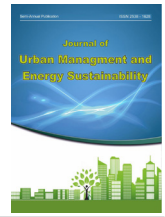
International Journal of Urban Management and Energy Sustainability (IJUMES)

Homepage: http://www.ijumes.com



CASE STUDY RESEARCH PAPER

# Enhancing The Mechanical Properties of Eco-Friendly GGBS-Based Geopolymer Concrete Through Combined Effects of Fibers and Nanosilica

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ARTICLE INFO

*Article History:*
Received 2026-03-06
Revised 2026-05-01
Accepted 2026-06-18

*Keywords:*
Alkali-resistant glass fiber; geopolymer concrete; ground granulated blast furnace slag; mechanical properties; Nanosilica

ABSTRACT

Geopolymer concrete produced from industrial by-products is a promising low-carbon alternative to Portland cement concrete, but its brittle behavior and limited tensile resistance restrict its structural use. This study investigates the combined effects of nanosilica and alkali-resistant (AR) glass fibers on the mechanical performance of ground granulated blast furnace slag-based geopolymer concrete. Sixteen mixtures were prepared with a constant GGBS content of 500 kg/m³ and an activator of 12 M sodium hydroxide and sodium silicate: a reference mixture and 15 mixtures combining five NS contents with three AR glass fiber dosages. Specimens were cured at ambient temperature, and compressive and splitting tensile strengths were determined at 7, 28, 56 and 180 days. Both properties depended non-linearly on the two constituents, showing an optimum rather than a continuously increasing relationship, with strength declining beyond 2% NS and 0.6% fibers. The mixture containing 2% NS and 0.6% AR glass fibers performed best at all ages, reaching estimated 28-day compressive and splitting tensile strengths of 59.6 and 4.89 MPa, 12.45% and 16.43% higher than those of the reference mixture. The larger gain in tensile strength is consistent with nanosilica densifying the binder matrix and the fibers bridging cracks and redistributing stress. Combining nanosilica modification with moderate AR glass fiber reinforcement is therefore an effective route to stronger GGBS-based geopolymer concrete, and microstructural and durability studies are recommended to confirm the proposed mechanisms.

DOI: 10.22034/ijumes.2026.743761

*Running Title: The Mechanical Properties of Eco-Friendly GGBS-Based Geopolymer Concrete*

| NUMBER OF REFERENCES | NUMBER OF FIGURES | NUMBER OF TABLES |
|---|---|---|
| 24 | 05 | 04 |

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## INTRODUCTION

The transition toward low-carbon construction materials has encouraged the development of alternative cementitious systems that can satisfy the increasing performance requirements of modern infrastructure while reducing dependence on conventional Portland cement (Khasawneh, 2025). Geopolymer concrete has emerged as a technically attractive option in this context, particularly when industrial by-products are used as the primary aluminosilicate precursor. Ground granulated blast furnace slag (GGBS) is particularly suitable for this purpose because its chemical composition supports alkali-activation reactions and the formation of calcium-rich binding phases (Amer et al., 2024; Wu et al., 2025). Unlike conventional cement hydration, the hardening process in slag-based geopolymer systems is governed by the dissolution of reactive constituents and their subsequent reorganization into a binding network (Adam et al., 2025). The resulting matrix can develop substantial mechanical strength; however, its performance is influenced by the extent of precursor dissolution, reaction-product distribution, pore connectivity, and the quality of the interfaces within the composite. These interdependent characteristics make the design of geopolymer concrete a materials-engineering challenge rather than simply a matter of selecting an appropriate binder content (Abdulkarim et al., 2025; Zhou et al., 2025). One of the major limitations affecting the structural performance of geopolymer concrete is the difficulty of simultaneously improving matrix strength and resistance to tensile-induced damage (Alagarsamy et al., 2026). Although a dense geopolymer matrix can provide considerable resistance to compressive loading, localized stress concentrations may still initiate microcracks, which subsequently develop into larger fractures under tensile and flexural actions (Yuan et al., 2024). This behavior highlights the importance of introducing reinforcement mechanisms that operate at different structural scales. Alkali-resistant (AR) glass fibers offer a suitable approach because of their tensile load-bearing capacity and potential to restrict crack development within highly alkaline cementitious environments (Angdiarto et al., 2025). Their contribution is not limited to increasing the nominal strength of the material; fiber bridging, stress redistribution, crack deflection, and resistance to crack opening can also influence the failure mechanism (Rossi et al., 2023). Nevertheless, the effectiveness of fiber reinforcement is closely associated with the relationship between fiber content and matrix characteristics. At insufficient dosages, the number of fibers available to intercept developing cracks may be inadequate, whereas excessive incorporation can promote fiber clustering and nonuniform distribution. Consequently, the mechanical contribution of glass fibers should be evaluated in relation to the characteristics of the surrounding geopolymer matrix rather than through fiber dosage alone (Bhina et al., 2023). Nanosilica provides a complementary modification strategy by targeting the internal structure of the geopolymer matrix. Its influence is associated with both particle-scale packing and changes in the chemical environment of alkali activation (Zheng et al., 2026). The incorporation of finely dispersed nanosilica can modify the distribution of solid particles, occupy spaces between larger constituents, and potentially contribute additional reactive silica to the formation of binding products. These effects may reduce the size and connectivity of internal pores and improve the continuity of the hardened matrix (Bheel et al., 2024; Singh & Tiwary, 2024; Srikrishna et al., 2025). More importantly, nanosilica modification may influence the quality of the interfacial region surrounding glass fibers, which is a critical factor governing stress transfer between the reinforcing phase and the geopolymer matrix. However, the effectiveness of this modification depends strongly on nanosilica concentration and dispersion. Increasing its content does not necessarily produce a proportional improvement in mechanical performance, since particle agglomeration and changes in the fresh-state characteristics

may counteract its beneficial effects. Therefore, the identification of an appropriate nanosilica content is essential for obtaining a matrix capable of effectively accommodating and mobilizing fiber reinforcement (Dinh et al., 2023).

