, with the goal of minimizing the carbon footprint connected to cement production and usage [3]. One viable strategy that has surfaced is the formulation of geopolymer concrete (GPC), which employs industrial by-products as binding agents instead of conventional Portland cement. GPC has attracted significant interest due to its capacity to provide early strength, outstanding thermal resistance, and markedly reduced carbon emissions compared to standard PCC [4,5]. Geopolymers are formed by activating materials that are high in aluminosilicate with alkalis, such as fly ash or ground granulated blast furnace slag, resulting in a solid and durable matrix. [5]. At the same time, the growing quantity of discarded tires presents an urgent environmental challenge. These durable materials take up extensive landfill space and create fire and health risks. Transforming waste tires into crumb rubber and integrating them into concrete mixes provides an innovative remedy to this issue [6]. This not only aids in waste management and recycling efforts but also helps in creating more resilient, flexible, and energy-absorbing construction materials [7–9]. A variety of research has indicated that adding crumb rubber to concrete enhances properties like ductility, sound insulation, and impact resistance, making it ideal for uses such as pavement blocks and shock-absorbing structures [7,10]. Nonetheless, this innovation faces difficulties. Many researchers have noted that the inclusion of crumb rubber in concrete leads to a significant decrease in mechanical strength properties, primarily due to poor bonding between rubber particles and the cement matrix, as well as increased porosity and air pockets [11,12]. Aiello and Leuzzi [6] noted that while rubber-reinforced concrete showed enhancements in certain durability aspects, the mechanical limitations—particularly with higher rubber content—often overshadowed the advantages. Likewise, Gupta et al. [7] documented a substantial reduction in compressive and impact strength as the crumb rubber content increased.

To overcome these challenges, Recent research has explored the integration of rubber aggregates into geopolymer concrete instead of traditional Portland cement-based systems. The distinctive binding mechanism and microstructural features of GPC are thought to improve the connection between rubber particles and the matrix around them.[13]. Furthermore, GPC generally performs better under ambient curing conditions than OPC-based rubberized concrete, providing a more practical and energy-efficient alternative for field applications [14]. These developments offer an avenue to merge the environmental advantages of utilizing recycled rubber with the enhanced durability and lower carbon emissions of geopolymer technology. Given the gaps identified in previous literature, this research seeks to examine the effect of different crumb rubber dosages on the fresh and hardened characteristics of high-strength geopolymer concrete. The primary aim is to identify the ideal mix that balances mechanical performance with sustainability, making it appropriate for non-load-bearing structural components, pedestrian pavements, and similar applications where flexibility and durability are preferred over compressive strength [15]. Through an extensive experimental program involving various mixes, curing methods, and standardized testing protocols, this study provides important insights into the feasibility and performance enhancement of rubberized geopolymer concrete.

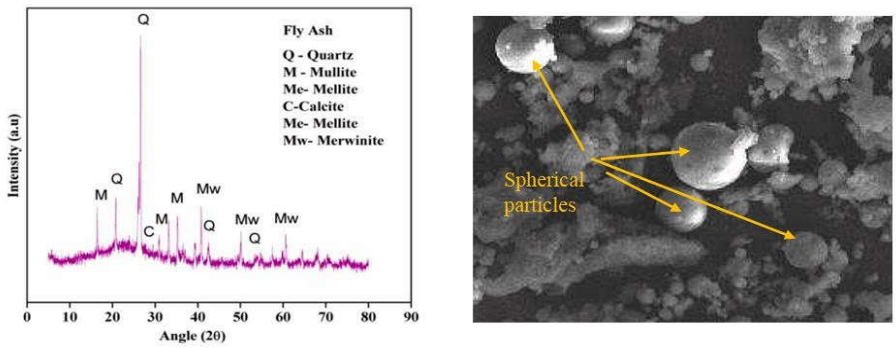
2. Materials Used

2.1 Fly ash

According to XRD analysis, which showed notable peaks for quartz, mullite, mellite, and calcite, the fly ash used in this research was primarily composed of amorphous silica and al umina.The majority of the particles were smooth and spherical, with both amorphous and crystalline features, according to SEM imaging at 100× magnification (Figure 1). The fly ash's physical and chemical properties are shown in Table 1.

