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Case study

Influence of polypropylene and steel fibers on the mechanical properties of ultra-high-performance fiber-reinforced geopolymer concrete

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ABSTRACT

Ultra-high-performance geopolymer concrete (UHPGPC) was investigated in this paper using microsilica and granulated blast furnace slag (GBFS) comprising polypropylene fiber (PF) and steel fiber (SF). The first group of mixing ratios was used to develop a control mixture with maximum compressive strength for this purpose. In the second group, nine mixtures were used to evaluate the effect of the fibers on the compressive strength, split strength, flexural strength, and modulus of elasticity of UHPGPC. Furthermore, the SEM analyses were performed to understand the mechanism of strength improvement based on the reaction products and micromorphology. The results indicate that the presence of PF in samples containing SF enhances its mechanical properties. Moreover, the results indicate that replacing PF with SF reduces mechanical strength while increasing durability.

1. Introduction

Because of the fast construction of infrastructure, the demand for concrete has expanded significantly since it was classified as the second most used source, following just water. Not only does the manufacture of cement contribute significantly to environmental degradation, but it also consumes a large amount of energy. By and large, one tonne of OPC consumes 1.5 tonnes of raw materials and emits a comparable quantity of carbon dioxide into the environment [1–6]. This has resulted in the creation of geopolymer concretes (GPC), which are composed completely of industrial waste like GBFS, and fly ash, which has been activated with sodium/potassium activators. Amongst various activators, the usage of sodium hydroxide (NaOH) in combination with sodium silicate (Na_2SiO_3) has the benefit of increasing compressive strength when used in conjunction with GBFS and fly ash as raw material [7–11]. GPs are three-dimensional crystalline aluminosilicate binders materials generated at temps ranging from 22 to 125 °C through alkaline activator of alumina-silicates derived from industrial waste [12–15]. alkaline activator, also known as geopolymerisation, is a chemical interaction that transforms an amorphous phase into a completely cementitious composite [16,17]. This compact structure is what gives the material its enhanced strength characteristics. Throughout the last twenty years, GPC manufacturing has centered on

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employing a variety of raw materials and activators to create standard and high-strength GPC that cures at increased temps. Recently, the focus of research has switched to the production of GPC that cures at ambient temp, hence reducing the amount of energy needed for curing [18–21]. Despite extensive research in GP innovation, little attention has been paid to the creation of UHPGPC. In cementitious concrete, an interaction powder concrete technique was created to produce UHPC. An interaction powder concrete is classified as high-strength concrete, which is obtained by the use of certain mixing, proportioning, and post-heat curing processes [22–26], and is therefore classified as UHPC. An interaction powder concrete is a technology in which OPC is partially substituted with pozzolana and coarse aggregates are totally substituted with quartz powder and finer fine aggregates in the range of 70–160 μm integrated with or without SFs [27–29].

UHPC concrete is defined as having a very packed structure devoid of pore spaces, enhanced mechanical characteristics, and better corrosion resistance. These mechanical characteristics can be further enhanced by the addition of SFs. With a high cement concentration of 800–1200 kg/m^3 [28–32] and a low liquid-binder ratio, the rate of hydration is reduced, leaving few unreacted cement grains that can be further reacted with the addition of filler components like quartz [33–36]. Recent research has been conducted to develop UHPC using GP technologies that have a performance comparable to UHPC [37,38]. Ambily, Ravisankar, Umarani, Dattatreya and Iyer [39] created an ultra-high-performance GPC using slag, fly ash, and microsilica as raw material and activating it with sodium and potassium hydroxides and silicates for maximum compressive strength and flexural strength of 175 MPa and 14 MPa, respectively, after 28-d of room temp. Even at greater strengths, there was no indication of microsilica affecting the rheological characteristics. Wetzel and Middendorf [40] studied the effect of microsilica incorporation as a partial substitute for slag in the synthesis of extremely high-performance GPC using a fixed quantity of metakaolin. The combination obtained a maximum compressive strength of 179 MPa with a 12.5 vol% substitution of slag with microsilica, and the strength was observed to decrease with 15 % microsilica. The findings indicate that a greater strength may be obtained by curing at 60 °C. Although the workability of the blends decreases with a microsilica concentration of 20–30 % compared to 10 %, the introduction of microsilica has a significant effect on the mechanical characteristics at a higher level of replacement [41–44]. The form of the fiber has a negligible effect on the flow characteristics of ultra-high-performance GPC mixtures, and the mechanical characteristics improve as the amount of fiber rises [45–52].