The interaction between nanosilica and AR glass fibers introduces a more complex dimension to the design of geopolymer composites (Zhang et al., 2023; Zheng et al., 2026). These materials operate through different but potentially complementary mechanisms: nanosilica modifies the characteristics of the continuous binding phase, whereas glass fibers provide localized resistance against crack propagation. This distinction is particularly important because the effectiveness of a fiber-reinforced composite depends not only on the intrinsic properties of its reinforcing elements but also on the mechanical integrity of the matrix in which they are embedded (Efe et al., 2024). A matrix with improved compactness and interfacial characteristics may facilitate more effective stress transfer to the fibers, while fiber bridging can help preserve structural integrity after the initiation of cracking. Nevertheless, the interaction between these two constituents may be influenced by their respective dosages, and an optimum combination cannot necessarily be predicted from the individual performance of each constituent. In particular, the balance between matrix densification, fiber dispersion, and interfacial resistance requires systematic experimental evaluation (Their et al., 2026). Understanding this relationship is essential for developing geopolymer composites in which nanoscale modification translates into measurable improvements at the structural material scale (Gebru et al., 2026). Despite the growing interest in nanomodified and fiber-reinforced geopolymer materials, the combined influence of nanosilica concentration and AR glass fiber dosage on the mechanical performance of GGBS-based geopolymer concrete requires further investigation. In particular, evaluating several combinations of these constituents under a constant binder and alkaline activation system can help distinguish their individual contributions from the effects associated with their simultaneous incorporation. This is relevant because improvements in one mechanical response do not necessarily imply equivalent improvements in other loading conditions (Gok & Sengul, 2024). For example, compressive resistance is strongly associated with matrix integrity and defect distribution, whereas tensile and flexural responses are additionally governed by crack initiation, fiber bridging, and interfacial load transfer (Guo et al., 2023). Accordingly, identifying an optimum mixture requires a comparative assessment of different mechanical responses rather than relying on a single strength indicator. To address this research need, the present study experimentally investigates GGBS-based geopolymer concrete incorporating different proportions of nanosilica and AR glass fibers. A constant GGBS content of 500 kg/m³ was considered, while nanosilica was introduced at five levels (1%, 1.5%, 2%, 2.5%, and 3%) in combination with three AR glass fiber dosages (0.4%, 0.6%, and 0.8%). A reference mixture without nanosilica and glass fibers was also included to establish a baseline for evaluating the modifications. The contents of coarse aggregate and fine aggregate, together with the alkaline activation system comprising 12 M sodium hydroxide solution and sodium silicate, were maintained constant throughout the mixture series. This experimental configuration enables the influence of the two reinforcing constituents to be investigated while minimizing variations arising from other mixture parameters. The principal objective is to elucidate how nanosilica and glass fiber contents influence the mechanical behavior of the developed geopolymer concrete, identify the most effective combinations, and examine whether their simultaneous incorporation produces complementary improvements in matrix performance and crack resistance (Li et al., 2025). The outcomes are expected to contribute to a more systematic understanding of the design of high-performance fiber-reinforced geopolymer concrete for structural applications. Fig. 1 pres-

ents a schematic illustration of the experimental framework for developing GGBS-based geopolymer concrete incorporating nanosilica and alkali-resistant glass fibers, including mixture design, specimen preparation, curing conditions, mechanical testing, and the main functional characteristics of the developed composite. (Fig. 1)

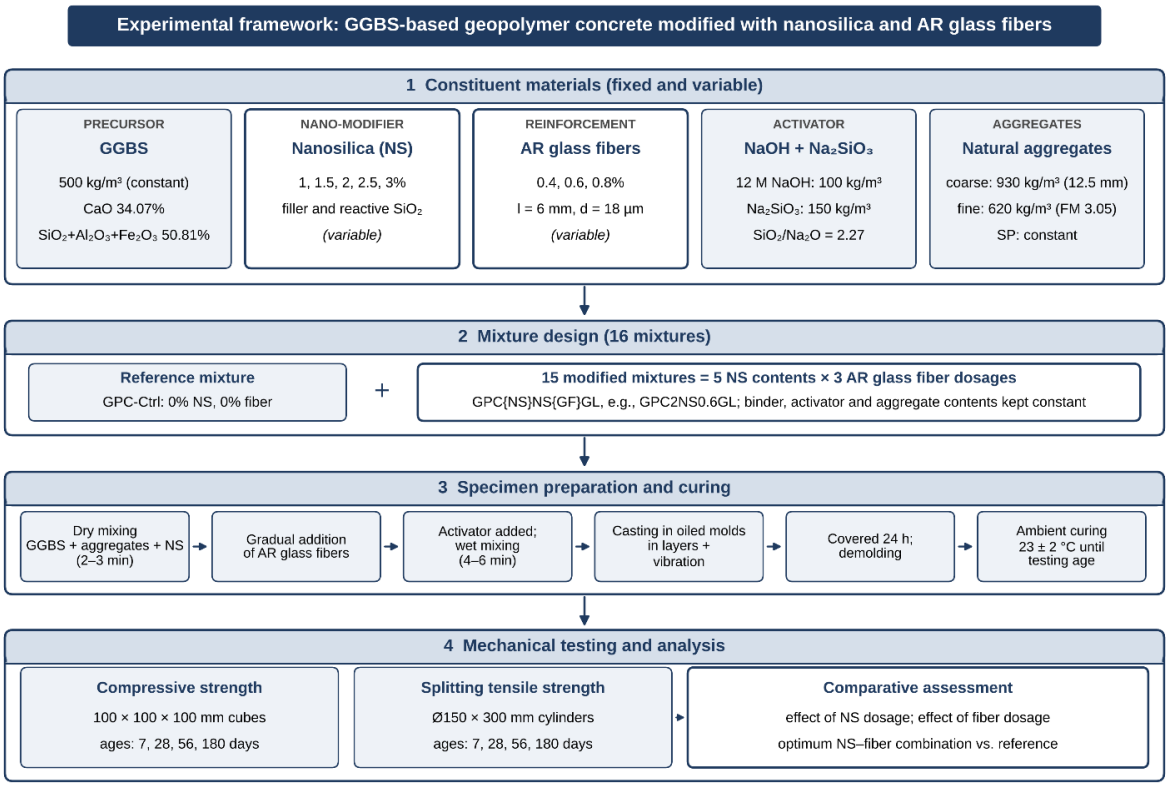



Figure 1: Schematic illustration of the experimental framework for developing GGBS-based geopolymer concrete