Table 1: Characteristics of fly ash

Physical characteristics of fly ash	
Characteristic	Values
Sp. density	1.10
Blaine's fineness (m2 /kg)	391
Mean particle size (μm)	21.44
Color	Gray
Chemical Composition of Fly ash	
Oxides	Weight (%)
Total silica (SiO_2)	61.39
Alumina (Al_2O_3)	21.67
Iron Oxide (Fe_2O_3)	6.86
Calcium Oxide (CaO)	7.58
Total Sulfur (SO_3)	1.16
Magnesium Oxide (MgO)	0.70



(a) XRD spectrum of fly ash (b) SEM image of fly ash

Fig 1. XRD analysis and SEM photograph of fly ash

2.2 Fine Aggregates and Crumb Rubber

Concrete's mechanical qualities and packing density are improved by the use of fine aggreg ates, usually sand.Recycled crumb rubber from old tires was employed in this study to incre ase ductility and lessen its environmental effect.Structural performance and sustainability ar e intended to be balanced by this combination.

2.3 Coarse Aggregate

For concrete to be strong, long-lasting, and cost-effective, coarse aggregate is essential. Its qualities affect workability and density, and it fills a sizable volume while using less cement and water. Good bonding and consistent performance are ensured by appropriate grading and proportioning. Table 2 displays the physical characteristics of CA.

Table 2: Physical properties of coarse aggregates

Physical Property	CA
Sp. Gravity	2.68
Fineness Modulus	6.92
Water Absorption	0.79

3. Mixing, Casting and Curing

Fly ash, aggregates, crumb rubber, and an alkaline activator were combined in precise amounts to create concrete mixtures. The right distribution of rubber particles was guaranteed by uniform mixing. After being poured into conventional molds, the mixes were left to cure naturally. In geopolymer systems, where polymerization depends on constant moisture and temperature control, curing is essential to the development of strength.

4. Result and Analysis

With an emphasis on its implementation in foamed concrete and paver block applications under low traffic load circumstances, This research investigates the durability and resilience of geopolymer concrete that includes crumb rubber. Compressive, tensile, and flexural strength tests were conducted over 7, 14, and 28 days. According to IRC: SP: 63-2004 rules, the study also looks at how crumb rubber affects water absorption, which is especially important for paver applications.

4.1 Compressive Strength of Foamed Concrete

The study examining the comp. strength and average density of six concrete formulations (FC0 to FC5) reveals a clear and notable decline in effectiveness as the mix designation moves from FC0 to FC5. After 28 days, FC0 demonstrated the highest compressive strength at 12.5 N/mm² and the greatest average density of 898 kg/m³, whereas FC5 recorded the lowest strength at 8.10 N/mm² and a density of 761 kg/m³. This pattern is also evident at 7 and 14 days, suggesting that the early strength development is adversely affected in the mixes with lower density. The findings indicate a strong and direct relationship between density and compressive strength, signifying that denser mixtures generally exhibit improved load-bearing capacity. The steady decline in both metrics implies that alterations in the mix design—like reduced binder content, increased porosity, or the use of lightweight aggregates—have a detrimental effect on the concrete's structural integrity. Therefore, FC0, with its superior values for strength and density, is highlighted as the most dependable mix for applications necessitating high mechanical performance, while mixes such as FC4 and FC5 are likely more appropriate for non-structural or lightweight purposes where strength is less critical.

Table 3: Compressive strength test results of foamed concrete with and without crumb rubber

Mix	Compressive Strength (N/mm^2)			Averag Densit y (kg/m3)
	7 days	14 days	28 days	
FC0	5.3	10.4	12.5	898
FC1	4.7	9.9	11.8	868
FC2	4.2	9.6	10.3	828
FC3	3.9	8.5	9.5	810
FC4	3.6	7.7	9.3	787
FC5	3.2	7.8	8.10	761

