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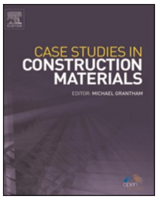

Influence of microsilica and polypropylene fibers on the fresh and mechanical properties of ultra-high performance geopolymer concrete (UHP-GPC)

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ABSTRACT

The goal of this research is to identify the impact of microsilica and polypropylene fibers (PF) on the mechanical characteristics of an ultra-high performance geopolymer concrete (UHP-GPC). The workability, compressive strength, modulus of elasticity, and splitting tensile strength of a total of 20 concrete mixtures were evaluated experimentally. To produce the mixtures, PF was utilized at four different volume fractions: 0 %, 0.75 %, 1.75 %, and 2.75 %. Moreover, five microsilica levels were employed in terms of the total mass of the binder: 0 %, 7.5 %, 15 %, 25 %, and 35 %. The findings showed that when 15 % microsilica was added to UHP-GPC, the mechanical characteristics were significantly degraded, but then enhanced when more than 15 % microsilica was added. Furthermore, PF contributes significantly to the mechanical characteristics of UHP-GPC and introducing 2.75 % PF minimizes a significant drop in the characteristics of UHP-GPC when 15 % microsilica is employed. ↱

1. Introduction

Ultra-high-performance concrete (UHPC) is “a generic term referring to a composite made of ordinary Portland cement (OPC) that has an ultra-high CS, better durability, and high toughness [1,2–5]. It is especially well suited for the construction of blast resistant structural elements [6], long span bridges [7], and structures exposed to severely aggressive environments [8]. Nonetheless, the mass of OPC in UHPC is typically 700–1200 kg/m^3, which is 2–3 times the amount in conventional concrete [9–15]; the production of OPC requires significant amounts of natural resources and energy and creates significant amounts of Carbon dioxide [16–18]. Producing one ton of clinker is predicted to require 6.65 Mega Joule of energy and emit approximately 0.83 tons of Carbon dioxide [19–24]. The researchers attempted to lower the binder volume and substitute extra cement-based materials for OPC. Yu, Spiesz and Brouwers [25] stated that a UHPC matrix with a reduced binder volume of 655 kg/m^3 was made, resulting in a 31 % reduction in Carbon emissions [5,

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Abbreviations: CS, Compressive strength; GBFS, Granulated blast furnace slag; MoE, Modulus of elasticity; OPC, Ordinary Portland cement; PF, Polypropylene fibers; SF, Steel fiber; STS, Splitting tensile strength; UHPC, Ultra-high-performance concrete; UHP-GPC, Ultra-high performance geopolymer concrete.

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Table 1↱
Chemical components of binder materials [49].↱.

“Chemical component	GBFS	FA	Microsilica
sodium silicate	96.44	56.90	35.31
CaO	1.55	1.85	38.51
Al_2O_3	–	31.88	16.56
K_2O	0.73	1.98	0.67
MgO	0.23	0.48	6.88
Na_2O	0.67	2.52	0.32
Fe_2O_3	0.56	2.55	0.57
SO_3	–	0.43	2.57
Others	0.85	–	–
LOI at 1000 °C	–	4.44	1.7″

21,26,27]. Wu, Shi and He [28] also discovered that substituting 40 % and 20 % OPC with granulated blast furnace slag (GBFS) and fly ash, respectively, could increase the ultimate FS of” UHPCs.↱ Here one can develop the overview: Substitution of 50 % of OPC with granulated blast furnace slag could increase the water-reducing effect of polycarboxylate superplasticizer and accordingly the strength of UHPCs [29,30].

In comparison to OPC, geopolymer (GP) is “a low-Carbon binder, and clinker-free[31]. It is made by activating solid alumino-silicate resources like fly ash [32], GBFS [33], waste glass [34], and metakaolin [35] with alkaline sols like silicate, alkali hydroxide, carbonate, and/or sulfate. It may be used to create GP concrete [36] with mechanical characteristics equal to those of OPC concrete [37] or with higher characteristics, for example, compressive strength, frost resistance[14]. The most recent advancement in sustainability has resulted in the endeavor to make UHP-GPC by employing GP as a binder. Ambily, Ravisankar, Umarani, Dattatreya and Iyer [38] showed that the greatest CS and flexural strength of UHP-GPC with 2 % steel fiber (SF) were 175 MPa and 13.5 MPa after 28-days (-d), respectively, when activated with alkali silicate and hydroxide sols. Wetzel and Middendorf [39] and Aydın and Baradan [40] also employed microsilica and GBFS to make UHP-GPC, achieving CS more than 150 MPa. Numerous publications have indicated that pure GBFS-based GPs exhibit difficulties like rapid setting [41], high shrinkage [42], low flowability [43], and mechanical property loss during carbonation [43]. Blending GBFS and fly ash appears to be more hopeful than utilizing pure GBFS for obtaining good fresh and hardened characteristics and durability of GP concrete [43]. There appears to be considerable space for improvement in these areas of UHP-GPC” composition. ↱.