## MATERIALS AND METHODS

An experimental program was established to investigate the mechanical performance of GGBS-based geopolymer concrete modified through the combined incorporation of nanosilica (NS) and alkali-resistant (AR) glass fibers. The experimental design was developed to distinguish the effects associated with nanoscale modification of the geopolymer binder from those arising from fiber reinforcement and, more importantly, to examine their combined contribution to the behavior of the hardened composite. For this purpose, the GGBS content, aggregate proportions, and alkaline activator composition were maintained constant, whereas the NS and AR glass fiber contents were systematically varied. The experimental matrix consisted of 16 geopolymer concrete mixtures, including one reference composition without NS and glass fibers and 15 modified mixtures. Nanosilica was introduced at five different levels (1%, 1.5%, 2%, 2.5%, and 3%), while the AR glass fiber content was varied between 0.4%, 0.6%, and 0.8%. This arrangement enabled the evaluation of five nanosilica concentrations at each fiber dosage, providing a comparative basis for investigating the influence of the two modification strategies on the resulting geopolymer composites. The binder was composed exclusively of GGBS, with a constant dosage of 500 kg/m³. The alkaline activation system consisted of sodium hydroxide (NaOH) solution with a con-

centration of 12 M and sodium silicate ($Na_2SiO_3$). The quantities of the alkaline constituents and aggregates were kept unchanged throughout the experimental program to minimize the influence of mixture-related variations on the interpretation of the results. The overall experimental configuration is intended to provide insight into the relationship between binder modification, fiber reinforcement, and the mechanical response of GGBS-based geopolymer concrete. Fig. 2 shows the materials used in this study. (Fig. 2)

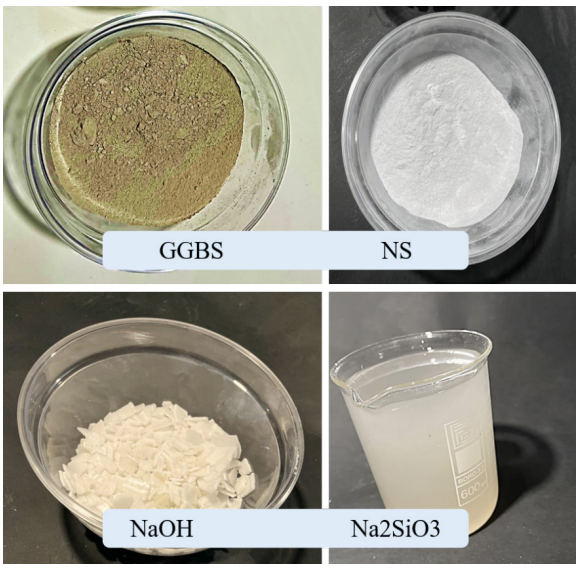



Figure 2: Materials used in this study: GGBS, nanosilica (NS), sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$).

*Constituent materials*

*Ground granulated blast furnace slag*

Ground granulated blast furnace slag was employed as the principal aluminosilicate precursor in the production of geopolymer concrete. The material was obtained from Foolad Mobarakeh, Isfahan, Iran, and exhibited a particle density of 2.66 g/cm³. Its chemical composition, determined in terms of the major oxide constituents, is presented in Table 1. The combined content of $SiO_2$, $Al_2O_3$, and $Fe_2O_3$ was approximately 50.81%, while CaO constituted the dominant individual oxide at 34.07%. The presence of calcium, together with reactive silica and alumina, provides a suitable chemical basis for the development of binding products during alkaline activation. (Tab. 1)

Table 1: Chemical composition of GGBS used in this investigation.

| Chemical constituent | Content (%) |
|---|---|
| $SiO_2$ | 32.57 |
| $Al_2O_3$ | 16.98 |
| $Fe_2O_3$ | 1.26 |
| CaO | 34.07 |
| MgO | 9.69 |
| $SO_3$ | 0.84 |
| Loss on ignition (LOI) | 0.39 |

*Nanosilica*

Nanosilica was incorporated as a mineral modifier to investigate the influence of fine-scale binder modification on the mechanical characteristics of the geopolymer concrete. Its incorporation was intended to modify the particle packing and microstructural characteristics of the slag-based binder and potentially contribute to the development of a more compact hardened matrix. Five NS contents were considered in the experimental mixtures: 1%, 1.5%, 2%, 2.5%, and 3%. By examining these concentrations at different fiber contents, the experimental design allowed the influence of nanosilica dosage to be evaluated under different reinforcement conditions.

*Alkaline activating solutions*

The geopolymerization process was initiated using a two-component alkaline activator comprising sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$). Sodium hydroxide solution was prepared at a concentration of 12 M and used in combination with sodium silicate to provide the alkaline environment required for the dissolution of reactive constituents in GGBS and the subsequent formation of binding products. The sodium silicate solution used in this investigation had a $SiO_2/Na_2O$ mass ratio of 2.27, with reported $SiO_2$ and $Na_2O$ contents of 35.9% and 15.8%, respectively. A constant dosage of 100 kg/m³ of NaOH

solution and 150 kg/m³ of sodium silicate was adopted for all mixtures. Maintaining an identical activator composition across the experimental series was particularly important for isolating the effects of NS and AR glass fiber incorporation from variations in alkaline activation conditions.

*Alkali-resistant glass fibers*

AR glass fibers were incorporated as discrete reinforcing elements to improve the resistance of the geopolymer concrete against tensile-induced cracking. The fibers were supplied by Sepahan Fibers Company, Isfahan, Iran. According to the manufacturer's specifications, they had a nominal length of 6 mm, a diameter of 0.018 mm, and a density of 2.56 g/cm³. Their reported tensile strength was 442 MPa. The selection of alkali-resistant glass fibers was based on their suitability for incorporation into highly alkaline cementitious environments. Their reinforcement mechanism is primarily associated with the transfer of tensile stresses across developing cracks, thereby restricting crack opening and contributing to improved integrity of the composite. Three fiber contents, namely 0.4%, 0.6%, and 0.8%, were investigated to assess the influence of reinforcement dosage on the mechanical performance of the geopolymer concrete.

