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Valorisation of Fly Ash, Ground Granulated Blast Furnace Slag (GGBFS), Silica Fume Along with Graphene in High-Performance Geopolymer Self-Compacting Concrete

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Abstract: ***The high carbon emissions connected with ordinary Portland cement (OPC) production have fuelled the search for sustainable alternatives in the construction industry. Geopolymer concrete (GPC), made from industrial byproducts including fly ash (FA) and ground granulated blast furnace slag (GGBFS), is a low carbon option. This study looks at the use of FA, GGBFS, silica fume (SF), and graphene oxide (GO) in the production of high-performance geopolymer self-compacting concrete (HPG-SCC).***

Two experimental series were developed to assess fresh, mechanical, durability, and microstructural characteristics. In the first series, a reference mix of 50% FA and 50% GGBFS was created, and FA was replaced with SF at 5%, 10%, 15%, and 20% to establish the best replacement level. In the second series, GO was added to the optimum SF-based combination at concentrations ranging from 0.01% to 0.05% by weight of geopolymer paste. European Federation of National Associations Representing for Concrete (EFNARC) recommendations were followed to assess workability through slump flow, T_{500}, V-funnel, L-box, and J-ring tests. Compressive and flexural strength tests were performed at 7 and 28 days to assess hardened characteristics, as well as water absorption and porosity measurements. scanning electron microscopy (SEM) and X-ray diffraction (XRD) were used to study the microstructural and mineralogical features. The results show that 15% SF replacement offers the best mechanical performance due to improved particle packing and matrix densification. Excessive SF content resulted in a minor strength drop. The addition of GO increased compressive and flexural strength, refined pore structure, and reduced water absorption and porosity via enhanced geo-polymerization and interfacial bonding. Although workability declined with increasing SF and GO concentration because to increased specific surface area and water demand, all optimized mixes met the self-compacting concrete criterion.

The synergistic integration of FA, GGBFS, SF, and GO has tremendous promise for developing long-lasting, high-performance, and environmentally sustainable geopolymer self-compacting concrete, thereby advancing green construction materials.

Table of Abbreviations

ASTM	American Society for Testing and Materials
EFNARC	European Federation of National Associations Representing for Concrete
FA	Fly ash
GGBFS	Ground granulated blast furnace slag
GO	Graphene oxide
HPGSCC	High-performance geopolymer self-compacting concrete
ITZ	Inter-transitional zone
OPC	Ordinary Portland cement
SCM	Supplementary cementitious materials
SEM	Scanning electron microscopy
SF	Silica fume
XRD	X-ray diffraction

I. INTRODUCTION

High-performance geopolymer self-compacting concrete (HPGSCC) is an innovative, eco-friendly alternative to regular portland cement concrete that has numerous environmental and performance benefits. Traditional manufacturing of cement is an important contributor to worldwide CO_2 emissions, which aid in climate change. The production of one ton of portland cement generates approximately 0.8 tons of CO_2 [1] which represents approximately 8% of the total CO_2 emissions released into the atmosphere [2]. The global demand for construction materials significantly impacts the environment. Therefore, it is essential to adopt sustainable construction materials that have minimal environmental effects to address future infrastructure needs [3]. To reduce the consumption of portland cement, researchers have developed geopolymer concrete (GPC). It has gained popularity due to being more environmentally friendly than traditional cement[4].

Geopolymers are alkali-activated aluminosilicate precursors derived from industrial byproducts or raw materials, such as silica fume (SF), ground granulated blast slag (GGBFS), and FA. These materials can be utilized as supplementary cementitious materials (SCMs). The process of geo-polymerization of aluminosilicate precursors occurs in the presence of alkaline activator solutions, including sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3)[5][6].

In contrast, geopolymer concrete (GPC), which uses industrial byproducts such as FA, GGBFS and SF as basic components, dramatically reduces carbon emissions. This makes GPC an environmentally friendly option for modern construction[7].

FA, a byproduct of coal combustion, and GGBFS, a byproduct of steel production, are used as aluminosilicate sources in geopolymerization, a chemical process that creates binder materials without the use of cement. Slag and FA are good pozzolanic materials that can be used to create environmentally acceptable binders by alkali activation[8][9]. When correctly prepared, these materials provide outstanding mechanical qualities, increased durability, and greater chemical resistance. The introduction of SF, a byproduct of silicon and ferro-silicon alloy manufacture, improves the mechanical strength and durability of the concrete by fine-tuning the microstructure and boosting matrix density[10]. Wang et al. 2022 [11] found complicated effect of SF dosage in GPC. They found that with increase in SF dosage at certain limit improved compressive strength of GPC. Slag consists mostly of CaO, SiO_2, MgO, and Al_2O_3. In contrast, the main components of low calcium FA are SiO_2 and Al_2O_3. Alkali activation produces distinct reaction products for slag and low calcium FA. It is widely recognized that C-S-H gel is the primary binding phase for alkali-activated slag. An aluminosilicate gel (N-A-S-H) is thought to be responsible for the binding properties of alkali-activated low calcium FA, namely geopolymer[11]. Previous researches have shown that SF improves the strength and durability of concrete[12]. Adding SF to fresh concrete reduces yield stress and viscosity, leading to smooth extrusion and good recovery behaviour[13].

In recent years, the use of innovative materials such as GO in GPC has received a lot of attention. GO, a derivative of graphene, is a two-dimensional nanomaterial with remarkable mechanical, thermal, and electrical properties. When integrated into GPC, even in tiny volumes, GO can considerably improve compressive and tensile strength, fracture toughness, and overall longevity [14] [15] [16]. Furthermore, the inclusion of GO increases the material's resistance to cracking, resulting in improved structural integrity over time[17]. Muthu et al. 2021 [18] the inclusion of GO sheets enhanced the heat of hydration by serving as nucleation sites. According to Liu et al. 2020 [19] GO acts as a catalyst for electron and mass transfer during the alkali-activated reaction of geopolymers, facilitates the breakdown of amorphous phases in FA microspheres by transferring free electrons and accelerates the evolution of geopolymer gels.

This study investigates the synergistic impacts of FA, GGBFS, SF, and GO in the development of HPGSCC. The study intends to investigate how these materials interact to improve the mechanical, durability, and sustainability properties of GPC, making it a viable option for future construction projects.

II. EXPERIMENTAL

A. Materials

The study utilized GGBFS, FA, SF, GO, fine and coarse aggregates, alkaline solution, and water. Alumino -silicate-based source material is activated with an alkaline solution to create geopolymer concrete. FA has a high silica and alumina concentration. It is therefore regarded as an appropriate raw material for the production of geopolymer concrete. Class F grade (American Society for Testing and Materials (ASTM) Class F) conforming to Indian standard (Indian Standards) (IS) 3812 (Part 1) [20]. FA was obtained from Suratgarh thermal power station, Shriganganagar district, Rajasthan, India. The specific gravity of FA was 2.32 and possess a fineness of 94 % (i.e., 45 μm sieve). Low calcium FA containing SiO_2 and Al_2O_3 in the majority. GGBFS contains SiO_2 and Calcium oxide (CaO) in excess. Source material with a high calcium concentration can be used to react with FA in order to remove oven-curing requirements from construction procedures. GGBFS is a good binder material for the synthesis of alkali-activated concrete because it contains more calcium oxides. SiO_2 (92.85%) is the primary component of the SF.

The particles have surface areas ranging from 13,000 to 30,000 kg/m^2. SF has a bulk density of 120–220 kg/m^3, making it extremely light when collected. Chemical composition of FA, GGBFS, and SF are shown in table 1.The graphene was acquired in yellowish black powder form from India-mart with a specific surface area of 350 m^2/g and a thickness of a ten nanometres range, carbon to oxygen ratio is 60:40. In the present investigation, a silica modulus (the ratio of SiO_2 to Na_2O) of =2.5 was chosen. To guarantee optimal mechanical performance and efficient activation, the mass ratio of Na_2SiO_3 to NaOH solutions was set at 2.5.