The two primary components of UHP-GPC are “SF and microsilica. The addition of SF improves impact resistance and ductility substantially. Wu, Shi and Khayat [44] found that adding 1–3 % straight SFs significantly improved the CS and flexural strength behavior of UHPC; however, it was concluded that there was an optimal fiber volume for improving the mechanical characteristics of UHPC. Once the SF content approached 2 %, the toughening and reinforcing characteristics of fibers deteriorated. Similarly, Aydın and Baradan [40] showed that when the SF volume was raised to 2 %, the addition of SFs with a length of 6 and 13 mm had a negligible effect on the CS, flexural strength, and toughness characteristics of UHP-GPC. Moreover, because of the relatively high cost of fiber, proper control of its composition is critical for commercialisation and” applications [45].

Microsilica plays “a vital part in strengthening the mechanical and long-term characteristics of OPC-based UHPC, namely throughout its dense packing impact [46]. Moreover, a previous study has shown that adding 10–15 % microsilica to UHPC improves its rheological characteristics [47]. Although numerous prior studies indicated that adding microsilica to GP concrete increased strength development, it decreased workability [48]. Wetzel and Middendorf [39] revealed that adding a sufficient amount of microsilica improved the workability and CS of” UHP-GPC. However, This study aims to determine the effect of microsilica and polypropylene fibers (PF) on the mechanical properties of ultra-high performance geopolymer concrete (UHP-GPC). Experiments were conducted to determine the workability, compressive strength, modulus of elasticity, and splitting tensile strength of 20 concrete mixes.

2. Research significance

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

3. Materials and samples characteristics

In this experiment, “the following raw materials are used to make UHP-GPC mixtures: fly ash, GBFS, and microsilica. The chemical content of various materials is summarized in Table 1. Fly ash, GBFS, and microsilica had effective surface areas of 290, 455, and 1860 m^2/kg, with average particle sizes of 38, 17, and 0.18 μm. An alkaline activator is employed to synthesize UHP-GPC. This activator is prepared using sodium silicate, sodium hydroxide (NaOH), and water that has been allowed to cool to ambient temperature for one day prior to the production of UHP-GPC. To begin, the binders (fly ash, GBFS, and microsilica) were dry blended for 3 min, followed by the addition of silica sand and another 2 min of blending. The activator was then applied to the mixture and blended for 3 min. The industrial-class NaOH in form of pellets is 95 % pure. The sodium silicate is a high-quality commercial waterglass composed of 64 % water, 28 % silicon dioxide, and 6 % sodium oxide by mass. PF was utilized to made fiber reinforced concrete. Table 2 summarizes the

Table 2
Properties ↱of PF.

Fibers	Specific weight (kg/m^3)	MoE (GPa)	Tensile strength (GPa)	Failure strain (%)
PF	940	2.95	275	3.5

Table 3↱
Concrete mix characteristics (kg/m^3).↱.

Samples	Microsilica	Fly ash	GBFS	Silica sand	NaOH	Water	Water-glass	PF
0mS-0PF	0	190	700	915	60	100	325	0
0mS-0.75PF								12
0mS-1.75PF								22
0mS-2.75PF								29
7.5mS-0PF	55	190	700	915	60	100	325	0
7.5mS-0.75PF								12
7.5mS-1.75PF								22
7.5mS-2.75PF								29
15mS-0PF	100	175	660	915	60	100	325	0
15mS-0.75PF								12
15mS-1.75PF								22
15mS-2.75PF								29
25mS-0PF	190	155	590	915	60	100	325	0
25mS-0.75PF								12
25mS-1.75PF								22
25mS-2.75PF								29
35mS-0PF	280	135	520	915	60	100	325	0
35mS-0.75PF								12
35mS-1.75PF								22
35mS-2.75PF								29

characteristics of PF. In this work, PF was introduced to UHP-GPC mixtures at four different volume volumes (0 %, 0.75 %, 1.75 %, and 2.75 %), in order to improve the mixture's mechanical characteristics. PF has a length of 50 mm and a diameter of 0.032 mm" [49].

