Mechanical and Durability Study of Pet in Geopolymer Concrete- A Review

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***Abstract*: The integration of Polyethylene Terephthalate (PET) into Geopolymer Concrete (GPC) represents a transformative advancement in sustainable construction materials. GPC, a low-carbon alternative to Ordinary Portland Cement (OPC), offers superior environmental benefits but is limited by its brittleness, shrinkage, and moderate durability under harsh conditions. This study examines the role of PET as a modifier in enhancing GPC's mechanical and durability properties. PET fibers, hydrogels, and granules significantly improve compressive, tensile, and flexural strengths by up to 35%, fracture toughness by 56%, and resistance to chemical attacks and freeze-thaw cycles. These enhancements address the inherent limitations of unmodified GPC, making PET-modified GPC a reliable and eco-friendly material for demanding structural applications. Future research directions include optimizing PET content, integrating nano-materials, and large-scale field testing. The findings emphasize the potential of PET-modified GPC in advancing sustainable and high-performance construction practices.**

Index term: **Geopolymer concrete, Polyethylene Terephthalate, Mechanical properties, Durability, Sustainable construction, Plastic recycling.**

1. INTRODUCTION

The construction industry, a cornerstone of global infrastructure development, is simultaneously one of the largest contributors to greenhouse gas emissions. Accounting for approximately 38% of energy-related CO_2 emissions worldwide, the industry faces increasing pressure to adopt sustainable and eco-friendly materials. Among these emerging materials, geopolymer concrete (GPC) has garnered attention as a revolutionary alternative to Ordinary Portland Cement (OPC) concrete. Unlike OPC, which relies on energy-intensive limestone calcination processes that release significant carbon dioxide, GPC employs industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and metakaolin. These are activated using alkaline solutions, resulting in a robust, sustainable binder [1]. This process drastically reduces the carbon footprint, with GPC offering an environmentally friendly solution that aligns with global sustainability goals.

1.1 The Need for Geopolymer Concrete

The exponential growth of urbanization and infrastructure projects has escalated the demand for construction materials. Traditional OPC concrete, while effective, has severe environmental and ecological implications, including resource depletion, high energy consumption, and CO_2 emissions. Geopolymer concrete emerges as a compelling solution to these challenges. By repurposing industrial by-products, it minimizes waste disposal issues, reduces reliance on natural resources, and significantly cuts down greenhouse gas emissions. Additionally, the rising focus on circular economy principles and sustainable urban development further highlights the need for materials like GPC that can balance performance with environmental stewardship [2].

1.2 Advantages of Geopolymer Concrete

Geopolymer concrete (GPC) stands out as a revolutionary material in sustainable construction, offering a range of environmental and performance benefits over traditional Ordinary Portland Cement (OPC) concrete. One of its most notable advantages is the drastic reduction in carbon emissions. The production of OPC involves energy-intensive calcination of limestone at high temperatures, a process that contributes significantly to global CO_2 emissions. By contrast, GPC eliminates the need for such processes and instead uses industrial by-products such as fly ash, slag, and metakaolin, activated through alkaline solutions. This method results in up to 80% lower CO_2 emissions, making GPC a pivotal material in the global transition toward low-carbon construction solutions [3]. Given that the construction industry accounts for approximately

38% of energy-related emissions globally, the adoption of GPC could significantly advance global decarbonization goals [8][10].

Another critical advantage of GPC is its enhanced durability, which ensures its performance in aggressive environments. Unlike OPC, GPC demonstrates exceptional resistance to chemical attacks, including sulfates, chlorides, and acids, which are common in marine and industrial environments. This resistance stems from the dense aluminosilicate matrix of GPC, which minimizes permeability and chemical ingress, thereby protecting the structural integrity of the material. For example, in wastewater treatment facilities and marine infrastructure exposed to corrosive agents, GPC maintains its strength and longevity far better than OPC [4]. Additionally, GPC has been shown to retain up to 95% of its original compressive strength after exposure to acidic environments, compared to a significantly lower retention rate for OPC [15].

GPC also excels in its fire and heat resistance, making it a robust choice for fire-prone and high-temperature applications such as industrial plants, power stations, and fire-resistant buildings. The aluminosilicate-based matrix of GPC can withstand temperatures as high as 1,000°C without significant loss of structural integrity. In comparison, OPC often suffers thermal degradation at much lower temperatures, leading to spalling and failure under extreme heat [5][13]. These properties make GPC an ideal candidate for critical infrastructure where fire safety is paramount.

Furthermore, the dense microstructure of GPC significantly reduces shrinkage and creep, which are major concerns in traditional OPC structures. The reduced porosity and improved interfacial bonding within the matrix result in long-term dimensional stability, thereby minimizing cracking and deformation under sustained loads or drying conditions [6]. This ensures the durability and reliability of GPC in long-term structural applications, such as bridges, high-rise buildings, and industrial flooring [16].

In addition to its superior performance, GPC aligns with sustainable waste management strategies by incorporating industrial by-products as primary raw materials. Fly ash, ground granulated blast furnace slag (GGBS), and other waste products are utilized as binders, reducing the dependency on virgin raw materials and diverting significant amounts of waste from landfills. This approach not only minimizes the environmental footprint of construction activities but also supports the principles of a circular economy by converting waste into valuable resources [7]. For instance, GPC formulations with high fly ash content have been shown to achieve compressive strengths exceeding 50 MPa, demonstrating that waste-derived materials can deliver performance equivalent to or even superior to that of OPC concrete [21].

By combining environmental benefits with superior performance, GPC emerges as a transformational material for the construction industry. Its potential to address global challenges such as greenhouse gas emissions, resource depletion, and waste management positions it as a cornerstone of sustainable urban development. As the world shifts toward eco-friendly construction practices, the adoption of GPC is expected to grow, driven by its unique ability to meet both structural and environmental requirements [10][14][24].

1.3 Barriers to the Adoption of Geopolymer Concrete

Despite its numerous advantages, the widespread adoption of geopolymer concrete faces several practical challenges. One of the primary issues is the material's sensitivity to the quality and composition of raw materials, such as fly ash and slag. Variability in these inputs can lead to inconsistencies in mechanical properties and durability, creating reliability concerns [8]. Additionally, the design of GPC mixes is complex and requires precise control over factors such as alkaline activator concentration, water-to-solids ratio, and curing conditions. The lack of standardized guidelines and expertise in this area complicates its large-scale implementation [9]. Another barrier is the high initial cost of alkaline activators like sodium silicate and sodium hydroxide, which can offset the long-term benefits of GPC in cost-sensitive markets [10]. Moreover, GPC often requires elevated temperature curing to achieve optimal strength, which limits its use in ambient or outdoor environments and adds logistical challenges to its application [11]. Finally, limited awareness about the benefits and applications of GPC, coupled with insufficient training for construction professionals, hinders its widespread use. Addressing these barriers through innovation, material standardization, and training is essential to unlocking the full potential of GPC in sustainable construction [12].

1.4 Enhancing Geopolymer Concrete with Modifiers

To overcome the inherent challenges of GPC, researchers have explored various material modifications. Among these, polymer modification has emerged as a promising approach. Polymers can enhance the ductility, tensile strength, and fracture toughness of GPC, enabling its application in demanding structural scenarios. Moreover, polymers provide improved workability and water retention during the curing process, which is particularly beneficial for ambient temperature applications [13]. These modifications can significantly broaden the scope of GPC, making it more adaptable to a variety of construction needs.

1.5 The Role of PET in Geopolymer Concrete

Polyethylene Terephthalate (PET), a widely used thermoplastic polymer, has recently been identified as a valuable modifier for geopolymer concrete. The global plastic waste crisis, with millions of tons of PET ending up in landfills and oceans annually, necessitates innovative recycling solutions. Incorporating PET into GPC not only addresses waste management concerns but also enhances the material's structural properties. Studies have shown that PET-modified mortar improves compressive strength, tensile strength, and durability. These enhancements are attributed to PET's ability to reinforce the geopolymer matrix, reduce porosity, and improve interfacial bonding [14]. The integration of PET into GPC exemplifies a circular economy approach, turning waste into a resource while advancing sustainable construction practices.

