

Research Article

Developing Geopolymer Concrete Properties by Using Nanomaterials and Steel Fibers

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This research investigates the simultaneous impact of two different types of steel fibers, nanometakaolin, and nanosilica on the mechanical properties of geopolymer concrete (GPC) mixes. To achieve this aim, different geopolymer concrete mixes were prepared. Firstly, with and without nanomaterials (nanosilica and nanometakaolin) of 0, 2%, 4%, 6%, and 8% from ground granulated blast furnace slag (GGBFS) were used. Secondly, steel fiber (hooked end and crimped) content of (0, 0.5%, 1, and 1.5%) was used. Thirdly, optimum values of nanomaterials with the optimum values of steel fiber were used. Crimped and hooked-end steel fibers were utilized with an aspect ratio of 60 and a length of 30 mm. Geopolymer mixes were manufactured by using a constant percentage of alkaline activator to binder proportion equal to 0.45 with GGBFS cured at ambient conditions. For alkaline activator, sodium hydroxide molar (NaOH) and sodium hydroxide solution (NaOH) were used according to a proportion ($\text{Na}_2\text{SiO}_3/\text{NaOH}$) of 2.33. The hardened concrete tests were performed through the usage of splitting tensile strength, flexural, and compressive experiments to determine the impact of steel fibers, nanometakaolin, and nanosilica individually and combined on performance of GPC specimens. The results illustrated that using a mix composed of the optimum steel fibers (1% content) accompanied by an optimum percentage of 6% nanometakaolin or 4% nanosilica demonstrated a significant enhancement in the mechanical properties of GPC specimens compared to all other mixtures. Besides, the impact of using nanomaterials individually was found to be predominant on compressive strength on GPC specimens especially with the usage of the optimum values. However, using nanomaterials individually compared to using the steel fibers individually was found to have approximately the same splitting tensile strength and flexural performance.

1. Introduction

Concrete is considered as the most commonly used structural material because of the ease of shaping and the availability of raw materials. Nevertheless, considerable quantity of greenhouse gases (CO_2) is found to be emitted to the atmosphere due to the limestone decarbonization of fossil fuel consumption throughout the production process of cement. Besides, manufacturing cement especially ordinary Portland cement (OPC) is recognized as the most consuming material of energy after steel and aluminum [1, 2]. Thus, a huge quantity of energy is required, and subsequently, the negative environmental impact of CO_2

energy is recognized as critical issues for both human beings and industry of cement. The usage of the recent modern environmentally friendly materials in structure has been recognized to be essential in order to overcome the environmental problems [3, 4]. Lately, an environmentally friendly concrete such as geopolymer concrete appeared to be an alternative for OPC [5–7]. The usage of geopolymer concretes has drawn the attention due to the worldwide need for reducing CO_2 emission and natural resources consumption. Unlike OPC, a reduction in energy consumption was observed due to the fabrication of the raw materials which do not demand a calcining process. It was claimed in other research that the quantity of CO_2 emitted from the

geopolymer concrete is around 5 to 6 times lower in comparison with the concrete made by OPC [8, 9]. Moreover, the geopolymer concrete could utilize the byproduct wastes of aluminosilicate composition to manufacture inventive construction materials besides reducing the emissions of CO₂ significantly [10, 11].

Supplementary cementitious materials (SCM) and mineral fillers were utilized to harden concretes state properties, improve the workability, and reduce the cost [7, 12, 13]. Ground granulated blast furnace slag (GGBFS) and fly ash were utilized in the scientific research widely as in SCM because of their significant contributions to the economy, environment, and concrete mechanical performance [11, 14].

Concrete is characterized by poor ductility and tensile strength, and thus generally steel fibers (SFs) were utilized to eradicate the previously mentioned disadvantage [15]. Steel fibers were utilized to enhance the concrete ductility, toughness, and postcracking [16, 17]. Moreover, steel fiber reinforced concrete afforded more tolerable costs/benefits proportion in comparison with the ordinary concrete [18]. The design procedure and optimization approach to accomplish the requirements of concrete relied on the content as well as characteristic of fiber [19–21]. Economically, 1% is recognized as the best steel fiber quantity of concrete volume in most structures [22].