The ratios of the UHP-GPC mixtures are shown in Table 3. The "water/binder ratio was maintained at 0.34. Moreover, a 4:1.1 mass ratio of GBFS to fly ash and a sand/binder ratio of 1.12 were considered while designing the mixtures. One specimen was used as a reference, devoid of PF and microsilica. Moreover, to investigate the effect of microsilica on the efficiency of UHP-GPC, microsilica was employed at five different mass volumes (0 %, 7.5 %, 15 %, 25 %, and 35 %).

All mixtures were produced at room temperature of 25 °C and relative humidity of 70 %. "To accomplish this, all ingredients were combined in a blender and gradually water was added, followed by the molding of the samples. They were coated and cured at room temperature in the steam curing box at 85 °C for 24 h following molding. They were then removed from the mold and kept in a curing water tank for 28-days before being evaluated" [49].

4. Experimental methods

Several experiments were "conducted in this work to determine the mechanical characteristics of PF-reinforced UHP-GPC. The subsequent sections outline the testing" procedure.

4.1. Workability

In accordance with ASTM C143–13 [50], "the influence of varied fiber inclusions on the workability of fresh ultra-high-performance geopolymer concrete composites was assessed in terms of flow diameter". Flow tests were performed immediately following the mixing of each batch, and each mix was tested twice.

4.2. Compressive strength and modulus of elasticity

The compressive behavior of the samples was "evaluated in this study using the CS and MoE. The CS test was conducted using 100 mm cubic samples in accordance with ASTM C39 [51]. Moreover, cylindrical samples of 100 × 300 mm in diameter were utilized to determine the MoE in accordance with ASTM C-469/C-469 M [52]. To accomplish this, a steel ring fitted with a strain gage was placed about the cylindrical ↱sample, the sample's stress-strain measurements were collected, and the MoE was calculated as the initial-tangential slope of the stress-strain" curve [52]. ↱.

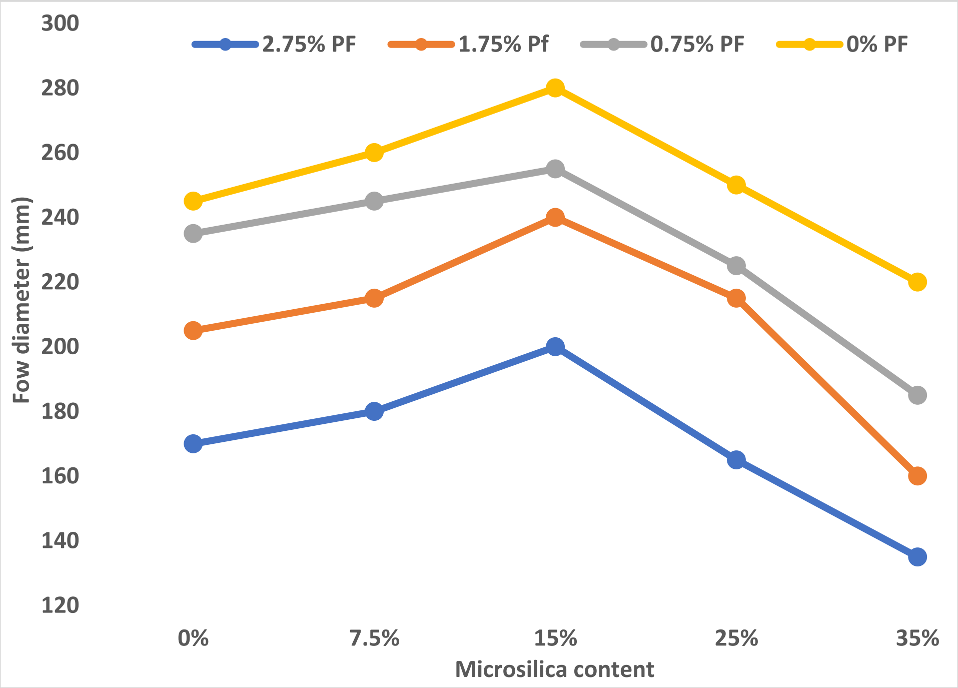

Fig. 1. The influence of various fiber mixes on the flowability of geopolymer composites.