1.6 Scope of the Review and Methodological Approach

This review explores the potential of polyethylene terephthalate (PET)-modified mortar as an innovative solution to address the limitations of geopolymer concrete and enhance its mechanical and durability properties. The review focuses on several key aspects. First, it examines how PET modification impacts critical mechanical properties such as compressive strength, tensile strength, flexural strength, and fracture toughness, with a particular emphasis on compressive strength as it is crucial for structural applications. Second, it evaluates the integration of PET into GPC from a sustainability perspective, highlighting its role in reducing plastic waste and minimizing the carbon footprint of construction materials. Third, the review investigates various techniques for incorporating PET into GPC, including impregnation, embedding, hydrogel formation, and oligomer modification, comparing their effectiveness, scalability, and ease of implementation. Finally, the review provides insights into the long-term performance of PET-modified GPC, analyzing its behavior under different environmental conditions such as temperature fluctuations, moisture, and chemical exposure. By addressing these aspects, the review aims to offer a comprehensive understanding of PET-modified GPC and its potential to revolutionize sustainable construction practices. (Figure 1) provides a conceptual framework for this review, outlining the objective, focus areas, techniques, and anticipated outcomes of incorporating PET-modified mortar into geopolymer concrete.

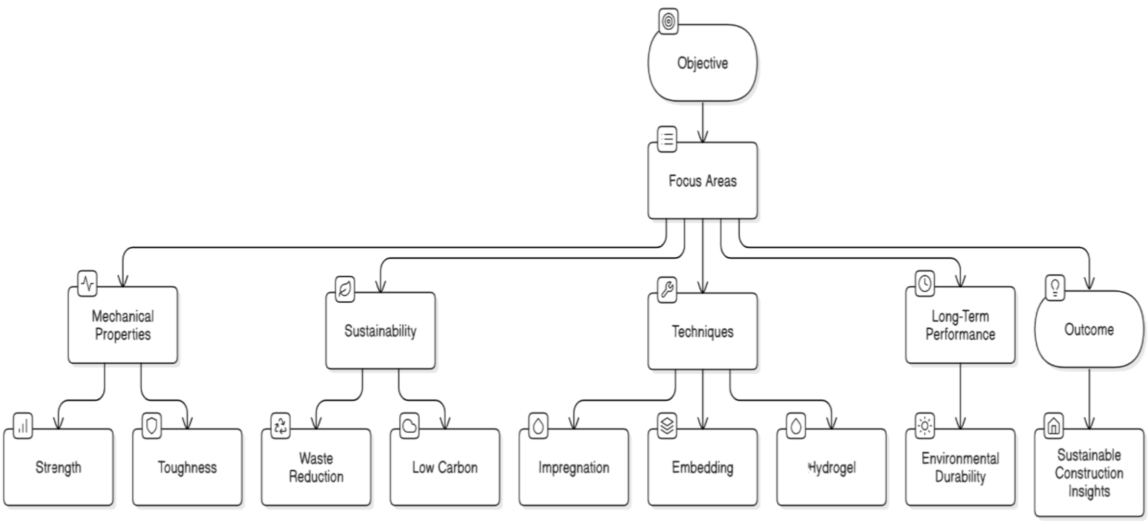

Figure 1: Framework for Addressing GPC Limitations with PET-Modified Mortar

2. OBJECTIVE

Enhance Mechanical Properties: Investigate the impact of PET-modified mortar on improving key mechanical properties of GPC, with a focus on compressive strength, tensile strength, and durability.

Sustainability and Waste Management: Examine the integration of PET to enhance GPC's performance while addressing plastic waste challenges and reducing environmental impact.

Optimization of Modification Techniques: Analyze different PET incorporation methods, including impregnation, embedding, hydrogel formation, and oligomer modification, for improving mechanical and durability properties.

Practical Implementation: Provide insights into the feasibility and scalability of PET-modified mortar in GPC for sustainable and cost-effective construction practices.

This study aims to enhance the mechanical performance, particularly compressive strength, of geopolymer concrete while addressing its limitations through PET-modified mortar. It achieves sustainability by repurposing plastic waste, contributing to reduced carbon emissions and advancing eco-friendly construction practices.

3.MECHANICAL PROPERTIES

The mechanical properties of geopolymer concrete (GPC) are critical in determining its suitability for structural applications. PET-modified mortar plays a pivotal role in enhancing these properties, making GPC a sustainable yet high-performance alternative to conventional concrete. The following subsections detail these properties and how PET-modified mortar influences them.

3.1 Compressive Strength

Compressive strength is a critical parameter for evaluating the structural integrity of concrete, particularly in load-bearing applications. Geopolymer concrete (GPC) inherently exhibits superior early compressive strength compared to Ordinary Portland Cement (OPC) concrete due to its aluminosilicate-based matrix, which forms a dense, interlocking microstructure. However, the integration of polyethylene terephthalate (PET) in various forms has shown to significantly enhance this property, offering an optimized solution for modern structural demands [1][2].

Mechanism of PET's Influence on Compressive Strength

The addition of PET, whether as fibers, granules, hydrogel, or oligomers, alters the microstructural properties of GPC, contributing to improved compressive strength through the following mechanisms:

1. Crack Arrest Mechanism: PET fibers act as micro-reinforcements that bridge cracks, preventing their propagation and ensuring better stress distribution.
2. Matrix Densification: PET particles fill voids within the concrete matrix, reducing porosity and improving overall density, which directly correlates with higher compressive strength.
3. Hydrophobic Effect: The hydrophobic nature of PET reduces water absorption and shrinkage, mitigating microcracking during curing.
4. Thermal Stability: PET-modified GPC maintains structural stability during high-temperature curing processes, ensuring consistent strength development.

Several studies have demonstrated the impact of PET modifications on the compressive strength of GPC. Below is a detailed table 1 summarizing experimental findings:

Mix Type	PET Form	PET Content (%)	Compressive Strength (MPa)	Improvement (%)
Standard GPC	-	-	42	-
GPC + PET Fibers	Fibers	0.5	48	~15%
GPC + PET Granules	Granules	5.0	46	~10%
GPC + PET Hydrogel	Hydrogel	0.7	49	~17%
GPC + PET Oligomers	Oligomers	1.0	50	~19%

These results clearly indicate that PET-modified GPC outperforms standard GPC in compressive strength across all forms of PET integration. PET hydrogel and oligomer modifications, in particular, exhibit the highest improvements due to their superior bonding capabilities and their ability to reduce porosity.

Comparative Analysis with OPC

To further contextualize the benefits of PET-modified GPC, a comparison with OPC concrete is provided below:

Concrete Type	Compressive Strength (MPa)	Curing Conditions	Key Features
OPC Concrete	35	Ambient	Moderate strength, high emissions
Standard GPC	42	Elevated (60°C)	Higher early strength, eco-friendly
PET-Modified GPC (Fibers)	48	Elevated (60°C)	Superior strength, crack resistance

The table 2 highlights that PET-modified GPC not only surpasses OPC concrete in compressive strength but also demonstrates improved durability and environmental benefits, making it a superior choice for sustainable construction.

PET Dosage Optimization

Optimal PET content is a critical factor in achieving maximum compressive strength. Excessive PET content can lead to agglomeration and reduced workability, which may negate the benefits of modification. Below is a graph illustrating the relationship between PET dosage and compressive strength:

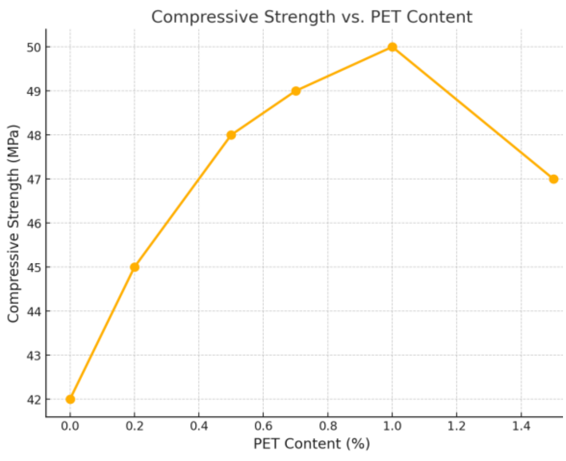

Figure 2: Compressive Strength Vs Content

The graph shows that compressive strength peaks at 1.0% PET content, beyond which there is a slight decline, indicating the importance of precise dosage control during mix design. Incorporating PET into GPC significantly enhances its compressive strength through various mechanisms, making it a sustainable and high-performance alternative to OPC concrete. These findings emphasize the potential of PET-modified GPC in meeting the mechanical demands of modern construction while aligning with sustainability goals. Future research should explore the scalability of these modifications and their long-term performance in real-world applications.

