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Geopolymer Concrete Pavement with Fly Ash, GGBS and Nylon Crystal Reinforcement: A Sustainable Approach for Enhanced Performances

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ABSTRACT

Nylon crystals show significant potential for improving the crack resistance and tensile strength of concrete, particularly in geopolymer concrete (GPC) pavements. This study investigates the synergistic effects of incorporating fly ash (FA), ground granulated blast furnace slag (GGBS), alkaline liquids (Na2SiO3 and NaOH) and nylon crystal reinforcement on the compressive strength (CS), flexural strength (FS) and splitting tensile strength (STS) of GPC- Topping. In addition, durability aspects, including resistance to chemical attack and water absorption (WA), are evaluated. The aim of the study is to contribute to reducing the environmental impact associated with cement production by optimizing the use of alternative materials. The basis of the study lies in the selection of FA, GGBS, alkaline liquids and nylon crystals, each selected for their specific properties and compatibility with geopolymerization. Preliminary mix design experiments are conducted to determine optimal proportions, and subsequent mechanical testing of GPC samples shows improved CS, FS and STS with the addition of 3% nylon crystals after 28 days. Chemical attack tests using hydrochloric acid (HCL) and sulfuric acid (H2SO4) evaluate the durability of GPC pavements, while WA tests measure moisture resistance. The results highlight the superior performance of the GPC+3%NC mix compared to conventional concrete (CC) mix (M20) in terms of both strength and durability properties. This comprehensive investigation provides insights into the effectiveness of FA, GGBS, alkaline fluids and nylon crystal reinforcements in GPC pavements. It provides a sustainable solution by minimizing the environmental impacts associated with cement production.

1. Introduction

Concrete infrastructure is widely regarded as the greatest concern for the nation [1]. Roads, highways, and various transportation infrastructures extensively utilize concrete pavement. Concrete pavement is highly preferred for constructing pavements because of its cost effectiveness, durability and strength. Modern transportation systems heavily depend on concrete pavement, which ensures safe and comfortable travel by providing a durable and smooth surface for vehicles [2]. Highways,

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airports, and industrial areas are appropriate locations for concrete pavements due to their ability to endure heavy loads and high traffic. Additionally, the low maintenance requirements of concrete pavements result in lower long-term infrastructure costs [3]. The manufacturing process of traditional concrete heavily relies on Portland cement, leading to substantial carbon dioxide (CO_2) emissions. It is crucial to discover different building materials and methods that reduce carbon emissions and conserve resources. Geopolymer concrete (GPC) provides a sustainable and innovative option to replace conventional Portland cement-based concrete [4]. GPC helps minimize waste and supports sustainable resource management through these materials. GPC can be manufactured using lower curing temperatures, which leads to energy savings in production compared to traditional concrete. As in a previous study by Gurbuz *et al.,* [5], sustainable energy and green buildings have become increasingly important in recent years. This trend highlights the need for innovative construction materials and processes that contributing to energy efficiency and environmental protection.

By utilizing industrial by-products instead of Portland cement, GPC effectively minimizes carbon dioxide emissions than conventional concrete. GPC is highly resistant to chemicals and corrosive substances, making it suitable for challenging environments. Compared to traditional concrete, it has less permeability, which decreases the risk of moisture seepage and corrosion of reinforcing steel. GPC is known for its superior compressive strength, fire resistance, and ability to withstand temperature changes, making it more durable than traditional concrete. It can handle heavy traffic and has an extended lifespan. GPC uses waste materials like FA or slag, typically discarded in industrial processes [6]. During coal combustion in power plants, fine powder residue known as FA is produced that contains silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3) [7-9]. In the production of GPC, FA is often employed as supplementary cementitious material (SCM) to substitute a portion of Portland cement. The iron-making industry produces Ground Granulated Blast Furnace Slag (GGBS) as a waste product [10, 11]. After rapidly cooling molten slag from a blast furnace using water or steam, the resulting product is dried, ground, and known as GGBS. GGBS primarily contains silicates and aluminates, like FA, and is suitable as an SCM in GPC. The presence of alkaline liquids leads to the formation of a 3D geopolymer network, which is responsible for bonding and strength in GPC [12, 13]. The performance of GPC pavement can be greatly enhanced by incorporating nylon crystals as reinforcement. Including nylon crystals in the material enhances its properties and boosts its performance for pavement purposes [14].

The following studies highlight various aspects of GPC and its properties when incorporating different materials. Badkul *et al.,* [15] investigated the influence of alkali concentration and GGBFS content on the durability and mechanical properties of pavement quality geopolymer concrete (PQGC). Increasing the activator concentration and GGBFS content leads to a substantial improvement in the performance of PQGC. The study conducted by Wongkvanklom *et al.,* [16] investigated the use of recycled asphaltic concrete aggregate (RACA) in the production of high calcium fly ash geopolymer concrete (HFGC). The test results showed an increase in the content of RACA led to a decrease in the compressive strength. However, using RACA can enhance the performance of GPC by improving its resistance to sulfuric acid and surface abrasion. Tahir *et al.,* [17] enhanced the formulation to create a geopolymer made from FA that achieves exceptional compressive strength. Additionally, they assessed and compared the durability of fly ash GPC and OPC concrete under acidic conditions. According to the findings, the FA geopolymer achieves a maximum compressive strength of 47 MPa when the sodium hydroxide concentration is 10 M, the Na_2SiO_3 to NaOH ratio is 2.0, and the solid-to-liquid ratio is 2.5. FA-based geopolymer was found to be more durable than OPC concrete, making it an ideal material for rigid pavements. Geopolymer materials produced by Yue *et al.,* [18] were used to stabilize road base macadam by incorporating slag and FA. A study was conducted on the resistance to freeze-thaw, mechanical properties, and dry shrinkage durability of stabilized macadam materials incorporating slag and FA. Increasing the number of geopolymers resulted in higher 28-day compressive elastic modulus as well as increased compressive and tensile strength in slag/fly ash-based stabilized macadam.

Jagadesh and Nagarajan [19] analyzed the mechanical characteristics of GPC made from Fly Ash Ground Granular Blast Furnace Slag (FGGPC). They investigated the effects of replacing different percentages of FA with Titanium Dioxide (TiO_2). The result showed that replacing up to 3% of FA with TiO_2 improves the mechanical properties of FGGPC. Validation of the relationships between conventional and FGGPC was done using Mean Absolute Error (MAE), Integral Absolute Error (IAE) and Root Mean Square Error (RMSE). At ambient curing conditions, Bellum *et al.,* [20] examined the mechanical behaviour of GPC using FA and GGBS. A new equation was suggested for estimating the MOE using the compressive strength data obtained from GPC experiments. The experimental results showed a clear correlation between the predicted and tested values. Sattar *et al.,* [21] investigated the use of GGBS in foamed concrete to improve electrical sensitivity and thermal conductivity. Foam concrete with a density of 800 kg/m3 was produced and evaluated, containing GGBS in proportions by weight of 10% to 50%. Durability properties were evaluated, including porosity, electrical sensitivity, thermal diffusivity, water absorption, and thermal conductivity. Experimental results showed that the optimal durability results were achieved with the incorporation of 30% GGBS, resulting in maximum compaction in the cement matrix and excellent uniformity of the mix. However, above 30% GGBS resulted in the enrichment and uneven distribution of GGBS particles, resulting in a decrease in the overall evaluated parameters.

The following studies examine the use of alkaline liquids in the production of GPC as well as the exploration of various additives and reinforcing materials. Girish *et al.,* [22] investigated the production of GPC for paving applications using a combination of FA and GGBS. 12 different combinations were examined, which involved various proportions of GGBS (25-100%), different concentrations of NaOH (8M, 10M, and 12M) and a constant ratio of NaOH solution to Na_2SiO_3 (S/S) at 2.5. The study determined that a suitable SFGC mixture for meeting paving grade concrete standards includes GGBS content between 25% and 30% and NaOH molarity between 8M and 10M. Abbass and Singh [23] used Rice husk ash (RHA) as a raw material in GPC. They created an alkaline activator by mixing NaOH and Na_2SiO_3 for the process. The results showed that the RHB10 mixture had a weight loss of just 27.43% when tested with acid, and it allowed chloride ions to penetrate up to 2 mm.

