



Effect of Nano-silica on the Performance of SBA-based Geopolymer Concrete

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ABSTRACT

Geopolymer concrete (GPC) is becoming a widely-known sustainable replacement of conventional cement-based materials. The advantage of nano-silica (NS) addition is further increased through the pore structure, reaction rate of the geopolymer and overall compactness of the matrix. The primary binders in this study were fly ash, Ground Granulated Blast Furnace Slag (GGBFS) and Sugarcane Bagasse Ash (SBA). Nano-silica was added with different proportions of 0% to 3.5% to test its effects on the performance of GPC. Eight mixes were prepared with a 12 M NaOH-based alkaline activator and experiment was performed to determine the workability, strength development, water absorption, and chloride permeability. The results showed that the compressive strength was enhanced up to 2.5 % NS content with the highest mechanical strength being recorded by A-6 mix. The durability results show reduced water absorption and improved resistance to chloride penetration for the optimum mix (A-6). The SEM micrographs revealed a lower porosity and better gel formation which confirmed the fact that the optimum mix had a better microstructure. The findings indicate NS can substantially enhance the strength and durability of SBA-based GPC.

Keywords: Nano-silica; Fly ash; Sugarcane bagasse ash; Porosity; Microstructure; Geopolymer concrete.

1. INTRODUCTION

The most extensively used construction material in the world is concrete although its major constituent, Portland cement (PC) presents serious environmental threats (Shivaprasad *et al.* 2024; Huntzinger and Eatmon, 2009). The manufacturing process of PC is linked to a large amount of carbon dioxide emission, large energy usage, and consumption of natural resources (Ali *et al.* 2011 and Aïtcin, 2000). As the level of CO₂ and the sustainability issues are increasing, researchers are demanding alternative materials to reduce the ecological footprint of construction (Althoey *et al.* 2023). The future is seen in GPC which is an alkaline, aluminosilicate binder produced by activating cement with alkaline solutions, rather than cement (Law *et al.* 2014). It is not based on cement hydration but rather it is produced by the alkaline activation of aluminosilicate products to form a binding gel without cement. Further, GPC provides some benefits as compared to the concrete cement including hinge carbon emission, high initial strength and durability in case of chemical exposure and exposure to high temperatures. The industrial by-products used in most geopolymer formulations include fly ash available in thermal power plant and GGBFS available in steel industries (Ojha and Aggarwal, 2021; Zerfu and Ekaputri, 2016).

These are reactive silica and alumina-based materials which can be used as desirable precursors to the

geopolymerization process as well as help resolve the problem of disposing industrial waste (Zhang *et al.* 2024). Nevertheless, the use of fly ash and GGBFS cannot be very sustainable in the long-term perspective because of possible fluctuations in their supply caused by the fluctuations in power production and industrial activity (Singh, 2018). To better enhance the sustainability and minimize reliance on industrial by-products, recent studies have been done on the use of agricultural wastes like SBA as the supplementary aluminosilicate precursors. The sugar industry produces SBA in large amounts which is usually discarded in open lands posing a problem to the environment (Rihan *et al.* 2024). There are two environmental advantages to using SBA in the construction of concrete in that it not only decreases the agricultural waste but also decreases the number of conventional precursors required. (Athira *et al.* 2020; Kathirvel *et al.* 2020; Murugesan *et al.* 2020). Nevertheless, raw SBA is usually distinguished by high carbon and particle size variability as well as crystalline impurities. These cause effect on the reactivity and may even obstruct the process of geopolymerization unless the ash is well processed by controlled burning or grinding (Prabhath *et al.* 2022).