*Fine and coarse aggregates*

Natural aggregates were used to produce the geopolymer concrete mixtures. The fine aggregate consisted of natural sand obtained from a local quarry, with a fineness modulus of 3.05. Its grading characteristics were considered in accordance with the requirements of ASTM C33. The coarse aggregate had a maximum nominal particle size of 12.5 mm, a specific gravity of 2.57, and a water absorption capacity of 1.52%. The particle-size distributions of both aggregate fractions are provided in Table 2. For the coarse aggregate, the percentage passing the 12.5, 8, 5.7, 4, 2, and 1 mm sieves was 100%, 76%, 47%, 22%, 4%, and 2%, respectively. The corresponding grading data for the fine aggregate are also reported in Table 2. These grading characteristics were maintained throughout the experimental program to ensure consistency in aggregate packing and reduce the influence of aggregate-related variations on the comparison of different mixtures.(Tab. 2)

Table 2: Sieve analysis of fine and coarse aggregates.

| Sieve size (mm) | Coarse aggregate /passing (%) | Sieve size (mm) | Fine aggregate /passing (%) |
|---|---|---|---|
| 12.5 | 100 | 9.5 | 100 |
| 8 | 76 | 4.75 | 87.6 |
| 5.7 | 47 | 2.36 | 63.5 |
| 4 | 22 | 1.18 | 41.9 |
| 2 | 4 | 0.60 | 23.3 |
| 1 | 2 | 0.30 | 4.5 |

*Mixture proportions and experimental variables*

The mixture proportions were established by adopting a controlled experimental strategy in which the binder content, alkaline activator quantities, and aggregate contents remained unchanged. This approach was intended to minimize the effects of confounding variables and provide a consistent basis for comparing the contribution of nanosilica and glass fiber reinforcement. As reported in Table 3, the GGBS content was fixed at 500 kg/m³, while coarse and fine aggregate contents were maintained at 930 and 620 kg/m³, respectively. The NaOH solution and sodium silicate contents were 100 and 150 kg/m³, respectively. The NaOH solution was prepared at a constant molarity of 12 M. Superplasticizer (SP) was also maintained at a dosage of 1 in all mixtures, based on the adopted mixture-design notation. The reference mixture (GPC-Ctrl) contained neither nanosilica nor AR

glass fibers. The remaining mixtures were divided into three groups according to their glass fiber contents. Within each group, five nanosilica dosages were investigated, ranging from 1% to 3%. This arrangement resulted in 15 modified mixtures and enabled the combined effects of NS and glass fiber incorporation to be assessed systematically. (Tab. 3)

Table 3: Mixture proportions of the investigated GGBS-based geopolymer concrete.

| Mixture code | GGBS (kg/m³) | NS (%) | Coarse aggregate (kg/m³) | Fine aggregate (kg/m³) | NaOH solution (kg/m³) | Molarity (M) | $Na_2SiO_3$ (kg/m³) | AR glass fiber (%) | SP |
|---|---|---|---|---|---|---|---|---|---|
| GPC-Ctrl | 500 | 0 | 930 | 620 | 100 | 12 | 150 | 0 | 1 |
| GPC1NS0.4GL | 500 | 1.0 | 930 | 620 | 100 | 12 | 150 | 0.4 | 1 |
| GPC1.5NS0.4GL | 500 | 1.5 | 930 | 620 | 100 | 12 | 150 | 0.4 | 1 |
| GPC2NS0.4GL | 500 | 2.0 | 930 | 620 | 100 | 12 | 150 | 0.4 | 1 |
| GPC2.5NS0.4GL | 500 | 2.5 | 930 | 620 | 100 | 12 | 150 | 0.4 | 1 |
| GPC3NS0.4GL | 500 | 3.0 | 930 | 620 | 100 | 12 | 150 | 0.4 | 1 |
| GPC1NS0.6GL | 500 | 1.0 | 930 | 620 | 100 | 12 | 150 | 0.6 | 1 |
| GPC1.5NS0.6GL | 500 | 1.5 | 930 | 620 | 100 | 12 | 150 | 0.6 | 1 |
| GPC2NS0.6GL | 500 | 2.0 | 930 | 620 | 100 | 12 | 150 | 0.6 | 1 |
| GPC2.5NS0.6GL | 500 | 2.5 | 930 | 620 | 100 | 12 | 150 | 0.6 | 1 |
| GPC3NS0.6GL | 500 | 3.0 | 930 | 620 | 100 | 12 | 150 | 0.6 | 1 |
| GPC1NS0.8GL | 500 | 1.0 | 930 | 620 | 100 | 12 | 150 | 0.8 | 1 |
| GPC1.5NS0.8GL | 500 | 1.5 | 930 | 620 | 100 | 12 | 150 | 0.8 | 1 |
| GPC2NS0.8GL | 500 | 2.0 | 930 | 620 | 100 | 12 | 150 | 0.8 | 1 |
| GPC2.5NS0.8GL | 500 | 2.5 | 930 | 620 | 100 | 12 | 150 | 0.8 | 1 |
| GPC3NS0.8GL | 500 | 3.0 | 930 | 620 | 100 | 12 | 150 | 0.8 | 1 |

Preparation and casting of geopolymer concrete specimens

The production procedure was designed to obtain homogeneous mixtures while minimizing the formation of localized fiber-rich regions and nonuniform distribution of the solid constituents. Initially, the dry components, including GGBS, aggregates, and nanosilica, were combined and mixed in a laboratory concrete mixer for approximately 2–3 min. This initial blending stage was intended to distribute the fine mineral particles throughout the aggregate–binder system before the introduction of the liquid constituents. Subsequently, the prescribed quantity of AR glass fibers was introduced gradually into the dry mixture. The gradual addition of fibers was adopted to reduce the possibility of fiber entanglement and agglomeration and to promote a more uniform reinforcing network. In a separate preparation stage, the alkaline activating constituents were combined to obtain a homogeneous liquid activator. The prepared activating solution was then introduced into the dry mixture, and mixing was continued for approximately 4–6 min until a visually uniform and workable geopolymer concrete was obtained. Immediately after mixing, the fresh mixtures were placed into previously oiled molds. Casting was performed in successive layers, followed by mechanical vibration to facilitate consolidation and remove entrapped air. Two specimen configurations were employed in the experimental program: cubic specimens

measuring 100 × 100 × 100 mm and cylindrical specimens measuring 150 × 300 mm. The selected specimen geometry was determined according to the requirements of the corresponding experimental evaluations. Following casting, the molds were covered to limit premature moisture loss, and the specimens were maintained under laboratory conditions for approximately 24 h. After demolding, the specimens were transferred to the curing environment and kept at ambient laboratory temperature (23 ± 2 °C) until the specified testing ages. Ambient curing was selected to examine the behavior of the developed geopolymer composites under conditions that are more representative of conventional construction practices, without relying on elevated-temperature curing.