Table 1 Chemical composition of FA, GGBFS, and SF

	FA (%)	GGBFS (%)	SF (%)
SiO_2	52.99	31.65	92.85
Al_2O_3	30.72	12.40	0.19
CaO	2.36	43.17	0.40
MgO	0.37	5.80	0.18
Fe_2O_3	3.05	0.3 7	0.96
SO_3	0.12	0.98	0.4
Na_2O	0.00	0.91	0.00
K_2O	1.34	0.18	0.67
TiO_2	2.95	0.40	0.48
MnO	0.00	0.58	0.74

In this research, we choose coarse and fine aggregates finer than 10 mm and 4.75 mm respectively. The proportion of coarse and fine aggregate is 60:40. The features of fine and coarse aggregates determined as per ASTM C128-15, 2015 [21] and IS 2386, 2002 part-4[22].The coarse aggregate used was granite, and having a specific gravity of 2.87, which was locally available in Bikaner, Rajasthan, India. Locally available fine sand with a specific gravity of 2.63 and fineness modulus of 2.72 conforming grading zone II as per IS 383-2016 [23]. Higher number of fine aggregates are used to increase the viscosity of mix as well as to avoid the segregation of coarse aggregates.

B. Preparation of Specimens

Twenty-four hours before the geopolymer composites were mixed, a 12 mol/L sodium hydroxide solution was made. The ratio of sodium hydroxide to sodium silicate was determined to be 2.5 in order to get the best compressive strength, as recommended by many researchers[24][25][26][27]. The sodium hydroxide solution and sodium silicate were combined after a 24-hour period. To prevent heat during the mortar mixing, this alkaline solution was left at room temperature for 30 minutes[28]. Graphene was ultrasonically treated with water for 30 minutes to improve the dispersion of GO.

Fig. 1. Flow diagram of the production of Geopolymer concrete

Aluminosilicate precursor (GGBFS, FA, and SF), Coarse and fine aggregates were dry mix in a mechanical mixer as per given proportion as shown in table 2 for various mixes for three minutes. The alkaline solution added in the dry mix and mixing done for 3 minutes. The remaining water was then added to the mixture and stirred for 2 minutes. Fig.1 shows a flow chart representation of the geopolymer concrete production process.

C. Mix Design

Two distinct series of GPC mixes are included in the current investigation. FA, GGBFS, and SF were combined in four distinct ratios in the first series FA: GGBFS: SF 45:50:5, 40:50:10, 35:50:15, and 30:50:20, which assigned the appropriate designations. GPC-MG5, GPC-MG10, GPC-MG15, and GPC-MG20.In the second series, GO is used at 0.01% to 0.05% at an interval of 0.01% by weight of geopolymer paste, which assigned the appropriate designation GPC-G1, GPC-G2, GPC-G3, GPC-G4, and GPC-G5. Fresh GPC properties were tested immediately after mixing and applied in molds for compressive strength, flexural strength and durability testing. Samples were covered until demolded to prevent moisture loss. After moulding, samples were cured in the lab under ambient conditions until testing.

Table 2 Summary of mix proportion of HPGSCC prepared in current study.

Sample	Cementitious Substances Kg/m^3(% w/w)			GO gram/m^3	Fine Aggregate Kg/m^3	Coarse Aggregate Kg/m^3	NaOH Kg/m^3	Na_2SiO_3 Kg/m^3
	FA	GGBFS	SF					
Reference Mix	213	213	-	-	596	1108	61	152
GPC-MG5	191	213	22	-	596	1108	61	152
GPC-MG10	170	213	43	-	596	1108	61	152
GPC-MG15	149	213	64	-	596	1108	61	152
GPC-MG20	127	213	86	-	596	1108	61	152
GPC-G1	149	213	64	43	596	1108	61	152
GPC-G2	149	213	64	85	596	1108	61	152
GPC-G3	149	213	64	128	596	1108	61	152
GPC-G4	149	213	64	170	596	1108	61	152
GPC-G5	149	213	64	213	596	1108	61	152

III. TESTING OF SPECIMEN

A. Fresh and Hardened Properties

Three essential SCC parameters were used to measure the fresh characteristics of HPGSCC blends i.e. resistance to segregation, filling ability, and passing ability. Slump flow test, V- funnel test, L-box test, T-500 test, J-ring test as per EFNARC[29] guidelines to analysed these characteristics. Concrete's horizontal free flow, or deformability, in the absence of obstruction is assessed using slump flow test. T_{500} mm slump flow is the term used to describe the time it takes to reach 500 mm diameter during the slump flow test. The diameter of the concrete spread was measured using the slump flow test to determine the flowability of HPGSCC. Concrete's filling capacity can be assessed using the V-funnel test in addition to the slump flow test. The apparatus's V shape limits the flow of concrete, and an increase in the flow's duration suggests that the concrete is blocked.

The concrete's time to empty the funnel is recorded, revealing the mix's viscosity. The J-ring test evaluates concrete's capacity to pass through reinforcing bars. The concrete has superior passing ability if the measured height difference between the inner and outer edges of the J-ring is closer to zero.

The L-box test describes HPGSCC's capacity to fill and pass. The L-box test is more susceptible to blocking. The blocking ratio (H_2/H_1) is calculated by measuring the concrete heights at the end of the horizontal portion (H_2) and the vertical section (H_1) when the concrete stops flowing. Concrete has good passing ability if blocking ration is 1.

A 1000-kN Digital Compressive Testing Machine was used to conduct a compressive strength test on three cubical specimens (100 mm x 100 mm x 100 mm) in compliance with IS 516 (Part1/Sec1):2021[30]. The compressive force was supplied at a rate of 14MPa/min throughout the test. The average strength of three specimens was the reported compressive strength. These were determined for test specimens at curing periods of 7 and 28 days. Flexural strength test was conducted on prism specimens (100 mm x 100 mm x 500 mm) in accordance with IS 516 (Part1/Sec1): 2021[30]. The specimens were placed on the support blocks of the testing machine, and the load was applied continuously at a constant rate of 14 N/mm^2/min without any shock until the specimen failed. Flexural strength, also known as the modulus of rupture, is a measure of a plain concrete beam to resist the failure in bending.

Water absorption and porosity of concrete specimens were evaluated using ASTM C642[31]. Specimens were dried in an oven at 110 ◦C ± 5 ◦C for 24 hours before immersing in water for 48 hours. The specimens were boiled for 5 hours in tap water in closed containers before cooling naturally for 14 hours. A specimen's mass was recorded at each step, and apparent mass was determined by suspending them in water. Three specimens (100 mm x 100 mm x 100 mm) were examined for each mix proportion to report average values. Equations for calculating water absorption and porosity are provided below.

$$\text{Water Absorption (\%)} = \left[\frac{B-A}{A}\right] \text{x}100$$

$$\text{Porosity (\%)} = \left[\frac{C-A}{C-D}\right] \text{x}100$$

Where

A = Mass of oven dried sample in air

B = Mass of surface dried sample in air after immersion

C = Mass of surface dry sample in air after immersion and boiling

D = Apparent mass of sample in air after immersion and boiling

B. Mineralogical and Microstructural properties

XRD analysis was used to identify crystalline phases in various materials and quantify these phases in addition to determining the mineralogical attributes. To assess the collected specimens' mineralogical composition and investigate the hydration mechanism. For additional analysis, the representative samples from each proportionate mix were sieved (45 μm) after being pounded into a fine powder using a mortar and pestle.

