



Strength and Durability Enhancement in Geopolymer Mortar Incorporating Nano-silica and Nano-GGBFS

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ABSTRACT

The construction sector is facing an increasing number of challenges due to the substantial carbon footprint associated with cement production, which significantly contributes to global CO₂ emissions. Geopolymer compounds are emerging as a sustainable alternative, as they reduce the necessity for cement while achieving comparable or better performance. Recent developments in the incorporation of nanomaterials into cementitious systems have demonstrated substantial improvements in microstructural densification, durability, and strength. Nanoparticles, such as nano silica (NS) and nano-GGBFS (N-GGBFS), accelerate geopolymerization, optimize pore structure, and improve the interfacial transition zone, resulting in improved mechanical and durability properties. The present research explores geopolymer mortar (GPM) and analyzes the influence of nanomaterials on its fresh and hardened properties. The inclusion of nanoparticles not only accelerated early strength development but also enhanced long-term performance by diminishing porosity and bolstering resilience to environmental degradation. The results indicate that nanomodified geopolymer mortar is a feasible, environmentally sustainable option for construction, aiding in the decrease of greenhouse gas emissions while upholding superior performance standards.

Keywords: Nano-silica; Nano-GGBFS; Sustainability; Geopolymerization; Carbon emissions; Geopolymer mortar (GPM).

1. INTRODUCTION

Portland cement is a significantly utilized construction material in the world, with an annual production of more than 4.1 billion tonnes. (Ige *et al.* 2024; Khaiyum *et al.* 2023). Nevertheless, the energy-intensive calcination of limestone and clinker manufacturing are the primary cause of approximately 8% to 9% of global CO₂ emissions, which is attributed to the production of cement (Nikolakopoulos *et al.* 2024; Barbhuiya *et al.* 2024). The demand for infrastructure, including roads, structures, and other facilities, is growing as urbanization continues to accelerate. This increased demand for construction typically results in increased cement consumption and, consequently, increased carbon emissions. The manufacture of cement consumes significant natural resources, contributes to urban heat island effects, causes environmental deterioration, and emits greenhouse gases. As a result, there is an increasing need for sustainable, alternative binder systems that can considerably reduce the carbon footprint of construction activities (Nilimaa, 2023).

Geopolymer technology has recently evolved as a viable alternative to conventional cementitious systems. Geopolymer concrete (GPC) is an ecologically friendly alternative to ordinary Portland cement concrete (Madirisha *et al.* 2024; Singh and Middendorf, 2020; Mulapeer and Omar, 2025). Geopolymers are produced by the alkaline activation of aluminosilicate-rich industrial residues such as fly ash, metakaolin, and ground granulated blast furnace slag (GGBFS), resulting in stable three-dimensional polymeric networks. These materials have equivalent or enhanced mechanical characteristics and long-term durability, accompanied by markedly reduced CO₂ emissions (Althoey *et al.* 2023; Yildirim *et al.* 2015; Cong and Cheng, 2021; Marathe and Sadowski, 2024; Perera and Ranjith, 2024).

To address these issues and enhance the microstructure of geopolymer systems, nanotechnology has been progressively utilized in cementitious and alkali-activated materials (Samuvel *et al.* 2023; Deb *et al.* 2022). Nanomaterials (NM), characterized as particles with dimensions under 100 nm, exhibit distinctive physicochemical features such as elevated surface area,

increased reactivity, and the capacity to occupy micropores within the matrix (Said *et al.* 2024). Nanomaterials in concrete and mortar are exceedingly small particles that can alter the material's structure at the microscopic level. Their use enhances strength, durability, and workability by saturating pores and accelerating the development of binding compounds. Addition of nanoparticles alters the microstructure of GPC at an atomic scale, which results in observable enhancement of the overall structural performance, without heat activation (Ahmed *et al.* 2022; Roy *et al.* 2018; Adak *et al.* 2017).