In order to overcome these drawbacks and improve the microstructure, researchers have started to use nano-materials. Nano-silica is one of the most effective nanomaterials since it has ultra-fine size (range of 1-100 nm), significant specific surface area, and

amorphous silica phase (Chiranjeevi *et al.* 2023; Mustakim *et al.* 2020). The utilization of NS in GPC has attracted attention due to the capability to improve the reaction mechanism and the microstructure of the material. Due its high surface area and fine particle, which assists in accelerating the geopolymerization and enhancing the creation of continuous and dense gel network. It can be used to fill micro-voids and supplement reactive silica as well as speed up the creation of the geopolymer gel due to its very fine particle size and high reactivity; consequently, its addition increases the level of densification of the matrix, refinement of pore structure, minimization of voids and better interfacial transition zone (ITZ) properties. These microstructural advancements result in increased compressive strength (CS), low permeability, high chemical resistance and general high strength (Rahmawati *et al.* 2021; Sharif, 2021; Shilar *et al.* 2022).

Even though the SBA-flyash-GGBFS-based GPC is a sustainable alternative, the strength and durability of the material remain to be determined by the effectiveness of the binder reaction and the increase in density of the final matrix. The reaction is also slow in most instances, the internal structure is porous as well, thus limiting performance. Nano-silica can overcome these problems, accelerate the reaction and close the micro-voids, and enhancing the gel development. Nevertheless, the precise effect of NS in this blended geopolymer is yet to be clear. Experimental studies demonstrating the effect of varying dosages of NS on the workability, strength, and durability are lacking when the NS is utilized along with SBA, fly ash and GGBFS. Due to this discrepancy, there is a need to examine the effect of NS in enhancing the overall performance of this geopolymer concrete and to determine the most appropriate quantity that should be used to increase the performance.

2. CONSTITUENT MATERIALS AND METHODS

This study developed GPC mixes using a combination of industrial by-products, agricultural waste, nano-materials, aggregates and alkaline activators. Prior to use, all the materials were stringently tested and checked for their suitability.

2.1 Fly Ash

Class F fly ash was used as one of main sources of aluminosilicate. It was sourced from a thermal power station and had a texture that was fine and powdery with high silica and alumina. The presence of amorphous phases in fly ash helps in the formation of the Sodium–Alumino–Silicate–Hydrate (N-A-S-H) in geopolymerization. The particles had spherical shape, and it offered an improved workability and the contribution to improved flow characteristics of the fresh mix.

2.2 Ground Granulated Blast Furnace Slag (GGBFS)

Ground granulated blast furnace slag has been obtained from a steel manufacturing plant. It contained a high percentage of calcium which helped in the development of early strength in the GPC. The finely ground slag was pale off-white in colour and had a high reactivity. When used in combination with fly ash, GGBFS enhanced both the mechanical strength and durability performance because of formation of additional calcium aluminosilicate hydrate (C-A-S-H) gel.

2.3 Sugarcane Bagasse Ash (SBA)

Sugarcane bagasse ash was collected from local sugar industry. The SBA was obtained through controlled burning at about 600°C and ground to attain the desired fineness. Before use, the ash was sieved and processed to remove impurities and larger unburnt particles. It contains a high silica in amorphous form, and thus can be used as a partial addition of fly ash and slag. Incorporating SBA supports recycling of waste and lesser pollution to the environment.

2.4 Nano-silica

Commercially available NS powder was used for the improvement of microstructure of GPC. The NS had very small particle sizes (usually <100 nm) and very high surface area (180–220 m²/g). Its addition improves the reaction rate, fills up the micro-voids and promotes the formation of a dense and refined geopolymer matrix. It also toughens the ITZ, which leads to better properties of GPC. The chemical analysis of fly ash and GGBFS was carried out based on the ASTM C618, respectively. Characteristics of the binders are outlined in Table 1. Fig. 1 exhibits the material samples of SBA and NS.

Table 1. Characteristics of binders

Binders	Specific Gravity	Fineness (m ² /kg)	Major Oxides (%)
Fly Ash (Class F)	2.21	315	SiO ₂ -54.36; Al ₂ O ₃ -27.60; Fe ₂ O ₃ -10.08
GGBFS	2.83	426	CaO -38.07; SiO ₂ -33.67; Al ₂ O ₃ -13.70; MgO -8.84
SBA	2.18	274	SiO ₂ -62.10; Al ₂ O ₃ -5.65; CaO- 3.20
NS	2.12	—	SiO ₂ - 96.56

2.5 Aggregates

Clean river sand, conforming to Zone II of IS:383 was exploited as fine aggregate. The sand was not contaminated with silt, clay, and organic matter. It has been well graded, which helped to achieve good workability and packing density.