Mayhoub et al. [53] studied GBFS-based reaction powder concrete mixtures with and without cement content under various curing environments and discovered that mixtures cured in a micro oven had a compressive strength greater than that of heat and air-cured samples at the 28-d. Liu et al. [54] investigated the influence of ceramic ball aggregate on the projectile impacting the behavior of SF reinforced UHPGPC and discovered that mixtures including ceramic ball aggregate absorbed more power than normal UHPGPC. Excluding the action of Ambily et al. [39], all previous studies concentrated on increased temp curing and used metakaolin as a precursor, resulting in an inadequate response for the impact of GBFS-based UHPGPC as well as the impact of substituting microsilica for GBFS. Using the goal of manufacturing UHPGPC without requiring a large quantity of cement, this action was designed to measure the influence of incorporating the RPC idea into GPC technologies utilizing GBFS as the precursor activated with sodium-based activators [52,55–57]. The fresh characteristics of the produced UHPGPC were evaluated by partially substituting microsilica for GBFS, natural sand for quartz powder, and two various grades of sand. Along with the aforementioned modifications, the influence of SFs and curing conditions on the compressive strength development at 7- and 28-d was investigated. Because of the large amount of raw resources needed in the production of UHPGPC, studies were designed using response surface methods to identify the optimal mix ratios of its components. To analyze the environmental context, ecology parameters of raw resources utilized in the manufacturing of UHPGPC were computed without considering the phases of transport and concrete formation, which are typical in all situations [58–63]. Due to the advantages and challenges specific to geopolymer concrete, especially the UHPGPC ones, additional studies are warranted. This paper aims to improve the understanding of UHPGPC by investigating its properties.

2. Research significance

Due to the advantages and challenges specific to the geopolymer concrete, especially the UHPGPC ones, additional studies are warranted. This paper aims to improve the understanding of UHPGPC by investigating its properties.

Table 1
Chemical compounds of microsilica and GBFS (%).

Compound	GBFS	Microsilica
SiO_2	36	95.1
Fe_2O_3	1.5	0.95
Al_2O_3	11	1.22
MgO	12.5	0.95
CaO	39	0.59
Na_2O	0.72	0.42
K_2O	0.76	1.2
MnO	1.68	–
L.O.I	2.44	2.61

3. Experimental program

3.1. Materials

To synthesize UHPGPC, materials having aluminosilicate resources including microsilica and GBFS with densities of 2960 and 2260 kg/m^3, respectively, were employed. The chemical characteristics of microsilica and GBFS are presented in Table 1. As alkaline activator sols, NaOH with a purity of 99 % and Na_2SiO_3 with a SiO_2/Na_2O ratio of two was utilized. Quartz sand was used as a fine aggregate and its average particle size was reduced to 2.30 mm to improve its uniformity. The two fibers utilized are PF and SF as seen in Fig. 1, and their characteristics are listed in Table 2.

3.2. Mix ratio

In this study, nine mix mixes were investigated in the first group for evaluating various sodium silicate/NaOH ratios as well as the volume of NaOH sol. Next, using a control mix with the highest compressive strength, the influence of PF and SF on the mechanical characteristics of ultra-high-performance fiber-reinforced geopolymer concrete (UHPGPC) in the second group of mix ratios was investigated. In all mixes, the proportion of microsilica and GBFS is fixed at 30 % and 70 %, respectively, while the proportion of alkaline activator sols to binder is fixed at 0.33. Table 3 illustrates the mixed proportions of the first and second groups. To prepare alkaline activator sols, the NaOH flakes are first diluted with water and then allowed to cool to ambient temp for 24 h. Subsequently, a Na_2SiO_3 sol is applied. Dry components including quartz sand, microsilica, and GBFS were combined in a blender for 3 min, or until a gray light-colored mix was formed. The alkaline activator sols were then gradually added to the mixture and mixed for another 2 min. After achieving a homogenous mix, the fibers were progressively added to the concrete to avoid agglomeration, and blending was continued till a homogeneity of the fibers was seen. Finally, the mix was placed into a mold and secured with a lid to minimize the loss of moisture. The specimens were tested from the mould after 24 h and maintained at ambient temp (22–29 °C).