Geopolymer or alkali-activated concrete is considered from the green material which is characterized by the hardened state performance that demands a lower energy quantity and produces a lower carbon dioxide quantity in comparison with the ordinary concrete in the production state [23]. Thus, the geopolymer material is considered as an alternative to the OPC as geopolymer is recognized to be an inorganic binding material [24]. Specifically, the utilization of the fly ash-based geopolymer concrete as an alternative for ordinary cement was taken into account due to the ability of absorption and immobilization for radioactive and toxic materials. The fly ash-based geopolymer concrete's durability and mechanical performance were considered as a major interest in the industry of concrete [25]. Besides the usage of fly ash, red mud [26], waste glass powder [24], and phosphate sludge [27] were also used as a cheap raw material for the preparation of geopolymer. In recent research, the utilization of waste materials such as silica fume and ground granulated furnace slag as a replacement for fly ash in geopolymer concrete (GPC) was investigated [24]. According to the previous research, the fly ash and ground granulated blast furnace slag- (GGBFS-) based geopolymer concrete were recognized as the common GPC type that has been used. For instance, the usage of 100% slag-based GPC is durable and stronger than the usage of 100% fly ash-based GPC because slag-based GPC possesses more strong and stable structure of cross-linked aluminosilicate polymer [28]. The fresh state properties were affected negatively when steel fiber and nanosilica were combined together [29]. Nevertheless, the usage of steel fiber and nanosilica combination obviously enhanced flexural performance and bond strength of the self-compacting GPC samples for 50% GGBFS and GPC-based 50% fly ash (FA). GPC with two types of low

calcium FA (FAI and FAII) without and with NS was produced and compared to OPC concrete by Çevik et al. in order to investigate the performance of short-term severe durability [30]. The results showed that under chemical attacks, the fly ash GPC concrete possesses much better performance compared to OPC concrete because of the low calcium content. Thus, it can be recognized that studying geopolymer concrete should be extended.

The enhancement in the concrete performance through using nanometakaolin (NMK) and nanosilica (NS) was observed in the previous conducted studies. So, NMK and NS are commonly used in the current research. Nevertheless, the literature is limited in the research area regarding the mechanical characteristics (flexural, splitting tensile, and compressive strength) of ground granulated blast furnace slag- (GGBFS-) based geopolymer concrete (GPC). Geopolymer concrete is not included in the structural applications and structural design codes because of the lack of knowledge about the material characterization of geopolymer concrete. Thus, additional research is required to enhance the knowledge regarding GPC mechanical properties. Hence, the aim of this research is to study the simultaneous influence of NS, NMK, and two different types of steel fibers (hooked end and crimped) individually or combined on the mechanical performance of the GPC specimens.

2. Experimental Details and Methodology

2.1. Materials. Geopolymer concrete (GPC) mixes without and with nanosilica (NS) and nanometakaolin (NMK) (0, 2, 4, 6, and 8%) and without and with steel fiber (SF) (0, 0.5, 1, and 1.5%) were manufactured for the analysis of the GPC mechanical performances and the simultaneous impact of SF and NS on the concrete. Ground granulated blast furnace slag (GGBFS) was utilized as the binder material in the current study. High-calcium precursor GGBFS was locally produced (from Iron and Steel Factory, Helwan, Egypt) accompanied by 2.84 specific gravity and 425 m²/kg specific surface area. NS particles have a specific surface area of 200 m²/g. Microstructure characteristics and the particle size distribution tests of (GGBFS, NS) were carried out with dry-dispersion laser diffraction and image analysis through the usage of scanning electron microscopy (SEM). The raw powder materials' physical and chemical characteristics are shown in Tables 1 and 2, while Figure 1 shows the GGBFS and NS microstructure images.