Nano silica (NS) is the most widely used nanomaterial because of highly active amorphous silica in it, which enhances secondary pozzolanic reactions and early strength (Chithra *et al.* 2016; Fallah and Nematzadeh, 2016; Rashad, 2019; Kavitha *et al.* 2024). It helps to densify the binder matrix by stimulating the production of new C-S-H gels in cement systems and N-A-S-H or C-A-S-H gels in geopolymer systems. Earlier studies have indicated an increased compressive strength, durability, and chemical attack resistance using NS-modified concrete and composite geopolymer (Mukharjee and Barai, 2020; Yang *et al.*, 2015). The introduction of NS to fly ash-based geopolymers renders the fly ash reactive. This accelerates the geopolymerization reaction and aids in bridging small gaps between particles. The fly ash and NS mutually interact and consequently, lead to a high density and stronger material due to the development of a strong, three-dimensional gel network of Si–Al–O bonds (Zhang *et al.* 2019). NS is also used to make geopolymers resistant to both heat and chemicals, thus being able to resist acids and alkalis better. Owing to these advantages, nano-silica-based geopolymers can be applied in numerous applications. They can produce stronger mortar and concrete in construction. Likewise, nano-GGBFS (N-GGBFS), the nano form of slag, possesses a high proportion of calcium, silica, and alumina similar to slag, but with a significantly smaller particle size, making it extremely reactive (Yang *et al.* 2022; Zhang *et al.* 2020). N-GGBFS accelerated the production of reaction products, optimized pore structure, and enhanced both the overall mechanical integrity and chemical resistance of the system when incorporated into geopolymer matrices (Srikanth *et al.* 2022).

The combined effect of these two nanomaterials in geopolymer mortar has not been extensively investigated, even though individual studies have highlighted the benefits of nano silica or nano slag in geopolymer systems. Because NS and N-GGBFS have different chemical compositions and reactivity, there could be possibilities of even generating a synergistic effect between them, which can provide distinct improvements in the performance, especially in early ages, water absorption, and acid resistance. Hence, the present study intends to examine the impact of NS and

N-GGBFS, either independently or combined, on the mechanical strength, workability, and durability of fly ash GGBFS-based geo polymer mortar. It helps to develop sustainable and high-performance geopolymer composites that incorporate industrial by-products and advanced nanotechnology into construction.

This present research is significant because it investigates the potential of nanomaterials such as NS and nano GGBFS for improving the performance of geopolymer mortar. There is an emerging environmental concern over the overuse of Portland cement and its carbon impact, and it is necessary to develop sustainable and high-performance alternatives. The usage of nanomaterials enhances not only the strength and durability, as well as the microstructural properties, but also provides a positive benefit regarding resource efficiency and environmentally friendly constructs. The results of this study will be beneficial towards supporting the implementation of geopolymer mortar in construction and building in real-life settings, setting forth a path towards more sustainable and longer-lasting infrastructure.

2. MATERIALS

2.1. Binders and Aggregates

The geopolymer mortar in this research study was made with Class F low-calcium fly ash supplied by MTPS, Mettur, Tamil Nadu, India, and GGBFS supplied by JSW Steel Ltd., Mecheri, Tamil Nadu, India. The binders were analyzed through X-ray fluorescence (XRF) to ascertain their chemical composition. Manufactured sand (M-sand) of Zone II grading requirements as per IS 383:2016 was used. The alkaline activator solution was produced using 98% pure sodium hydroxide (NaOH) pellets and sodium silicate (Na_2SiO_3) solution, which has a silica modulus ($\text{SiO}_2/\text{Na}_2\text{O}$) of 2.5, sourced from Astraa Chemicals, Chennai, India.

2.2. Nanomaterials

Two nanomaterials were added to the binder system, namely Nano silica and N-GGBFS. Powdered commercial nano silica was used and placed in airtight vessels to avoid moisture uptake. It was dry-dispersed in the binder by using a high-shear mixer to achieve homogenous dispersion throughout the structure and prevent agglomeration before mixing. The capability of GGBFS to withstand drying, thermal exposure, and chemical degradation renders it a highly stable and efficient binder to use for construction applications.

GGBFS was also put at room temperature by heating raw GGBFS at 800°C in an electric muffle furnace and cooling it down at room temperature over a period of 24 hours. The calcined GGBFS was subjected to further treatment in a high-energy ball mill to give N-

GGBFS. This milling process minimizes particle size to the nanometer scale, which leads to a fine nano-sized powder suitable for usage as a nanomaterial in concrete. The characteristics of NS and N-GGBFS are represented in Table 1. The samples of nanomaterials used in this research are depicted in Fig. 1.