3.3. Testing methods

The effect of different fiber inclusions on the workability of fresh ultra-high-performance geopolymer concrete composites was measured in terms of flow diameter as per ASTM C1437-13 [64]. The flow tests were conducted immediately after mixing each batch, and all the mixtures were tested twice.

The compressive strength was determined using cubic specimens with sizes of 70.5 × 70.5 × 70.5 mm per ASTM C109 [65]. The splitting tensile strength and modulus of elasticity were determined using cylindrical specimens having a diameter of 150 mm and a height of 300 mm, per ASTM C-496 [66] and ASTM C-469 [67], respectively. The flexural strength is determined using prism specimens with sizes of 40 × 40 × 160 mm per ASTM C-1609 [68].

Three specimens with a 50 mm thickness were constructed for the chloride penetration test using cylinders (100 × 200 mm). After saturation with freshwater for 24 h, the specimens were kept in the device's cell for testing. On one side, the specimens are in interface with 0.32 molarity NaOH sol and on the other, with 3.5 % sodium chloride sol. Six hrs after applying a 70 V to the specimens, the charges traveling through them are measured. Lastly, the total charge carried by the specimens was determined in coulombs.

4. Findings and discussions

4.1. Workability

The effect of different fiber inclusions on the workability of fresh ultra-high-performance geopolymer concrete composites is compared in Fig. 2. As can be seen, the fresh state properties of geopolymer change significantly with the addition of fibers. It can be established that as the volume fraction of steel fibers increased, the flow diameter decreased respectively. Moreover, it should be noted

Polypropylene fibers

Steel fibers

Fig. 1. Polypropylene and steel fibers utilized in this investigation.

Table 2
Characteristics of fibers.

Materials	Dia. (mm)	Length (mm)	Elastic modulus (GPa)	Tensile strength (MPa)	Density (kg/m^3)
Polypropylene	0.033	8	3.65	430	915
Steel	0.12	15	230	2050	7865

Table 3
Mix ratio.

Mixture	Microsilica (kg/m^3)	GBFS (kg/m^3)	Na_2SiO_3 /NaOH ratio	NaOH	Quartz sand	PF (vol%)	SF (vol%)
Group 1							
SS/SH-1.5-M6	285	860	1.5	6	832	–	–
SS/SH-1.5-M10	285	860	1.5	10	832	–	–
SS/SH-1.5-M14	285	860	1.5	14	832	–	–
SS/SH-2.5-M6	285	860	2.5	6	845	–	–
SS/SH-2.5-M10	285	860	2.5	10	845	–	–
SS/SH-2.5-M14	285	860	2.5	14	845	–	–
SS/SH-3.5-M6	285	860	3.5	6	850	–	–
SS/SH-3.5-M10	285	860	3.5	10	850	–	–
SS/SH-3.5-M14	285	860	3.5	14	850	–	–
Group 2							
1.0-SF	285	860	3.5	14	850	–	1
1.25-SF	285	860	3.5	14	850	–	1.25
1.5-SF	285	860	3.5	14	850	–	1.5
1.75-SF	285	860	3.5	14	850	–	1.75
2.0-SF	285	860	3.5	14	850	–	2
2.25-SF	285	860	3.5	14	850	–	2.25
1.0-SF-0.25-PF	285	860	3.5	14	850	0.25	1
1.5-SF-0.25-PF	285	860	3.5	14	850	0.25	1.5
2.0-SF-0.25-PF	285	860	3.5	14	850	0.25	2

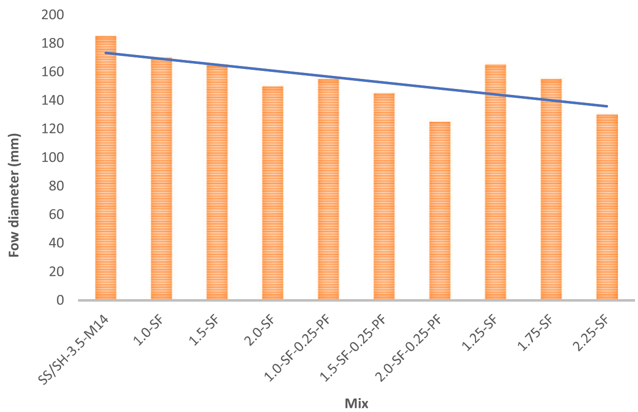

Fig. 2. Effect of different fiber combinations on flowability of the geopolymer composites.

that the addition of higher volume fraction of steel fibers (> 1.75 %), produced slightly harsh mixes in the fresh state under the static mode.