A mixture of sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) solutions was used as geopolymerization alkaline activator. In this research, potable water was utilized to dissolve the pellets of pure NaOH to provide an aqueous compound accompanied by the demanded concentration. The potable water glass chemical composition includes 30% silicon dioxide (SiO₂), 12% sodium oxide (Na₂O), and the remainder is water. Superplasticizer based on polycarboxylic-ether formulation with 4.3–4.7 pH value and 1.06 kg/liter density (20°C) was utilized in all mixtures to achieve the demanded workability for geopolymer concrete.

TABLE 1: Physical properties and XRF analysis results of fly ash, slag, and nanosilica.

Content	GGBFS (%)	NS (%)	NMK (%)
SiO ₂	35.59	99.65	45.5
TiO ₂	0.51	0.02	1.5
Al ₂ O ₃	11.01	0.01	37
Fe ₂ O ₃	1.38	0.012	0.2
MnO	3.24	<0.01	
MgO	5.43	<0.01	0.02
CaO	34.07	<0.01	0.01
Na ₂ O	1.39	<0.01	0.03
K ₂ O	0.73	<0.01	0.07
P ₂ O ₅	0.12	<0.01	—
SiO ₃	3.62	—	—
Cl	0.06	—	—
LOI	2.68	0.25	12.5

GGBFS: ground granulated blast surface slag; NS: nanosilica; NMK: nanometakaolin.

TABLE 2: Physical properties of NS and GGBFS.

Description	Results		
	NS	NMK	GGBFS
Particle size	14 nm	88.7 nm	
% passing through 45-micron sieve (wet sieving)	—	—	92.55
Surface area (m ² /g)	200	140.792	—
Blaine fineness (m ² /kg)	—	—	425

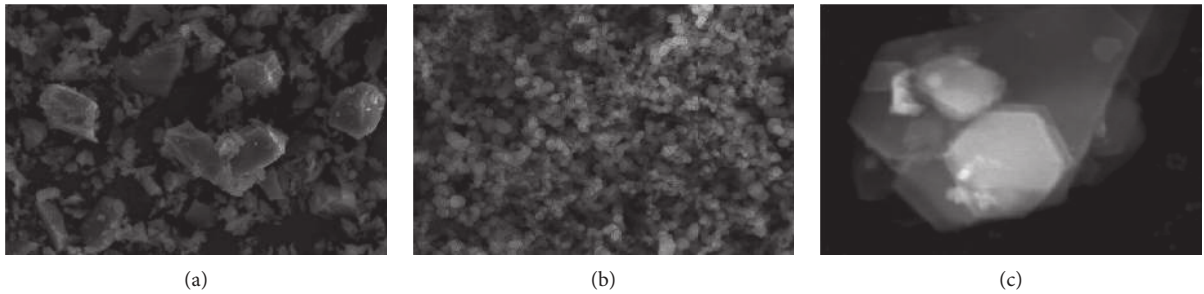


FIGURE 1: SEM image of (a) GGBFS, (b) NS, and (c) NMK used in this study.

In this study, two types of steel fiber, hooked end and crimped type, are utilized. Hooked-end SF was used accompanied by a tension strength of 1100 MPa, Young's modulus $E = 205$ GPa, density $\rho = 7850$ kg/m³, length $L = 30$ mm, and aspect ratio $L/d = 60$ following ASTM A820. The length of the used crimped type SF is 30 mm while the diameter is 1 mm accompanied by crimped type cross section and $60 L/d$ ratios. The two steel fibers (hooked-end SF and crimped type) were used at various volume fractions such as 0, 0.5, 1, and 1.5% and added to the optimum geopolymer concrete mixture where Figures 2 and 3 present the two SF types used in the GPC production.

The aggregates utilized in this paper were composed of river sand and crushed dolomite. The coarse aggregate was washed for 48 h before being utilized and left to dry in order to avoid the fine material impact.