Table 1. Physical and chemical properties of NS and N-GGBFS

Property	Nano Silica (NS)	Nano GGBFS (N-GGBFS)
Average particle size (μm)	55	90
Density (g/cm^3)	2.20	2.90
Specific surface area (m^2/g)	226	140
Purity (%)	>99	>95
SiO_2 content (%)	99.2	33.5
Al_2O_3 content (%)	0.3	13.02
CaO content (%)	—	40.30
Color	White	Light grey

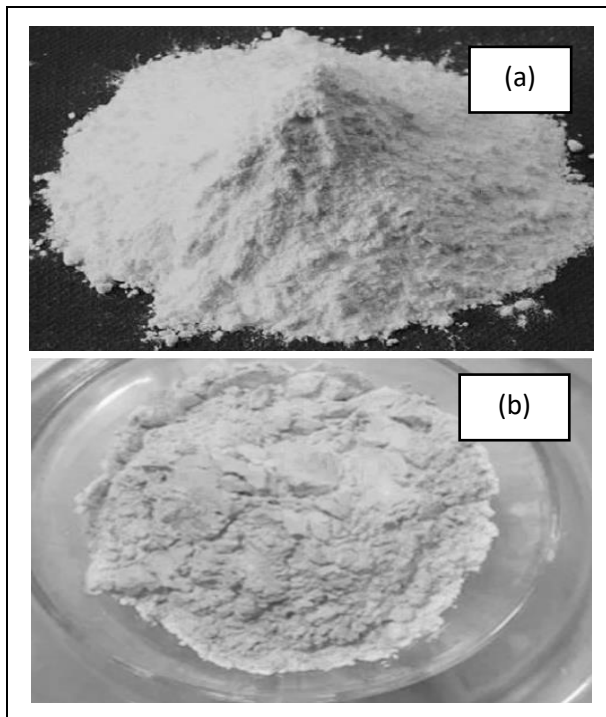


Fig. 1: Representative samples of nanomaterials used in this study: (a) NS and (b) N-GGBFS

3. MIX PROPORTIONS AND EXPERIMENTAL DETAILS

The experimental program included the preparation of a geopolymer mortar mix containing

different percentages of NS and N-GGBFS. The base binder was composed of Fly Ash and GGBFS, where the content of Fly Ash was kept constant at 70% and that of GGBFS proportionally reduced to allow incorporation of the nanomaterials. Mixes were prepared in seven different mixes, characterized as NM0 to NM6, in which Nano Silica and N-GGBFS gradually replaced GGBFS. Alkaline activator solution was composed of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), with a molarity of 12M of NaOH . Alkaline/Binder ratio was constant at 0.5, and the mortar mix ratio (Binder: fine aggregate) was constant at 1:2. The activator solution was premixed 24 hours in advance to ensure appropriate dissolution and cooling. Table 2 indicates the combination proportions along with their corresponding mix IDs.

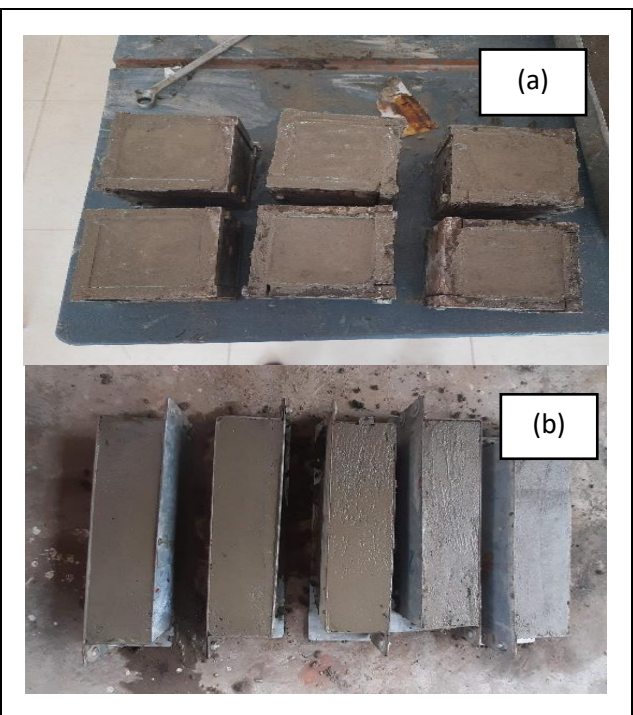


Fig. 2: Casting process for nano-modified geopolymer mortar specimens: (a) cube moulds and (b) prism moulds