In order to observe microstructural changes in the geopolymer concrete, such as cracks and the formation of hydration products like C-A-S-H gel, N-A-S-H gel compounds, $Ca(OH)_2$, and ettringite linked to the addition of additional cementitious materials used in the study, crushed concrete samples were subjected to SEM. SEM technique is particularly useful for observing inter-transitional zone (ITZ) augmentation in GPCs. To Stop the hydration process, the crushed samples were submerged in isopropanol alcohol for a full day before being kept in a vacuum until testing.

IV. RESULT AND DISCUSSION

A. Workability

Workability of different concrete mix including reference mix tested through different workability test are shown in table No. 4. Results indicate that the reference mix exhibits higher slump flow, which decreases as SF and GO content in the mix increases. Higher specific surface area of SF and GO particles dur to their fineness reduce the free water content in the concrete resulted reduction in workability of concrete. Partial replacement of FA with SF, reduce the workability of fresh concrete because SF have higher specific surface area than FA absorbed the excessive water in GPC.

Table No. 3, Standard test value as per EFNARC[29]

Test Method	Minimum value	Maximum Value	Unit	Property
Slump Flow	650	800	mm	Filling Ability
T500mm Slump Flow	2	5	Sec	Filling Ability
V-funnel Flow Time	6	12	Sec	Filling Ability
L-Box Ratio	0.8	1	ratio	Passing Ability
J-Ring Blocking	0	10	mm	Passing Ability

Table No. 4, Summary of workability test result

Mix ID	Slump flow (mm)	T-500 Slump flow (s)	V-funnel flow time (s)	L-box ratio (H_2/H_1)	J-ring blocking (mm)
Reference Mix	705	2.5	9	0.96	6
GPC-MG5	698	2.6	9	0.94	6.5
GPC-MG10	695	3	10	0.93	7
GPC-MG15	687	3.4	10	0.9	8
GPC-MG20	680	4	11	0.88	8
GPC-G1	678	4	11	0.87	8.5
GPC-G2	670	4.6	11	0.85	9
GPC-G3	655	5	12	0.85	9
GPC-G4	640	5.4	13	0.83	10
GPC-G5	635	6.4	15	0.82	11

Akarsh et al. 2021 [32] also found that workability of concrete is reduced by addition of SF and GO due to their large specific surface area. Similar result was also reported Pan et al. 2024 [33] who reported an increase in SF content reduce the workability of concrete. Singh et al. 2023 [27] reported proportion of SF in the mix also had a negative effect on the workability of fresh GPC. Because of the oxygen-containing functional groups on their surface, GO nanoparticles are often hydrophilic, or water-attracting. They do, however, still have certain hydrophobic (water-repellent) properties from the original graphene structure.
GO's hydrophobic properties may result in inadequate wetting and little contact with the water-based concrete mixture, making dispersion difficult. GO's large surface area is another factor, which may lead to more surface energy and a greater propensity for aggregation [34]. Fig. 2-6 shows various workability results.

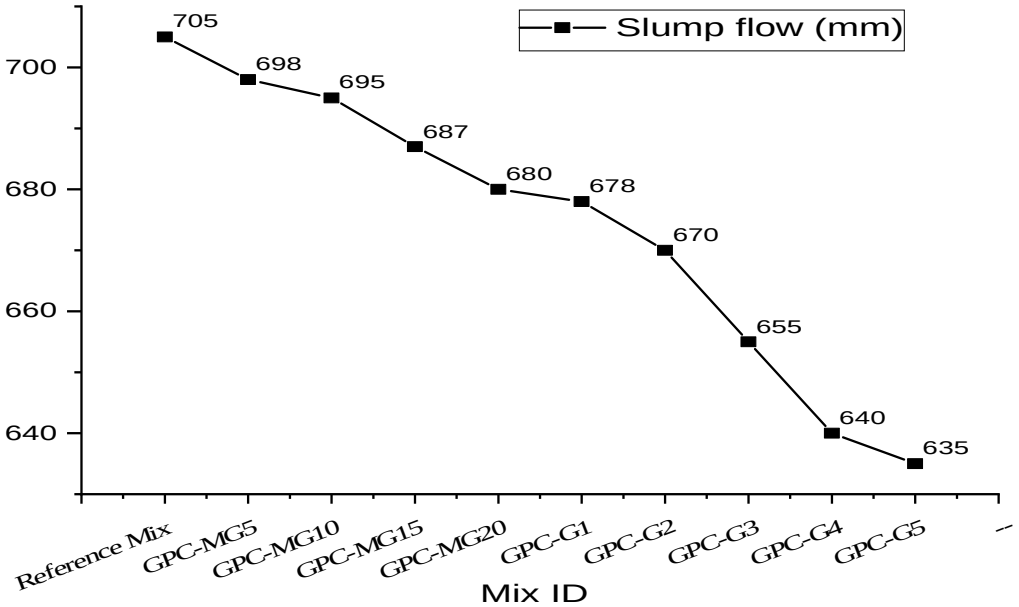

Fig. 2. Slump flow test result

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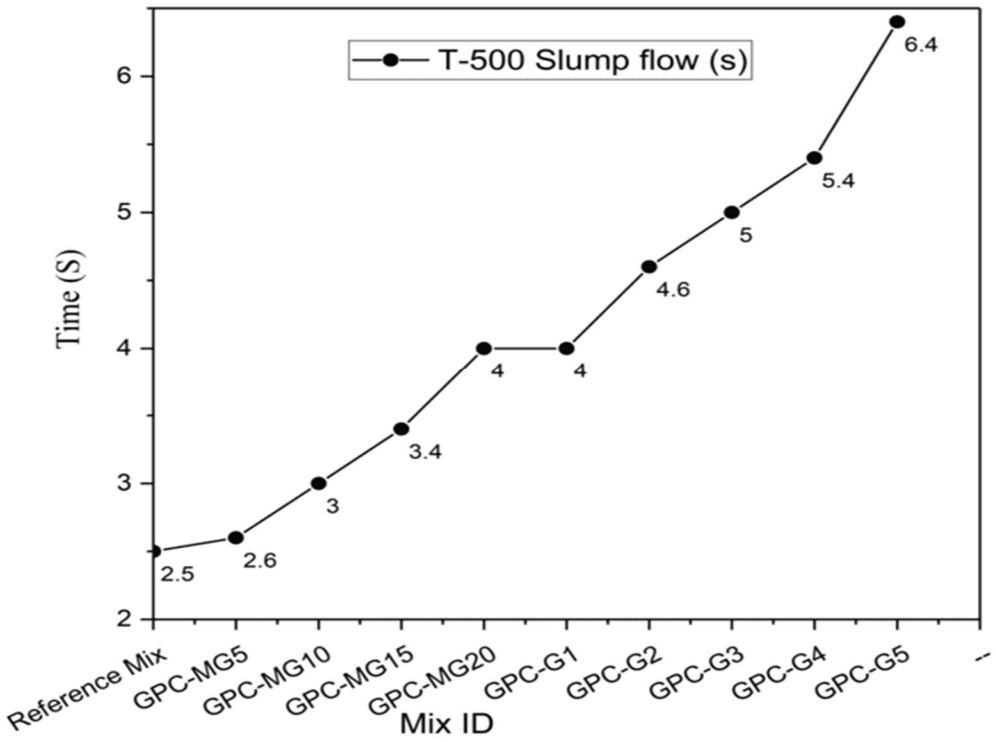