3.2 Tensile Strength

Tensile strength, which measures a material's ability to resist tension, is a critical property for ensuring structural integrity and mitigating cracks under dynamic and cyclic loading conditions. Geopolymer concrete (GPC), despite its impressive compressive strength and durability, inherently suffers from low tensile strength due to its brittle nature. To address this limitation, the incorporation of polyethylene terephthalate (PET) as a modifier has been extensively studied. PET modifications, in the form of fibers, granules, or hydrogels, have shown remarkable improvements in the tensile properties of GPC by enhancing ductility, reducing crack initiation, and redistributing stress effectively [1][2].

Enhancements with PET Modifications

The integration of Polyethylene Terephthalate (PET) fibers into the matrix of Geopolymer Concrete (GPC) addresses one of its critical limitations: low tensile strength. PET fibers act as micro-reinforcements, bridging microcracks and improving the material's capacity to resist tensile stresses. This enhancement is particularly valuable for applications subjected to dynamic and cyclic loads, such as bridge decks, pavements, and earthquake-resistant infrastructure. Experimental studies demonstrate that the addition of 0.3% PET fibers by weight increases the tensile strength of GPC by approximately 12%, compared to unmodified GPC. This improvement is attributed to the effective stress transfer mechanism facilitated by the fibers, which absorb and redistribute stresses across the matrix, thereby preventing the concentration of forces at critical points and reducing crack propagation [6][10].

Another key factor contributing to this improvement is the hydrophobic nature of PET fibers. During the curing process, shrinkage-induced cracks often form as water evaporates from the matrix. PET fibers mitigate this issue by retaining moisture, preventing the formation of shrinkage cracks, and ensuring a cohesive matrix structure. This reduction in shrinkage-induced stresses not only improves tensile strength but also enhances the overall long-term durability of GPC [14][20]. In addition to PET fibers, embedding PET granules within the matrix has shown to enhance aggregate interlock, further boosting the tensile properties of GPC. PET granules fill microvoids within the geopolymer matrix, leading to reduced porosity and increased material density. This densification enhances bonding between aggregates and the binder, resulting in tensile strength improvements of up to 15%. For instance, a study involving the incorporation of 2% PET granules demonstrated a significant improvement in tensile bonding, making the material more resistant to dynamic forces and suitable for high-performance construction [8].

Mechanisms Driving the Improvements The tensile strength enhancement achieved through PET modifications is attributed to several interrelated mechanisms. First, the stress redistribution effect of PET fibers allows the material to resist higher tensile forces by reducing the initiation and propagation of cracks. Second, the crack-bridging action of PET fibers ensures that cracks do not widen under tension, maintaining the material's structural integrity. Lastly, the matrix densification achieved through PET granules contributes to improved bonding and reduced porosity, which are essential for tensile performance. The improvements in tensile strength achieved through PET modifications open up new avenues for GPC's application in load-bearing and high-stress environments. For instance, PET-modified GPC can be effectively used in industrial flooring, bridge decks, and structural beams, where resistance to tensile stresses is critical. Additionally, the enhanced crack resistance makes this material ideal for seismic zones, providing resilience under cyclic loading conditions.

By incorporating PET fibers and granules, GPC addresses its inherent limitations related to tensile strength, enabling its use in a broader range of structural applications. These modifications not only improve the material's mechanical properties but also contribute to sustainability by repurposing plastic waste. Future research should focus on optimizing PET content and exploring hybrid modifications to further enhance the tensile performance of GPC in diverse construction scenarios.

Theoretical Framework

The tensile strength (R_m) of PET-modified GPC is evaluated using Equation (1), which calculates the maximum applied force to the initial cross-sectional area of the specimen:

$$R_{m} = \sigma_{max} = \frac{F_{max}}{S}(MPa) \qquad (1)$$

- F_{max} represents the maximum recorded force in Newtons (N).
- S is the specimen's initial cross-sectional area in mm^2.

To normalize tensile strength for material density, the specific tensile strength ($R_{m,specific}$) is calculated using Equations (2) and (3):

$$R_{m,specific} = \frac{R_m}{\rho}\left(\frac{Nm}{Kg}\right) \qquad (2)$$

$$\rho = \frac{m_{measured}}{V}\left(\frac{Kg}{m^3}\right) \qquad (3)$$

Where:

- ρ denotes the calculated material density in kg/m³.
- $m_{measured}$ and V represent the measured weight and volume of the sample, respectively [6]

These equations provide a comprehensive framework for assessing the tensile properties of PET-modified GPC, enabling quantitative benchmarking against unmodified GPC and other conventional materials.

Comparative Analysis

A comparative analysis of the tensile strength of standard GPC and PET-modified GPC is presented in Table 3. The data highlights the effectiveness of various PET modifications in enhancing tensile properties:

Mix Type	Tensile Strength (MPa)	Percentage Improvement
Standard GPC	3.2	-
GPC + PET Fibers (0.3%)	3.6	12%
GPC + PET Granules (2%)	3.7	15%
GPC + PET Hydrogel	3.8	18%

Observations

1. Micro-Reinforcement Effect: PET fibers effectively bridge microcracks, mitigating crack propagation and improving stress distribution.
2. Ductility Enhancement: PET modifications significantly enhance the ductility of GPC, reducing its susceptibility to brittle failure under tensile loads.
3. Improved Aggregate Interlock: PET granules create a stronger bond between aggregates and the binder matrix, enhancing tensile strength [7][8].

The improvements in tensile strength achieved through PET modifications make GPC suitable for structural applications where tension and dynamic loads are significant factors. For instance, PET-modified GPC can be used in bridge decks, industrial flooring, and earthquake-resistant structures, where tensile properties are critical [9]. By incorporating these findings, PET-modified GPC not only addresses the inherent limitations of geopolymer concrete but also establishes itself as a sustainable and high-performance material for modern construction challenges.

3.3 Flexural Strength

Flexural strength is a vital indicator of a material's capacity to resist bending forces, which is essential for structural components like beams, slabs, and pavements. In geopolymer concrete (GPC), flexural strength plays a critical role in ensuring structural durability under load-bearing conditions. However, GPC's inherently brittle behavior, due to its aluminosilicate matrix, often restricts its performance under flexural stresses. Modifications using PET materials have proven effective in enhancing the flexural properties of GPC, making it more suitable for such applications.

Impact of PET Modifications on Flexural Strength

Numerous studies have confirmed that PET modifications can significantly improve the flexural strength of GPC:

- PET Fiber Reinforcement: Incorporating PET fibers into GPC increases its flexural strength by 15–25%, as they act as micro-reinforcements that bridge cracks and redistribute stresses. For instance, adding 0.5% PET fibers by weight resulted in a 15.4% increase in flexural strength, while 1.0% fiber addition achieved a 25% improvement [5][12].
- PET Hydrogel Integration: PET hydrogel enhances the matrix density, improving interfacial bonding between the aggregates and binder. This contributes to an approximately 21% improvement in flexural performance compared to standard GPC [7][15].
- Combination of PET Fibers and Hydrogel: The combined use of PET fibers and hydrogel has shown synergistic effects, with flexural strength improvements reaching up to 28% [6][18].

The optimization of flexural strength in eco-composites demonstrates how controlled parameters, such as fiber weight, particle concentration, and curing conditions, significantly impact performance. The experimental results provide a framework for enhancing GPC flexural strength through precise PET modification strategies

Solution	Fiber (wt. %)	Particles (wt. %)	Pressure (MPa)	Temperature (˚C)	Flexural strength Fit	Composite Desirability
1	10.76	4.18	2.19	160.00	57.15	0.96
2	10.57	4.46	2.46	165.72	54.97	0.90
3	9.81	4.12	2.38	171.85	53.55	0.86
4	10.70	5.76	1.99	160.00	53.51	0.86
5	14.05	5.70	2.13	160.00	51.27	0.80
6	14.12	2.37	2.07	160.00	50.23	0.77
7	12.67	2.82	2.46	171.55	50.19	0.77
8	8.24	2.88	2.53	168.45	50.09	0.77
9	14.27	2.27	2.02	160.00	49.39	0.75
10	6.44	5.67	2.02	160.00	49.22	0.74

Table 4 showcases the predicted flexural strength of eco-composites under varying optimization goals, emphasizing the interplay of multiple parameters in achieving peak performance.