Crushed angular coarse aggregates of 10 mm sizes were used in a suitable proportion. The aggregates were clean, dry, and free from dust and deleterious materials. The angular shape provided better interlocking and enhanced the overall strength of the GPC. Characteristics of both aggregates are listed in Table 2.

Table 2. Characteristics of aggregates

Property	Coarse Aggregate	Fine Aggregate
Fineness Modulus	6.80	2.74
Specific Gravity	2.70	2.59
Bulk Density (kg/m ³)	1687	1470

2.6 Alkaline Activator Solution

The NaOH solution was prepared using solid NaOH flakes of 98 % purity. The solution was made 24 hours before. NaOH solution was added to commercial sodium silicate immediately before preparation of concrete. All mixes were maintained at the same Na₂SiO₃ to NaOH ratio in order to ensure similar activation.

2.7 Water

The alkaline solution was prepared with potable tap water that had no impurities, oils, or organic contaminants and used to regulate the workability of the mixes.



Fig. 1: Sample of (a) SBA and (b) Nano-silica

The experimental programme was aimed at the production of M30-grade GPC in the presence of 12 M NaOH solution as the main activator. All the binder materials, fly ash, GGBFS, SBA and NS were dried, sieved and homogenised and then mixed. A ratio of 2.5 (Na₂SiO₃:NaOH) was maintained. The total solution/binder ratio was kept at 0.45 and the dry materials were mixed first to a uniform mixture, followed by a gradual addition of the prepared activator solution. Preparation of all eight mixes was conducted in the same process, to make it uniform across the study. The moulds were packed in two layers and compacted using gentle vibrations to eliminate air pockets. The specimens were

allowed to remain undisturbed after 24 hours at room temperature and thereafter demoulded with care. After demoulding, all the samples were put in a controlled curing environment so that geopolymerization process could be allowed to fully develop.

After curing, the GPC specimens were tested on various strength and durable performances. The CS was determined in compliance with IS 516:2018, split tensile strength (STS) according to IS 5816:1999, and flexural strength (FS) according to IS 516 Part 2:2021. The water absorption (WA) was calculated based on ASTM C642, and Rapid Chloride Permeability Test (RCPT) was carried out based on ASTM C1202. The mix combinations of NS modified mixes are represented in Table 3. Fig. 2 illustrates the specimen preparation and the key tests conducted in the study, comprising casting, strength measurement, and durability assessment.

Table 3. Mix combinations

Mix ID	NS (%)	GGBFS (%)	Fly Ash (%)	SBA (%)
A-1	0.0	30	50	20
A-2	0.5	30	50	20
A-3	1.0	30	50	20
A-4	1.5	30	50	20
A-5	2.0	30	50	20
A-6	2.5	30	50	20
A-7	3.0	30	50	20
A-8	3.5	30	50	20

3. RESULTS AND DISCUSSION

3.1 Workability Test

The slump values of all the mixtures were between 52 and 78 mm (Fig. 3). It was observed that there was a substantial decrease in depression as the NS content increased to 3.5%. This reduction has been mainly due to the high level of minute particle size of the NS leading to a larger surface area requiring more water to be used in its lubrication (Belkowitz *et al.* 2015). The mixtures that had the highest value of slump included A-1 (0% NS) with its highest value being 78 mm and A-8 (3.5% NS) with its lowest value being 52 mm. The good slump value of mix A-6 (2.5% NS) was 60 mm and is within the range of workable slump values.

3.2 Mechanical Strength Test

Mechanical strength tests were used to evaluate the performance of the NS-based GPC mixes. The results of these experiments on all eight mixes are presented in Table 4.