Fig. 3 T-500 test result

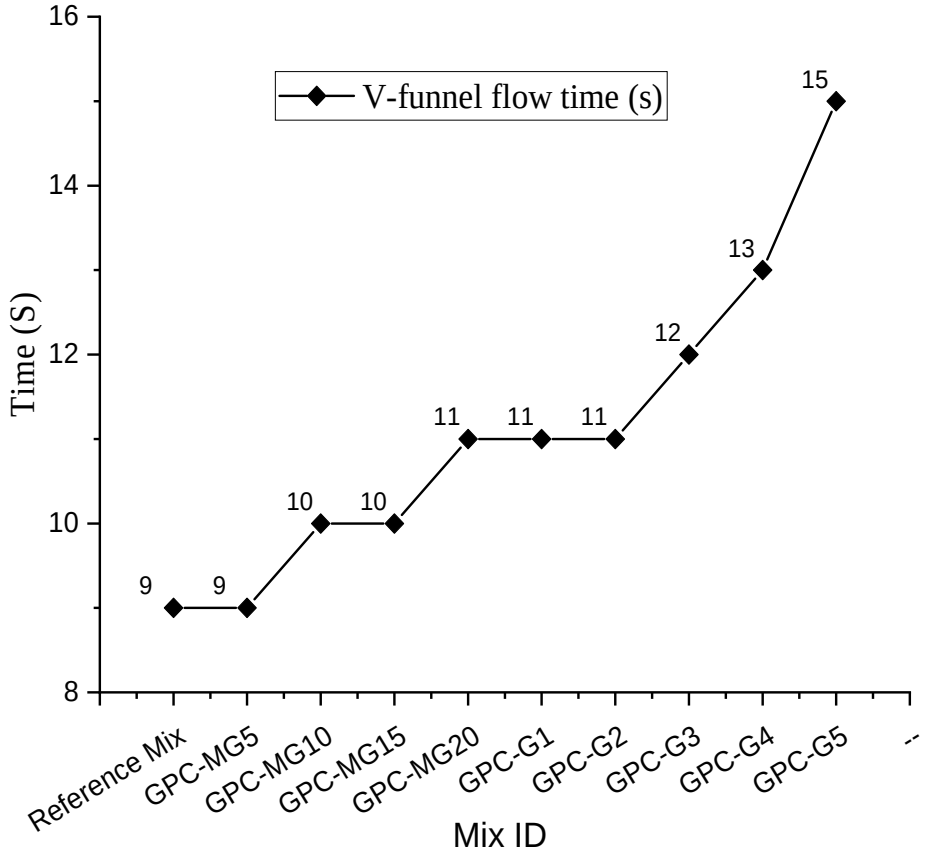


Fig. 4. V-funnel flow time test result

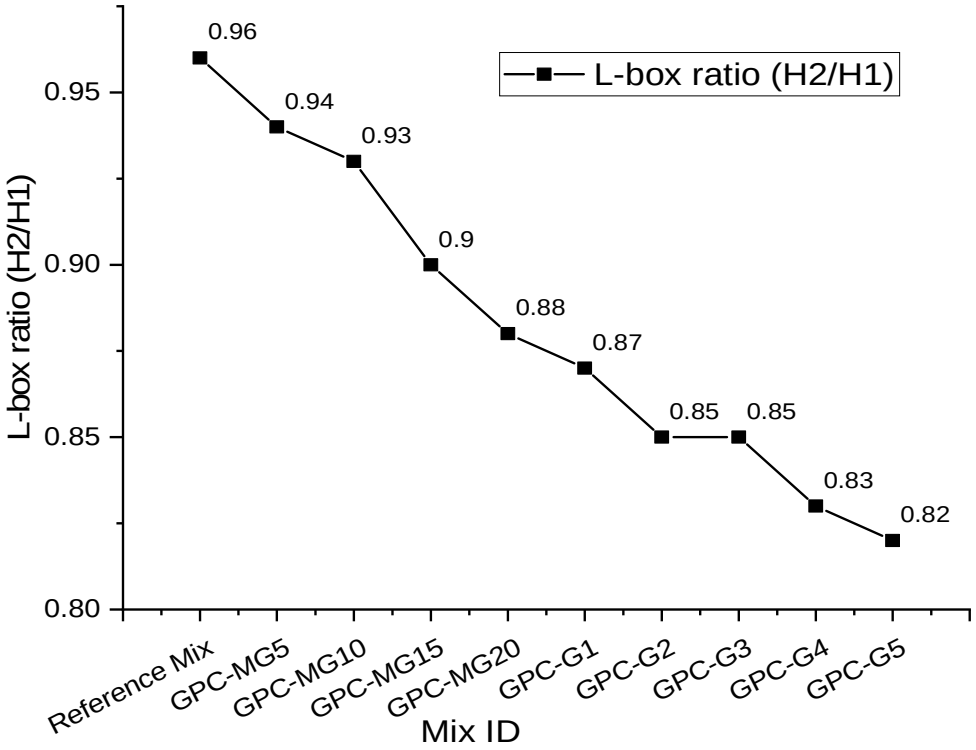


Fig. 5. L-box test result

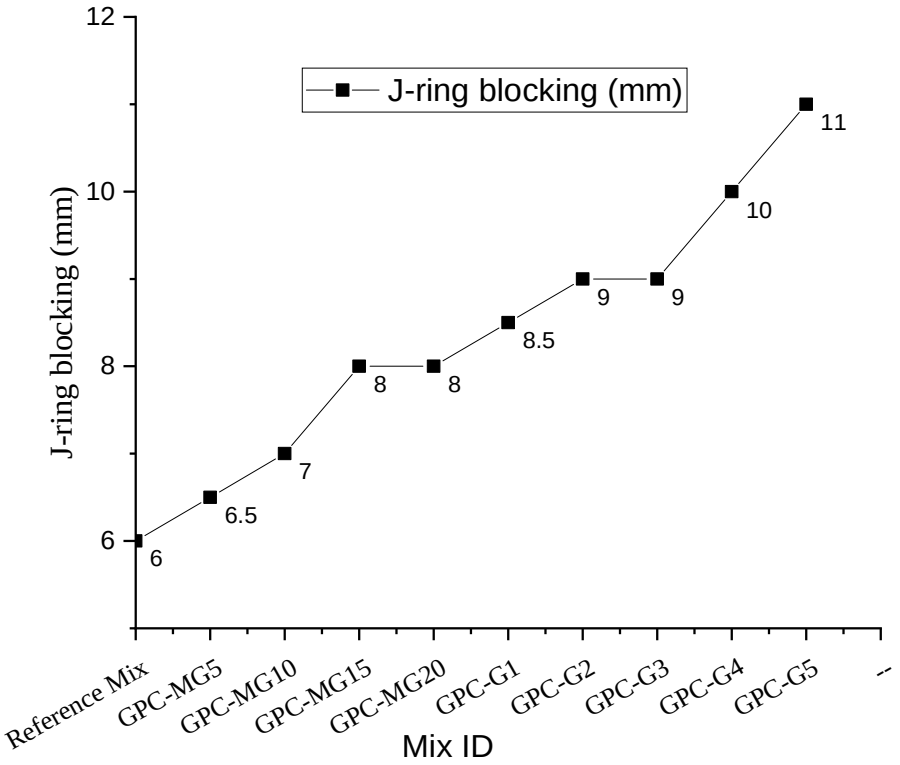


Fig. 6. J-ring blocking test result

B. Compressive Strength

Compressive strength test was carried out on 100 x 100 x 100 mm cubes. In Fig. 7, the compressive strength test results for each concrete mix after 7 and 28 days of curing are shown. It is well known that SF enhances concrete's mechanical properties. From Fig.7, it can be seen that the compare to reference mix compressive strengths of HPGSCC increase with increasing SF content, which could be seen in GPC-MG5, GPC-MG10, GPC-MG15, and GPC-MG20 concrete mix by 3%, 15%, 27%, and 9% respectively at 7 days and 3%, 18%, 25%, and 13% higher at 28 days. Similarly, Sevinç and Durgun 2020 [35] and Jalilifar and Sajedi 2021 [36] found that adding SF improved strength significantly by both a physical action and a pozzolanic reaction, the addition of SF to concrete significantly alters the matrix's structure.