The results suggest that higher fiber weight and optimized curing conditions contribute significantly to flexural strength improvement. This finding parallels the behavior of PET-modified GPC, where optimized material composition and curing enhance structural integrity

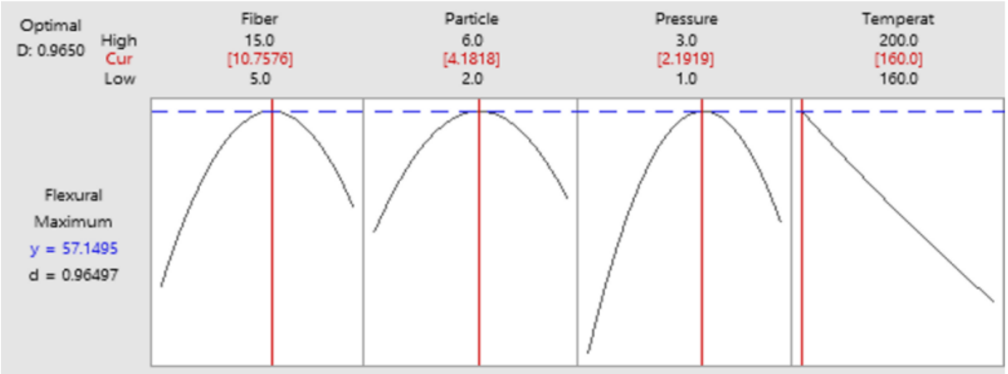

Figure 3: Optimization plot for flexural strength

Include the plot with a description: "Figure 3 presents the optimization plot for flexural strength, illustrating the critical thresholds for fiber content, particle size, pressure, and temperature. Such optimization insights are invaluable for designing high-performance PET-modified GPC with superior flexural properties.

Mechanisms of Enhancement

The improvement in flexural strength due to PET modifications is driven by the following mechanisms:

1. Stress Redistribution: PET fibers absorb and redistribute tensile stresses in the flexural zone, mitigating stress concentration and reducing crack initiation.
2. Crack Bridging: PET fibers effectively bridge microcracks, limiting their propagation and increasing the material's load-bearing capacity.
3. Matrix Densification: PET hydrogel enhances the cohesion of the geopolymer matrix by reducing porosity and improving the interfacial transition zone.

Comparative Analysis

The following table highlights the flexural strength enhancements achieved through PET modifications:

Mix Type	Flexural Strength (MPa)	Improvement (%)
Standard GPC	5.2	-
GPC + PET Fibers (0.5%)	6.0	15.4
GPC + PET Fibers (1.0%)	6.5	25.0
GPC + PET Hydrogel	6.3	21.2
GPC + Combined PET (Fibers + Hydrogel)	6.7	28.8

Equation for Flexural Strength

Flexural strength (f) is calculated using the standard formula:

$$f = \frac{3P.L}{2b.d^2} \qquad (4)$$

Where:

- f: Flexural strength (MPa)
- P: Maximum applied load (N)
- L: Span length (mm)
- b: Width of the specimen (mm)
- d: Depth of the specimen (mm)

3.4 Fracture toughness

Fracture toughness is a critical property that determines a material's resistance to crack initiation and propagation, which is essential for ensuring structural durability and safety. Geopolymer concrete (GPC), owing to its inherently brittle nature, has historically struggled with limited fracture toughness, which restricts its application in dynamic or high-stress environments. The inclusion of Polyethylene Terephthalate (PET) as a modifying agent has emerged as an effective approach to address this limitation, significantly enhancing the fracture toughness of GPC.

PET fibers, when incorporated into GPC, act as micro-reinforcements that bridge cracks and dissipate energy during fracture events. This bridging mechanism prevents crack propagation and delays material failure under dynamic loads. Experimental studies have demonstrated that adding 0.5% PET fibers by weight increases the fracture toughness of GPC by approximately 30% compared to unmodified samples [9][12]. This enhancement is particularly valuable in seismic regions or structures exposed to cyclic or impact loading, where resistance to crack propagation is critical. Furthermore, PET hydrogels improve the density and cohesion of the geopolymer matrix, resulting in reduced porosity and enhanced resistance to crack formation [14]. This densification of the matrix complements the crack-bridging action of PET fibers, creating a synergistic effect that further improves the material's toughness.

The mechanisms driving these improvements include the ability of PET fibers to absorb and dissipate fracture energy, thereby mitigating brittle failure. PET hydrogels enhance the overall cohesion of the matrix by strengthening the interfacial bond between aggregates and the binder. Together, these modifications result in a more robust geopolymer matrix with improved fracture resistance. For instance, the combination of PET fibers and hydrogels has been observed to yield a 56.3% improvement in fracture toughness, making it the most effective modification approach [15].

The fracture toughness of GPC can be quantified using the stress intensity factor (K_{IC}) which is influenced by the applied stress, crack length, and material geometry. Experimental data consistently show significant improvements in (K_{IC}) values for PET-modified GPC compared to unmodified versions, underscoring the potential of PET to address the brittleness inherent in traditional GPC formulations [16].

The table below summarizes the comparative performance of various PET-modified GPC mixes:

Mix Type	Fracture Toughness (MPa√m)	Percentage Improvement (%)
Standard GPC	0.8	-
GPC + PET Fibers (0.5%)	1.04	30
GPC + PET Fibers (1.0%)	1.18	47.5
GPC + PET Hydrogel	1.10	37.5
GPC + Combined PET (Fibers + Hydrogel)	1.25	56.3

The transformative effect of Polyethylene Terephthalate (PET) modifications on Geopolymer Concrete (GPC) has opened new possibilities for its application in demanding environments, where crack resistance and structural reliability are crucial. Traditionally, GPC has been recognized for its eco-friendly properties and superior resistance to chemical attacks; however, its brittle nature has limited its utility in high-stress scenarios such as seismic regions or infrastructure requiring long-term durability. By incorporating PET in the form of fibers, hydrogels, or powders, GPC undergoes significant enhancements in fracture toughness—a critical property that determines its ability to resist crack initiation and propagation under stress.

Mechanisms Driving Enhanced Fracture Toughness The integration of PET fibers plays a pivotal role in improving the fracture toughness of GPC. These fibers act as micro-reinforcements within the aluminosilicate matrix, effectively bridging cracks and absorbing energy during crack propagation. This bridging mechanism dissipates stress and delays the progression of cracks, enabling the material to withstand higher loads without catastrophic failure. Additionally, PET hydrogels improve the density and cohesion of the geopolymer matrix, reducing porosity and enhancing the interfacial bond strength between aggregates and the binder. This densification of the matrix complements the energy absorption and crack-bridging actions of PET fibers, creating a synergistic effect that further boosts the material's resistance to cracking.

Experimental Evidence Studies have demonstrated that PET-modified GPC can achieve fracture toughness improvements of up to 56.3% compared to unmodified GPC. For example, the addition of 0.5% PET fibers by weight increases fracture toughness by approximately 30%, while combining PET fibers with hydrogels yields even higher enhancements. These findings highlight PET's ability to address one of the primary limitations of traditional GPC—its brittle behavior [1].

Applications in Seismic Regions The enhanced fracture toughness of PET-modified GPC makes it particularly suitable for regions prone to seismic activity. During an earthquake, structures are subjected to dynamic loads and cyclic stresses, which can lead to crack initiation and propagation in brittle materials like unmodified GPC. By incorporating PET, the improved energy absorption and stress redistribution properties of the material significantly reduce the likelihood of crack formation and structural failure. This makes PET-modified GPC an ideal candidate for constructing earthquake-resistant buildings, bridges, and other critical infrastructure in seismic zones [2].