Additionally, it had a low water absorption rate of 1.54% and expanded by 12mm after 28 weeks due to sulfate attack. Thakur *et al.,* [24] established a sustainable material called GGBS-Based GPC with the addition of Polypropylene (PP) Fibers. The experiment used a design with three factors and their levels, namely GGBS percentage at 80 to 100%, alkali ratio ($NaOH:Na_2SiO_3$) at ratios of 1:1.5 (8M NaOH), 1:2 (10M NaOH), and 1:2.5 (12M NaOH), and PP fibers at 1.5 to 2.5%. The ideal levels for compressive strength and flexural strength were a 1:2 (10M) alkali ratio of 80% GGBS with 2.5% and 1.5% PP fibers, respectively. Previous authors have conducted research into the effectiveness of various reinforcement materials, including glass fibers, Pp fibers, and biaxial geogrids. These studies have contributed to a better understanding of the reinforcement options available for GPC. Additionally, researchers have explored the utilization of basalt fibers (BF) as a reinforcement in GPC originating from basaltic rock or volcanic eruptions [25, 26]. These studies have revealed significant improvements in both strength and fatigue performance. Furthermore, researchers have also explored using steel fibers as reinforcement in GPC, yielding promising results [27-30]. Zhong *et al.,* [31] studied lightweight slag-based geopolymer (LW-SG) with different densities achieved by incorporating expanded perlite (EP). The results showed that increasing EP content decreased dry density and wave speed while increasing porosity. Quasi-static compressive strength and elastic modulus increase with the age of cure but decrease with higher EP contents. The dynamic compressive strength and the strain energy density show a dependence on the strain rate and decrease with increasing EP content at the same strain rate. Using low-cost calcined natural clay, Zhong *et al.,* [32] focused on the production of highly ductile engineered geopolymer composites (EGC). The composite, which contains GGBFS and polyvinyl alcohol (PVA) fibers, is subjected to mini-slump and uniaxial tensile tests. The results showed improved tensile properties with higher fiber content. Slag improves tensile properties, but excessive content reduces performance. The optimal EGC formulation containing 10.0% slag and 2.5% fibers showed the highest ductility with improved tensile strength and elongation capacity. Zhong *et al.,* [33] investigated the influence of polydimethylsiloxane (PDMS) content on the waterproofing and mechanical properties of GPC. Hydrophobically modified geopolymer composites (HM-GC) are prepared with different PDMS content. The results showed that increasing PDMS content increased surface hydrophobicity, improved waterproofing, and reduced water absorption. The incorporation of PDMS improved the compressive properties but reduced the tensile strength. The study proposed an optimal PDMS content of 4% for practical applications in shipbuilding, balancing waterproofing and mechanical performance.

The literature review identified several research gaps. While studies have been conducted on the individual and combined performance of FA and GGBS in GPC pavements, there is a need to investigate the optimal combination of these two materials with nylon crystal reinforcement. Previous research has investigated the use of alkaline activators such as Na_2SiO_3 and NaOH in GPC pavements. However, their combined effect with FA, GGBS, alkaline fluids (Na_2SiO_3 and NaOH) and nylon crystal reinforcement on the performance of GPC pavements remains unexplored. Numerous research studies have investigated using glass fibers, PP fibers, biaxial geogrids, basalt fibers and steel fibers as reinforcing materials. However, there is limited research on the use of nylon crystals as a reinforcing component in GPC pavements.

By closing these research gaps, the proposed study aims to contribute to the advancement of knowledge in this field. The following are the main innovations and contributions of the study: The study investigates the novel combination of FA, GGBS, alkaline liquids (Na_2SiO_3 and NaOH) and nylon crystal reinforcement in GPC pavements. This combination has not been extensively studied before and represents a novel approach to improving the mechanical properties and durability properties of GPC. The use of nylon crystal reinforcements in GPC pavements is a unique aspect of the proposed study. While previous research has examined various reinforcing materials, the application of nylon crystals in this environment is relatively unexplored. This adds a new dimension to the understanding of the strengthening mechanisms in GPC pavements. The aim of the study is to conduct a comprehensive performance evaluation of the GPC pavement by considering multiple factors such as compressive strength (CS), flexural strength (FS), splitting tensile strength (STS), durability and water absorption (WA). This holistic approach enables a more comprehensive understanding of material behavior under different conditions. The research aims to determine the optimal mixing ratios and dosage levels of FA, GGBS, alkaline liquids and nylon crystal reinforcement. This optimization process is critical to achieving desired performance improvements and ensuring a balance between materials to improve both strength and durability. The aim of the study is to compare the performance of the proposed GPC pavement with a conventional concrete mix (CC) (M20) in terms of strength and durability properties. This comparative analysis provides insights into the performance of GPC compared to traditional concrete mixes and provides valuable information for practical applications and infrastructure projects. While previous research has investigated the use of alkaline activators in GPC pavements, the proposed study specifically aims to understand their combined effect with FA, GGBS, alkaline liquids (Na_2SiO_3 and NaOH) and nylon crystal reinforcement. This approach fills a research gap and contributes to a more comprehensive understanding of the interaction between these components. Overall, the proposed study not only fills existing research gaps but also introduces a novel material combination, investigates the potential of nylon crystal reinforcement, conducts a thorough performance evaluation, optimizes mix ratios, and provides a comparative analysis with conventional concrete. These contributions can significantly advance the field of GPC technology and its application in pavements.

The motivation behind this study is the need to improve the performance of GPC by incorporating various additives and reinforcing materials. The environmental impacts of traditional cement production as well as the growing demand for sustainable construction materials, highlight the importance of exploring alternative materials such as FA and GGBS. The use of these materials in combination with alkaline liquids aims to activate pozzolanic reactions, thus improving strength and durability. Furthermore, incorporating nylon crystal reinforcement into GPC results in a novel approach to improving pavement properties. Nylon crystals are known for their resistance to chemical degradation, making them a promising material for reinforcing concrete structures exposed to harsh environmental conditions. The motivation of the study is not only to improve the mechanical properties of GPC but also to reduce the ecological impacts associated with traditional methods of cement production.

The proposed study aims to achieve the following objectives:

i. To study the effects of incorporation of FA, GGBS, alkaline liquids (Na_2SiO_3 and NaOH) and nylon crystal reinforcement on CS, FS and STS of GPC pavement.
ii. To evaluate the durability properties of the GPC pavement, including its resistance to chemical attack and its WA behavior.
iii. Determine the optimal blend ratios and dosage levels of FA, GGBS, alkaline fluids and nylon crystal reinforcement required to achieve desired performance improvements for GPC pavements.
iv. To compare the performance of the proposed GPC pavement with a conventional concrete (CC) mix (M20) in terms of strength and durability properties.

The proposed study is organized as follows: Section 2 covers the materials and methodology, explaining the materials used, the mix design, and the laboratory testing details. Section 3 presents the study's results and discussions. Finally, section 4 presents the study's conclusions and suggestions for future research.

2. Methodology

2.1 Material Used

The following materials are utilized in the experimental study to examine their effects on the properties and performance of GPC. This study aims to assess the viability of using these materials as alternatives or additives in concrete production, potentially enhancing its strength, durability, or other characteristics.

2.1.1 Fly ash

The finest particles of coal ash are known as FA. Burning pulverized coal in coal power plants is a method used to generate electricity, and it produces a dangerous substance called FA. Previously, it was emitted into the air, resulting in adverse impacts on air quality. Consequently, measures were implemented to regulate its disposal. It is gathered and stored at coal-based power facilities or transported to designated waste disposal sites. However, the risks to wildlife, humans, and the environment associated with the generation of FA can be reduced by utilizing it to enhance concrete structures. Typically, FA has a light tan type and is predominantly composed of small glassy spheres with silt and clay sizes, as shown in Figure 1.

Fig. 1. Fly ash

The properties of FA can vary greatly depending on the composition of the coal and the operating conditions of the power plant. Each year, approximately 50 million tons of FA are reused in the United States. FA can be classified as either cementitious or pozzolanic. When combined with water, a cementitious material undergoes hardening. On the other hand, a pozzolanic material requires activation with an alkaline substance like lime in order to harden when mixed with water. The pozzolanic and cementitious characteristics of certain FAs enable their valuable application as substitutes for cement in concrete and various construction uses. When FA contains adequate calcium, its aluminous and siliceous components can combine with water and form cement. In this study, FA has a specific gravity of 2.133. Table 1 shows the chemical composition of FA used in this study.

Table 1
Chemical composition of FA

Components	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	CaO	K_2O	TiO_2	SO_3	MgO	SiO_2/ Al_2O_3
Composition (Wt. %)	18.9	15.2	10.6	0.988	1.18	2.23	0.468	0.366	0.348	1.2

2.1.2 Ground granulated blast furnace slag

GGBFS is a leftover material from making iron in a blast furnace. It forms when hot slag from the furnace is quickly cooled, creating a glassy and grainy substance. Table 2 displays the chemical composition of GGBS, which includes various components. The focus of this study is to utilize GGBS as the primary substitute for cement in GPC. Before the mixing process, it is necessary to perform a specific gravity test. The specific gravity value of GGBS in this study was measured to be 2.92.