The micro-voids left by free water in the matrix can be filled by the finer, spherical SF particles. Concrete's microstructure is improved by this particle packing effect, which also produces a significantly denser pore structure and improves the material's mechanical qualities [37]. It has been shown that partial replacement of FA by SF in HPGSCC improves the concrete's hardened qualities. Additionally, the development of sodium aluminosilicates hydrate gel (N-A-S-H) as a result of SF's extremely pozzolanic nature and its ultra-fineness may possibly be significant causes. Strength development reduces with 20wt% SF compare to 15wt% addition of SF because agglomeration of SF is taking place in GPC. Singh et al. 2024 [38] and Memon et al. 2013 [39],also reported that SF is finer than FA, it causes dense particle packing, pore size refinement, and a denser concrete matrix, which may be the reason for the increase in compressive strength. The addition of fine SF provides active SiO2, which is beneficial for the formation of siloxo bridges (–Si–O–Si–O–) during the geo-polymerization process.

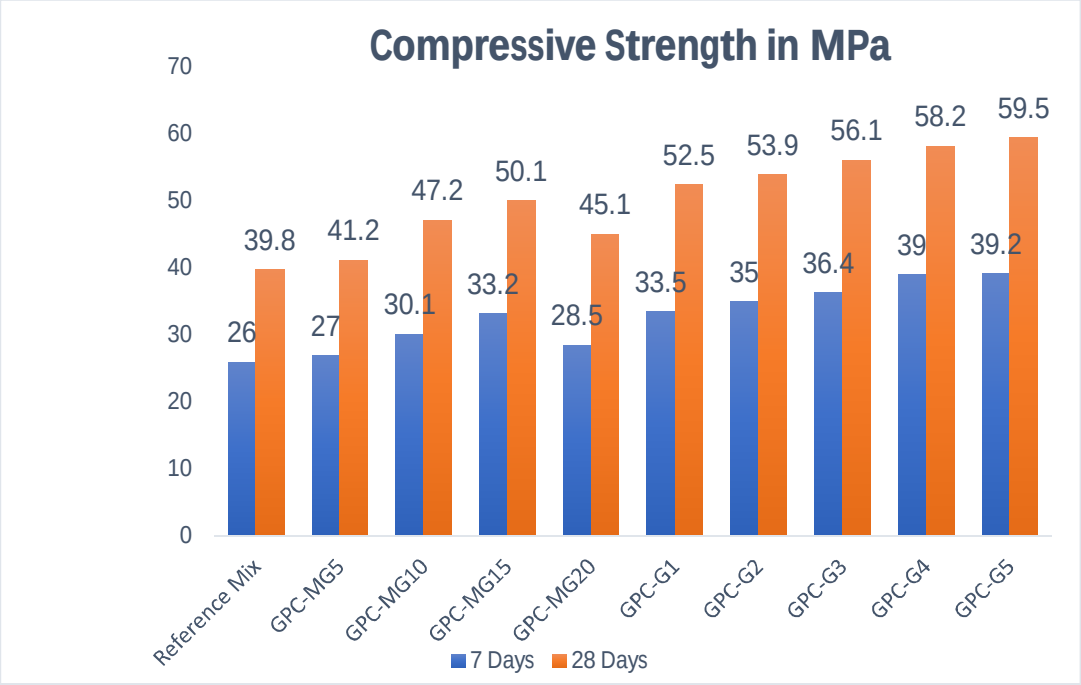


Fig. 7. Compressive strength test result

Additionally, by forming a denser structure, GO functions as a mechanical filler material in GPC, improving compressive strength at early age. Addition of GO improve compressive strength by 4%, 7%, 11%, 16%, and 18% compare to GPC-MG15 at 28 days which could be seen in GPC-G1, GPC-G2, GPC-G3, GPC-G4 and GPC-G5. Similar result observed by Sajjad et al. 2022 [40].

C. Flexural Strength

Flexural strength tests were carried out on specimen size in range of 100mm x100mm x500mm. In Fig. 8, flexural strength test result shown below. Flexural strength test shown similar trend as we observed in compressive strength test.

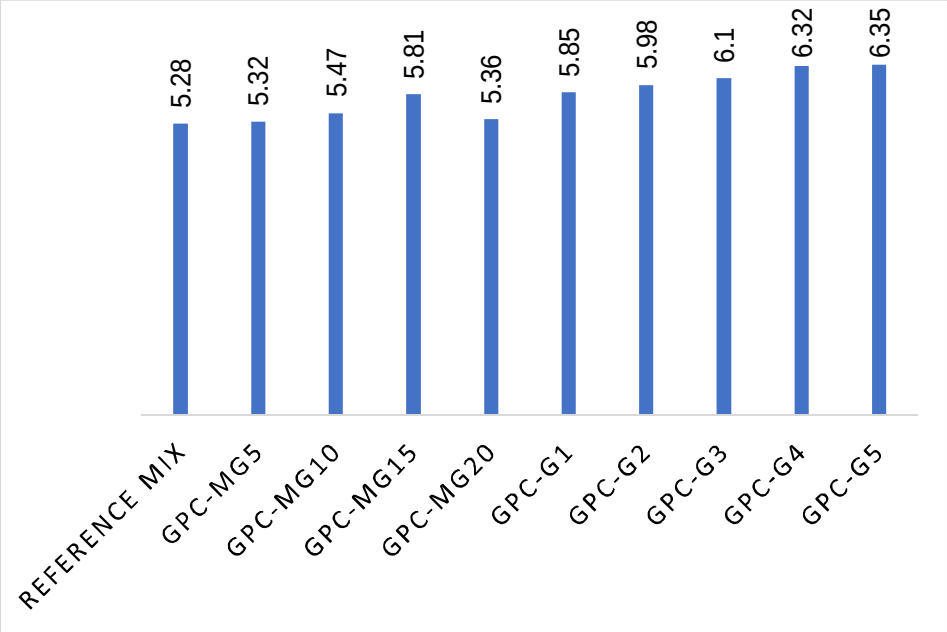


Fig. 8. Flexural strength test result

D. Water Absorption and Porosity

Fig. 9 (a and b), respectively, displayed the results of the water absorption and porosity tests. The water absorption and porosity values fall between 2.25 to 4.1% and 5.4% to 8%, respectively. The results demonstrate that replacing FA with SF gradually reduces water absorption from 3.2% (GPC-MG5) to 2.7% (GPC-MG15), which is about 34% less than the reference mix. Nonetheless, a minor rise in GPC-MG20 was noted, indicating that excessive SF replacement could result in unstable pore structures or insufficient geo-polymerization. Singh et al. 2024[38] also find similar trend.

The addition of GO to GPC improved its durability performance by reducing its porosity and water absorption. Water absorption was reduced by 2.25% (about 45% from the reference mix) and porosity was reduced by 5.4% (roughly 32% from the reference mix) when GO was added to GPC at a rate of 0.03%. The efficiency of GO in lowering water absorption and porosity is associated with the refining of pores in GPC due to the filling impact of nanoparticles. The efficiency of GO in lowering water absorption and porosity is associated with the refining of pores in GPC due to the filling impact of nanosized particles[41]. According to Wang et al. 2023 [42] GO increased the gap between pores by reducing the formation of linked pores and refining the pore size distribution.