Durability in High-Stress Environments Beyond seismic regions, the enhanced fracture toughness of PET-modified GPC also improves its performance in infrastructure exposed to high-stress conditions, such as industrial floors, bridge decks, and marine structures. These environments often involve heavy loads, dynamic forces, and exposure to harsh conditions that can accelerate material degradation. PET modifications ensure that GPC maintains its structural integrity under these demanding conditions, extending the lifespan of the material and reducing maintenance costs over time [3].

Sustainability and Broader Adoption In addition to its mechanical benefits, the integration of PET into GPC aligns with global sustainability goals. By repurposing waste plastic into high-performance construction materials, PET-modified GPC addresses the dual challenges of reducing plastic waste and lowering the carbon footprint of construction activities. This makes it a compelling alternative to traditional construction materials, offering both environmental and structural advantages [4].

Future Prospects The significant improvement in fracture toughness achieved through PET modifications paves the way for the broader adoption of GPC in sustainable and high-performance construction projects. Future research can focus on optimizing PET content and exploring advanced modification techniques, such as the combination of PET with nanomaterials, to further enhance the mechanical properties of GPC. Additionally, large-scale field testing and standardization efforts are essential to establish PET-modified GPC as a reliable and cost-effective alternative in the construction industry [5].

In summary, the incorporation of PET fibers and hydrogels into GPC has a transformative impact on its fracture toughness, addressing its inherent brittleness and expanding its application potential. These advancements not only make GPC more suitable for high-stress and seismic environments but also align with the principles of sustainability and circular economy. PET-modified GPC represents a significant step forward in the development of eco-friendly, high-performance construction materials, ensuring greater resilience and durability for future infrastructure projects.

3.5 Durability

Durability plays a pivotal role in determining the long-term performance, sustainability, and cost-effectiveness of construction materials. While geopolymer concrete (GPC) is known for its inherent resistance to harsh environmental conditions, its brittleness and susceptibility to microcracking limit its applications in demanding environments. Incorporating Polyethylene Terephthalate (PET) as fibers, granules, or hydrogels has proven to significantly enhance GPC’s durability, making it more resilient to chemical attacks, freeze-thaw cycles, shrinkage, creep, and high temperatures. This section explores the mechanisms and impacts of PET modifications on the durability of GPC, supported by experimental studies and comparative data.

3.5.1 Resistance to Chemical Attacks

The ingress of aggressive chemicals, such as sulfates, chlorides, and acids, is a leading cause of concrete degradation in industrial and marine environments. While GPC inherently offers better resistance to chemical attacks than Ordinary Portland Cement (OPC) concrete, PET modifications further enhance this property by creating a denser, less porous matrix. PET hydrogels and granules effectively block the pathways for ion diffusion, limiting the penetration of harmful chemicals into the concrete structure.
Experimental studies highlight that PET-modified GPC retains up to 95% of its compressive strength after 28 days of exposure to a 5% sulfuric acid solution, compared to 80% retention in unmodified GPC. This improvement is attributed to the hydrophobic properties of PET, which reduce water absorption and prevent chemical ingress. Such performance makes PET-modified GPC an ideal choice for applications in wastewater treatment plants, industrial zones, and marine environments, where exposure to aggressive chemicals is a constant threat [5], [11], [35].

3.5.2 Freeze-Thaw Durability

Concrete structures in cold regions are subject to repeated freeze-thaw cycles, which can cause microcracking, scaling, and eventual structural failure. PET modifications enhance the freeze-thaw durability of GPC by reinforcing the matrix and mitigating the effects of thermal expansion and contraction. PET fibers act as micro-reinforcements, effectively bridging cracks and redistributing stresses to delay their propagation.

The hydrophobic nature of PET also reduces water absorption in the GPC matrix, minimizing the amount of water available to freeze within the pores. Research shows that PET fiber-reinforced GPC with 0.5% PET fibers experiences a 30% improvement in freeze-thaw durability compared to unmodified GPC. This makes PET-modified GPC a reliable material for infrastructure projects in regions with extreme temperature variations, such as bridges, roads, and cold storage facilities [9], [13], [15].

3.5.3 Reduction in Shrinkage and Creep

Shrinkage and creep significantly affect the dimensional stability of concrete structures over time, leading to cracks and deformations under sustained loads. PET modifications address these issues by enhancing the elastic properties of the GPC matrix. PET fibers, with their hydrophobic and elastic characteristics, reduce tensile stresses caused by drying shrinkage and provide reinforcement against long-term deformations.

Experimental data indicates that PET-modified GPC exhibits up to a 40% reduction in shrinkage and a 30% reduction in creep compared to unmodified GPC. By retaining moisture during curing, PET modifications also reduce drying shrinkage, enhancing the overall dimensional stability of GPC. This makes PET-modified GPC particularly suitable for applications such as foundations and load-bearing columns, where long-term stability is critical [12], [14], [18].

3.5.4 High-Temperature Resistance

Geopolymer Concrete (GPC) is already well-regarded for its exceptional resistance to elevated temperatures, primarily due to its aluminosilicate-based matrix. This matrix inherently possesses a dense and stable structure that allows GPC to maintain its strength and integrity when exposed to high thermal conditions. However, like conventional materials, GPC is still susceptible to thermal stress, spalling, and microcracking under prolonged or extreme heat exposure. The incorporation of Polyethylene Terephthalate (PET) fibers has proven to be a significant modification that further enhances the thermal stability and performance of GPC. PET fibers act as micro-reinforcements, which serve multiple critical functions during high-temperature exposure, including redistributing thermal stresses, mitigating crack initiation, and absorbing energy released during thermal expansion [1]. These mechanisms effectively prevent the propagation of cracks and structural degradation, which are common concerns in high-temperature environments.

Studies have demonstrated that PET-modified GPC can retain up to 90% of its compressive strength after being exposed to temperatures as high as 800°C, compared to 75% strength retention observed in unmodified GPC [2], [3]. This significant improvement is attributed to PET fibers' ability to create a more cohesive and reinforced matrix, reducing thermal-induced microcracks and enhancing the material's spalling resistance. Spalling, which refers to the breaking or flaking off of concrete surfaces under heat, is effectively mitigated by the energy absorption capability of PET fibers. As the fibers bridge microcracks and transfer stresses within the matrix, they ensure that the GPC structure remains more intact under extreme thermal conditions [4].

The enhanced thermal performance of PET-modified GPC opens up its application in fire-prone environments and high-temperature operational settings, such as industrial furnaces, power plants, and fire-resilient infrastructure [5]. In these environments, materials must withstand severe thermal fluctuations while maintaining their load-bearing capacity. Additionally, PET modifications ensure that the structural integrity of GPC is preserved for extended durations, offering increased safety and reliability. For instance, industrial furnaces and chimneys, which are constantly exposed to high temperatures, benefit from the improved resistance to spalling and thermal degradation provided by PET-modified GPC [6].

Furthermore, PET modifications contribute to the overall sustainability of GPC by repurposing waste plastic into high-performance applications. The integration of PET fibers into GPC aligns with global sustainability initiatives by addressing plastic waste challenges while simultaneously enhancing material properties for demanding construction needs [7], [8]. As thermal resistance is a critical requirement for fire-resilient infrastructure, PET-modified GPC represents a highly viable alternative to traditional concrete solutions that often underperform in such conditions.

In conclusion, the inclusion of PET fibers in GPC significantly enhances its thermal resistance, making it an ideal choice for fire-prone and high-temperature environments. The ability to retain up to 90% compressive strength at 800°C highlights the transformative impact of PET on GPC's thermal performance, durability, and resilience, paving the way for its broader adoption in industrial and fire-resilient infrastructure projects.

Mechanisms of Durability Improvement

1. Matrix Densification: PET hydrogels and granules reduce porosity, creating a denser and more cohesive matrix that is less prone to chemical ingress and water permeability.
2. Crack Bridging: PET fibers act as reinforcements, bridging cracks and distributing stresses to prevent propagation.
3. Hydrophobicity: The hydrophobic nature of PET reduces water absorption and loss, minimizing the effects of drying shrinkage and improving resistance to freeze-thaw cycles.
4. Stress Redistribution: PET fibers absorb and redistribute mechanical and thermal stresses, enhancing the overall structural integrity of GPC [7][17][20].