Table 4. Mechanical properties of NS modified blends

Mix ID	CS, (MPa)			STS, (MPa)		FS, (MPa)	
	3 d	7d	28 d	7 d	28 d	7 d	28 d
A-1	18.65	26.40	34.20	2.04	3.60	4.82	5.90
A-2	19.80	27.91	36.10	2.17	3.75	5.04	6.10
A-3	21.04	29.33	38.44	2.28	3.89	5.25	6.35
A-4	22.42	31.01	40.70	2.40	4.03	5.50	6.57
A-5	23.15	32.25	42.53	2.52	4.15	5.73	6.68
A-6	24.63	34.14	45.31	2.64	4.31	5.90	6.75
A-7	23.80	33.00	43.13	2.55	4.20	5.74	6.60
A-8	22.92	31.84	41.24	2.47	4.13	5.61	6.45

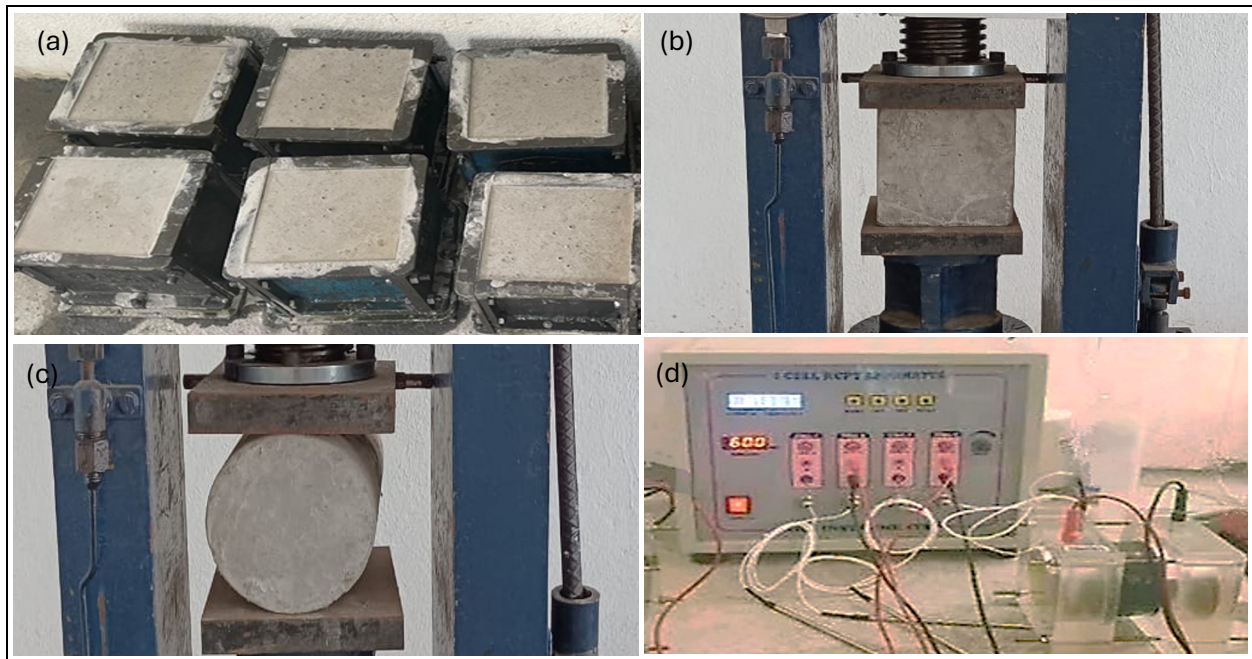
3.2.1 Compressive Strength

The CS results for all eight mixtures exhibited the predicted progressive increase with curing age, which indicates the occurrence of geopolymerization and matrix formation. The 3-day strength was fluctuated from 18.65 MPa to 24.63 MPa, whereas the 7-day strength ranged between 26.40 MPa and 34.14 MPa. At 28 days, the mixes had strengths of between 34.20 Mpa to 45.31 Mpa. The increase of strength on increasing NS content (Mix A-1 and A-6) proves the positive impact of NS on geopolymer matrix. Nano-silica improves early dissolution of aluminosilicate sources and formation of a denser gel structure, which leads to improved bonding and reduced pore spaces (Kavitha *et al.* 2024). The CS of the optimum mix (A-6) was 32.48% higher than that of the control mix (A-1).