Furthermore, because high strength polyethylene fibers are hydrophobic in nature, they are less impacted by the wet nature of geopolymer binder and are less susceptible to a fiber balling effect during the mixing process. However, because polyethylene fibers were compounded with steel fibers in the current study, the reduced fluidity of mixes containing them is largely related to the low density of these fibers, as for a very small volume fraction, a much larger fiber quantity was included into the respective individual mix, inducing a higher number of interactions between the fiber and the matrix, resulting in greater internal resistance against flow.

On the other hand, fluctuations in the flow diameters were measured for composites prepared from the ternary blending of fly ash and slag. The lower workability of mixes containing fly ash or slag is attributed to the increase in calcium content and its rapid reaction with the alkaline activator, where additional calcium served as nuclei for the precipitation of dissolved species from fly ash and affected the coagulation rate.

4.2. Compressive strength

Fig. 3 illustrates the test research findings for compressive strength in the first group of mix ratios. Because of the fact that the GP interaction is dependent on the dissolve rate of aluminum and silicon ions in an alkaline sol, the re-interaction of these two ions results in the production of a new gel throughout all mixes. With rising NaOH dosage, the value of compressive strength improvements attributed to the rise in geopolymerisation reaction with growing three-dimensional networks, which increases aluminosilicate dissolve rate [39,69]. Comparing the mixes with Na_2SiO_3/NaOH ratios of 1.5, 2.5, and 3.5, it was found that increasing the NaOH ratio from 6 to 14 molarity reduced the water/binder ratio by 18 %, 14 %, and 10 %, respectively, increasing the compressive strength of 38 %, 33 %, and 31 %. This alteration in the water/binder ratio and the compressive strength in the Na_2SiO_3/NaOH ratio of one is more substantial than the changes in the other ratio. The rise in the Na_2SiO_3/NaOH ratio has caused a reduction in the water/binder ratio, which helps to improve the performance of compressive strength's upward tendency. For instance, when the ratio of Na_2SiO_3 to NaOH is raised from 1.5 to 3.5, the ratio of water/binder decreases by 7 % and 9 %, respectively, and compressive strength increases by 7 % and 14 %, respectively, compared with a Na_2SiO_3/NaOH ratio of one. These alterations are more noticeable with a Na_2SiO_3/NaOH ratio of 3.5 vs 2.5. The SS/SH-1.5-M6 and SS/SH-3.5-M14 mixes, respectively, showed the lowest and greatest 28-d compressive strength, demonstrating that increasing the molarity of the NaOH sol and the sodium silicate/NaOH ratio resulted in a 46 % in compressive strength. According to Fig. 3, molarity, and the sodium silicate/NaOH ratio have a direct relationship with compressive strength.

The SS/SH-3.5-M14 mix with the highest compressive strength has been selected as the group 2 control mix. According to Table 4, the inclusion of fibers significantly raises the compressive strength of all mixes. The maximal compressive strength is associated with the SF mix at all ages. Substitution 0.50 vol% of SF with PF in composite mixes decreased compressive strength; conversely, introducing PF to mixes containing SF increased compressive strength, indicating that PF has a beneficial influence on composites mixes. The compressive strength of the 2.25-SF mix is 123, 155, and 170 MPa at the ages of 7-, 28-, and 90-d, respectively, indicating a continuing upward tendency. At the same ages, using a 2 % by volume proportion of SF resulted in increases of 25 %, 37 %, and 43 % compared with the control mix. At 7-, 28-, and 90-d, substituting 0.50 % by volume of PF in the mixed design of 2.0-SF-0.25-PF resulted in strength improvements of 23 %, 31 %, and 39 % compared with the control mix and declines of 1.9 %, 3.3 %, and 3.1 % compared to the 2.25-SF mix. Comparing the 2.0-SF and 2.0-SF-0.25-PF mixes demonstrates the beneficial impact of PF on boosting strength. This rise in strength occurs at ages 7-, 28-, and 90-d and is 1.2 %, 0.7 %, and 1.5 %, respectively. This little rise is because of the low tensile strength of PF, which has allowed for a slight increase in strength. By comparing the ages of 7, 28, and 90-d in control and 2.25-SF mixes, it can be inferred that these two mixes gained strength by 16 % and 26 %, respectively, at the 28-d and 90-d ages, and by 23 % and 40 %, respectively, at the 90-d ages. Moreover, when compared to 28-d, strength rose by 7 % and 13 %, respectively, at 90-d. And by comparing these two ages, it can be shown that as the age increases, the rates of strength development decreases, indicating that the microstructure of the concrete has improved through time.