Table 2. Mix proportions and corresponding mix ID

Mix ID	Fly Ash (%)	GGBFS (%)	Nano Silica (%)	Nano GGBFS (%)
NM0	70	30	0	0
NM1	70	25	0	5
NM2	70	25	1	4
NM3	70	25	2	3
NM4	70	25	3	2
NM5	70	25	4	1
NM6	70	25	5	0



Fig.3: Compressive strength testing of nano-modified geopolymer mortar specimens

3.1 Preparation and Curing of Specimens

Fly ash, GGBFS, NS, N-GGBFS, and sand were mechanically mixed in a mortar machine's mixer for 2 minutes to obtain a well-mixed mixture. The subsequent phase involved the gradual incorporation of the pre-measured alkaline activation solution, followed by mixing after an additional 3 minutes. The mortar obtained was confirmed to be homogeneous, and it was poured into the mould of 50 mm cubes. The cube molds were filled with three layers of fresh mortar, and the confined air was eliminated by compacting all the layers using a vibrating table for 30 seconds. The upper layer was trimmed off using a trowel. The specimens were covered with cling film to prevent water evaporation and left to cure at an ambient temperature of $27 \pm 2^\circ\text{C}$ over 24 hours. Upon demoulding, all the specimens were taken to an oven at 60°C for 24 hours to enhance the geopolymerization process and then subjected to laboratory conditions until testing. Fig. 2 shows the process of casting a geopolymer mortar specimen.

The compressive, flexural, and bond strength tests tested the mechanical performance of the mortar. Compressive strength (CS) was also measured to determine the structural weight supporting abilities of the mortar subject to the axial load using a 50 mm cube specimen, prepared and cured as per the IS 4031 (Part 6):1988 and ASTM C109. Flexural strength (FS), which defines how a cement mortar can resist bending or cracking when subjected to transverse loads, was determined on $40 \times 40 \times 160$ mm prism specimens in compliance with ASTM C348. The pull-off test on $50 \text{ mm} \times 100 \text{ mm}$ cylindrical specimens was utilized to assess bond strength (BS) according to ASTM C882, which differs from the direct tensile test. All the tests were carried out following the appropriate curing

periods, and the results obtained were used in the analysis.

The geopolymer mortar was subjected to durability tests that included moisture penetration and resistance to chemical attack as evaluated in a series of tests. The procedure of water absorption and sorptivity was done to test the amount of water that the mortar could absorb and its ability to carry the same through capillary movement according to ASTM C642 and ASTM C1585, respectively. Fig.3 illustrates the test findings of the compressive strength test, whereas Fig.4 displays oven-dried, nano-modified geopolymer mortar specimens before the water absorption test.



Fig. 4: Oven-dried specimens before water absorption test

4. RESEARCH FINDINGS

4.1 Setting Time of Nano-Modified Geopolymer Mortars

The setting time values indicate that incorporation of NS and N-GGBFS plays a substantial role in the reactivity of the geopolymer mixes. The control mix NM0 was recorded at 128 minutes and 220 minutes for its initial and final setting times. The addition of nano additives resulted in a consistent increase in both the initial and final setting time. The 5% N-GGBFS (mix NM1) exhibited lower setting times of 116 minutes and 207 minutes, as represented in Fig.5. As NS content was raised to NM6, setting times decreased further, with the quickest reaction at NM6, with initial and final times of 87 minutes and 160 minutes, respectively. This tendency affirms that because of its high surface area and reactive pozzolan, NS is faster in geopolymerization as it introduces more nucleation sites (Phoo-ngernkham *et al.* 2014). Although this accelerated set has a beneficial effect of improving early strength development and shortening the construction time, a very rapid one, such as that observed in NM6, can impact workability and species of handling. Hence, it is significant to balance the

NS materials so that one both performs well in addition to the workability factor as well.