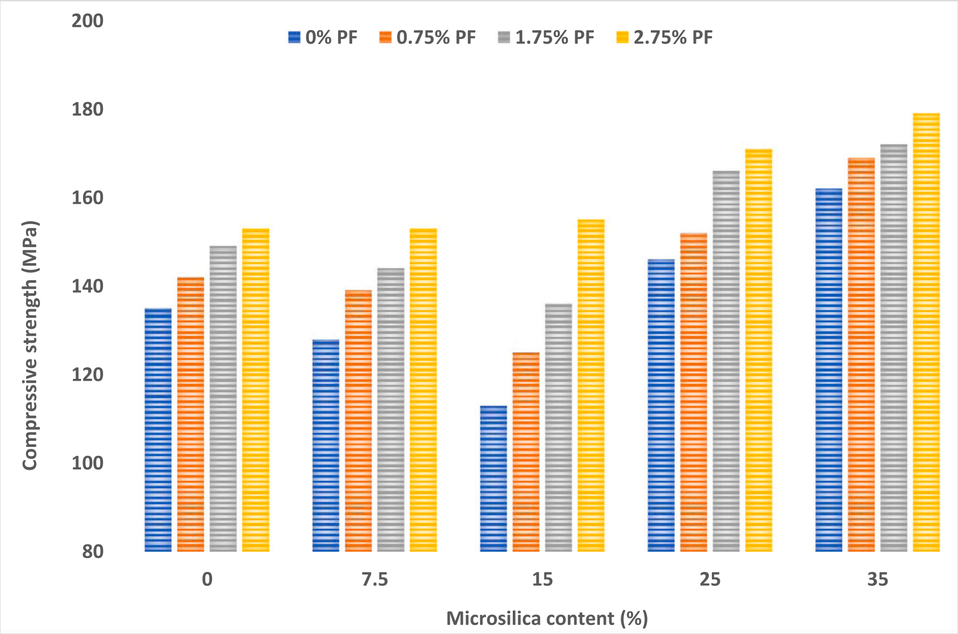

Fig. 2. Impact of microsilica and PF on the compressive strength of UHP-GPC.

4.3. *Splitting tensile strength*

To determine the STS of the mixtures, "the Brazilian-test in accordance with ASTM C-469 was utilized [53]. To conduct this experiment, 150 × 300 mm cylindrical concrete samples were placed on the lateral surface of a hydraulic jack". ↱.

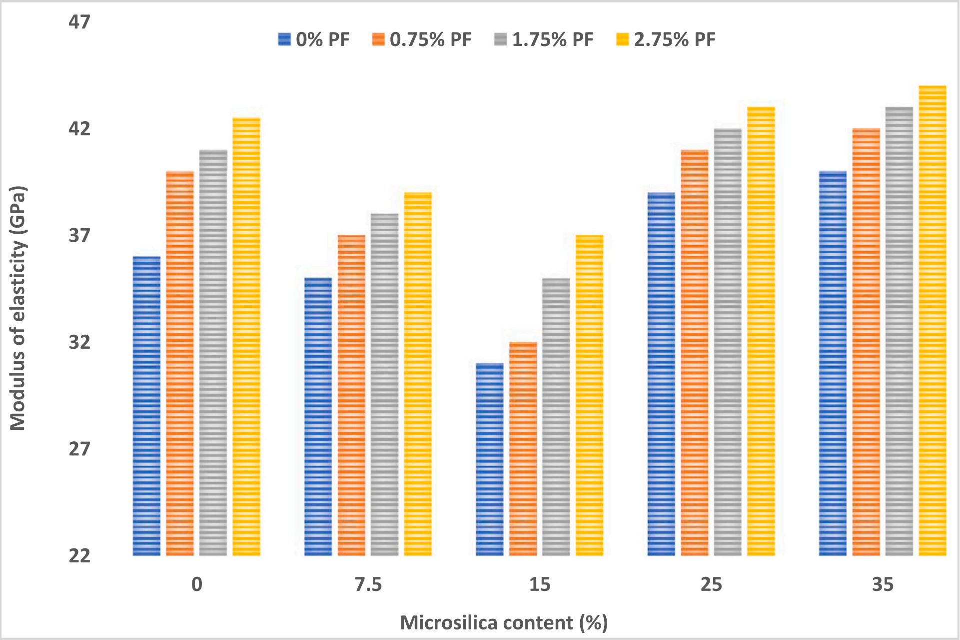

Fig. 3. Impact of microsilica and PF on the MoE of UHP-GPC.