*Experimental evaluation*

The hardened geopolymer concrete mixtures were subjected to the experimental assessments defined in the research program to evaluate the contribution of nanosilica and AR glass fiber reinforcement to their mechanical performance. The reference mixture served as the baseline for quantifying changes associated with the incorporation of the two modifying constituents. Comparisons were established across the three fiber dosage groups and five nanosilica concentrations to identify the sensitivity of the resulting properties to variations in mixture composition. The testing procedures, specimen dimensions, loading configurations, curing ages, and applicable ASTM or EN standards are to be specified separately for each mechanical test. For each test condition, replicate specimens were prepared to support the reliability and reproducibility of the experimental observations.

## MATERIALS AND METHODS

*Compressive Strength*

The compressive strength development of the GGBS-based geopolymer concrete mixtures was evaluated at 7, 28, 56, and 180 days to investigate the individual and combined contributions of nanosilica (NS) and alkali-resistant (AR) glass fibers. The results indicate that incorporating these two constituents can improve the compressive performance of geopolymer concrete, although the magnitude of improvement depends considerably on their respective dosages. In particular, the combined influence of NS content and fiber volume appears to be non-linear, suggesting that the beneficial effects of these constituents are governed by an optimum balance between matrix densification and fiber dispersion. The reference mixture (GPC-Ctrl), which contained neither nanosilica nor glass fibers, exhibited estimated compressive strengths of 42.0, 53.0, 56.0, and 58.0 MPa at 7, 28, 56, and 180 days, respectively. The continuous increase in strength with curing age can be attributed primarily to the progressive development of the geopolymeric reaction products and the associated refinement of the binder matrix. In GGBS-based geopolymer systems, the dissolution of reactive aluminosilicate species under alkaline conditions facilitates the formation of calcium-rich aluminosilicate hydrate-type reaction products, commonly described as C-(A)-S-H or hybrid geopolymeric gels, depending on the precursor composition and reaction environment. The progressive formation and spatial distribution of these binding products contribute to improved cohesion within the hardened matrix and enhanced resistance to externally applied compressive stresses. Figure 3 presents the compressive strength of the mixtures at the three AR glass fiber contents.(Fig. 3). A comparison between the reference and modified mixtures reveals that the incorporation of nanosilica generally enhances compressive strength up to an intermediate dosage. At a constant AR glass fiber content of 0.4%, increasing the NS content from 1% to 2% resulted in an increase in the estimated 28-day compressive strength from 56.3 to 58.8 MPa. A similar trend was observed in the mixtures containing 0.6% and 0.8% glass fibers. This improvement can be associated with the high specific surface area and fine particle size of nanosilica, which may promote the

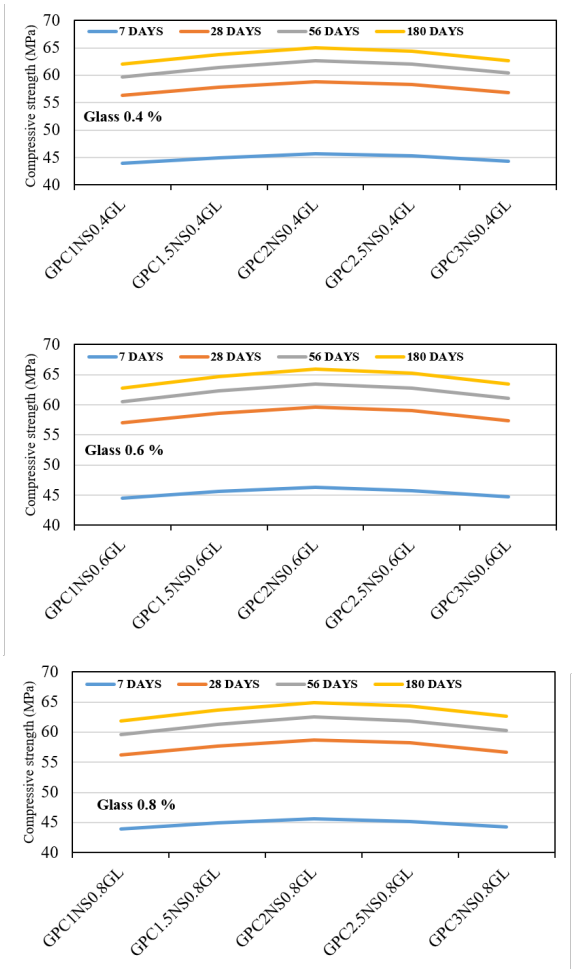



Figure 3: Compressive strength of the mixtures at AR glass fiber contents of 0.4%, 0.6% and 0.8% (top to bottom) and curing ages of 7, 28, 56 and 180 days

filling of capillary-scale voids and improve the packing characteristics of the binder system. Furthermore, the reactive silica supplied by NS may participate in the alkaline reaction process, contributing to the formation of additional silicate-rich reaction products and improving the compactness of the hardened geopolymer matrix. Table 4 compares the compressive strength of the optimum mixture (GPC2NS0.6GL) with that of the reference mixture (GPC-Ctrl). (Tab. 4)

Table 4: Compressive strength of the optimum mixture (GPC2NS0.6GL) and the reference mixture (GPC-Ctrl)

| Curing age (days) | GPC-Ctrl (MPa) | GPC2NS0.6GL (MPa) | Improvement (%) |
|---|---|---|---|
| 7 DAYS | 42.0 | 46.3 | 10.24 |
| 28 DAYS | 53.0 | 59.6 | 12.45 |
| 56 DAYS | 56.0 | 63.5 | 13.39 |
| 180 DAYS | 58.0 | 65.9 | 13.62 |