2.1.3 Cement

In this study, cement is used for manufacturing M20 grade cement concrete. The specific gravity of cement refers to the density of the cement compared to the density of water. The specific gravity of cement used is 3.16, which means that the cement is 3.16 times denser than water. The fineness of cement is a measure of the particle size distribution of the cement particles. It is typically determined by sieving the cement through a set of standard sieves. A fineness of 92.3% indicates that 92.3% of the cement particles passed through the sieves and are of the desired fineness. The initial setting time refers to the time taken by cement to change from a plastic state to a solid state after mixing with water. In this case, the cement used takes 51 minutes to set up initially, which is greater than the minimum requirement of 30 minutes. The final setting time refers to the time taken by cement to completely set and harden after mixing with water. The cement takes 5 hours and 20 minutes to achieve its final setting, less than the maximum allowed time of 10 hours. These properties of the cement indicate that it meets the specified requirements for specific gravity, fineness, and setting time. This study utilizes OPC 53 Grade cement, which follows the IS 12269:2013 [34] standard.

Table 2
Chemical composition of GGBS

Chemical component	Chemical symbol	Weight percentage
Alumina	Al_2O_3	7-15
Calcium Oxide	CaO	34-43
Ferric Oxide	Fe_2O_3	0.2-1.6
Loss on Ignition	-	0.20-0.85
Manganese Oxide	MnO	0.15-0.76
Potassium Oxide	K_2O	0.08-1.83
Silica	SiO_2	27-38
Sodium Oxide	Na_2O	0.20-0.48
Sulphur Trioxide	SO_3	up to 0.07

2.1.4 Fine aggregates

Fine aggregate, commonly referred to as sand, is a substance that can fit through a BIS test sieve labeled as number 4, with a size of 4.75mm. In most cases, fine aggregate consists of natural sand. However, when natural sand is unavailable, crushed stone can be replaced in this study. The fine aggregate has a specific gravity of 2.74, which signifies its density relative to the density of water. After conducting a sieve analysis on the fine aggregate, it was determined that the sand falls under zone III as per the IS 383:1970 [35] standard. This classification offers insight into the particle size distribution and the sand's suitability for this study. Figure 2 depicts the grading curve of the fine aggregate obtained from the sieve analysis.

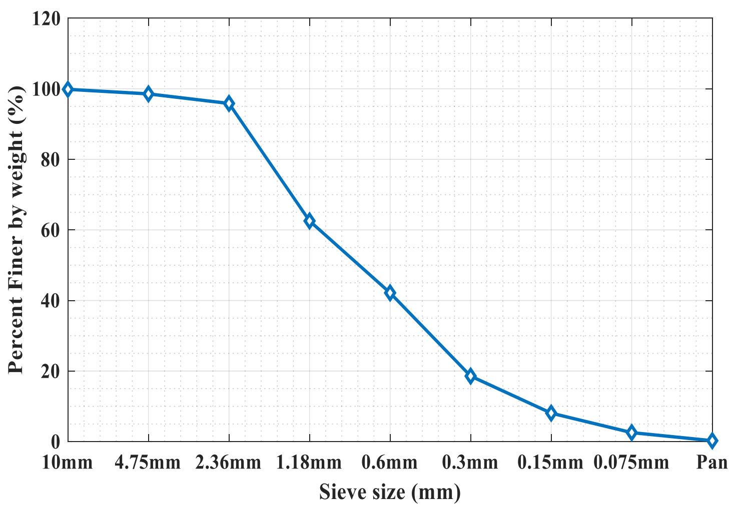

Fig. 2. Sieve analysis grading curve for fine aggregate

2.1.5 Coarse aggregates

Coarse aggregate is used for the material that stays on the BIS test sieve and is larger than 4.75mm. Broken stone is a popular choice for coarse aggregate in construction. The size of the coarse aggregate used depends on the specific project requirements. This study used locally sourced coarse aggregate with a maximum size of 20mm, conforming to IS 383:1970 [35]. The specific gravity of the 20mm coarse aggregate is 2.64, while the 10mm coarse aggregate has a specific gravity of 2.57. The average impact value of the aggregate sample is 21.43%. The average abrasion value of the aggregate sample is 15.82%. Lastly, the average crushing value of the aggregate sample is 19.81%.

2.1.6 Alkaline liquids

For this study, Na_2SiO_3 and NaOH, which are alkaline liquids, were used to make GPC pavement. The geopolymerization process relies on alkaline liquids to bind the materials and create a solid concrete matrix. GPC, made with Na_2SiO_3 and NaOH, has numerous benefits, including strong mechanical properties, quick strength development, and durability against environmental elements. The alkaline liquids are mixed with FA, GGBS and other ingredients in precise proportions to make a geopolymer binder that can substitute conventional cement materials. Both the Na_2SiO_3 and NaOH were obtained in large quantities from a local supplier, as shown in Figure 3.

Fig. 3. Na_2SiO_3 and NaOH solutions

2.1.7 Super plasticizer

Admixtures called super plasticizers are utilized in making high-strength concrete by reducing water content. The main objective of super plasticizers is to enhance the WA of GPC, making it easier to mix, place, and finish. Also, it improves its CS, FS, and other mechanical properties by reducing the amount of water used. The purpose of incorporating the super plasticizer is to improve the concrete's strength and durability, facilitating its handling during pavement construction. The super plasticizer is included in different mixtures according to the guidelines specified in the IS 9103:1999 [36].

2.1.8 Water

Water is an important component in the manufacturing process of concrete. The durability and strength of the samples are greatly influenced by the amount and quality of water used during the concrete mixing process. Using contaminated or substandard water can lead to several problems that affect the durability and strength of concrete. Water pollution is a significant environmental problem and can have negative impacts on both human health and ecosystems [37]. When contaminated water is used in the concrete mixing process, harmful substances can leach into the concrete, potentially affecting its structural integrity and long-term performance. It is generally acceptable to use potable water, which is safe for drinking, for mixing concrete. Potable water is usually clean and devoid of impurities or contaminants that might impact the properties or long-term performance of the concrete. The water utilized in concrete mixing adheres to the necessary standards for potable water, ensuring cleanliness and safety. Excessive water content weakens the concrete and reduces its durability, whereas insufficient water content makes it difficult to mix and place the concrete. Water is essential for mixing GPC, and it is generally acceptable to use clean water for this study.

2.1.9 Nylon crystals

Nylon Crystal, a type of nylon textile fiber, possesses remarkable characteristics, including strong tensile strength, good elasticity, resilience, excellent draping qualities, and lightweight composition. These unique properties make it an ideal material for the proposed study. Nylon crystals possess notable mechanical properties, including a tensile strength of 55 MPa and an elongation at a break of 36%. In terms of Young's Modulus, multiple tests yielded values of 2 GPa, 2.1 GPa, and 2.214 GPa (average), indicating its stiffness under various conditions. The compressive strength of nylon crystals averages 36 MPa, while flexural strength is observed at 90 MPa in the first test and 96 MPa in the second test. These values reflect the material's ability to withstand bending forces. Additionally, nylon crystals demonstrate good creep resistance over time under load. Furthermore, they exhibit excellent friction and wear resistance, with wear rates falling within the range of 20 to 35 (10^{-7} mm^3/Nm). Finally, the coefficient of linear thermal expansion for nylon crystals typically ranges from 80 to 94 µm/(mK), indicating their response to temperature changes. Overall, these mechanical characteristics of nylon crystals serve as a versatile and resilient material with GPC. Figure 4 shows an image of the nylon crystals used in this study. Table 3 presents the properties of the Nylon Crystals utilized in this study.

Fig. 4. Nylon crystals

Table 3
Properties of nylon crystals used in this study

Properties	Performances
Strength	Good tenacity, excellent abrasion resistance and strongest textile fiber.
Elasticity	Strong elasticity and extensive elongation characteristics.
Resilience	Polished finish, resistant to wrinkling.
Drapability	Superb draping characteristics are evident in both lightweight sheer variants (exhibiting high draping quality) and medium-weight variations (showing fine draping attributes).
Structure	The typical cross-sectional shape of NC is circular.
Density	A low density of 1.14 g/cc, making it a lightweight material.
Effect of sunlight	Fair resistance to sunlight.