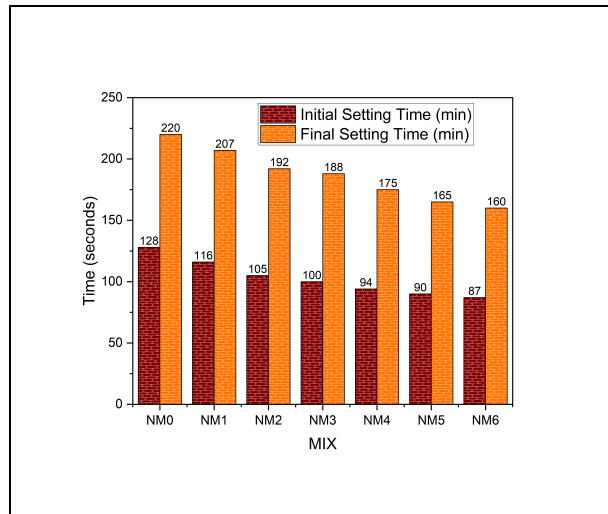


Fig. 5: Setting time of various GP mortar mixes

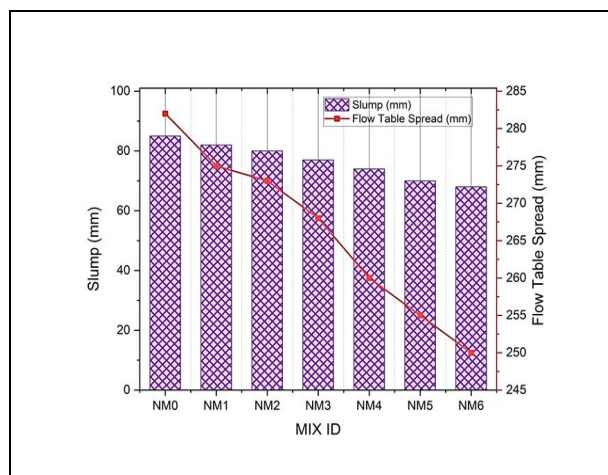


Fig. 6: Slump and flow values of nano-modified GP mortars

4.2 Fresh State Properties

The workability of the GPM mixtures decreased gradually as the quantity of NS and N-GGBFS was increased. Control mix (NM0) demonstrated the maximum slump value of 85 mm, and the greatest flow spread of 280 mm, which signified high flow capacity and comfort of placement. The slump and flow table spread declined with a rise in nano additive content, of which the slump dropped to 68 mm and flow table spread dropped to 250 mm, at NS replacement rate of NM6 as seen in Fig. 6. This workability is primarily impeded by the nanomaterials' large specific surface area and fine particle size, which increase the viscosity of fresh mortar and the water demand (Regalla and Kumar, 2025; Gao *et al.* 2015). Further, the smaller particle size of NS than N-GGBFS is expected to exert a greater influence on flowability suppression, as reflected in mixes with more

than half NS content (NM4-NM6) (Si *et al.* 2025). Nevertheless, each of these mixes demonstrated sufficient workability for casting and compacting without indicating segregation or bleeding.

4.3 Mechanical Properties of Nano-modified GP Mortars

Nanomaterials addition in geopolymer mortars enhances the mechanical behaviour through the microstructure and densification of the matrix. These properties are used to assess the efficiency of the structure and overall performance of nano-modified GPM. Table 3 illustrates the overall improvement in the mechanical performance of nano-modified GPM relative to that of the control mix.