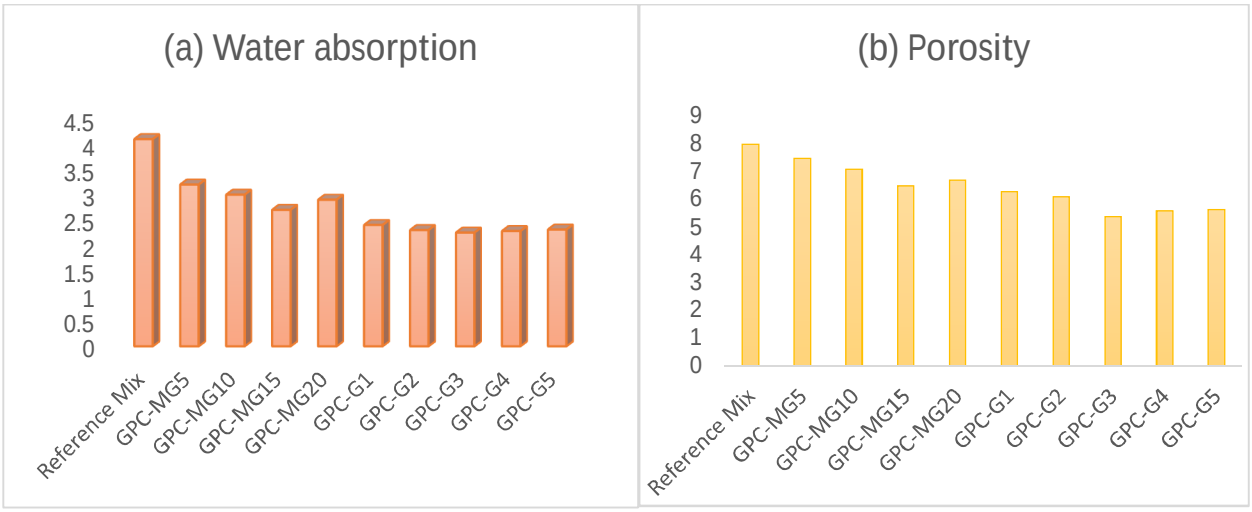


Fig. 9. (a) Water absorption (%) of specimen (b) Porosity of specimen

E. Mineralogical And Microstructural Properties

1) XRD Analysis

Fig. 10 shows the XRD curves of various GPC mixes, which all featured a halo at a 2θ angle of 20°-40°. The halo on geo-polymeric materials is caused by the creation of sodium aluminosilicate gel (N-A-S-H), which is responsible to contribute to their strength. Fig. 10 illustrates that the GPC exhibits more distinct peaks of quartz and mullite. This phenomenon may be attributed to the FA being the most crystallized variant of quartz and mullite, in contrast to the more amorphous nature of GGBFS. Fig. 10 shows that because of the aggregate's predominance; quartz is a prominent mineral in nearly all of the samples. Diffraction peak of quartz was observed at 2θ = 26.4º in XRD curve indicating the presence of unreacted FA in the mix. Adding SF reduces the intensity of the quartz peak, indicating increased Silica dissolution during alkali activation[43].

The prepared samples also contain additional important minerals, such as ettringite, mullite, C-A-S-H, and N-A-S-H, which affect the mixtures' characteristics. GPC's strong development results from the interaction of N-A-S-H and C-A-S-H. The mineral cancrinite, which adds strength to GPC, may have formed as a result of a silica-based chemical and sodium aluminosilicate hydrate (N-A-S-H). However, the hydration of calcium in the GPC in alkaline media results in the introduction of an external mineral, ettringite, from a calcium-based compound (C-A-S-H). No new crystalline phase was found in the graphene/geopolymer composites as compared to control geopolymers. The high SF dosage reflects a high unreacted SF content. Excess unreacted SFs aggregate and produce cracks, leading in decreased strength. Thus, the compressive strength of GPC-MG20 is lower than that of GPC-MG15.Similar result also reported by wang et al. 2022 [11]. In addition, because graphene is nanoscale and has a low content, no distinctive GO peaks were found in the geopolymer composites. The XRD patterns of samples with varying GO contents were all dispersive diffraction peaks in the range of 2θ = 18°–35°, as seen in Fig. 10. The quartz and mullite diffraction peaks were also scattered in this range, suggesting that the amorphous fraction contained the aluminosilicate gels, which were the reaction product of geo-polymerization, and the vitreous component of the unreacted raw materials [44]. The intensities of the amorphous humps in GPC-G1 to GPC-G5 were marginally greater than reference mix, suggesting that the addition of GO accelerated the geo-polymerization reaction and resulted in more N-A-S-H gels. Furthermore, XRD patterns were comparable, indicating that the addition of GO did not result in the creation of a new product. This result is in line with the findings of Luo et al. 2019 [45] study on GO-modified recycled concrete.