2.2 Mix Design

Numerous publications, including several from India, have already reported in-depth research on the production and development of GPC using low-calcium FA. In this study, the mix design for GPC pavement was formulated using a Research Report by Hardjito and Rangan [38]. Plain concrete was designed under IS 10262:2009 [39]. The preparation process for the GPC proposed in this study involves the use of low-calcium FA, GGBS alkaline liquids (Na_2SiO_3 and NaOH), aggregates, water, and superplasticizers. The process is outlined below, and mixture proportions for GPC per m^3 are as follows in Table 4.

i. Determine the unit mass of concrete:
   - Unit-mass of concrete = 2400 kg/m³
ii. Calculate the mass of aggregates:
   - Mass of combined aggregates = 77% of unit mass = 0.77 x 2400 = 1848 kg/m³
iii. Calculate the mass of fly ash + GGBS and alkaline liquid:
   - Mass of fly ash + GGBS and alkaline liquid = 2400 - 1848 = 552 kg/m³
iv. Determine alkaline liquid-to-fly-ash + GGBS ratio:
   - Alkaline liquid-to-fly-ash + GGBS ratio by mass = 0.35
v. Calculate the mass of fly ash, GGBS and alkaline liquid:
   - Mass of fly ash + GGBS = 552 / (1 + 0.35) = 408 kg/m³
   - Mass of fly ash =102 kg/m³
   - Mass of GGBS =306 kg/m³
   - Mass of alkaline liquid = 552 - 408 = 144 kg/m³
vi. Consider Sodium Silicate to Sodium Hydroxide Ratio:
   - Sodium silicate to sodium hydroxide solution ratio by weight = 2.5
vii. Calculate the Mass of Sodium Hydroxide and Sodium Silicate Solution:
   - Mass of sodium hydroxide solution = 144 / (1 + 2.5) = 41 kg/m³
   - Mass of sodium silicate solution = 144 - 41 = 103 kg/m³
viii. Determine Mixture Proportions:
   - Mass density of aggregates 20 mm = 776 kg/m³
   - Mass density of aggregates 10 mm = 517 kg/m³
   - Mass density of fine sand = 554 kg/m³
   - Mass density of low-calcium fly ash (ASTM class) =102 kg/m³
   - Mass density of GGBS =306 kg/m³
   - Mass density of sodium silicate solution = 103 kg/m³
   - Mass density of sodium hydroxide solution = 41 kg/m³

Combine 20mm and 10mm coarse aggregates, fine aggregates, FA, GGBS, Na2SiO3 solution, NaOH solution, superplasticizer and water in the specified mixing ratios. Mix thoroughly until an even and homogeneous mixture is obtained. The recommended mixing time is 4 minutes for wet mixing. After mixing, pour the mixture into molds and let it harden after pouring. Once the curing is complete, the samples for this study undergo mechanical testing. Figure 5 shows the proportions of concrete materials with previously added solution. Figure 6 shows the prepared concrete samples for testing.

Table 4
Mixture Proportions for this study

Material	Weight in kg/m^3
20mm coarse aggregate	776
10mm coarse aggregate	517
Fine aggregate	554
FA	102.2
GGBS	306.2
Na_2SiO_3	102
NaOH	41
Super plasticizers	20
Water	55
Nylon crystals	Starting from 1% of GGBS

Fig. 5. Proportions of concrete materials with previously added solution

Fig. 6. Prepared concrete specimens for testing

2.3 Laboratory Testing
2.3.1 Compression strength test

Cubes measuring 150mm x 150mm x 150mm were made for GPC according to the mix design specs in Table 4 of IS 516:1959 [40]. After the specified curing period (28 days), the cubes are removed from the curing tank and cleaned to remove any loose particles or debris. Prepare the compression testing machine, calibrating it to handle up to 2000kN load. Position the cube on the machine's lower plate, ensuring its smooth surface contacts the plate directly. Align the cube to be centered and perpendicular to the machine's loading axis. Apply a compressive load to the cube at a constant rate, usually given as a specific load per second. Continue loading until the cube fails completely, typically indicated by a sudden drop in load or visible cracks. The failure load of the cube was recorded, and the cross-sectional area of the cube's smooth surface was measured as per IS: 516-2021 (Part I Sec I) [41]. The CS of the cube was calculated by the ratio of the failure load to the cross-sectional area as expressed in Eq. (1). Figure 7 displays the process of conducting CS testing on cube specimens.

$$\text{Compressive strength} = \frac{\text{Failure load}}{\text{Cross-sectional area}} \tag{1}$$

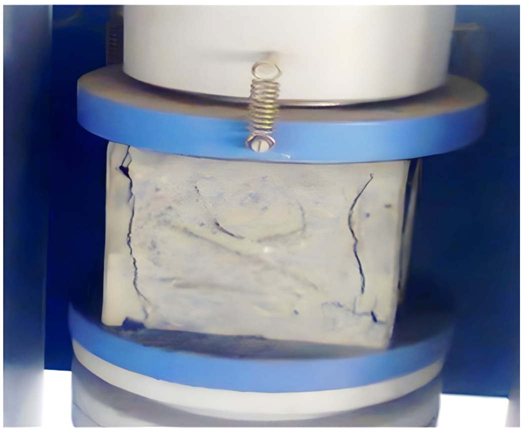

Fig. 7. Compressive strength testing of cube specimens

2.3.2 Flexural strength test

The samples are prepared and cured in a controlled laboratory setting for the given duration of 28 days, according to IS 516:1959 [40]. Once the curing process is complete, place each sample onto the supports of a flexural testing machine and ensure they are properly aligned. Gradually apply a load at the center of the sample at a predetermined rate until the sample breaks due to bending as per IS: 516-2021(Part I Sec I) [41]. The FS was determined by calculating the modulus of rupture as expressed in Eq. (2), which is denoted as f_b.

$$\text{Flexural strength, } f_b = \frac{pl}{bd^2} \tag{2}$$

where, b is the calculated width (cm), d is the calculated depth (cm), l is the length of the specimen (cm) and p is the peak load (kg), respectively. Figure 8 shows the FS testing of the sample.

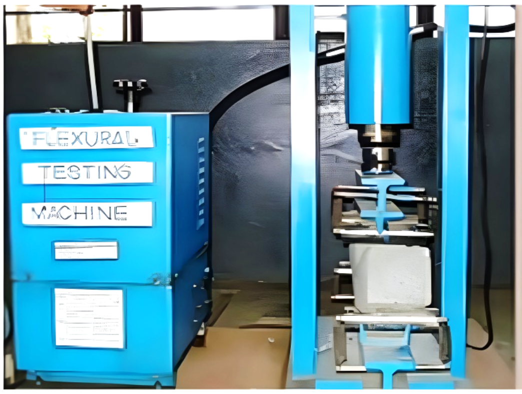

Fig. 8. Flexural strength testing of sample

2.3.3 Split tensile strength test

Test samples were prepared and cured under standard laboratory conditions for 28 days according to IS: 5816-1999 [42]. Place the sample in a horizontal position on the supports of a splitting tensile testing machine. Apply force to both ends of the specimen gradually until it breaks due to tension as per the IS:516-2021(Part I Sec I) [41]. Record the peak load for each sample and calculate the STS using Eq. (3). Figure 9 illustrates the STS testing in this study.

$$\text{Split tensile strength} = \frac{2\text{P}}{\pi \text{ld}} \tag{3}$$

where, *d* is depth (mm), *l* is specimen length (mm), and P is the maximum load (N), respectively.

Fig. 9. Testing of split tensile strength

2.3.4 Water absorption test

Prepare the samples for the WA test and take the initial weight of the samples. The samples were immersed in water for a certain time (24 hours). Take the samples out of the water, dry off any extra moisture, and measure how much they weigh now. By using the following formula, the percentage of water absorbed was calculated as expressed in Eq. (4).

$$\text{Water absorption percentage} = \frac{(\text{Final weight-Initial weight})}{\text{Initial weight}} \times 100 \tag{4}$$

2.3.5 Durability test

For durability testing, GPC samples with different percentages of NC cubes (1%, 2%, 3%, and 4%) were prepared as shown in Figure 10. Additionally, a control sample (CC) without any NC was also prepared for comparison. Maintain the samples in a curing chamber at a specified temperature for 28 days. Each sample (CC, GPC+1%-4%NC) was initially weighed, and their weights were recorded. Two acid solutions were prepared, one with HCl and another with H_2SO_4. Each sample was placed in a separate container with the respective acid solution. Keep the samples immersed in the acid solutions for a specified period, such as 28 days. After the specified testing period, remove the samples from the acid solutions. Thoroughly rinse each sample with clean water to remove any residual acid. Pat dries the samples gently using a clean cloth and weigh each sample again using the same precision scale used earlier. The final weight of each sample was recorded. The weight loss percentage for each sample was calculated by using the following Eq. (5).