The effectiveness of nanosilica, however, did not continue to increase proportionally with its dosage. Increasing the NS content beyond 2% generally produced a slight reduction in the estimated compressive strength. For instance, in the mixture containing 0.6% AR glass fibers, the estimated 28-day compressive strength decreased from 59.6 MPa at 2% NS to 59.0 and 57.4 MPa at 2.5% and 3% NS, respectively. This response suggests that the beneficial contribution of nanosilica may reach a threshold beyond which its additional incorporation does not translate into further mechanical improvement. Excessive nanosilica may increase the water and activator demand of the fresh mixture because of its high surface area. It may also increase the tendency of fine particles to agglomerate when dispersion is insufficient. Such phenomena can adversely affect the homogeneity of the binder matrix and potentially generate localized defects that reduce the effectiveness of the additional nanosilica. Therefore, the observed trend supports the existence of an optimum NS dosage rather than a continuously increasing relationship between nanosilica content and compressive strength. The incorporation of AR glass fibers also influenced the compressive response, although their contribution is expected to be more pronounced in tensile and flexural loading conditions. Comparing the mixtures with identical nanosilica contents demonstrates that the 0.6% fiber dosage generally provided higher compressive strength than the corresponding 0.4% and 0.8% fiber mixtures. For example, at 2% NS, the estimated 28-day compressive strengths

of the mixtures containing 0.4%, 0.6%, and 0.8% AR glass fibers were 58.8, 59.6, and 58.7 MPa, respectively. This behavior indicates that a moderate fiber dosage may improve the integrity of the hardened composite by restricting the development and propagation of microcracks generated during loading. The fibers can act as discrete reinforcing elements within the geopolymer matrix, contributing to stress redistribution and limiting the rapid coalescence of localized cracks.

Nevertheless, increasing the fiber content to 0.8% did not produce a further improvement in compressive strength. A possible explanation is that higher fiber concentrations may complicate the mixing process and reduce the uniformity of fiber distribution. Fiber clustering, insufficient matrix coating, and the formation of localized voids can reduce the effective load-bearing area and offset the potential reinforcing contribution of the additional fibers. Consequently, the intermediate fiber dosage appears to provide a more favorable balance between crack-bridging capacity and mixture homogeneity. It should be emphasized that this interpretation is a plausible mechanism and requires confirmation through fresh-state observations and microstructural characterization. Among all investigated mixtures, GPC2NS0.6GL exhibited the highest estimated compressive strength at all curing ages, reaching 46.3, 59.6, 63.5, and 65.9 MPa at 7, 28, 56, and 180 days, respectively. Relative to the reference mixture, these values correspond to improvements of approximately 10.24%, 12.45%, 13.39%, and 13.62%, respectively. The consistent superiority of this mixture suggests that the combined incorporation of 2% nanosilica and 0.6% AR glass fibers may provide a favorable interaction between matrix modification and fiber reinforcement. In this combination, nanosilica is expected to improve the compactness of the geopolymer binder, while the fibers may contribute to the restriction of internal cracking and the maintenance of structural integrity under compressive loading. The effect of curing age is also noteworthy. The estimated compressive strength of the reference mixture increased from 42.0 MPa at 7 days to 58.0 MPa at 180 days, representing an increase of approximately 38.10%. For GPC2NS0.6GL, the corresponding increase was from 46.3 to 65.9 MPa, equivalent to approximately 42.33%. The higher relative strength development of the modified mixture may indicate that the combined presence of nanosilica and glass fibers provides a more favorable environment for the development and preservation of the hardened composite structure. Nevertheless, the contribution of each constituent to long-term strength development should be distinguished through appropriate statistical analysis and microstructural investigation (Oti et al., 2023, 2024). Overall, the compressive strength results suggest that the mechanical response of GGBS-based geopolymer concrete is sensitive to the combined dosage of nanosilica and AR glass fibers. Although both constituents can provide beneficial effects, their performance is controlled by an optimum dosage range. Within the investigated mixtures, the combination of 2% NS and 0.6% AR glass fibers represents the most favorable configuration for compressive strength development.

*Splitting Tensile Strength*

The splitting tensile strength is an important mechanical parameter for evaluating the resistance of concrete to tensile-induced cracking and assessing the effectiveness of fiber reinforcement. Unlike compressive loading, which is primarily governed by the load-bearing capacity and compactness of the hardened matrix, splitting tensile behavior is strongly influenced by the initiation and propagation of internal cracks, matrix–fiber interaction, and the ability of reinforcing fibers to transfer tensile stresses across developing fracture surfaces. Therefore, the combined incorporation of nanosilica and AR glass fibers is expected to influence splitting tensile strength through complementary mechanisms. The reference geopolymer concrete exhibited estimated splitting tensile strengths of 3.00, 4.20, 4.45, and 4.60 MPa at 7, 28, 56, and 180 days, respective-

ly. The increase in tensile strength with curing age follows the general trend observed in compressive strength and can be attributed to the progressive development of the geopolymeric binding matrix. As the reaction products develop, the cohesion and integrity of the hardened material improve, resulting in a greater resistance to tensile-induced crack initiation. However, the relative contribution of matrix development to tensile strength is not necessarily identical to that observed under compression because tensile failure is particularly sensitive to localized defects and the weakest regions within the specimen. Figure 4 presents the splitting tensile strength of all mixtures. (Fig. 4)

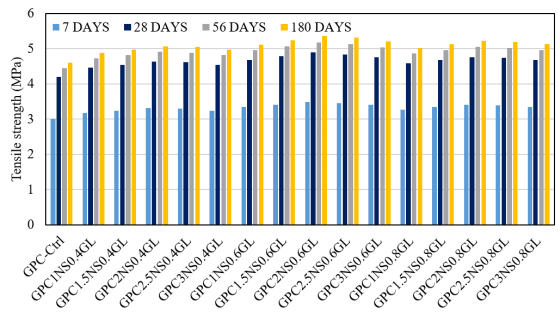



Figure 4: Splitting tensile strength of all mixtures at curing ages of 7, 28, 56 and 180 days

The addition of nanosilica generally improved the estimated splitting tensile strength, particularly when its dosage increased from 1% to 2%. For mixtures containing 0.4% AR glass fibers, the estimated 28-day splitting tensile strength increased from 4.46 MPa at 1% NS to 4.63 MPa at 2% NS. Similar improvements were predicted for the mixtures containing 0.6% and 0.8% fibers. This behavior can be explained by the potential contribution of nanosilica to matrix densification and the improvement of the interfacial region surrounding the fibers. A more compact binder matrix may enhance the mechanical interaction between the geopolymeric matrix and the reinforcing fibers, thereby facilitating stress transfer and reducing the likelihood of premature debonding. In addition, a refined pore structure may reduce the presence of critical defects that can act as preferential locations for tensile crack initiation. However, increasing the nanosilica content beyond 2% did not result in further tensile strength improvement. The estimated results indicate a slight reduction in splitting tensile strength at 2.5% and 3% NS compared with the corresponding mixtures containing 2% NS. This behavior may be associated with the increasing tendency of nanosilica particles to agglomerate when their concentration exceeds the effective dispersion capacity of the mixing system. Agglomerated particles can generate local heterogeneities and compromise the continuity of the binder matrix. Furthermore, an excessive fine-particle content may influence the fresh-state characteristics and the uniform distribution of reinforcing fibers. These effects are particularly relevant to tensile behavior because even relatively small defects can act as crack initiation sites and accelerate tensile failure. Figure 5 presents the splitting tensile strength of the mixtures at the three AR glass fiber contents. (Fig. 5)