The optimum amount of NS addition was found in Mix A-6 with the highest 28-day strength of 45.31 Mpa. At a higher concentration (mixes A-7 and A-8), the strength slightly diminished, possibly because more water was required and excess NS might be agglomerated to impede the formation of uniform gels. The findings overall validate the fact that the controlled additions of NS have a profound positive effect on the compressive behaviour of GPC.

3.2.2 Split Tensile Strength

The STS showed a progressive increase with the addition of NS until 2.5% showing a steady increase in the tensile resistance of the material. Across all mixes, the 28-day tensile strength was observed to be within the range 3.60 MPa to 4.31 MPa, which indicates that NS has a significant effect in increasing the crack resisting capacity of the produced concrete. The control mix (A-1) had a strength of 3.60 MPa over a period of 28 days and the optimum mix (A-6) had a strength of 4.31 MPa, which is a significant improvement. This enhancement can be ascribed to the ultra-fine nature of NS which leads to enhanced matrix densification, improved ITZ and enhanced stress transfer under splitting load. A slight decrease for A-7 and A-8 indicated that a higher NS dosage can result in agglomeration of particles and diminishing workability, which in turn affects tensile strength development. Overall, 2.5% NS gave the best efficiency and confirmed that it is the optimum level for this geopolymer system.

**Fig. 2: (a) Casting of cubes; (b) CS testing; (c) STS testing and (d) RCPT**

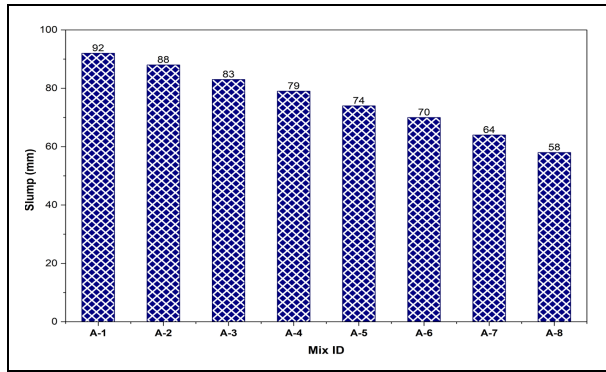


Fig. 3: Test findings on slump cone test

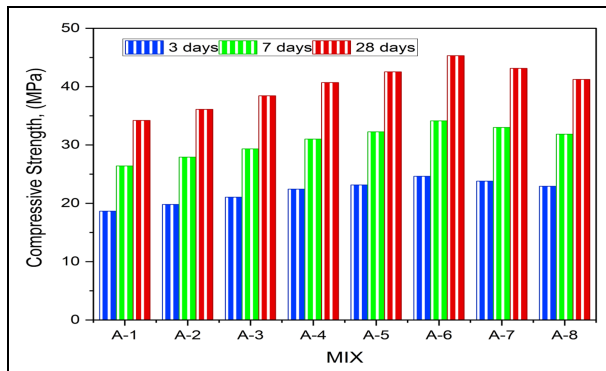


Fig. 4: CS performance of the various mix combinations

3.2.3 Flexural Strength

The FS results clearly show a good improvement with the increase in the content of NS up to 2.5% and then the values start to slightly decrease. Across all mixtures, the 28-day FS was in the range 5.90 to 6.75 MPa, which suggests the NS contributed an important role in improving the resistance of the concrete to bending.

The control mix A-1 showed an FS of 5.90 MPa at 28 days and optimum mix A-6 showed the highest value of FS which is 6.75 MPa, as depicted in Fig. 5. This enhancement is largely attributed to the fine particle size of NS, which fills up micro-voids, promotes matrix compaction and strengthens the interfacial transition zone of aggregates. These effects have a combined effect on enhancing the material's capacity to withstand tensile stresses in the flexural plane.

Slight decreases in flexural performance were found for A-7 and A-8. At higher values of NS dosages, the tendency towards agglomeration and decreased workability of the particles may affect the proper dispersion of the particles, resulting in somewhat lower values of FS. Overall, the results confirm that the use of 2.5% NS gives the best enhancement in flexural behaviour for this GPC system.