$$\text{Weight loss percentage} = \frac{\text{(Final weight-Initial weight)}}{\text{Initial weight}} \times 100 \quad (5)$$

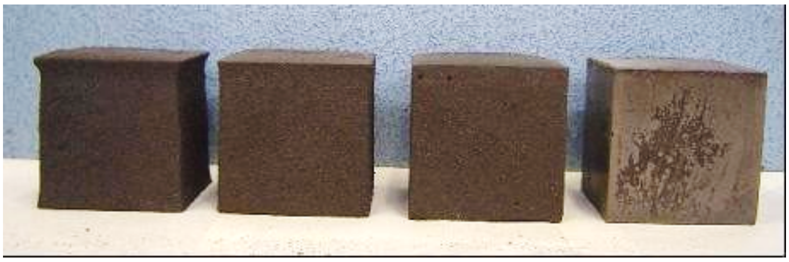

Fig. 10. Durability testing samples

2.4 Proposed Methodology

The selection of suitable FA and GGBS was based on their properties, availability, and compatibility with geopolymerization. These materials underwent characterization through various tests. Furthermore, the concentrations and reinforcement capabilities of alkaline liquids (Na_2SiO_3 and NaOH) and nylon crystals were evaluated, along with their properties. The optimal mix proportions for GPC were determined through preliminary mix design trials. GPC samples were prepared in accordance with the determined mix proportions. Mechanical testing was conducted on the GPC samples to evaluate their compressive, flexural, and STS. These tests were performed using standard procedures to ensure the accuracy and reliability of the results. The data was recorded and analyzed to assess the effect of incorporating FA, GGBS, alkaline liquids, and nylon crystal reinforcement on the GPC's mechanical properties. Figure 11 displays the layout of the proposed methodology.

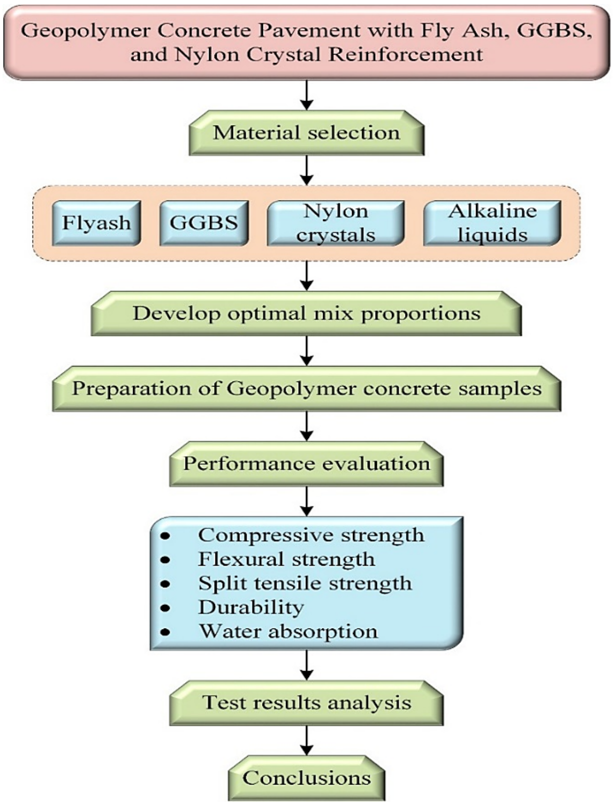

Fig. 11. Layout of proposed methodology

The durability characteristics of GPC pavement were evaluated through a chemical attack using acid solutions such as hydrochloric acid (HCL) and sulfuric acid (H_2SO_4). The weight loss was monitored to determine GPC's resistance to chemical attack. The WA behavior of GPC pavement was analyzed by immersing samples in water and measuring the change in weight over time. The WA percentage was determined to assess the concrete's permeability and moisture resistance. The test results were analyzed to determine the optimal mix proportions and dosage of FA, GGBS, alkaline liquids, and nylon crystal reinforcement required to achieve the desired performance enhancements in GPC pavement. A comparison was made between the performance of the proposed GPC pavement and the CC mix. The findings were summarized, and recommendations were provided for further research on GPC.

3. Results

3.1 Compressive Strength

Figure 12 shows CS for various concrete mixtures at 7, 14, and 28 days. After 7 days, the CS of OPC concrete (CC M20) is 18.3 MPa. In comparison, the addition of NC additives in various proportions to the GPC enhances the strength: GPC+1%NC (23.23 MPa), GPC+2%NC (24.23 MPa), GPC+3%NC (25.45 MPa), and GPC+4%NC (24.25 MPa). After 14 days, the compressive strength of CC M20 reaches 19.43 MPa. Meanwhile, the GPC mixtures with different levels of NC additives exhibit increased strength: GPC+1%NC (27.14 MPa), GPC+2%NC (28.24 MPa), GPC+3%NC (28.56 MPa), and GPC+4%NC (28.45 MPa). At 28 days, CC M20 achieves a compressive strength of 21.23 MPa. In contrast, GPC mixtures with increasing percentages of NC additives demonstrate higher strengths: GPC+1%NC (29.36 MPa), GPC+2%NC (30.36 MPa), GPC+3%NC (31.02 MPa), and GPC+4%NC (29.36 MPa).

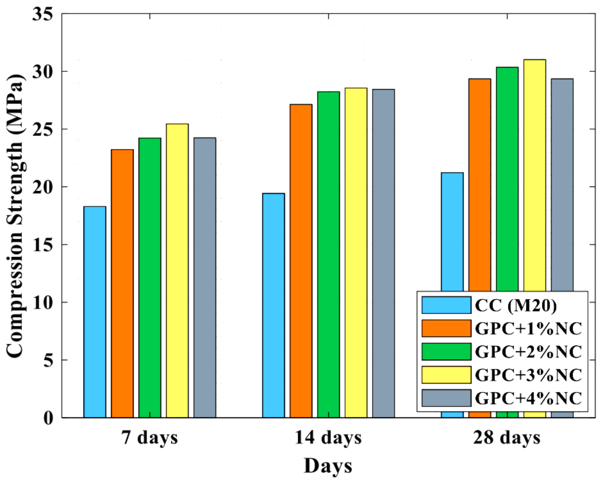

Fig. 12. Compression strength performances

The analysis begins by noting that GPC blends consistently exhibit higher compressive strength than CC across ages (7, 14, and 28 days). This means that GPC generally has better early strength development than conventional concrete. The study then investigates the influence of different amounts of NC additives on the compressive strength of GPC. It can be observed that an increase in the NC additive content leads to a corresponding increase in compressive strength. Increasing the percentage of NC additive leads to higher compression strength. These findings further confirm that the inclusion of NC improves the strength at this stage. Similar to earlier stages, including NC results in increased compression strength, suggesting enhanced long-term strength development. The consistent trend suggests that including NC improves both the early and long-term development of compressive strength in GPC, which is consistent with the findings of Estabragh *et al.,* [43]. It is noteworthy that the maximum compressive strength after 28 days in the GPC+3%NC mixture is 31.02 MPa. This suggests that adding 3% NC to GPC contributes to improved bonding and interlocking of the particles, resulting in improved compressive strength development. The specific percentage of 3% NC is identified as the optimal dosage in this context. However, a trend is observed for the GPC+4%NC mixture, where a slight reduction in compressive strength is observed compared to GPC+3%NC. This decrease is attributed to a possible overdose of the NC additive. Exceeding the optimal NC range leads to an imbalance in the mixture composition, which affects the bonding between particles and consequently reduces the compressive strength. The excessive dosage of NC is suspected to cause a decrease in compression strength at GPC+4% NC. This excessive amount disrupts the ideal balance in the mixture and negatively affects the bonding between particles, as shown by Tayebi and Mahdi [44].