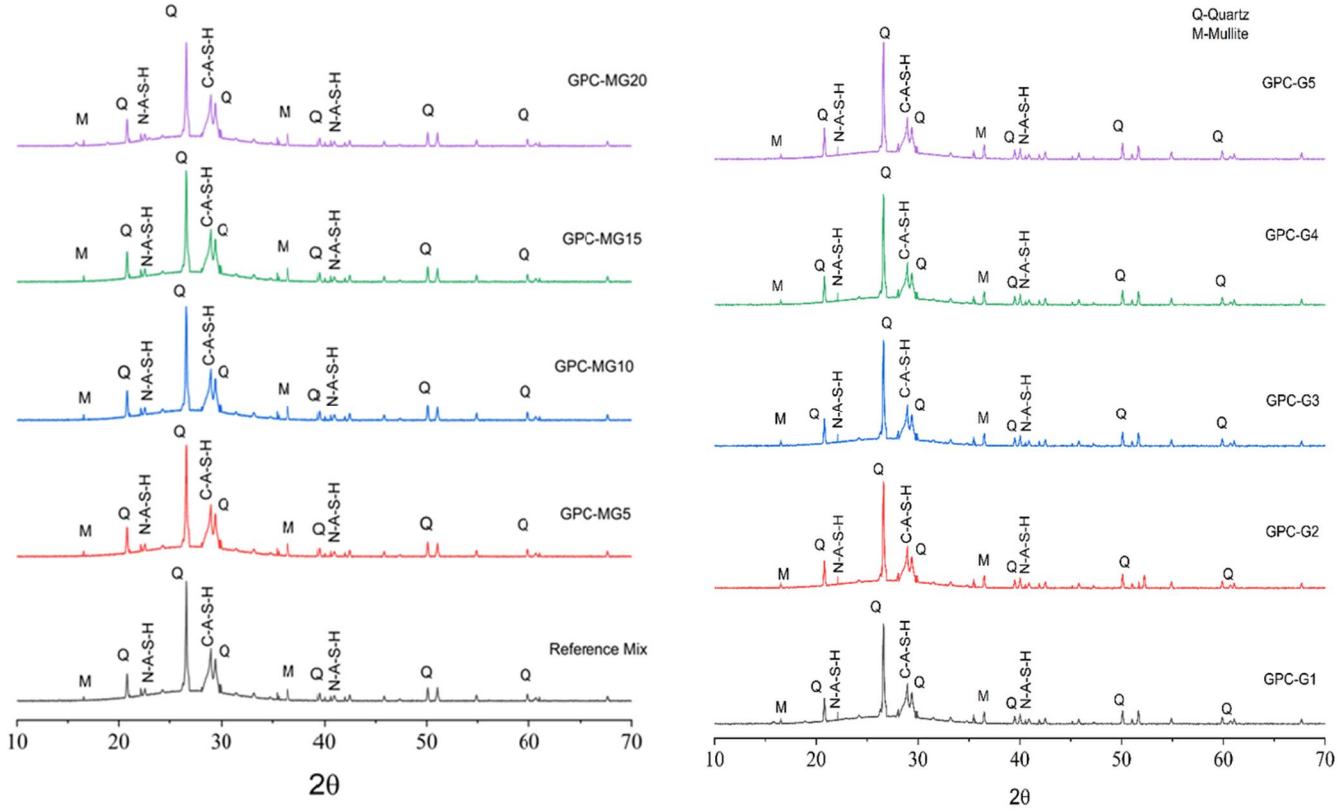


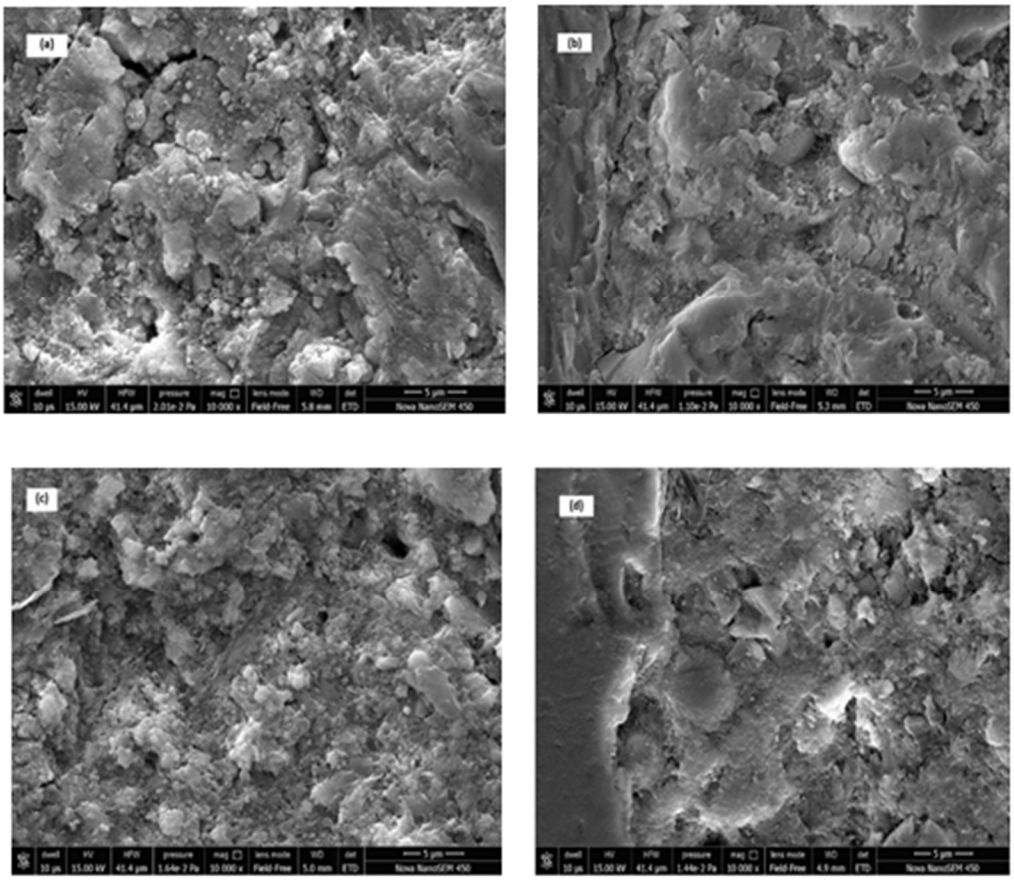
Fig.10. X-Ray diffractograms of reference mix and different GPC mixes

2) SEM Analysis

Fig.11 shows the surface morphological properties of GPC mixtures. SEM images of the GPC mixtures showed no significant differences. Due to the fact that SEM study samples were obtained from fractured cube specimens, cracks are visible on the SEM samples, which may be the result of mechanical damage sustained during sample preparation or stress in the matrix brought on by the application of axial pressure. According to Duan et al. 2017 [46] the presence of SF increases the formation of the dense matrix, which results in a more compact and denser microstructure, improved its mechanical characteristics. In GPC-MG20, unreacted SF is seen. However, a denser composite and a stronger bond ITZ between aggregate and the geopolymer matrix might have resulted from the filling mechanism of SF.

The SEM pictures of the GPC matrix did not show GO. This may be because GO was added in extremely small amounts, and the dispersed GO will be nanoscale in size, making it challenging detect in the concrete matrix[47]. Liu et al. 2020 [19] found GO encourages geo-polymerization, according to the microstructure analysis of the FA based GO-geopolymer composite. FA's amorphous phases quickly dissolve in the alkaline solution and take part in the initial stages of geo-polymerization [27]. There are many crystals visible on the surface of FA microspheres because the crystals are stable and resistant to dissolve in alkali solution. GO is either immersed in the GPC matrix's fissure or adsorbed on the surface of binder microspheres, resulting in the formation of many crystal particles and pores nearby [48]. When GO comes into contact with the crystal nucleus, it most likely promotes the creation of a monocrystalline layer and a zeolite like phase. In this manner, GO encourages FA to dissolve and zeolite crystals to form, changing the geopolymer's pore diameter distribution.

On the other hand, because GGBFS was present as a binder, C-A-S-H gel co-exists in the GPC matrix. C-A-S-H gels have a higher degree of polymerization. The microstructure of C-A-S-H gels becomes compact and the cohesive forces within the matrix improve when GO is filled into the gel pores. The strength and durability analysis of the GPC mixtures in the current study clearly showed the benefits of adding GO. The action of GO has been found to be mediated by two mechanisms. The first is GO's chemical action, which means that widely distributed GO can improve aluminosilicate precursors' geo-polymerization. The second is the physical activity, where GO can have a bridging effect by acting as a micropore or crack filler.