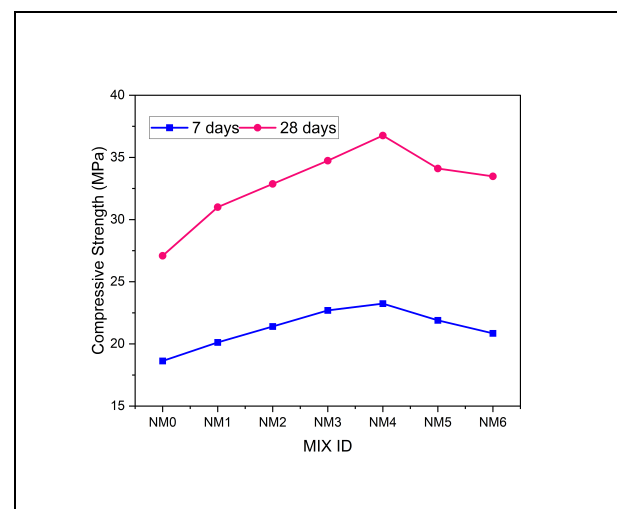


Fig. 7: Compressive strength of nano-modified GP mortars

Table 3. Mechanical performance of nano-modified GP mortars

Mix ID	Compressive Strength (MPa)		Flexural strength (MPa)	Bond strength (MPa)
	7 Days	28 days	28 days	28 days
NM0	18.63	27.09	4.23	2.10
NM1	20.12	31.00	4.70	2.56
NM2	21.40	32.87	4.95	2.82
NM3	22.70	34.74	5.06	3.15
NM4	23.24	36.76	4.98	3.92
NM5	22.90	34.11	4.82	2.94
NM6	21.85	33.48	4.77	2.25

4.3.1 Compressive Strength (CS)

The CS of the GPM showed a consistent improvement with the inclusion of NS and N-GGBFS up to an optimal dosage. At 7 days, strength increased from 18.63 MPa for the control (NM0) to 23.24 MPa for NM4, while the 28-day values increased from 27.09 MPa to 36.76 MPa over the same range. This enhancement can

be ascribed to the pozzolanic reactivity of nanoparticles, which promotes the formation of additional geopolymer gels, and the filler effect of nanoparticles, which increases the packing density (Li *et al.* 2023; Phoo-ngernkham *et al.* 2014). The optimal performance at NM4 suggests a balanced contribution from nano silica's high surface reactivity and nano GGBFS's latent hydraulic properties. A slight decline in strength is noticed beyond this dosage (NM5, NM6), which is likely the result of an increase in water demand and the agglomeration of nanoparticles. This could potentially impede the complete geopolymerization process (Raj *et al.* 2023).

4.3.2 Flexural Strength (FS)

The FS of the geopolymer mixes increased with the incorporation of NS and N-GGBFS in comparison to the control mix. The lowest strength of 4.23 MPa was measured on the control mix NM0, whereas the modified mixes tested higher. The strength was progressively built up between NM1-NM3, where NM3 obtained the highest value as measured at 5.06 MPa, as illustrated in Fig.8. This development can be attributed to the NS contribution in improving the pore structure through refinement, enhancing particle packing, and strengthening the matrix-particle bonding, enabling the composite to be better able to resist bending stresses (Phoo-ngernkham *et al.* 2014; Ridha and Yerikania, 2015). There was a marginal reduction in strength after NM3, NM4, NM5, and NM6, although the values were still greater than the control. The lower values at higher NS contents could be attributed to particle agglomeration and diminished workability since improvement could not be achieved further. These findings show that the NS content that yields the highest FS is found in mix ID NM3.

4.3.3 Bond Strength (BS)

The BS of the mixes indicates that adding NS and N-GGBFS increases the performance over the control mix. The control mix, designated as NM0, exhibited the lowest bond strength value of 2.10 MPa. The presence of nanomaterials increased the strength gradually until the NM4 showed the highest strength of 3.92 MPa, as shown in Fig. 8. The enhancement is a result of the small grains of NS caused by filling the pores, thus making a denser matrix, hence enhancing adhesion between the aggregate and the paste (Wang *et al.* 2019). However, upon further increases in NS content in NM5 and NM6, the bond strength began to reduce to 2.94 MPa and 2.25 MPa, respectively. This decrease at higher concentrations can be attributed to a lack of dispersion when excess NS is added, leading to agglomerates and lower workability. These findings indicate that NM4 produces the best NS proportion to attain optimum bond strength in the mixes.