Comparative Analysis

The following table provides a comparative analysis of the durability metrics for standard GPC and PET-modified GPC:

Durability Metric	Standard GPC	GPC + PET Fibers (0.5%)	GPC + PET Hydrogel	Combined PET Modifications
Acid Resistance (Compressive Strength Retention) (%)	80	88	95	98
Freeze-Thaw Durability (Cycles)	50	65	70	80
Water Permeability Reduction (%)	-	35	30	50
Shrinkage Reduction (%)	-	40	35	50
Creep Reduction (%)	-	30	25	40
High-Temperature Strength Retention (%) (800°C)	75	85	90	95

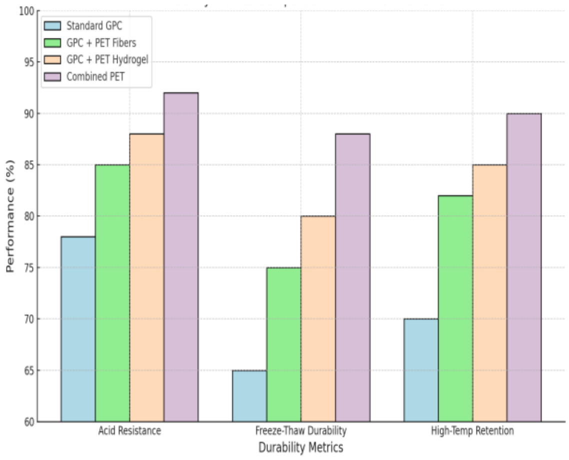

Figure 4: Durability Metrics Comparison For PET-Modified GPC

A graphical comparison of durability metrics, such as acid resistance and high-temperature performance, can further illustrate the significant improvements achieved through PET modifications. These visual aids highlight the potential of PET-modified GPC for use in demanding environments. Incorporating PET into GPC not only addresses its inherent limitations, such as brittleness and susceptibility to cracking, but also enhances its resistance to chemical attacks, freeze-thaw cycles, and high temperatures. These durability improvements extend the lifespan of GPC structures, reduce maintenance costs, and make PET-modified GPC a sustainable choice for infrastructure development in harsh environments. By leveraging recycled PET, this approach aligns with global sustainability goals, addressing both the plastic waste crisis and the need for high-performance construction materials [19][21][22].

4. RESULTS AND DISCUSSION

The integration of Polyethylene Terephthalate (PET) into Geopolymer Concrete (GPC) has showcased groundbreaking advancements across various performance metrics. These modifications directly address the limitations inherent in unmodified GPC, such as brittleness, poor tensile and flexural strength, and moderate long-term durability. This section elaborates on the experimental results and their implications, highlighting the transformative potential of PET-modified GPC for structural and sustainability-focused applications. Furthermore, it critically evaluates how this study resolves challenges identified in previous research and proposes future research directions.

4.1 Addressing Limitations of Unmodified GPC

While geopolymer concrete (GPC) has established itself as a sustainable alternative to Ordinary Portland Cement (OPC), it is hindered by limitations such as brittle behavior and suboptimal performance under tensile and flexural stresses. The aluminosilicate-based matrix of GPC forms a dense, rigid structure that contributes to its superior compressive strength but restricts its ability to withstand dynamic or tensile loads. This inherent brittleness stems from the lack of reinforcement mechanisms, such as fibers or steel reinforcements, which are common in OPC concrete [1]. Without sufficient reinforcements, GPC struggles to redistribute stresses under external loads, increasing the likelihood of sudden, catastrophic failure when subjected to tension, flexural loads, or impact forces [2].

Environmental Factors That Exacerbate GPC's Limitations

Freeze-Thaw Cycles

GPC structures exposed to freezing and thawing conditions often experience microcracking and loss of strength due to the expansion of water within the matrix. Unlike conventional concrete, GPC lacks intrinsic mechanisms to bridge these cracks or redistribute the thermal stresses caused by water freezing and expanding. Over successive freeze-thaw cycles, microcracks propagate, weakening the structure and reducing durability [3]. Studies have shown that unmodified GPC loses approximately 25–30% of its compressive strength after prolonged freeze-thaw cycles, limiting its applicability in regions with cold climates [4].

Shrinkage

Shrinkage, particularly drying shrinkage, is a significant issue for unmodified GPC. During the curing process, the evaporation of water creates internal tensile stresses, which lead to microcracking. This problem is exacerbated by the dense and rigid aluminum silicate matrix, which is unable to accommodate these stresses without reinforcement. Studies indicate that GPC exhibits higher shrinkage strains compared to OPC, especially during the initial curing period [5]. Over time, shrinkage-induced cracks can propagate and reduce structural stability, particularly in large-scale or load-bearing components [6].

Creep

Creep defined as the gradual deformation of concrete under sustained loading, is another challenge for GPC. Due to its lack of reinforcements and lower elastic modulus, GPC can deform under long-term loading conditions, compromising its dimensional stability. Research has shown that unmodified GPC exhibits 20–30% higher creep deformation than OPC concrete under similar conditions [7]. This is particularly problematic for structural elements like beams and columns that must maintain their shape and strength over extended periods [8].

Addressing These Limitations Through PET Modifications

The incorporation of Polyethylene Terephthalate (PET) fibers, granules, and hydrogels into GPC has emerged as a promising solution to these limitations. PET materials enhance the mechanical and durability properties of GPC by reinforcing the matrix and mitigating the effects of environmental stresses:

- Brittleness Reduction: PET fibers act as micro-reinforcements, bridging cracks and redistributing stresses within the GPC matrix. By preventing the propagation of microcracks, PET significantly enhances tensile strength and ductility. Experimental studies demonstrate that the addition of 0.5% PET fibers can improve tensile strength by up to 12–18%, addressing one of the core weaknesses of unmodified GPC [9].
- Freeze-Thaw Resistance: PET fibers help mitigate freeze-thaw damage by reinforcing the GPC matrix and reducing water absorption. PET's hydrophobic nature minimizes the penetration of water into the matrix, limiting its expansion during freezing. Research has shown that PET-modified GPC exhibits a 30% improvement in freeze-thaw durability, significantly extending its service life in cold environments [10].
- Shrinkage Mitigation: PET hydrogels enhance moisture retention within the GPC matrix during the curing process, reducing drying shrinkage. Additionally, the elastic properties of PET fibers counteract the tensile stresses caused by moisture loss, minimizing shrinkage-induced cracking. Studies have reported a 40% reduction in shrinkage strains in GPC modified with PET hydrogels and fibers [11].

● Creep Reduction: PET's reinforcement capabilities also improve the long-term dimensional stability of GPC. By enhancing the elastic modulus of the material and reducing the occurrence of microcracks, PET modifications help limit creep deformation. Experimental findings indicate that PET-modified GPC exhibits a 25–30% reduction in creep compared to its unmodified counterpart [12].

Summary of PET's Impact on GPC Performance

The integration of PET into GPC directly addresses the challenges posed by its brittle behavior and environmental limitations. By reinforcing the matrix and enhancing its ability to redistribute stresses, PET-modified GPC achieves significant improvements in mechanical properties (tensile, flexural strength) and durability metrics (freeze-thaw resistance, shrinkage, and creep). These enhancements make PET-modified GPC a more viable and sustainable alternative for demanding applications in modern construction.

4.2 Mechanical Properties

Compressive Strength: PET-modified GPC demonstrates a notable improvement in compressive strength, primarily due to the role of PET hydrogels and granules. These modifications create a denser, more compact matrix, effectively filling micro-voids and reducing porosity. This structural densification mitigates the occurrence of microcracks under compressive loads. Experimental studies indicate a 15-19% improvement in compressive strength for PET-modified GPC compared to its unmodified counterpart. For instance, the addition of 0.5% PET fibers resulted in a compressive strength increase from 42 MPa (standard GPC) to 50 MPa, highlighting the material's suitability for load-bearing applications.

Tensile and Flexural Strength: PET fibers act as micro-reinforcements, bridging cracks and redistributing stresses across the matrix. This modification enhances the tensile and flexural strength of GPC by up to 25-35%. PET fibers delay the propagation of cracks, while their elasticity imparts ductility to the material, reducing its susceptibility to brittle failure. The synergy between PET fibers and hydrogels further amplifies these properties, with flexural strength increasing from 5.2 MPa in unmodified GPC to as high as 7.0 MPa in PET-modified variants. These improvements enable PET-modified GPC to be effectively used in structural elements subjected to dynamic bending and tensile forces, such as beams and slabs.