3.2 Flexural Strength

Flexural strength is a critical parameter used to assess the ability of a material, such as concrete, to withstand bending forces without fracturing. Various concrete mixtures, including GPC with different levels of NC additive, were assessed for their FS at 7, 14, and 28 days of curing. Figure 13 shows the FS values for a CC and GPC with increasing percentages of NC (1%, 2%, 3%, and 4%) at each curing period. At 7 days, the flexural strength of OPC concrete (CC M20) is 2.3 MPa. The incorporation of NC additives in GPC enhances flexural strength, with GPC+1%NC measuring 2.52 MPa, GPC+2%NC at 2.75 MPa, GPC+3%NC reaching 2.93 MPa, and GPC+4%NC showing a strength of 2.81 MPa. After 14 days, the flexural strength of CC M20 increases to 4.1 MPa. Similarly, GPC mixtures with varying percentages of NC additives exhibit improved flexural strengths: GPC+1%NC (4.35 MPa), GPC+2%NC (4.52 MPa), GPC+3%NC (4.78 MPa), and GPC+4%NC (4.54 MPa). At 28 days, CC M20 achieves a flexural strength of 5.2 MPa. The GPC mixtures with increasing levels of NC additives show a continued enhancement in flexural strength: GPC+1%NC (5.36 MPa), GPC+2%NC (5.44 MPa), GPC+3%NC (5.573 MPa), and GPC+4%NC (5.3 MPa). This indicates that the addition of NC positively influences the early flexural strength development in the concrete mix. The trend suggests that the positive influence of NC on flexural strength persists and becomes more evident at this stage, as highlighted in Alhazmi *et al.,* [45]. It also confirms that the beneficial impact of NC on flexural strength persists throughout the curing period, contributing to both early and long-term development.

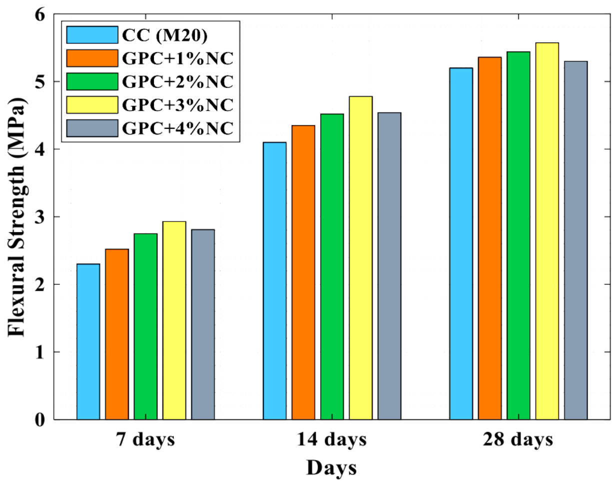

Fig. 13. Flexural strength performances

The highest flexural strength recorded was 5.573 MPa, and this was achieved with a GPC+3%NC blend. The primary factor contributing to this superior strength was identified as the improved bond between GPC and NC fibers within the optimized mix. The GPC+3%NC blend demonstrated superior flexural strength, indicating that the interaction between GPC and NC fibers was optimized. Improved bonding is crucial in concrete as it facilitates better load distribution, enhancing the overall strength of the material. The synergy between GPC and NC in the mixture likely contributed to a more robust and coherent structure. The GPC+4%NC mix, despite having a higher percentage of nylon crystals, exhibited lower flexural strength compared to the GPC+3%NC blend. The reduction in strength is attributed to the excessive amount of nylon crystals in the mix. An abundance of NC can disrupt the uniform distribution and bonding within the concrete matrix. The excessive presence of nylon crystals causes clumping, which negatively impacts the overall packing density of the concrete mixture. Clumping can create voids or weak points in the concrete, compromising its structural integrity and resulting in reduced flexural strength. The even distribution of components within the concrete matrix is crucial to achieving optimal strength. Too much NC can hinder the even distribution of materials and lead to uneven packing density. Negative consequences of reduced packing density include reduced strength and load-bearing capacity, a finding consistent with Vickers *et al.,* [46]. The results highlight the importance of careful optimization of the proportions of GPC and NC in the concrete mix. The right balance is crucial to ensure the positive effects of each component, such as improved bonding, can be maximized without compromising overall structural integrity.

3.3 Split Tensile Strength

A material's STS measures its ability to withstand tensile stress in a direction perpendicular to its axis. Figure 14 displays the STS results of GPC mixes with different percentages of NC at 7, 14, and 28-time intervals. The STS values after 7 days are as follows: plain cement concrete (CC) is 2.19MPa, GPC with 1% NC is 2.48 MPa, GPC with 2% NC is 2.76 MPa, GPC with 3% NC is 3.2 MPa, and GPC with 4% NC is 2.9 MPa. After 14 days, the STS for various concrete mixes is as follows: CC is 3.03 MPa, GPC+1%NC is 3.34 MPa, GPC+2%NC is 3.48 MPa, GPC+3%NC is 3.98 MPa, and GPC+4%NC is 3.86 MPa, respectively. After 28 days, the STS of various concrete mixes was recorded as follows: CC achieved a strength of 3.15 MPa, GPC+1%NC exhibited a strength of 3.58 MPa, GPC+2%NC demonstrated a strength of 3.86 MPa, GPC+3%NC showcased a strength of 4.28 MPa, and GPC+4%NC displayed a strength of 4.18 MPa. The results indicate that as the percentage of NC in the GPC mix increases, there is a general increase in the STS. With each time interval, compared to the CC mix, there is a noticeable enhancement in the STS when the percentage of NC is increased. The increase in STS is attributed to the improved bonding between aggregates and the matrix due to the introduction of NC, resulting in improved interfacial strength. The gradual hydration of GPC contributes to the continuous development of the cementitious matrix and crystal interlocking and progressively increases STS, as reported by Ahmad *et al.,* [47].

Among the different mixes, the maximum STS value at 28 days is observed in the GPC+3%NC mix, which achieves a strength of 4.28 MPa. Several factors contribute to the rise in STS. One key factor is the introduction of NC into the GPC mixture, which strengthens the connection between the aggregates and the matrix. This enhanced bond improves the interfacial strength and subsequently increases the resistance to tensile forces, resulting in a higher STS. The hydration process of the GPC mix continues, leading to the continuous development of the cementitious matrix and interlocking of the crystals. This gradual hydration is responsible for the progressive enhancement of STS at different time intervals. The decrease in STS in the GPC+4%NC mix can be attributed to an excessive NC content. When the percentage of NC exceeds, it increases the concentration of non-reactive material, ultimately weakening the concrete's bond formation and overall strength. Excessive NC content weakens bond formation, resulting in a slight reduction in STS compared to lower NC percentages. The inclusion of higher NC percentages leads to a slight reduction in STS compared to GPC mixes containing lower amounts of NC, as demonstrated by Ali *et al.,* [48]. Various factors, including the curing conditions, dispersion and distribution of NC particles, and the interfacial bonding between NC and the geopolymer matrix, can cause slight variations in the STS of the concrete.

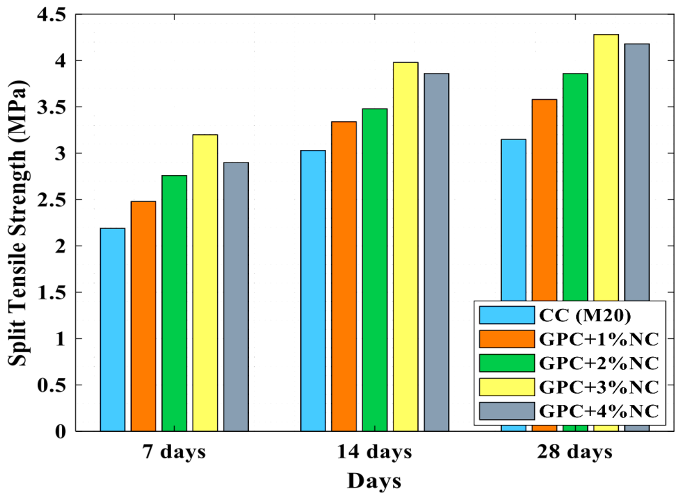

Fig. 14. Split tensile strength performances

3.4 Water Absorption

Figure 15 displays concrete sample performance over time (14, 28, and 56 days) regarding WA. The concrete samples are CC and GPC with 1%, 2%, 3%, and 4% added NC. The amount of water absorbed by concrete is crucial for its durability and long-term effectiveness, with lower absorption values indicating denser and stronger concrete. Figure 15 shows that an increase in the percentage of NC in GPC leads to a decrease in WA. This pattern remains consistent across all three-time intervals. At 14 days, the WA of CC is 3.94, surpassing GPC with 1%, 2%, 3%, and 4% NC additives. As the percentage of NC increases from 1% to 3%, the WA gradually decreases, indicating that adding nylon crystal to GPC can enhance water resistance. At 28 and 56 days, the GPC samples consistently show lower WA values than CC. The minimum WA value of 1.405 is observed in GPC+3%NC after 56 days. Increasing the percentage of NC further decreases WA, demonstrating that including nylon crystal in GPC progressively reduces WA over time. Increasing NC decreases WA, indicating improved water resistance. NC fills empty spaces, making concrete denser, less porous and preventing water penetration. NC improves the bond between aggregate and matrix, resulting in a stronger, less permeable structure.