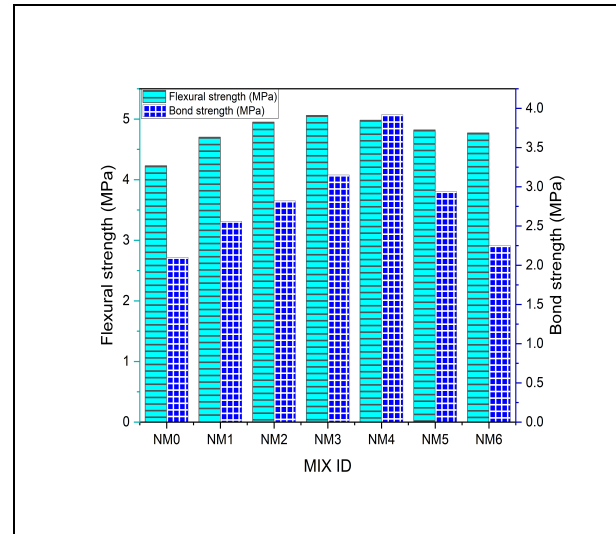


Fig.8: Bond strength and flexural strength performance of nano-modified GP mortars

4.4 Durability Performance of Nano-modified GP Mortars

Water absorption and sorptivity tests were used to investigate the durability of nano-modified GPM. Such tests help determine the mortar's capacity to absorb water and the rate at which it is absorbed into the material. Table 4 shows the results of both tests.

Table 4. Durability results of GPM mixes

Mix ID	Water Absorption (%)	Sorptivity (mm/ $\sqrt{\text{min}}$)			
		1 min	5 min	30 min	60 min
NM0	4.82	0.235	0.210	0.185	0.172
NM1	3.24	0.218	0.196	0.172	0.160
NM2	2.92	0.210	0.190	0.165	0.154
NM3	2.58	0.202	0.183	0.160	0.149
NM4	2.35	0.198	0.179	0.156	0.146
NM5	2.44	0.201	0.182	0.159	0.148
NM6	2.72	0.205	0.185	0.162	0.150

4.4.1 Water Absorption

The outcomes clearly indicate that the addition of NS and N-GGBFS is seen to decrease the water absorption capacity of geopolymer mixes relative to the control. The highest absorption of 4.82 percent was recorded in the control mix NM0, and this indicates a porous matrix. As the nano materials are added, the water absorption decreased gradually, with the lowest rate in NM4, at 2.35 percent. Such a significant decrease can be justified by the micro-filling effect of NS filling the capillary pores, and by the high pozzolanic reactivity, which forms additional gel phases condensing the matrix (Çevik *et al.* 2018). Consequently, fewer pathways allow water to infiltrate. In NM6 and NM5, however, where the NS concentration was higher, there is a slight increase to 2.44% and 2.72%, respectively. This is possibly due to

the agglomeration of particles and reduced dispersion with higher dosages, which can lead to local weak areas and poor workability during mixing.

4.4.2 Sorptivity

A similar tendency is noted in the sorptivity measurements as in water absorption. The control mixture NM0 recorded the highest sorptivity at all time durations; The values ranged between 0.235 mm/ $\sqrt{\text{min}}$ and 0.172 mm/ $\sqrt{\text{min}}$ at 1 minute and 60 minutes respectively, as illustrated in Fig.9. Such a high sorptivity indicates that the mix is more likely to suck the water in by capillary suction since it is porous (Deb *et al.* 2016). Conversely, NM4 exhibited the lowest sorptivity values, with the nano-modified mixes performing consistently across all mixes. The decreased sorptivity in NM4 indicates that the capillary pore system was substantially refined, thereby reducing the velocity of water entering the mix. At higher NS levels, the sorptivity values of NM5 and NM6 were slightly raised compared to those of the control, but lower than those of NM4. It was concluded that the detrimental impact of excessive NS, which may aggregate rather than disperse uniformly, thereby diminishing its efficacy in refining the pore structure.