A more pronounced influence on splitting tensile strength was associated with the incorporation of AR glass fibers. At a constant nanosilica content, increasing the fiber dosage from 0.4% to 0.6% generally improved the estimated tensile strength. For example, at 2% NS, the estimated 28-day splitting tensile strengths were 4.63, 4.89, and 4.76 MPa for the mixtures containing 0.4%, 0.6%, and 0.8% AR glass fibers, respectively. This trend highlights the importance of fiber reinforcement in improving the tensile response of geopolymer concrete. The beneficial contribution of AR glass fibers can be primarily attributed to their crack-bridging mechanism. During the development of tensile stresses, microcracks initially form within the geopolymer matrix and subsequently propagate as the applied load increases. Fibers intersecting these cracks can transfer part of the tensile stress across the crack surfaces, delay crack opening, and reduce the rate of crack propagation. Depending on the fiber–matrix bond characteris-

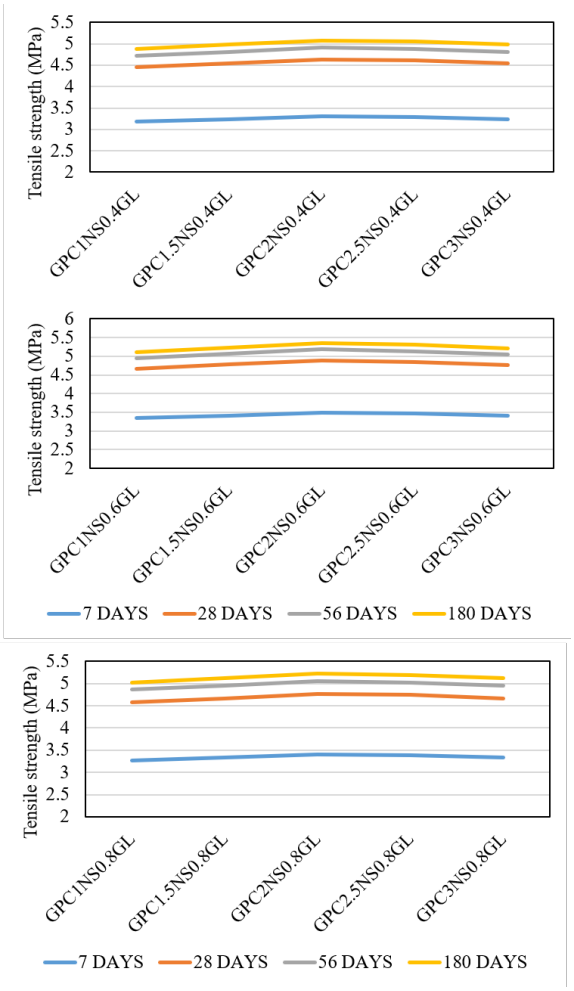



Figure5: Splitting tensile strength of the mixtures at AR glass fiber contents of 0.4%, 0.6% and 0.8% (top to bottom)

tics, this mechanism may involve fiber debonding, interfacial friction, and fiber pull-out. Consequently, the presence of well-dispersed fibers can improve the ability of the composite to sustain tensile loading after the initiation of localized cracking. The reduction in the estimated tensile strength when the fiber dosage increased from 0.6% to 0.8% indicates that the reinforcing contribution of glass fibers may be limited by their dispersion and distribution within the matrix. At higher fiber contents, fiber–fiber interactions and localized clustering may become more pronounced, potentially resulting in non-uniform reinforcement and the formation of entrapped air voids. These defects can weaken the effective matrix–fiber interface and provide preferential pathways for crack propagation. Therefore, although a higher fiber dosage increases the nominal amount of reinforcing material, it does not necessarily result in a proportional improvement in tensile strength. The results suggest that an intermediate fiber content may provide the most effective balance between crack bridging and matrix uniformity. The highest estimated splitting tensile strength was obtained for GPC2NS0.6GL, which reached 3.49, 4.89, 5.18, and 5.36 MPa at 7, 28, 56, and 180 days, respectively. Compared with the reference mixture, the corresponding improvements were approximately 16.33%, 16.43%, 16.40%, and 16.52%. These improvements are greater than those estimated for compressive strength, indicating that the combined modification of the geopolymer matrix and fiber reinforcement may be particularly beneficial under tensile loading. This difference is consistent with the expected role of fibers, which are generally more effective in restricting crack propagation and improving tensile resistance than in directly increasing the intrinsic compressive capacity of the matrix. The age-dependent development of splitting tensile strength further supports the importance of matrix maturation. The reference mixture increased from 3.00 MPa at 7 days to 4.60 MPa at 180 days, corresponding to an increase of approximately 53.33%. The GPC2NS0.6GL mixture exhibited a similar relative increase, from 3.49 to 5.36 MPa, representing approximately 53.58%. The continuous improvement over the investigated curing period can be related to the progressive development of reaction products and the resulting improvement in matrix cohesion and fiber–matrix interaction. As the binder matrix becomes more consolidated, the ability to transfer tensile stresses between the matrix and reinforcing fibers may also improve, provided that the interfacial bond remains effective. The comparison between the compressive and

splitting tensile responses provides further insight into the role of the two modifying constituents. Nanosilica primarily contributes to the refinement and densification of the geopolymeric matrix, whereas AR glass fibers provide a bridging mechanism that becomes particularly important after the formation of tensile cracks. The combination of these mechanisms can explain why the relative improvement in splitting tensile strength is higher than the corresponding improvement in compressive strength for the estimated optimum mixture. In other words, nanosilica may improve the matrix in which the fibers are embedded, while the fibers provide an additional mechanism for resisting tensile crack development. This complementary contribution is particularly relevant to the development of geopolymer concrete with improved resistance to brittle fracture.