4.2 Split Tensile Strength of Foamed Concrete

The evaluation of split tensile strength and average density for concrete mixtures FC0 to FC5 across 7, 14, and 28 days indicates a distinct and gradual decrease in both characteristics as the mix transitions from FC0 to FC5. FC0 showed the highest tensile strength readings for all curing durations, reaching 1.15 N/mm² at 7 days, 1.52 N/mm² at 14 days, and 1.98 N/mm² at 28 days, along with the greatest average density of 898 kg/m³. Conversely, FC5 had the lowest tensile strength, recording values of 0.72 N/mm², 1.03 N/mm², and 1.29 N/mm² at 7, 14, and 28 days respectively, in addition to the lowest density at 761 kg/m³. This ongoing drop in tensile strength in conjunction with reduced density suggests a strong link between the compactness of the material and its ability to withstand tensile forces. The probable reasons for this pattern could include alterations in mix formulation, such as a decrease in binder or cementitious content, more air voids, or the use of lightweight aggregates, all of which lead to a less dense and structurally weaker concrete. The findings also imply that the rate at which strength increases is lower in mixes with reduced density, indicating that their internal composition might not facilitate effective hydration or strength development over time. As a result, FC0, with its outstanding performance in both tensile strength and density, is the most suitable choice for structural components facing tensile stresses, while FC5 might only be suitable for lightweight or non-load-bearing applications where strength is not a crucial element.

Table 4: Split tensile strength results of crumb rubber foamed concrete

Mix	Split Tensile Strength (N/mm^2)			Averag Densit y (kg/m^3)
	7 days	14 days	28 days	
FC0	1.15	1.52	1.98	898
FC1	1.03	1.45	1.85	868
FC2	0.98	1.38	1.62	828
FC3	0.93	1.25	1.50	810
FC4	0.86	1.10	1.41	787
FC5	0.72	1.03	1.29	761

With R2 values of 0.9574 (7 days), 0.9957 (14 days), and 0.9763 (28 days), the graph in Figure 2 illustrates a significant positive linear correlation between compressive strength and split tensile strength at 7, 14, and 28 days, demonstrating excellent linearity in every case. Across all curing ages, the compressive strength steadily rises as the split tensile strength does. The regression line's slope rises from 5.053 (7 days) to 6.5344 (14 days) and then significantly falls to 5.3852 (28 days), indicating that the two strengths' association gets stronger up to 14 days before stabilizing. This suggests that split tensile strength is a helpful non-destructive metric for structural performance since it can accurately predict compressive strength, particularly after early curing stages.

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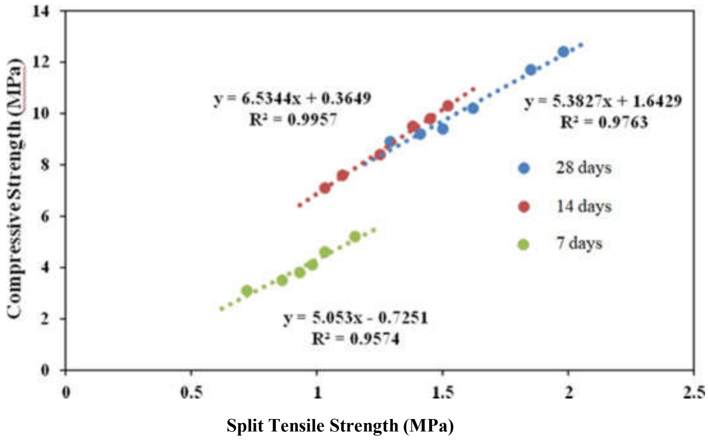

Figure 2: Relationship between compressive strength and split tensile strength

4.3 Flexural Strength of Foamed Concrete

Flexural strength tests were conducted on crumb rubber foamed concrete using prism-shaped specimens, following the standard procedures typically applied to conventional concrete. Prior to testing, the prisms were cast and water-cured for the designated amounts of time, as seen in Figure 3. When crumb rubber is used as a partial replacement for fly ash., the results, which are compiled in Table 4, show a discernible drop in flexural strength. With a 15% incriment of crumb rubber, the flexural strength dropped from 2.45 MPa to 1.75 MPa after 28 days, a 28% decline. At 7 and 14 days, similar strength decreases were also noted. Concrete density increased slightly despite the strength decline, ranging from 774 to 9xx kg/m³ (precise value incomplete). Additionally, Figure 3 shows