4.3. Flexural strength

According to Table 4, the 2.25-SF mix with a flexural strength of 13.7 MPa had the greatest flexural strength, and the addition of 2.25 vol% SF enhanced the strength by 91 % when compared to the control mix. The addition of PF to the 2.0-SF-0.25-PF mix decreased the strength by 1.75 % to the 2.25-SF mix. In comparison to the 2.0-SF-0.25-PF mix, adding 0.5 vol% PF boosted the strength by 3.65 %. Abbas, Soliman and Nehdi [70] indicated that the adhesion and high stiffness of mortar and SF in UHPC result in the creation of various tiny fractures in the area of contact during fiber pull-out. However, unlike SF fibers, PF fibers are more prone to breakage, and in a limited instance, PF has been extracted from mortar without causing damage to the contact surface. Introducing fibers enhances the flexural strength and ductility of UHPGPC [39], but the extent to which this increase occurs is dependent on the kind, material, size, and volume of fibers used, among other factors. The hardness, splitting tensile strength, and flexural strength of

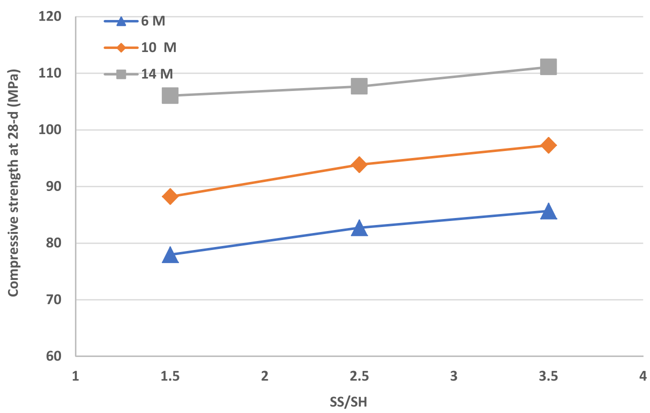

Fig. 3. Compressive strength of group 1.

Table 4
Mechanical characteristics of UHPGPC.

Mix	Density (kg/m^3)	Compressive strength (MPa)			Modulus of elasticity (GPa)	Flexural strength (MPa)	Splitting tensile strength (MPa)
	28-d	7-d	28-d	90-d	28-d	28-d	28-d
SS/SH-3.5-M14	2284	101	115	120	44	7.6	6.1
1.0-SF	2347	115	140	149	46	11.2	7.5
1.5-SF	2410	123	144	157	48	12.4	7.1
2.0-SF	2469	127	150	165	49	13.3	8.6
1.0-SF-0.25-PF	2354	123	145	155	47	11.5	7.4
1.5-SF-0.25-PF	2429	127	153	160	48	12.7	7.3
2.0-SF-0.25-PF	2495	128	154	168	49	13.6	8.4
1.25-SF	2374	122	147	159	47	11.7	7.5
1.75-SF	2447	126	152	158	48	12.8	8.5
2.25-SF	2497	129	162	175	48	13.7	7.7

UHPC are all dependent on parameters like the fiber surface, the roughness of the surface, and the binding strength between the aggregate and mortar. PF strengthens and enhances the matrix of GP cement paste, preventing the release of microcracks and altering the pattern of crack propagation [71]. SFs have a tougher surface than aggregates, and this fiber, also minimizing pores, strengthens the binding between the SF and mortar in the transitional contact zone [72]. In general, GPs are composed of the produced GP gel, unreacted aluminosilicate particles, and numerous voids [73,74].