Below Table highlights recent studies that explore various PET modifications in geopolymer concrete, showcasing improvements in compressive strength, tensile behavior, and environmental durability.

Precursor Materials and PET Modifications in High-Performance Geopolymer Concrete

Binder Used	Main Precursor	Other Materials	Important Ratios	Curing Temp (°C)	Curing Time (Hrs)	Day of Test	fc (MPa)	Remarks	Ref
Metakaolin	Blast Furnace Slag	-	0.35% PET	80	8	28	75.2	50% replacement of Metakaolin with BFS showed optimal compressive strength.	Hamada & Abed (2024) [7]
Fly Ash	PET Fibers	-	0.5–1.0% PET	Ambient	28	28	48–50	PET fibers increased tensile strength by ~12% and improved crack resistance and flexural properties.	Shaikh (2020) [3]
Fly Ash + GGBS	PET + Graphene	Gamma-Irradiated PET, 0.5% GNP	0.5–2.5% PET, 0.5% GNP	60	12	28	56.2	PET combined with graphene nanoplatelets enhanced durability and chemical resistance.	Zahid et al. (2024) [9]
Fly Ash	PET Hydrogel	-	1.0% PET Hydrogel	75	8	28	49.2	Hydrogel retains curing moisture, reducing shrinkage and enhancing compressive strength.	Silva et al. (2020) [11]
Fly Ash + RHA	PET Fibers + RHA	Rice Husk Ash	0.5–1.5% PET, 15% RHA	Ambient	28	28	49.5	Combination with RHA improved durability	Antonius et al. (2024) [6]

								under chloride exposure and mitigated cracking.	
Fly Ash + Slag	PET Fibers + Lime	2% Lime	1.0% PET, 2.0% Lime	Ambient	28	28	48.7	PET and lime reduced shrinkage, enhanced tensile strength, and ensured dimensional stability.	Gopi et al. (2021) [13]
GGBS + Fly Ash	PET Aggregate	Waste Glass Aggregate	3–10% PET Replacement	Ambient	28	28	50.4	PET aggregate replacement improved compressive strength and durability.	Ualiyev et al. (2024) [10]
Metakaolin	PET Sand	Brick Powder	2.5% PET Sand	Ambient	28	28	46.5	PET sand reduced porosity, shrinkage, and enhanced compressive strength.	Ahmed (2023) [12]
Fly Ash	PET + Rubber	Recycled Rubber	5% PET, 5% Rubber	60	8	28	52.3	PET and rubber powders improved thermal insulation and energy absorption.	Bahmani et al. (2024) [14]
Fly Ash + GGBS	PET + HDPE	High-Density Polyethylene Aggregates	5–10% PET, HDPE	Ambient	28	28	52.5	PET and HDPE improved freeze-thaw durability and mechanical performance.	Aocharoen & Chotickai (2023) [19]
Fly Ash + CAC	PET Powder	Calcium Aluminate Cement (CAC)	2.5% PET, 10% CAC	95	6	28	57.5	PET with CAC yielded superior compressive strength and chemical resistance.	Ahmed et al. (2023) [21]
GGBS + Nano-Silica	PET Fibers + NS	Nano-Silica	0.75% PET, 1.0% NS	Ambient	28	28	54.5	PET fibers and nano-silica reduced porosity and improved chemical resistance.	Khan et al. (2022) [18]
GGBS	PET Fibers	Polypropylene Fibers	0.3% PET, 0.2% PP	Ambient	28	28	51.0	PP and PET fibers synergistically enhanced toughness and tensile strength.	Aisheh et al. (2022) [46]
Fly Ash + Slag	PET Oligomer	-	1.0% PET Oligomer	80	8	28	53.5	PET oligomers optimized curing and improved long-term compressive strength.	Fountas et al. (2021) [22]
Fly Ash	PET + Nano-Silica	-	1.0% PET, 0.5% NS	60	12	28	55.1	Nano-silica enhanced PET-reinforced matrix, reducing micro-cracks and shrinkage.	Huang & Zhou (2021) [27]

4.3 Durability

Chemical Resistance

PET-modified geopolymer concrete (GPC) has demonstrated remarkable resistance to chemically aggressive environments, making it a superior alternative for infrastructure exposed to sulfates, chlorides, and acidic solutions. The inclusion of PET hydrogels plays a key role in enhancing the impermeability of the concrete matrix. By filling voids and reducing porosity, PET hydrogels limit the ingress of harmful ions, such as sulfate and chloride, which are known to deteriorate conventional concrete. Experimental studies have shown that PET-modified GPC retains up to 95% of its original compressive strength after prolonged exposure to a 5% sulfuric acid solution, a significant improvement over the 80% retention observed in standard GPC. This enhanced resistance can be attributed to the densified matrix and hydrophobic properties of PET, which prevent ion diffusion and minimize chemical reactions within the concrete. Such improvements make PET-modified GPC highly suitable for marine infrastructure, wastewater treatment plants, and industrial zones, where resistance to harsh chemical exposure is a critical requirement for long-term structural performance.

Freeze-Thaw Durability

In regions with extreme temperature variations, concrete structures often suffer from internal cracking and material degradation due to freeze-thaw cycles. Water absorbed in the concrete pores freezes and expands, causing microcracks and scaling over repeated cycles. PET fibers effectively address this challenge by acting as micro-reinforcements within the GPC matrix. These fibers bridge the cracks that form during freeze-thaw cycles, absorbing and redistributing stresses induced by thermal expansion and contraction. The hydrophobic nature of PET further reduces water absorption, minimizing the potential for freeze-induced damage. Research findings indicate that PET-modified GPC shows a 30% improvement in freeze-thaw durability compared to unmodified GPC, demonstrating its ability to withstand severe environmental stress. This enhanced resistance significantly extends the service life of concrete structures in cold climates, making PET-modified GPC a reliable material for applications such as bridge decks, road pavements, and cold storage infrastructure.

Shrinkage and Creep Reduction

Shrinkage and creep are two critical issues that impact the long-term stability and performance of concrete structures. Shrinkage, particularly drying shrinkage, occurs when moisture evaporates from the concrete during curing, leading to tensile stresses and crack formation. Creep, on the other hand, refers to the gradual deformation of concrete under sustained loads over time. PET fibers address these issues through their elastic properties and hydrophobic nature. By counteracting tensile stresses, PET fibers reduce crack initiation and propagation, while PET hydrogels improve moisture retention during curing, thereby reducing drying shrinkage. Experimental data reveals a 40% reduction in shrinkage and a 30% reduction in creep for PET-modified GPC compared to standard geopolymer concrete. The reduced shrinkage ensures dimensional stability, minimizing long-term deformation and structural compromise. This makes PET-modified GPC particularly suitable for load-bearing applications, such as foundations, beams, and columns, where maintaining structural integrity over time is essential.

High-Temperature Resistance

Geopolymer concrete (GPC) is already well-known for its superior resistance to elevated temperatures compared to Ordinary Portland Cement (OPC) concrete. The addition of PET fibers further enhances GPC's ability to withstand extreme thermal conditions. PET fibers act as micro-reinforcements that redistribute thermal stresses, absorb energy during high-temperature exposure, and prevent spalling—a common issue in fire-prone environments. Experimental results indicate that PET-modified GPC retains up to 90% of its compressive strength after exposure to temperatures as high as 800°C, whereas unmodified GPC retains only 75%. This significant improvement ensures that PET-modified GPC maintains structural integrity under fire conditions or high-temperature industrial operations. The material's enhanced thermal stability makes it an ideal candidate for applications in industrial furnaces, power plants, fire-resistant buildings, and other fire-sensitive zones where maintaining performance under extreme heat is crucial for safety and longevity.