5. Results and discussions

5.1. Workability

The effect of different PF inclusions on the workability of fresh ultra-high-performance geopolymer concrete composites is compared in Fig. 1. 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 PF increased [54–56], the flow diameter decreased respectively. Moreover, it should be noted that the addition of higher volume fraction of PF, such as 1.75 % and 2.75 % produced slightly harsh mixes in the fresh state under the static mode [57–59]. Variations in flow diameters, on the other hand, were measured for composites made from ternary mixing of fly ash and slag. The decreased workability of fly ash or slag-containing mixes is due to an increase in calcium content and its quick reactivity with the alkaline activator, where extra calcium functioned as nuclei for the precipitation of dissolved species from fly ash and influenced the coagulation rate” [60–64].

5.2. Compressive strength (CS) and modulus of elasticity (MoE)↱

The CS and MoE are investigated in this work to determine the effect of microsilica and PF on the CS behavior at age of 28 days of UHP-GPC. Figs. 2 and 3 present the findings. In this study, the minimum CS and MoE of UHP-GPC were determined when 15 % microsilica was utilized. The primary explanation for UHP-brittle GPC’s behavior is activator incorporation. Moreover, microsilica aids in altering the activator’s characteristics [65–68]. Nevertheless, the inclusion of upto 15 % microsilica has no effect on the activator’s characteristics, and the CS of UHP-GPC decreases. In contrast, the high effective surface area and activity of microsilica resulted in a large rise in the amount of $(SiO_4)^{4-}$ in the activator, leading to a boost in the activators-activity when 35 % microsilica was utilized. As a result, the largest CS and MoE values were recorded when 35 % microsilica was applied. Even though the greatest MoE was attained with 35 % microsilica, the variation in MoE between UHP-GPC comprising 25 % and 35 % microsilica was minor. As a result, the microsilica volume might be restricted to 25 % in terms of the maximum MoE as shown in Fig. 3.

Moreover, the inclusion of PF increased the CS and MoE of UHP-GPC substantially, and these characteristics were further improved by increasing the PF volume. The primary reason that PF improves the compressive behavior of UHP-GPC is that they act as a bridging agent [69], forming a high core strength inside the concrete specimen during compression and preventing lateral-expansion. When a sample is compressed, a lateral-expansion happens in the center of the sample’s height. The bridging function of PF enhanced the cohesiveness between the concrete aggregates and paste and the tensile strength of the concrete matrix [34,35,70–72], which limits lateral-expansion and therefore improves the compressive behavior of PF-reinforced UHP-GPC. As a result, the maximum CS and MoE values were reached when 2.75 % PF was introduced, and much more so when 35 % microsilica was introduced well as. ↱.

Thus, the inclusion of 35 % microsilica with 0 %, 0.75 %, 1.75 %, and 2.75 % PF increased the CS by around 20 %, 19 %, 15 %, and 17 %, respectively, as compared to the reference mix without microsilica, as shown in Fig. 2. In Fig. 3, the MoE was increased by 8.3 %, 2.5 %, 2.4 %, and 2.3 % when 25 % microsilica was blended with 0 %, 0.75 %, 1.75 %, and 2.75 % PF, respectively. The CS and MoE patterns are comparable with those seen in prior research on steel fiber reinforced GP concrete [73] and UHPC [74,75]. Investigators