By encircling the GP matrix with its two ends, fiber can act as a bridge element for fractures and holes, increasing the strength and stiffness of the GP matrix [73]. Thus, fiber blends have greater splitting tensile strength and flexural strength than non-fiber mixtures. Combining fibers of varied sizes, materials, and types results in the fiber effect. In general, the hybrid fiber's beneficial benefits on crack restriction may be clarified by two methodologies: first, there are more short fibers per volume due to their lower size in contrast to the same amount of added fibers. This event can optimally result in the creation of a bridge between the tiny fractures. Because of the short length of short fibers, they are less impacted by the integration of micro-fractures and the creation of bigger ones with greater crack widths. Second, in the event of macrocracks, long fibers are more efficient since they function as an impediment for short fibers and also restrict the rotation of short fibers, allowing short and long fibers to better match and work optimally together [75,76]. According to the findings, adding PF to SF in hybrid mixes has a beneficial impact, whereas substituting SF in mixtures has a negative impact [77]. As seen in Fig. 4, there is a high correlation between flexural strength and splitting tensile strength in the case of UHPGPC with an R^2 of 0.9557.

4.4. Splitting tensile strength

Based on Table 4, the addition of 2.25 vol% of SF to control concrete enhances splitting tensile strength by 33 %. In the 2.0-SF-0.25-PF mix, substituting the PF lowered tensile strength by 4.5 % to the 2.25-SF mix, while introducing PF increased tensile strength by 1.9 % to the 2.0-SF mix. According to the findings, introducing PF to the 2.0-SF mix had a favorable impact. Tensile strength in fiber specimens is higher than in non-fiber specimens because of the bridging effect on fractures [78]. Fig. 5 depicts the significant relation between compressive strength and splitting tensile strength in the context of UHPGPC with a correlation coefficient (R^2) of 0.9467.

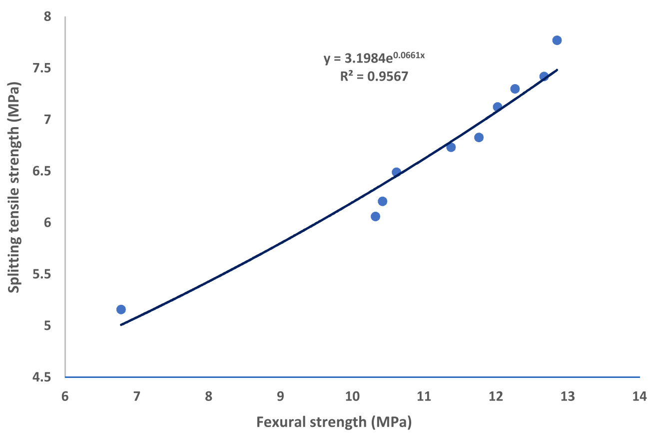

Fig. 4. Relationship between flexural strength and splitting tensile strength.

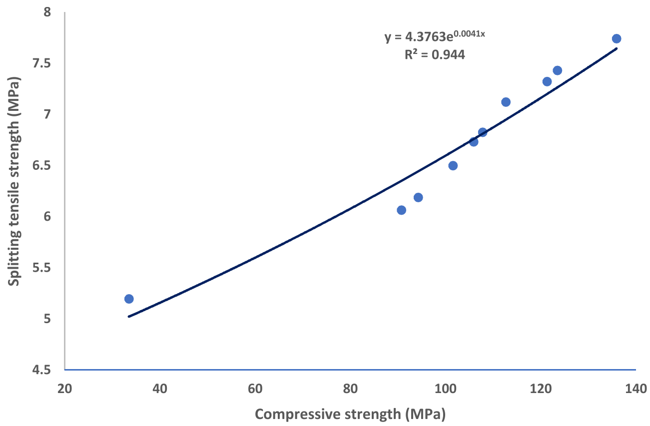

Fig. 5. Relationship between compressive strength and splitting tensile strength.

4.5. Modulus of elasticity

The findings imply that raising the volumetric percent of fibers affects the UHPGPC modulus of elasticity and results in its enhancement. According to Table 4, increasing the SF content by 2.25 vol% results in a 131 % over the control mix. By substituting 0.5 vol% of PF for 2.0 vol% of SF in the 2.0-SF-0.25-PF mix, a 1.24 % reduction compared to the 2.25-SF mix. In comparison to the 2.0-SF-0.25-PF mix, introducing this volume of PF results in a 0.38 % modulus of elasticity.