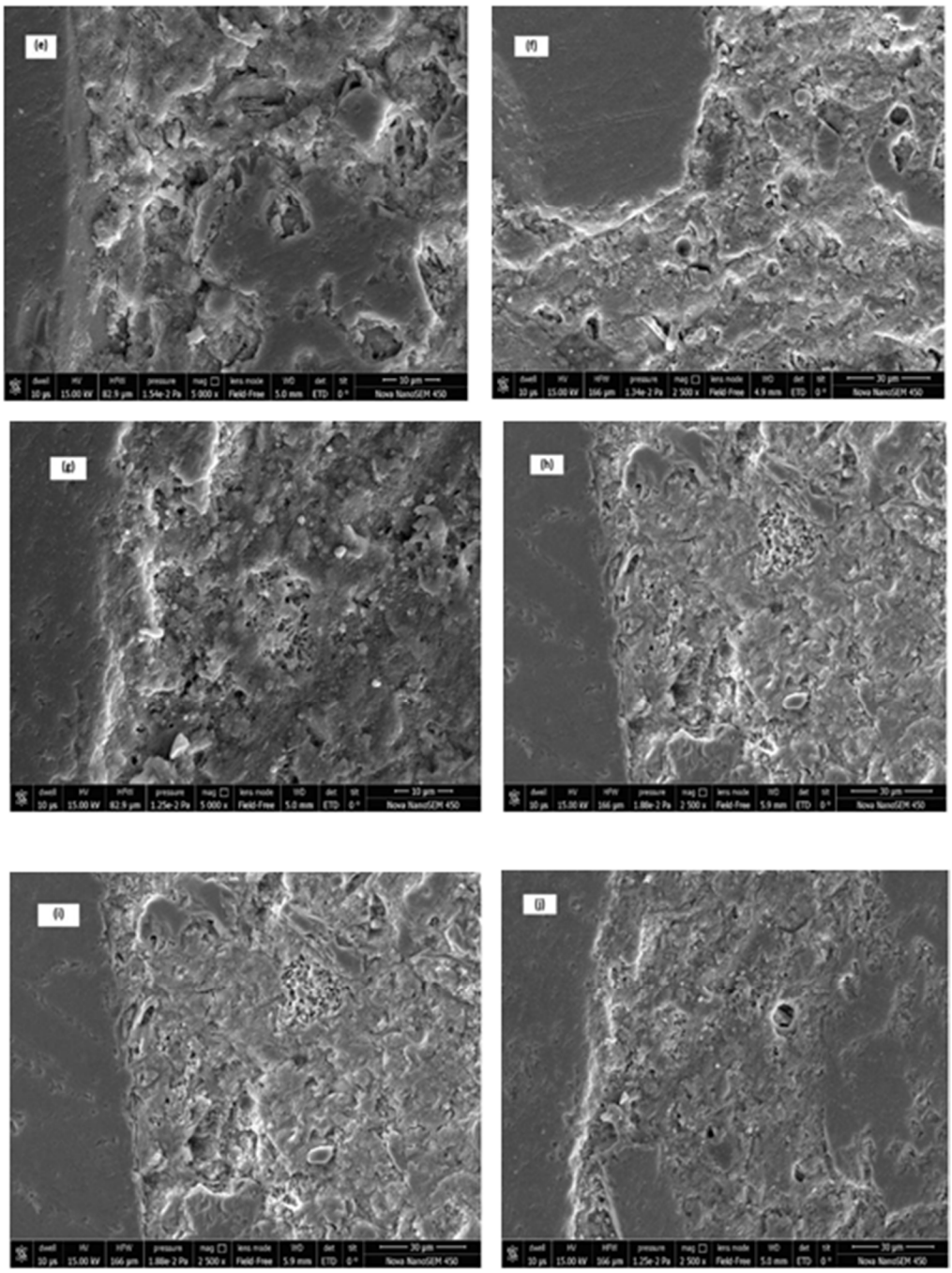


Fig. 11 Surface Morphology of reference mix and GPC mixes (a) reference mix (b) GPC-MG5 (c) GPC-MG10 (d) GPC-MG15 (e) GPC-MG20 (f) GPC-G1 (g) GPC-G2 (h) GPC-G3 (i) GPC-G4 (j) GPC-G5

V. CONCLUSION

This study focuses on the synergistic effects of FA, GGBFS, SF and GO in producing HPGSCC. Conclusions drawn from experimental observations and analytical results are: -

1) Due to their high specific surface area and water demand, the workability of HPGSCC mixtures is found to decrease with increasing SF and GO contents with respect to reference mix. Still, all optimized mixes fulfil the EFNARC guidelines for self-compacting concrete except mix GPC-G4 and GPC-G5.

2) The addition of silica fume as a partial replacement for FA greatly improved the mechanical and durability qualities of HPGSCC. Among the examined mixes, the optimal replacement amount was 15% SF, which resulted in increased compressive and

flexural strength due to improved particle packing and matrix density. However, increasing the SF concentration resulted in a slight loss in strength, mostly due to agglomeration of SF particles in the mix and lower workability.

3) The addition of GO enhanced the optimized mix's performance qualities. GO helped to increase compressive and flexural strength, minimize water absorption, and reduce porosity. These enhancements are ascribed to better pore structure, geopolymerization, and interfacial bonding within the matrix. The capacity of GO to fill cracks and bridge them was critical in improving the microstructure.

4) Microstructural study using SEM and XRD revealed the development of dense and compact geopolymer matrices containing C-A-S-H and N-A-S-H gels. The addition of SF and GO resulted in a more refined microstructure, fewer voids, and improved interfacial transition zones, which were directly associated to improved mechanical and durability performance.

5) Overall, the study shows that combining FA, GGBFS, SF, and GO can result in a sustainable, high-performance construction material with low environmental impact. The proposed HPGSCC has tremendous potential as an alternative to conventional Portland cement-based concrete, helping to promote greener construction practices.

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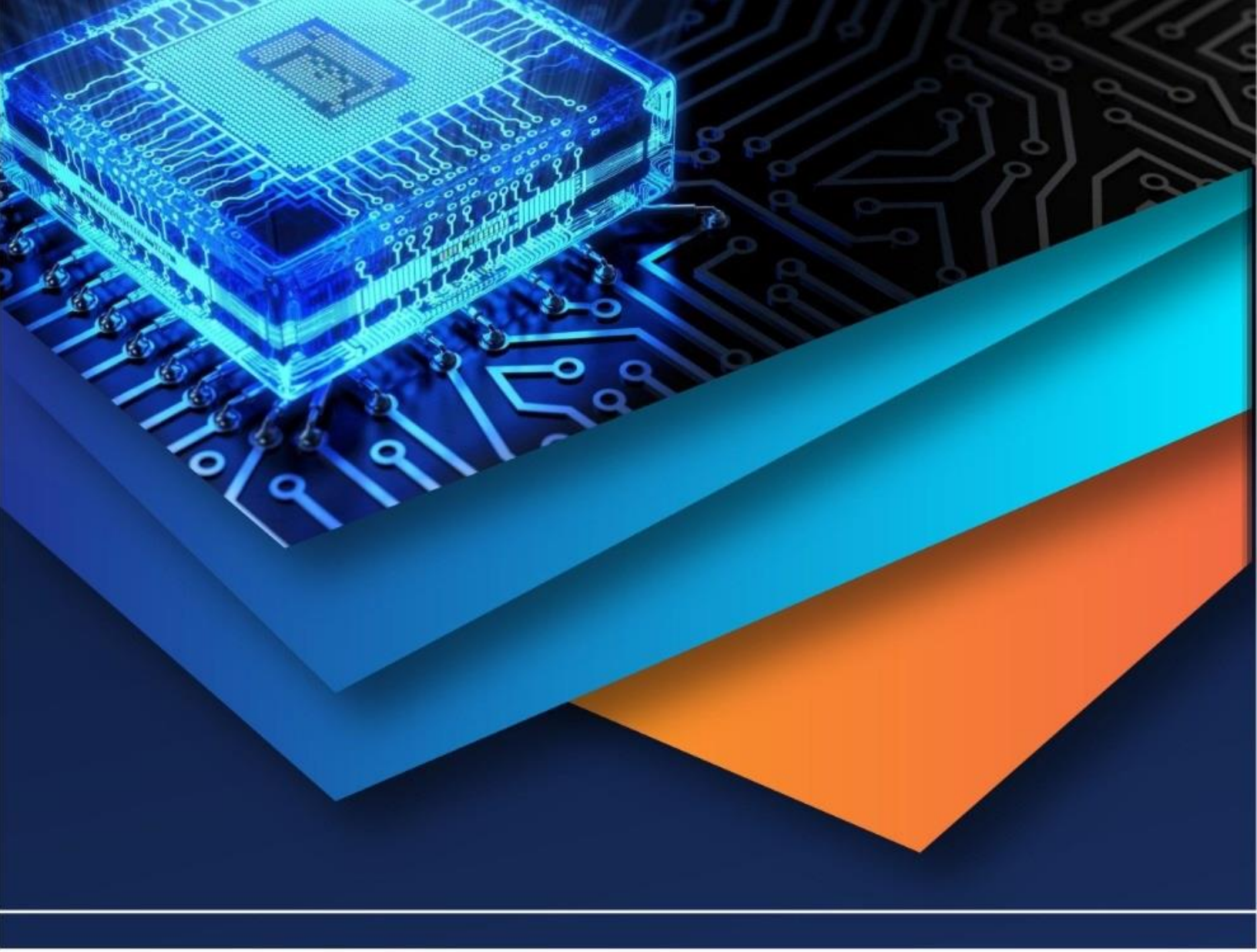

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