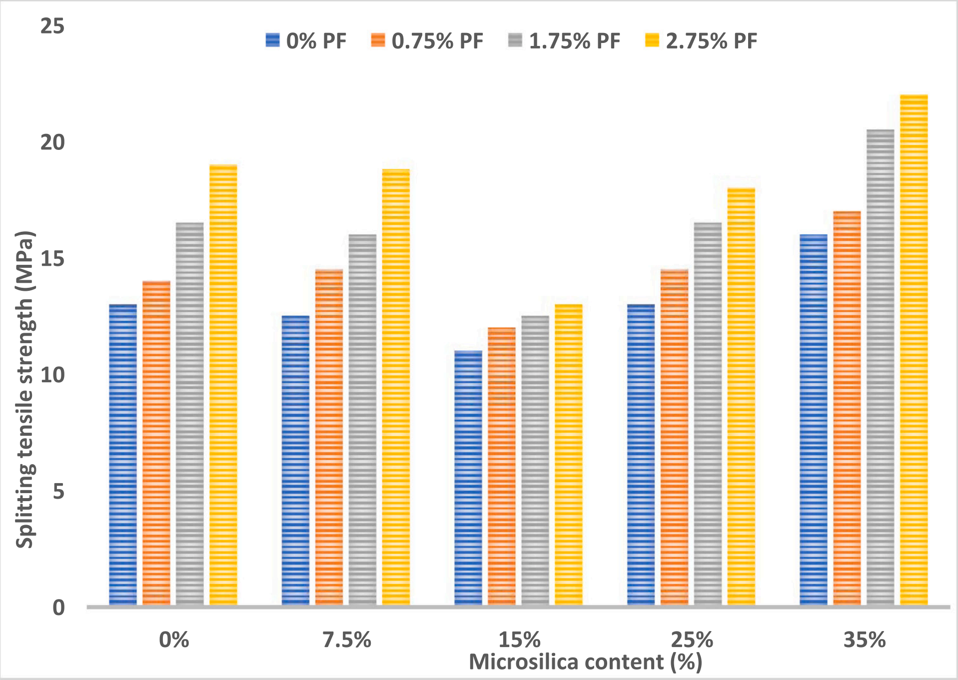

Fig. 4. Impact of microsilica and PF on the STS of UHP-GPC.

demonstrated that increasing the fiber volume resulted in a decrease in the area between fibers, which constrained the spread of cracks in the samples [76,77]. Moreover, the greater MoE of fibers compared to paste led to an increase in the MoE of fiber-containing concrete samples. According to Liu, Shi, Zhang, Li and Shi [78] investigation on the mechanical properties of UHP-GPC with microsilica and microsilica powder, adding microsilica improved the CS of UHP-GPC [68,79–83]. It increased by around 22 % when 15 % microsilica was added to the mix, compared to 7.5 % microsilica.

5.3. Splitting tensile strength (STS)

A previous study demonstrated that adding fibers to fiber reinforced fly ash/GBFS-based GP concrete had no effect on CS while increasing bond strength owing to the fibers' better adherence to the paste [84–86]. Moreover, when the microsilica volume was raised to 15 %, the activator's characteristics altered, affecting the generation of strength development and interaction products. Nevertheless, as seen in Fig. 4, the STS of UHP-GPC improve as the PF volume increased, owing to the reduction of fracture width and arrest occurs. Moreover, the MoE of PF is significantly greater than that of concrete paste, resulting in an improvement in STS. In comparison to samples without microsilica, introducing 0.75 %, 1.75 %, and 2.75 % PF increased the STS by 7 %, 26 %, and 46 %, respectively, since the tensile strength of the cement matrix increased owing to the bridge's role and higher MoE of PF. According to the CS and MoE, the STS of UHP-GPC first decreased with the addition of upto 15 % microsilica and subsequently rose as the volume was raised. As a result, the highest STS was seen when 35 % microsilica was utilized, and much more so when 2.75 % PF was introduced as well, as shown in Fig. 4. As the microsilica content grew to 35 %, the contribution of micro-structure enhancement concrete increased proportionately [87–89].

The matrix enhanced the activator's action, which resulted in an increase in STS. Thus, including 35 % microsilica with 0 %, 0.75 %, 1.75 %, and 2.75 % PF increased the STS by 21 %, 21 %, 24 %, and 15 %, respectively, as compared to the reference mixture.↱

6. Conclusions↱

As per the experiments, the following conclusions can be drawn: ↱.

1. The addition of steel fibers to fresh ultra-high-performance geopolymer concrete composite mixes decreased their workability. The workability decreased as the amount of fiber increased.
2. Using water-glass as an activator, on the other hand, had a fluidizing impact and increased the workability of UHP-GPC in comparison to UHPC. ↱
3. MoE, CS, and STS of UHP-GPC were reduced to a minimal value when 15 % microsilica was used and then significantly increased when more than 15 % microsilica was used.

4. Including 35 % microsilica with 0 %, 0.75 %, 1.75 %, and 2.75 % PF enhanced the CS by about 20 %, 19 %, 15 %, and 17 %, respectively, when compared to the reference mix without microsilica.
5. Including 35 % microsilica with 0 %, 0.75 %, 1.75 %, and 2.75 % PF increased the STS by 21 %, 21 %, 24 %, and 15 %, respectively, as compared to the reference mixture. ↱↱

7. Future studies

In future research, it will be necessary to investigate the impacts of curing method, activator, binder materials, and **fibre** type on the performance of mechanical UHP-GPC in full depth.

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.

Data Availability

No data was used for the research described in the article.

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