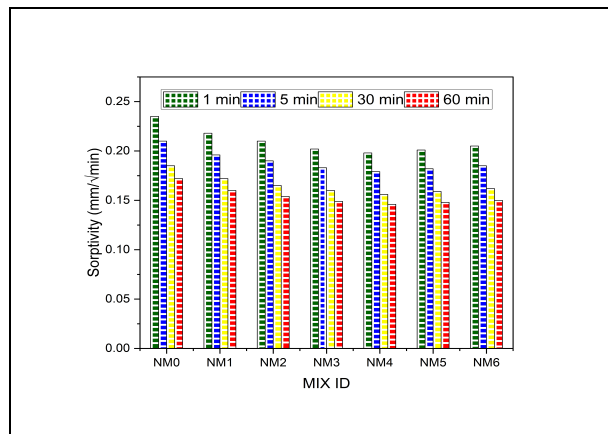


Fig.9: Variation in sorptivity of nano-modified GP mortars

4.5 SEM Morphological Studies

SEM micrograph of the NM4 at 28 days had a dense and compact microstructure, as illustrated in Fig. 10, wherein there were many fewer pores visible relative to those of the control mix. The matrix showed a continuous gel phase, which mostly consisted of sodium aluminosilicate hydrate (N-A-S-H) gel. However, the calcium aluminosilicate hydrate (C-A-S-H) phases are also observed as a result of a synergistic reaction between GGBFS and nano silica. The presence of the nano additives simulated the nucleation sites, which drove geopolymerization, sped up the rate of formation of other gel products that blocked microvoid spaces, and optimized the pore structure (Khater, 2016; Rodríguez *et*

al., 2013). Fly ash particles, which had not reacted, were very few and were spread inside the gel matrix, meaning that they had responded well and were well-bonded to the other phases. The morphology also incorporated reduced microcracks, which implies reduced shrinkage sensitivity and fostered structure. This enhanced microstructure contributes to the improved overall properties of NM4, where the highly permeated gel network limits the penetration of aggressive substances (Lo *et al.* 2017).

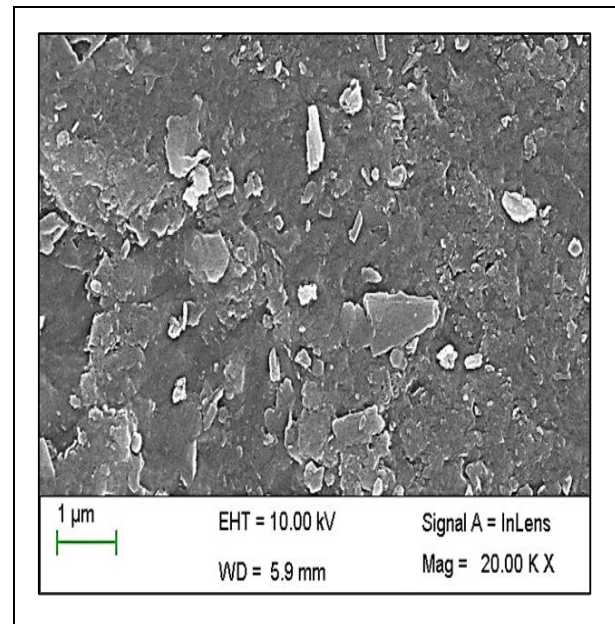


Fig. 10: SEM image of Nano-GPM NM4 mix

5. CONCLUSIONS

Based on the experimental research of nano-modified GP mortar, the following inferences were drawn;

- The performance of geopolymer mortar was significantly improved by the addition of Nano-Silica (NS) and nano-GGBFS.
- A small reduction in slump and flow table values was observed with the addition of NS and N-GGBFS, which is attributed to their large surface area, increasing water demand. Still, the mixtures were manageable and within reasonable parameters. Both NS and n-GGBFS improved strength at all curing ages in comparison to the control mix. The enhancement resulted from expedited geopolymerization and the generation of supplementary binding gels.
- The optimal dosage of NS and N-GGBFS resulted in nearly a 35% increase in strength compared to the control mix. The NM 4 mix, containing 3% NS and 2% N-GGBFS, exhibited the best compressive strength of all the mixes evaluated.

- The flexural strength increased, validating the improved microstructural bonding and crack-bridging capabilities of nano-silica and nano-GGBFS, which collectively facilitate denser gel formation and superior stress distribution within the matrix.
- SEM analysis demonstrated that NS and n-GGBFS enhanced the pore structure, resulting in reduced porosity and a denser matrix.
- The mortar exhibited decreased voids and enhanced interfacial adhesion between the paste and particles.
- Durability tests demonstrated an enhancement in water absorption and sorptivity, indicating a decrease in porosity and improved refinement of the pore structure.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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