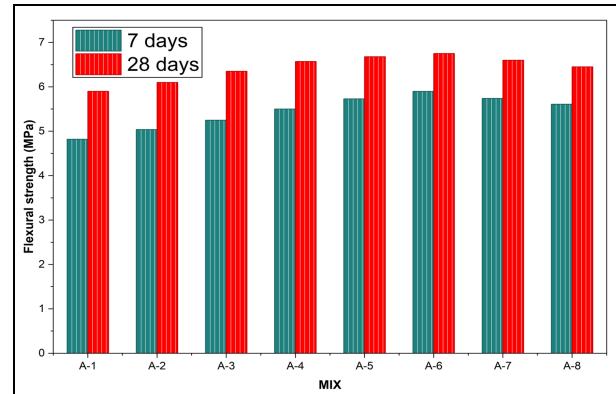


Fig. 5: FS performance of the various mix combinations

3.3 Durability Assessment

3.3.1 Water Absorption Performance

The results of the WA indicate a steady decline in the WA with an increase in the NS content of all the mixes as depicted in Fig. 6. A-1 control mix had the highest absorption at 5.82% which is more porous. The more NS was added, the lower the absorption became because of the small particle size and high reactivity of NS used that help to fill micro voids and create denser geopolymer structure (Mansourghanaei *et al.* 2022).

The decrease was further high in mixes A-5 to A-8 with the lowest mix being A-8 at 4.07. This tendency shows that the larger contents of NS make pore network finer, increase packing density, and decrease interconnected voids that take in moisture. The findings concluded that NS is very effective in decreasing permeability of GPC, and the lowest WA was recorded at 3.5% NS (A-8). This implies that there is improved durability performance in regard to moisture resistance.

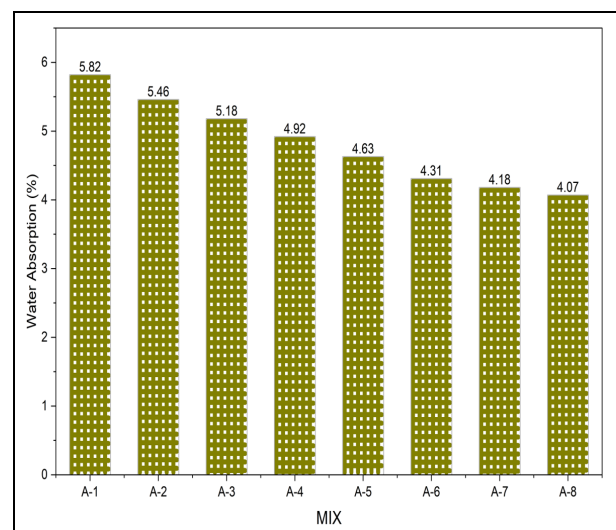


Fig. 6: Variation in WA among the prepared specimens

3.3.2 Assessment of Chloride Ion Permeability

The results of RCPT indicate that there is a gradual decrease in the charge passed with increasing NS content, which implies gradual increase in chloride resistance as shown in Fig.7. The charge passed at 30 days decreased to 1728 C in A-7 compared to 2380 C in the control mix (A-1) indicating that NS highly refines the pore structure and limits the movement of ions. This was also the same trend at 90 days where the values decreased between 1740 C (A-1) and 1194 C (A-8) which is the long-term improvement of continued geopolymerisation.

Notably, the lowest value of 30-days was observed in A-7 and that of 90-days in A-8 implying that, the NS level is more effective at the later ages. It is possible that this lagging performance benefit is due to the slow secondary reactions between NS and aluminosilicate gels, which enhance the further densification of the matrix as time goes on.

Generally, the findings validate the presence of NS in the reduction of chloride permeability. Despite the fact that A-6 is the optimum mix exhibited by mechanical strengths, RCPT results reveal that A-7 and A-8 have better long-term resistance thus a positive impact of increased NS content in particular to the durability. According to ASTM C1202, the all NS-mixtures have moderate to low chloride permeability.