4.6. Scanning electron microscopy (SEM) analysis

The microstructure of UHPGPC as revealed by SEM is depicted in Fig. 6. Overall, it was observed that UHP-mechanical GPC's behavior was linked to its microstructure. It was discovered that a thick microstructure, in particular, improves mechanical behavior. Fig. 6-a show that essentially no unreacted material was found, indicating that a significant amount of GBFS was dissolved and then participated in the polymerization.

Meanwhile, globular sodium hydro-aluminosilicate (N-A-S-H), silicates, and aluminates were present in the system. It should be noted that the silicates and aluminates discovered here contained highly crystallized hydro-silicates and hydro-aluminates, as seen in Fig. 6-b.

Furthermore, it was discovered that the interaction transition zone (ITZ) between the binding phase and aggregate was substantially denser and less apparent. As a result, the much larger interfacial transition zone and microstructure seen in Fig. 6-c provided a superior bonding feature with the aggregates, as discovered by Xie, Wang, Rao, Wang and Fang [79].

Fig. 6-c depicts the ITZ between steel fiber and UHP-GPC. The ITZ between the UHPGPC and the steel fiber was nearly faultless, suggesting a superb bonding. It improved the mechanical behavior of UHPGPC by ensuring the synergy of the steel fiber and matrix.

4.7. Rapid chloride penetration test

The chloride penetration test makes the assumption that the flow is carried through the specimen by the concrete's pore sol, which functions as an electrolyte. Because of the fact that the number and consistency of pores in concrete specimens affect the passing of ions and hence the current rate, it is predicted that porous specimens with continuous pores would have a high passing flow, whereas specimens with limited porosity will have a small-passing-flow. Due to the low water/binder ratio in UHPC, an extremely thick microstructure forms in the hardened paste, significantly reducing permeability [72]. Based on Fig. 7, the inclusion of fibers decreased the current rate and enhanced the concrete durability by reducing drying and plastic shrinkage cracks, leading to decreased permeability [70,80]. Ramezanianpour et al. [78] determined that coating the fibers with calcium silicate hydrate gel and building a link among them lowers the conductance of pores and voids, hence improving the concrete resistance to chloride ion penetration [70].

Abbas et al. [70] demonstrated that the introduction of SF decreased porosity and hence enhanced durability using mercury intrusion porosimetry. Furthermore, Scanning electron microscopy (SEM) inspection revealed a thick border region between the matrix–aggregate and fiber–matrix, implying limited permeability because of decreased porosity. The largest and lowest passing flows are associated with control and 2.0-SF-0.25-PF, respectively, and the current is lowered by about 47 % in comparison to the control mix. On the contrary, substituting PF for SF in the 2.0-SF-0.25-PF mixes results in a 6.2 % drop in current-flow compared with the 2.25-SF mix, owing to the PF's extremely low conductivity in comparison to SF [81,82]. As PF is added to the 2.0-SF-0.25-PF mix, the passing flow is reduced by 12.2 % to the 2.0-SF mix. Raising the volume fraction of fibers usually results in a drop in flow rate in all mixes, whereas PF has a beneficial impact on hybrid mixes owing to its high low conductivity. Permeability of all mixes versus chloride ion has been set to a very-low value dependent on the flow rate of ASTM-1202 [83].