This behavior can be attributed to the formation of GPC through a chemical reaction involving an alkaline solution and an alumino-silicate material. They are adding nylon crystal to GPC, resulting in denser and more compact structures and reducing the pathways for water penetration. Nylon crystals fill empty spaces in the concrete, making it denser and less porous. This prevents water from moving through the concrete easily and reduces WA. Nylon crystals in GPC enhance the bond between aggregate and matrix, leading to a stronger structure with lower permeability and WA. The presence of nylon crystals leads to the development of smaller pores, which limits WA by hindering the movement of water molecules, as observed by Shafei *et al.,* [49]. The greater WA seen in GPC with 4% nylon crystal inclusion compared to lower NC percentages can be attributed to a number of causes. Larger pores with a higher WA capacity are produced when the NC concentration is raised above the ideal threshold for pore size refinement. The tendency of nylon crystals to combine and form bigger particles or clusters is observed at higher concentrations of NC. These clusters can form bigger holes that are easier for water to enter. Increased water permeability results from a weaker connection and less effective interaction between them at high concentrations of NC. In addition, adding a larger amount of NC leads to an uneven distribution of NC particles, which increases WA. If the curing process is inadequate or moisture is not properly controlled, this can potentially result in higher WA.

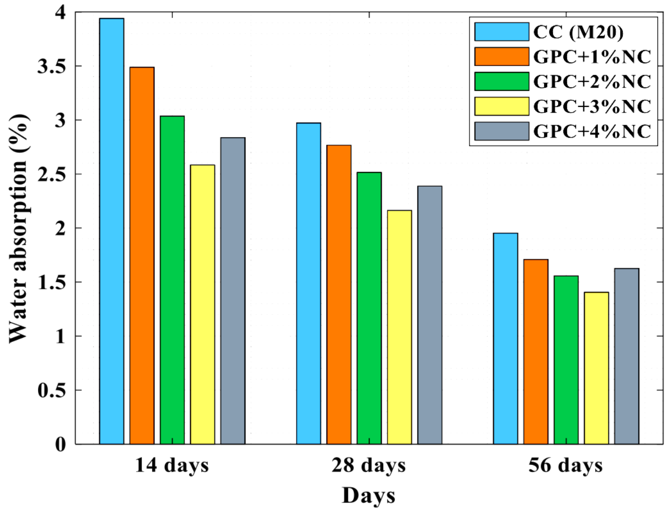

Fig. 15. Water absorption performances

3.5 Durability

3.5.1 Weight loss percentage with HCL

Figure 16 shows the weight loss percentage of GPC cubes with varying amounts of NC l when exposed to HCL in 28 days. The weight loss percentage indicates the durability of the material and its resistance to chemical degradation. In the case of GPC cubes without any NC (CC), the weight loss percentage for 1% HCL concentration at 28 days is 2.27%. Higher NC percentages lead to reduced weight loss, signifying enhanced durability. For example, when 1% NC is added to GPC, the weight loss percentage decreases to 2.2%. This trend continues as the proportion of NC increases, with corresponding weight loss values of 2.14%, 2.1%, and 2.23% observed for 2%, 3%, and 4% NC, respectively. Similarly, for 2% HCL concentration, the weight loss percentage of CC cubes is 3.6%. As NC is incorporated into the GPC, the weight loss percentage decreases across all concentrations. The addition of 1% NC results in a weight loss percentage of 3.54%, and the values further decrease to 3.47%, 3.45%, and 3.67% for 2%, 3%, and 4% NC, respectively. In the case of 3% HCL concentration, the weight loss percentage of CC GPC cubes is 4.7%; as NC is introduced, the weight loss percentage decreases, but not uniformly. For 1% NC, the weight loss percentage is 4.34%, slightly lower than the value for CC. However, with 2% and 3% NC, the weight loss percentage decreases to 4.29% and 4.02%, respectively. Surprisingly, the weight loss percentage increases to 4.45% when 4% NC is added. Increasing NC leads to reduced weight loss, indicating enhanced durability against acid attack. NC in GPC acts as a barrier, slowing the reaction between acid and concrete components. NC particles may undergo reactions forming stable compounds with lower solubility, enhancing acid resistance.

Figure 16 highlights the positive influence of NC addition on the durability of GPC cubes exposed to HCL. The weight loss percentage decreases as the concentration of NC increases, indicating enhanced resistance to acid attack. This positive influence can be attributed to several reasons: The inclusion of NC in the GPC matrix forms a barrier that delays material permeability, reducing its susceptibility to acid penetration. Consequently, the reaction between the acid and the concrete components is slowed down, leading to a decrease in weight loss percentage. This decrease indicates an improved ability to withstand acid attack. When exposed to acid, NC particles can undergo reactions that result in the formation of stable compounds. These compounds have lower solubility and are less vulnerable to acid attack. These chemical reactions can bring about changes in the microstructure of the GPC, enhancing its ability to withstand corrosion caused by acid. Adding NC to GPC improves the material's strength and reduces WA. This results in a denser matrix that is more resistant to acid penetration and degradation. The GPC cubes enhanced durability against acid attacks can be attributed to their improved mechanical properties. The acid resistance of the GPC cubes improves due to the decreased porosity, resulting in a lower percentage of weight loss. The rise in weight loss percentage as NC percentage increases (for 4% NC in GPC) is due to various factors. When the percentage of NC rises, the significance of chemical reactions between NC and alkaline components increases. These reactions can potentially degrade the concrete matrix, increasing weight loss. As the percentage of NC increases, the strength of the bonds in the concrete decreases, making it more prone to weight loss. When NC is added to GPC, it can affect the cohesion between particles in the concrete mix and potentially lead to weight loss.

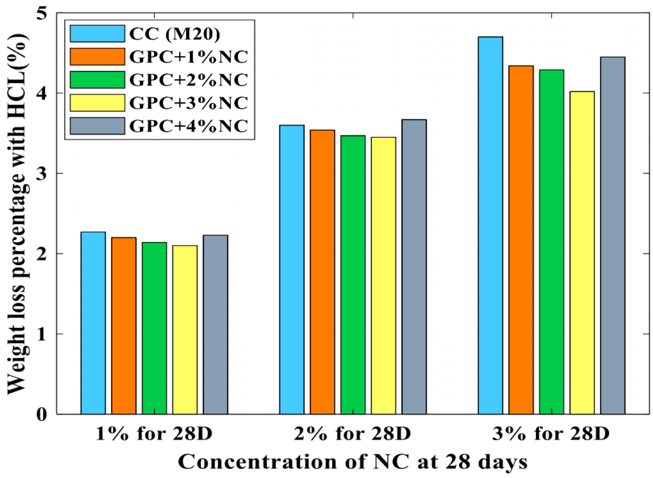

Fig. 16. Weight loss percentage with HCL

3.5.2 Weight loss percentage with H_2SO_4

The weight loss percentage of GPC cubes with different percentages of NC when exposed to Sulfuric Acid (H_2SO_4) for 28 days is depicted in Figure 17. Without any NC in the GPC cubes (CC), the weight loss percentage after 28 days of exposure to 1% H_2SO_4 concentration is 2.8%. When 1% NC is added to the GPC, the weight loss percentage decreases to 2.64%, indicating enhanced durability. Increasing the NC content leads to a continued decrease in weight loss percentage. Specifically, the values are 2.48%, 2.1%, and 2.25% for 2%, 3%, and 4% NC, respectively. In the case of CC cubes, when exposed to 2% H_2SO_4 concentration, the weight loss percentage is 4.1%. When NC is added to GPC, there is a noticeable decrease in the percentage of weight loss consistently. The weight loss percentage is 3.9% when 1% NC is present, and for 2%, 3%, and 4% NC, the percentages decrease to 3.69%, 3.3%, and 3.8% respectively. CC cubes experience a weight loss percentage of 5.8% when exposed to a concentration of 3% H_2SO_4. The presence of NC in the GPC leads to a significant reduction in the percentage of weight loss. When 1% NC is added, the weight loss percentage is 5.34%. The weight loss percentage decreases to 4.95% when 2% NC is added, followed by 4.73% with

3% NC and 5.54% with 4% NC. The results clearly show that NC benefits the durability of GPC cubes when exposed to H_2SO_4. The findings indicate that NC positively influences the durability of GPC cubes when they come into contact with H_2SO_4. According to the findings, the addition of NC in GPC is an effective method to reduce the degradation caused by exposure to sulfuric acid. Similar to HCL, NC addition reduces weight loss when exposed to sulfuric acid. NC enhances chemical resistance against sulfuric acid, providing an effective diffusion barrier, as highlighted by Chaudhari *et al.,* [50]. The interaction between NC and sulfuric acid is complex, leading to variations in weight loss percentages. The inclusion of 3% NC in GPC provides additional chemical resistance against the sulfuric acid present in H_2SO_4. Also, NC acts as an effective diffusion barrier, leading to the improved performance observed in GPC+3%NC cubes exposed to H_2SO_4. The impact of NC on the weight loss percentage is not consistent for all concentrations. An instance of this is observed when 4% NC is added, increasing the weight loss percentage. The complex nature of the interaction between NC and sulfuric acid leads to an increase in the weight loss percentage.