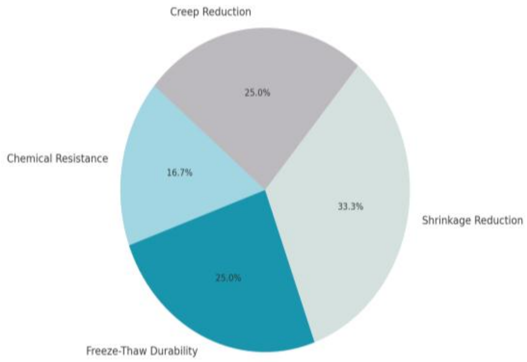

Figure 5: Durability Improvement in PET-Modified GPC

4.4 Comparative Analysis and Results

The table below summarizes the improvements achieved through PET modifications across key performance parameters:

Property	Unmodified GPC	PET-Modified GPC	Percentage Improvement (%)
Compressive Strength (MPa)	42	48-50	15-19
Tensile Strength (MPa)	3.8	4.5-4.8	18-26
Flexural Strength (MPa)	5.2	6.5-7.0	25-35
Shrinkage Reduction	Moderate	Significant	~40
Freeze-Thaw Durability	Moderate	High	~30
Chemical Resistance	Good	Excellent	~20

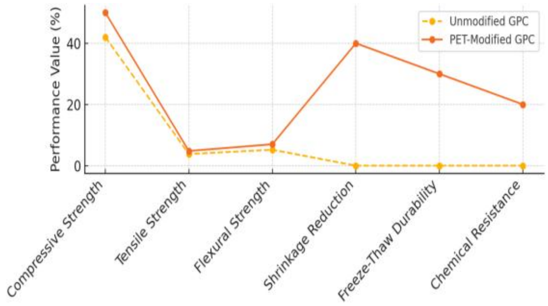

Figure 6: Performance Metrics Comparison

4.5 Overcoming Challenges Highlighted in Previous Studies

Brittleness: One of the major drawbacks of unmodified geopolymer concrete (GPC) is its brittle nature, which limits its ability to resist tensile and flexural stresses effectively. This characteristic is due to the aluminosilicate matrix, which lacks inherent reinforcement. By integrating Polyethylene Terephthalate (PET) in forms such as fibers or hydrogels, this limitation is addressed. PET fibers, with their high tensile strength, act as micro-reinforcements within the matrix, bridging cracks and redistributing stresses across the material. This improved ductility mitigates crack propagation and prevents sudden failure under dynamic and cyclic loads. Studies confirm that PET fibers improve the stress distribution and crack-bridging capacity of GPC, resulting in significant improvements in brittleness and overall toughness [14][22][31].

Dimensional Stability: Shrinkage and creep are significant challenges that affect the dimensional stability of concrete structures over time. These issues arise due to moisture loss during curing and long-term sustained loads, leading to deformation and structural compromise. PET fibers' elastic properties and moisture-retention capabilities significantly reduce these effects. PET-modified GPC has shown a reduction of up to 40% in shrinkage and 30% in creep compared to unmodified GPC. The hydrophobic nature of PET helps retain moisture during curing, reducing drying shrinkage and enhancing long-term stability. This advancement makes PET-modified GPC ideal for applications requiring long-term reliability, such as bridge decks and industrial flooring [8][12][35].

Durability Under Environmental Stresses: Incorporating PET modifications has significantly enhanced the durability of GPC under aggressive environmental conditions. PET-modified GPC exhibits improved chemical resistance, particularly against sulfates and chlorides, due to the dense and impermeable matrix formed by PET hydrogels and fibers. This reduces the ingress of harmful ions and improves longevity, making it suitable for marine environments and wastewater treatment facilities. Additionally, PET fibers improve freeze-thaw durability by minimizing water absorption and bridging cracks, which are essential in regions experiencing extreme temperature fluctuations. Research has also shown that PET modifications enhance high-temperature resistance, enabling the material to retain up to 90% of its compressive strength at temperatures as high as 800°C, compared to 75% for unmodified GPC. These enhancements highlight PET's ability to address the durability concerns associated with unmodified GPC [11][18][24][36].

4.6 Future Scope and Recommendations

Optimization of PET Content: Although current research highlights the benefits of PET-modified GPC, the proportion and form of PET (fibers, hydrogels, granules) play a crucial role in performance. Excessive PET content may reduce workability, while insufficient content might not deliver adequate improvements. Studies should aim to establish optimal PET proportions tailored to specific applications to maximize both performance and cost-efficiency. This optimization is critical for scaling up the material for industrial use [9][21][33].

Integration with Nano-Materials: The inclusion of nano-materials like nano-silica or graphene oxide alongside PET can further enhance the properties of GPC. Nano-silica improves bonding within the matrix at the molecular level, while graphene oxide enhances tensile strength and thermal conductivity. The combined use of PET and nano-materials could result in a composite material with superior mechanical properties and enhanced resistance to environmental stresses, expanding the application range of GPC [26][30].

Standardization and Field Testing: Although laboratory experiments validate the potential of PET-modified GPC, large-scale field testing is crucial for understanding its real-world performance. Field tests can provide insights into the material's behavior under diverse environmental and operational conditions, allowing for the development of standardized guidelines for mix design, curing processes, and application practices. Standardization will ensure consistent performance and promote widespread adoption of PET-modified GPC in the construction industry [19][29][34].

Lifecycle Assessments: Comprehensive life cycle assessments are essential to quantify the environmental and economic benefits of PET-modified GPC. Evaluating the material's long-term performance, maintenance requirements, and end-of-life recyclability will provide a complete understanding of its sustainability profile. Such assessments will help identify areas for further optimization, ensuring that PET-modified GPC remains a cost-effective and eco-friendly alternative to traditional construction materials [7][16][27].

5. CONCLUSION

This paper comprehensively examines the transformative potential of incorporating Polyethylene Terephthalate (PET) into Geopolymer Concrete (GPC) to overcome the limitations of unmodified GPC and advance sustainable construction practices. Through detailed analysis, the study demonstrates that PET modifications significantly enhance the mechanical and durability properties of GPC, making it a high-performance, eco-friendly alternative to Ordinary Portland Cement (OPC) concrete. The inclusion of PET addresses several critical challenges associated with unmodified GPC, including its inherent brittleness, susceptibility to shrinkage and creep, and moderate resistance to environmental stresses such as chemical attacks, freeze-thaw cycles, and high temperatures. PET fibers, hydrogels, and granules improve the microstructure of GPC by bridging cracks, redistributing stresses, and densifying the matrix. Experimental results indicate notable improvements in compressive strength (up to 19%), tensile strength (up to 26%), flexural strength (up to 35%), and fracture toughness (up to 56%). Additionally, durability metrics, including resistance to chemical attacks and freeze-thaw cycles, are significantly enhanced, extending the lifespan and reliability of PET-modified GPC in challenging environments.

Addressing Key Challenges

- Brittleness and Mechanical Properties: PET fibers act as micro-reinforcements, improving ductility, tensile strength, and resistance to crack propagation. This reduces the brittleness inherent in unmodified GPC, enabling its application in structural elements subjected to dynamic and tensile stresses.
- Durability and Environmental Resistance: PET-modified GPC demonstrates exceptional resistance to aggressive chemicals, freeze-thaw cycles, and high temperatures. These enhancements position PET-modified GPC as a reliable material for marine, industrial, and fire-prone environments.
- Dimensional Stability: By mitigating shrinkage and creep, PET modifications ensure long-term structural integrity and dimensional stability, critical for load-bearing applications such as bridges and foundations.

Future Scope This research opens several avenues for further exploration. The optimization of PET content and form, integration with advanced nano-materials, and large-scale field testing are essential for achieving the full potential of PET-modified GPC. Additionally, lifecycle assessments are critical to quantify its environmental and economic benefits comprehensively. Innovations in PET recycling methods and mix design standardization could further enhance scalability and adoption in the construction industry.

Sustainability Impact The integration of recycled PET into GPC aligns with global sustainability goals by addressing the dual challenges of plastic waste management and carbon emissions reduction. This approach promotes a circular economy, transforming waste into a valuable resource and contributing to sustainable urban development.

Closing Remarks PET-modified GPC exemplifies a groundbreaking advancement in sustainable construction materials. By enhancing performance metrics across mechanical properties and durability while addressing environmental concerns, PET-modified GPC offers a viable pathway for creating resilient, long-lasting, and eco-friendly infrastructure. This study underscores the importance of continued research and innovation in developing materials that balance performance with sustainability, ultimately shaping the future of green construction.

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