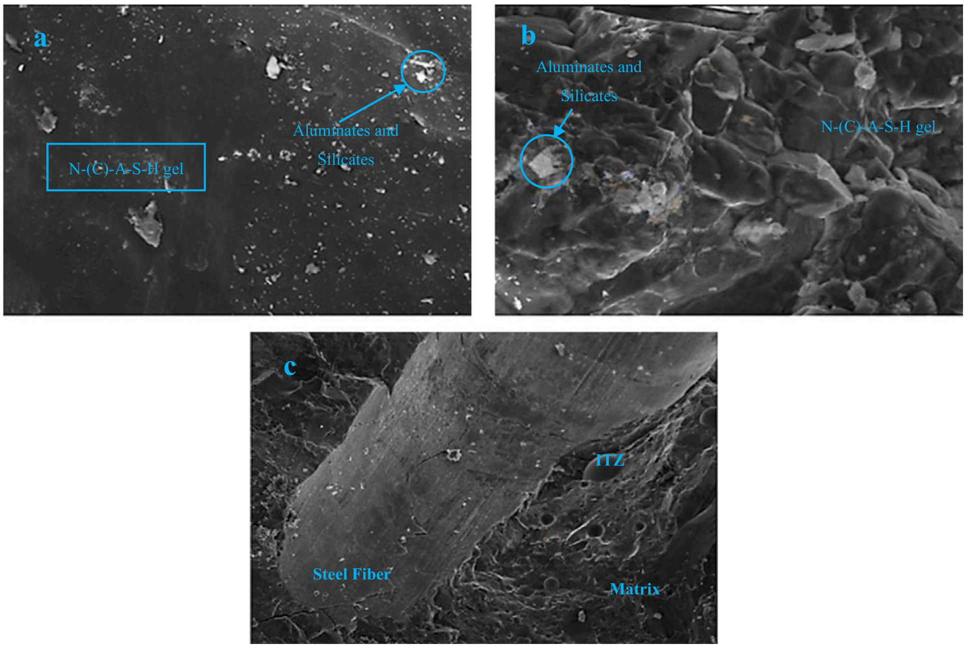

Fig. 6. SEM analysis.

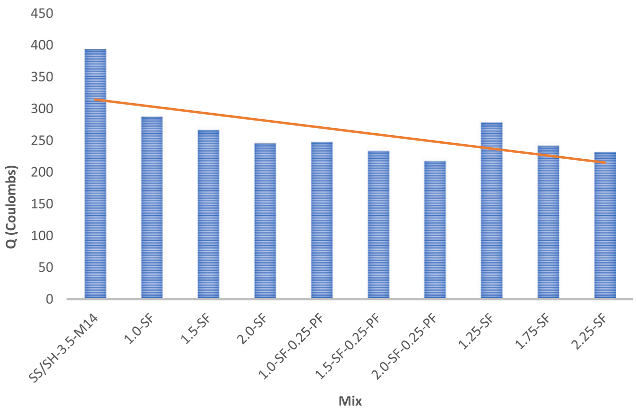

Fig. 7. Chloride penetration test findings.

4.8. Further discussion

Introduction of polypropylene fiber (PF) and steel fiber (SF) comprising microsilica and granulated blast furnace slag (GBFS) in UHPGPC improves mechanical characteristics. Increased steel fiber content significantly improves the mechanical behavior of UHPGPC, in line with previous studies on Portland cement-based UHPC [84]. This is because introducing more steel fiber reduces the mean space between the steel fibers and increases the pressure between the matrix and the steel fibers, which reduces the inception and propagation of cracks. Nevertheless, substituting SF for PF results in a decrease in the mechanical characteristics of UHPGPC. This might be because PF has a lower tensile strength than SF.

5. Conclusions

The main conclusions are as follows:

1. The inclusion of steel fibers reduced the workability of fresh ultra-high-performance geopolymer concrete composite mixtures. The workability reduced as the fiber dose increased.
2. Mechanical characteristics dramatically improve as the volume fraction of fibers in UHPGPC increases. The UHPGPC with a 2.25 % volume percentage of SF exhibits the optimum mechanical strength.

3. According to the findings, substituting SF for PF results in a decrease in the mechanical characteristics of UHPGPC. This might be because PF has a lower tensile strength than SF.
4. According to the findings obtained, the specimen with the highest 28-d compressive strength is a plain UHPGPC specimen with a 14 molar NaOH sol and a Na_2SiO_3/NaOH ratio of 3.5. This mixture was chosen as the optimal one for synthesizing the UHPGPC.
5. The findings indicate that raising the dosage of NaOH sol from 6 to 14 molarity and the ratio of Na_2SiO_3/NaOH from 1.5 to 3.5 enhances the compressive strength of plain UHPGPC specimens.
6. According to the SEM examination, the primary reaction products were zeolite, dolomite, C-(N)-AS-H gel, and N-(C)-A-S-H gel. At a microsilica volume of 25 %, a substantially adequate polymerization reaction and a densified micromorphology were produced. Meanwhile, SEM investigation revealed the faultless ITZ between UHPGPC and steel fiber.

6. Future studies

In future studies, more detailed investigations need to be conducted on mechanical UHPGPC, including the effects of curing procedure, binder materials, activator, and fiber type on the mechanical performance and durability of UHPGPC.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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