*Comparative Assessment of Compressive and Splitting Tensile Strength*

A comparative assessment of compressive and splitting tensile strength demonstrates that the incorporation of nanosilica and AR glass fibers can potentially improve different aspects of the mechanical response of GGBS-based geopolymer concrete. The maximum estimated compressive and splitting tensile strengths were both associated with GPC2NS0.6GL, indicating that the combination of 2% nanosilica and 0.6% AR glass fibers provides the most favorable overall mechanical performance among the investigated mixtures. At 28 days, the optimum mixture exhibited estimated improvements of 12.45% in compressive strength and 16.43% in splitting tensile strength relative to the reference concrete. This difference suggests that the reinforcing contribution of AR glass fibers is more influential in tensile loading, where crack bridging and stress transfer across developing cracks play a central role. In contrast, compressive strength is more directly affected by matrix compactness, pore structure, and the continuity of the hardened binder network. The results also indicate that the optimum dosage should be determined by considering the combined effects of nanosilica and glass fibers rather than evaluating each constituent independently. Increasing nanosilica beyond 2% or increasing the fiber dosage beyond 0.6% did not provide additional improvements in the estimated mechanical performance. This finding emphasizes the importance of balancing particle dispersion, matrix homogeneity, fiber distribution, and interfacial bonding when designing high-performance geopolymer concrete. From an engineering perspective, the simultaneous improvement in compressive and splitting tensile strength is important because these properties jointly influence the structural performance of concrete elements. Higher compressive strength contributes to load-bearing capacity, whereas improved tensile resistance can delay crack initiation and propagation under service loading. Nevertheless, the mechanical benefits identified here should be interpreted alongside other performance indicators, including flexural strength, water absorption, shrinkage, and durability under aggressive exposure conditions, to establish whether the optimum mixture also provides a balanced long-term performance.

In summary, the combined incorporation of 2% nanosilica and 0.6% AR glass fibers was identified as the most promising mixture in the present estimated dataset. The observed trends provide a basis for further experimental investigation of the interaction between nanosilica-induced matrix refinement and fiber-induced crack control in GGBS-based geopolymer concrete.

## RESULTS AND CONCLUSION

•This study investigated the combined effects of nanosilica (NS) and alkali-resistant (AR) glass fibers on the mechanical performance of ground granulated blast furnace slag (GGBS)-based geopolymer concrete. Based on the comparative assessment of compressive and splitting tensile strength at different curing ages, the following

conclusions can be drawn:

•Nanosilica exhibited a dosage-dependent influence on compressive strength. Increasing the NS content from 1% to 2% generally improved the compressive performance of the investigated mixtures. This improvement can be associated with the potential filler effect of nanosilica, enhanced particle packing, and its contribution to the development of a denser geopolymeric binder structure. Nevertheless, increasing the nanosilica content beyond 2% did not provide further strength enhancement, suggesting that excessive nanoparticle incorporation may compromise the benefits associated with matrix refinement.

•The AR glass fiber content played an important role in determining the compressive response of the geopolymer concrete. Among the investigated fiber dosages, 0.6% generally provided a more favorable mechanical response than 0.4% and 0.8%. Although glass fibers primarily contribute to tensile resistance and crack control, their presence may also improve the integrity of the hardened composite by restricting the development and propagation of internal microcracks. The comparatively lower performance predicted at 0.8% may be associated with potential fiber clustering, non-uniform dispersion, and the formation of localized defects.

•The optimum estimated compressive performance was associated with the mixture containing 2% nanosilica and 0.6% AR glass fibers (GPC2NS0.6GL). This mixture achieved compressive strengths of 46.3, 59.6, 63.5, and 65.9 MPa at 7, 28, 56, and 180 days, respectively. Compared with the reference mixture, the corresponding improvements were approximately 10.24%, 12.45%, 13.39%, and 13.62%. These results indicate that the combined modification of the geopolymeric matrix and fiber reinforcement can provide a favorable contribution to compressive strength development.

•The mixture containing 2% NS and 0.6% AR glass fibers also exhibited the highest estimated splitting tensile strength. Its splitting tensile strengths were 3.49, 4.89, 5.18, and 5.36 MPa at 7, 28, 56, and 180 days, respectively. Relative to the reference mixture, these values represented improvements of approximately 16.33%, 16.43%, 16.40%, and 16.52%, respectively. The greater relative improvement in tensile strength compared with compressive strength highlights the potential importance of fiber reinforcement in improving the resistance of geopolymer concrete to tensile-induced cracking.

•From a mixture-design perspective, the combination of 2% nanosilica and 0.6% AR glass fibers represents the most promising configuration among the investigated mixtures. This combination provided the highest estimated compressive and splitting tensile strengths and demonstrated a balanced response under both loading conditions. Nevertheless, the identification of a definitive optimum mixture should also consider fresh-state workability, fiber dispersion, flexural behavior, durability, and long-term dimensional stability. The findings provide a basis for further development of sustainable GGBS-based geopolymer composites through the combined application of nanoscale modification and fiber reinforcement. Future investigations should examine the microstructural characteristics of the modified binder, particularly the distribution of reaction products, pore structure, and fiber–matrix interfacial transition zone. In addition, statistical modeling and multi-objective optimization could be employed to establish the relationships between constituent proportions and mechanical performance while considering both strength and practical mixture-design constraints. Overall, the investigated modification strategy highlights the potential of combining nanosilica with AR glass fibers to develop GGBS-based geopolymer concrete with improved compressive and tensile characteristics. The intermediate combination of 2% NS and 0.6% AR glass fibers emerged as the most favorable composition in the present estimated dataset, emphasizing the importance of optimizing the interaction between matrix modification and fiber reinforcement rather than relying solely on increasing the content of indi-

vidual constituents.

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HOW TO CITE THIS ARTICLE

Nikkhah Khajeh Ataei, H., Lork, A. & Salami, B. (2026). Enhancing The Mechanical Properties of Eco-Friendly GGBS-Based Geopolymer Concrete Through Combined Effects of Fibers and Nanosilica. (e743761). International Journal of Urban Management and Energy Sustainability, 7(2), e743761

DOI:10.22034/ijumes.2026.743761