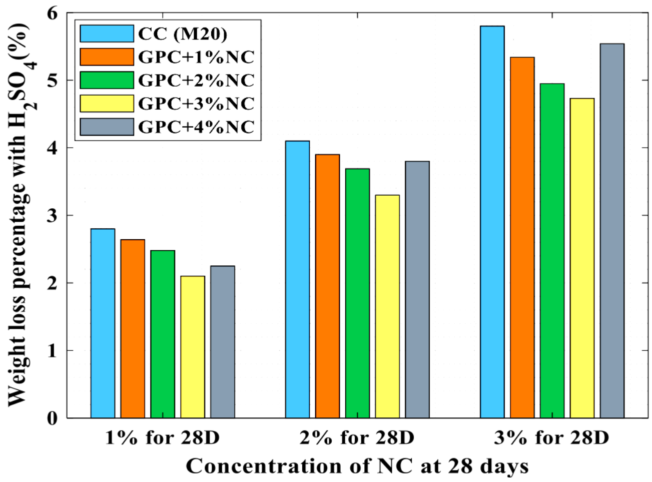

Fig. 17. Weight loss percentage with H_2SO_4

3.6 Comparison of Proposed Study with Existing Geopolymer Concrete Studies

Table 5 shows the comparison of the proposed study with existing studies. The proposed study aims to enhance the crack resistance and strength of GPC pavements by incorporating FA, GGBS, Na_2SiO_3, NaOH and Nylon Crystals reinforcement. Unlike existing studies, which mainly focus on the influence of activators, binders, and curing conditions on GPC properties, the proposed study uniquely integrates nylon crystals to improve mechanical performance and durability. While Ghafoor *et al.,* [51] investigated the impact of alkaline activators on fly ash-based GPC, the proposed study extends the exploration by introducing nylon crystals as a reinforcement material, showcasing improved compressive strength, flexural strength, and split tensile strength. Similarly, Bellum *et al.,* [52] explored the influence of activator solutions on microstructural and mechanical properties. In contrast, the proposed study focuses on the synergistic effects of FA, GGBS, alkaline liquids, and nylon crystal reinforcement.

Additionally, Pratap *et al.*, [53] examined the influence of NaOH molarity on mechanical and durability properties with the incorporation of phosphogypsum, while the proposed study emphasizes the role of nylon crystals in enhancing sustainability and reducing environmental impact. Finally, Divvala [54] investigated the early strength properties of GPC composites by replacing cement with various binders, while the proposed study uniquely introduces nylon crystal reinforcement for improved mechanical and durability performance. In contrast, Zannerni *et al.,* [55] explored ambient-cured GPC with a single alkali activator, highlighting its sustainability benefits but lacking the specific focus on nylon crystal reinforcement seen in the proposed study. Therefore, the proposed study contributes novel insights into optimizing GPC pavement with a comprehensive approach, emphasizing the unique benefits of nylon crystal reinforcement.

Table 5
Comparison of the proposed study with existing studies

Aspect	Materials used	Alkaline used	Key findings
Proposed study	FA, GGBS, Nylon Crystals	Na_2SiO_3, NaOH	Improved CS, FS, and STS with 3% nylon crystals. Superior performance compared to M20 CC and enhanced durability.
Ghafoor *et al.*, [51]	FA	NaOH, Na_2SiO_3	Optimal CS (21.5 MPa) with 14 M NaOH, Na_2SiO_3 /NaOH of 1.5, AA/FA of 0.5. Optimal FS (5 MPa) with 16 M NaOH, 1.5 ratio.
Bellum *et al.*, [52]	FA, GGBS	Alkaline Solution (lab-prepared), Commercial Activator Solution	Alkaline solution-based mixes had enhanced mechanical properties compared to activator solution-based GC samples.
Pratap *et al.*, [53]	FA, Phosphogypsum,	NaOH	Optimal GPC with 30% PG and 12 M NaOH, achieving 47.97 MPa. Optimal dosage prevents the release of toxic elements.
Divvala [54]	FA, GGBS, Silica Fume, Metakaolin, Rice Husk Ash	Alkaline Activating Solutions (NaOH, KOH, $Ba(OH)_2$, LiOH)	Improved mechanical properties.
Zannerni *et al.*, [55]	FA, GGBS, Silica Fume	Single Alkali Activator	GPC with 100% GGBS replacement achieved 36 MPa compressive strength without heat curing. Decreased carbon emissions by over 60%.

4. Conclusions

This study contributes novel understandings into the enhancement of GPC pavement by incorporating FA, GGBS, alkaline liquids (Na_2SiO_3 and NaOH), and nylon crystal reinforcement. The key contributions and novelty of this study are summarized as follows:

i. The investigation establishes optimal mix proportions for GPC through systematic trials, considering the properties of FA, GGBS, alkaline liquids, and nylon crystals. This provides a valuable guide for practitioners and researchers in achieving a balanced composition for enhanced GPC performance.
ii. The study demonstrates that the inclusion of nylon crystal reinforcement in GPC significantly improves CS, FS, and STS at various curing periods. The GPC+3%NC mixture exhibits superior performance with a compression strength of 31.02 MPa, maximum FS of 5.573 MPa, and highest STS of 4.28 MPa at 28 days.
iii. The investigation reveals that the GPC+3%NC blend showcases improved durability characteristics, as evidenced by the lowest WA value of 1.405 after 56 days. The study further demonstrates enhanced resistance to acid and sulfuric attacks, resulting in reduced weight loss, indicating the potential for prolonged service life of GPC pavements.
iv. The utilization of nylon crystal reinforcement not only enhances the mechanical properties of GPC but also contributes to the sustainability of the pavement system. The study

suggests that the incorporation of nylon crystals reduces material and energy requirements compared to traditional reinforcement methods.

v. Overall, this study presents a comprehensive exploration of the contributions and novelty associated with the incorporation of FA, GGBS, Na_2SiO_3, NaOH, and nylon crystal reinforcement in GPC pavement. The findings highlight the optimized composition, improved mechanical performance, enhanced durability, and sustainability impact, providing valuable understanding for the advancement of geopolymer concrete technology.

The proposed GPC mixture incorporating FA, GGBS, Na_2SiO_3, NaOH, and nylon crystal reinforcement exhibits promising mechanical properties, including enhanced CS, FS, STS, WA, and durability. These improvements are essential not only for structural performance but also for the broader practical applications of GPC in real-world construction projects. The incorporation of supplementary cementitious materials (FA and GGBS) in GPC contributes to cost savings by partially replacing traditional Portland cement. Additionally, using nylon crystal reinforcement offers a sustainable alternative to conventional methods, potentially reducing material and energy requirements. The study underscores the ecological benefits of the proposed GPC by reducing the reliance on Portland cement, which is a significant source of carbon emissions. The nylon crystal reinforcement further enhances the sustainability of the pavement system. This is crucial for achieving environmental goals and addressing the ecological impact associated with cement production. The enhanced durability of the GPC, as demonstrated through resistance to chemical attacks and reduced water absorption, suggests a prolonged service life for structures constructed with this material. This could result in long-term cost savings by minimizing maintenance and repair needs. The study contributes to the broader goal of reducing the ecological impact of construction activities by offering a viable alternative to conventional concrete. The optimized GPC mixture aligns with sustainable construction practices and addresses concerns related to resource depletion and environmental degradation.

While the current study provides a foundation for understanding the mechanical properties of GPC, future research and real-world applications will explore these practical implications in detail. Further investigations should consider field trials, life-cycle assessments, and economic analyses to validate the proposed GPC's performance and benefits in actual construction scenarios. This study primarily focuses on the mechanical properties of GPC pavement, such as CS, FS, and STS. Other important properties, such as fatigue resistance, skid resistance, and rutting resistance, were not investigated. Future studies should consider a more comprehensive evaluation of GPC pavement properties. The study only incorporates specific additives and reinforcement materials (FA, GGBS, Na_2SiO_3, NaOH, and nylon crystal). Further research can explore the optimal combination and proportions of different additives and reinforcement materials to improve the performance of GPC pavement. Further study can develop deep learning models that accurately predict the performance of GPC pavement based on their composition, curing conditions, and environmental factors.

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