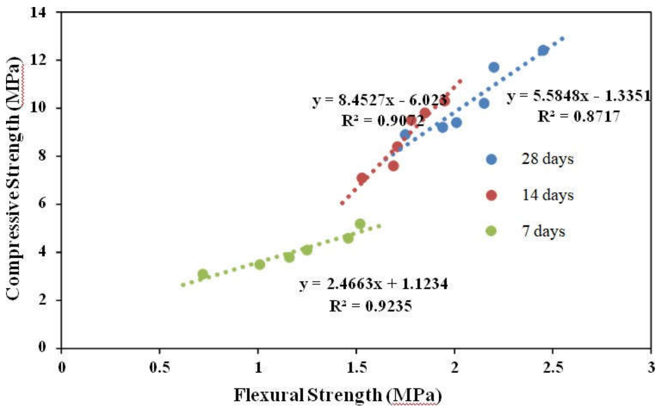

Figure 3:Rrelation between compressive strength and flexural strength

4.4 Water Absorption

The bar graph presents the the proportion of water uptakefor three distinct concrete samples with different mix formulations or additive levels, indicated by the values 0, 6, and 9 on the x-axis. The water absorption rates rise with alterations in the mix formulation: the control mix (0) has the lowest absorption, just under 2%, while the mix marked 6 shows a greater absorption of roughly 2.4%, and the mix tagged 9 displays the highest absorption, nearing 2.7%.This pattern suggests that as the mix formulation changes (potentially due to a greater replacement of cement with supplementary materials or the introduction of more porous elements), the porosity of the concrete increases, resulting in elevated water absorption. Higher water absorption usually indicates a larger quantity of interconnected pores within the structure, which can negatively impact the durability and long-term efficacy of the concrete. It may also signify diminished compactness or increased permeability, making the material more vulnerable to moisture penetration, freeze-thaw deterioration, and chemical assaults.Consequently, although the modified mixes may fulfill certain objectives (such as sustainability or cost savings), the rise in water absorption must be carefully evaluated in scenarios where durability and resistance to environmental factors are essential. Additional refinement or the application of sealing agents could be necessary to achieve a balance between mechanical performance and durability features.

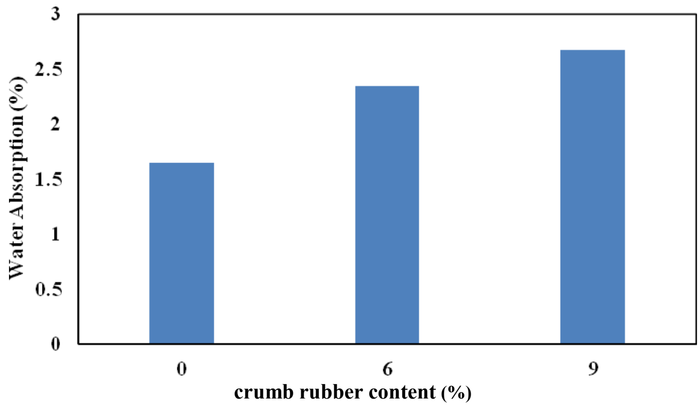

Figure 4: Relationship between crumb rubber content and water absorption.

5. Conclusion

In order to strike a balance between sustainability and practicality, this study assessed the T his research effectively assesses the mechanical characteristics and longevity of high-strength geopolymer concrete (GPC) with varying amounts of crumb rubber tire aggregates. Although the addition of crumb rubber presents environmental and sustainability benefits, it caused significant declines in compressive, split tensile, and flexural strengths during all curing periods. These strength reductions were linked to higher rubber content and decreased density, likely resulting from poor adhesion between the rubber particles and the binder matrix, along with increased porosity. Nevertheless, despite the strength losses, the mixtures still demonstrated performance levels deemed acceptable for non-structural uses. Specifically, FC0, the control mix without crumb rubber, consistently showed the greatest mechanical strength and density, while FC5, which contained the maximum rubber content, performed the weakest yet offered the highest environmental advantage. Furthermore, results from water absorption tests indicated that increased rubber content leads to greater porosity and permeability, raising concerns regarding long-term durability in severe conditions.

However, the linear correlation found between compressive and tensile strengths, along with the moderate decrease in flexural strength, implies that carefully optimizing rubber content could result in a balanced mix that maintains adequate mechanical performance while also providing significant environmental benefits. These results confirm that geopolymer concrete with a well-planned crumb rubber dosage can be a cost-effective and eco-friendly option to traditional Portland cement concrete, particularly for uses like as paver blocks, walkways, and other low-load or non-structural components. Additional investigationshould aim at enhancing the connection between crumb rubber and the geopolymer matrix, to improve performance without sacrificing sustainability..

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