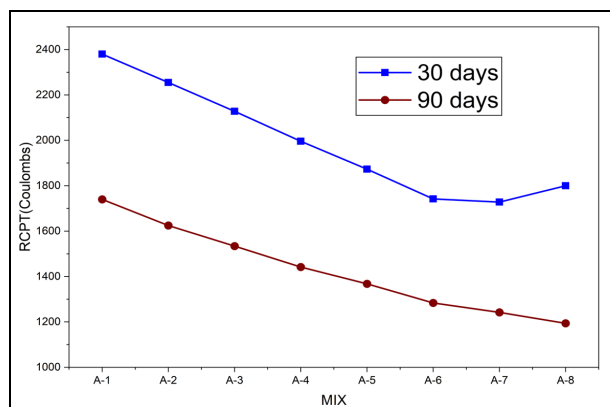


Fig. 7: Results on RCPT

3.4 Morphological Features

The scanning electron microscopy (SEM) of the optimum composition of geopolymer (A-6) with NS indicates a well-reacted and densely packed structure which is characteristic of accelerated kinetics of geopolymerization as shown in Fig. 8. The micrograph represents very tight layers with significantly less porosity which indicates that NS actively participated in the reaction and helped to fill the micro-voids. The plate-like structures and cohesive gel prove the creation of N-A-S-H gel that is essential in binding and supporting the

geopolymer network (Shivasakthivadivelan *et al.* 2025). Furthermore, there are small spherical unreacted or partially reacted NS particles that also lead to densification of the matrix further. It is concluded that the microstructure of A-6 has a highly refined, stable, and compact structure of geopolymer matrix which supports the high CS and durability in this mix. The enhancement was largely attributed to the capability of NS to occupy the micro-pores and accelerate the geopolymerization reaction. The SEM image of A-6 mix supported this as the mix had a compact and well-bonded matrix with fewer voids and a continuous gel structure. The findings validate that NS improves the matrix quality of GPC, resulting in a stronger, denser, and more durable material relative to the control mix.

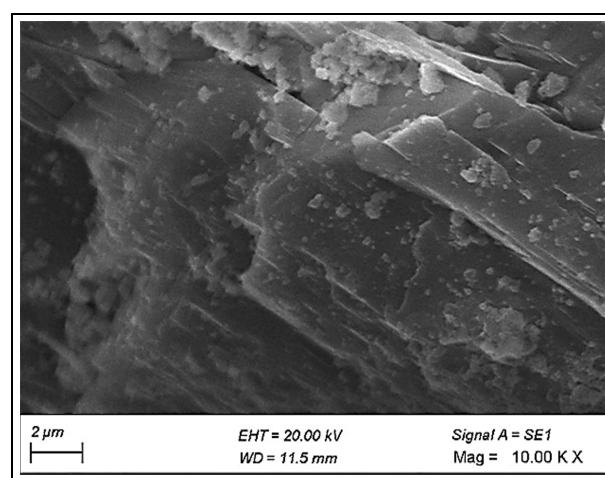


Fig. 8: SEM analysis on A-6 MIX (NS 2.5%)

4. CONCLUSIONS

This study demonstrated that the incorporation of nano-silica significantly enhances the strength, matrix quality, and durability of geopolymer concrete. Increasing nano-silica content led to a denser and more refined microstructure, resulting in improved compressive, split tensile, and flexural strengths. The mix containing 2.5% nano-silica (A-6) exhibited the highest mechanical performance, while the 3.5% nano-silica mix (A-8) showed superior durability, evidenced by reduced water absorption and enhanced resistance to chloride penetration. These improvements are mainly attributed to the pore filling effect of nano-silica and its ability to accelerate the geopolymerization process, which was further confirmed by SEM analysis showing a dense, well bonded matrix with minimal voids. Overall, the results confirm that nano-silica improves the structural integrity and durability of geopolymer concrete compared to the control mix. The study also emphasizes the potential of incorporating sugarcane bagasse ash and nano-silica in geopolymer concrete to reduce cement consumption, promote waste valorization, and achieve enhanced mechanical and durability performance.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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