Crushed dolomite from Elmenia quarry was utilized as coarse aggregate (CA) to produce GPC. The crushed granite

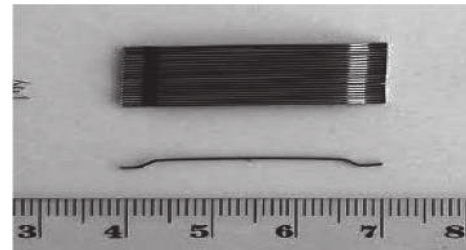


FIGURE 2: Steel fiber with hooked end.

was utilized in two sizes, whereas the maximum nominal dimension was 10 mm. The coarse aggregate was tested following ASTM C127. Table 3 illustrates the crushed granite's physical characteristics.

Fine aggregate (FA) was composed of river sand mix which was utilized in all geopolymer mixtures. Table 3 shows the aggregates' physical characteristics.

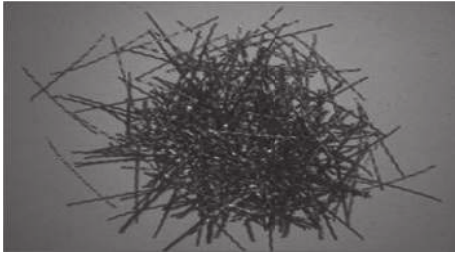


FIGURE 3: Geometry and shape of crimped steel fiber (corrugated round).

TABLE 3: Physical properties of aggregates.

Properties	Results	
	CA	FA
Specific gravity	2.65	2.62
Bulk density (kg/m ³)	1610	1850
Void ratio (%)	39.11	37.73

2.2. Production of Geopolymer Concrete. The contents of the geopolymer concrete (GPC) mixes are illustrated in Table 4. Three various series are demonstrated as shown in Table 4 which were formulated based on 500 kg/m³ constant binder content and alkaline activator solution with various concentration ratio of 2.33 (sodium silicate (Na₂SiO₃)/sodium hydroxide (NaOH)). In order to validate the procedure of mix design, the GPC design was considered with 0.45 activators/precursors ratio and the percentage of solids in NaOH and Na₂SiO₃ are 12 and 30% by weight of precursors, respectively. Thus, to acquire the optimum mixes, for each mix, the total binder content is not equal to the NaOH and GGBFS weight.

Flakes of NaOH were dissolved in water for the preparation of a liquid containing a 12 M concentration. The selection of NaOH was based on avoiding the polycondensation reaction hindrance [25]. The solution of alkali activator was formed through mixing NaOH solution (after cooling the NaOH solution down to an ambient temperature of 27–30°C accompanied by water glass). Following the previous procedure, the blended solution was put in the containers of plastic for around 1 day (24 h) at room temperature prior to utilization. Table 4 illustrates a total of four geopolymer series from 0 to 1.5% steel fiber (SF) with 0.5% increment. Besides, each series is composed of two groups with and without the incorporation of nanosilica and nanometakaolin. Thus, in this paper, the experimental program included 24 GPC mixes. The proposed geopolymer mix designation was established on the basis of the examined parameters (i.e., NS content, NMK content, and SF volume fraction). The process of mixing samples is as follows.

The fine and coarse aggregate was mixed together for around one minute using a concrete mixer. After that the gradual addition for blended powder raw materials and alkali activator solution containing superplasticizer into the concrete mixer was carried out. They were blended for around six minutes where two-minute rest was taken between three-minute intervals of blending. The design of GPC

was modified through changing the dosage of superplasticizer for each mix in order to accomplish a particular workability where the value of slump in the range of 7 ± 2 cm. After finishing the process of mixing, the resulted fresh mix was poured into preoiled molds in three layers and compacted well using a vibrator table. However, for mixes containing steel fibers and nanomaterials, the following procedures was carried out. At first, blending nanoparticles (NMK and NS) with the solution of alkaline through the usage of electric mixer as nano materials may not disband well through moistening which led to the agglomerations within the mix. Thus, disbanding the nanoparticles is vital to avoid agglomeration that may negatively impact the reaction. The nanosilica is distributed in the liquid of alkaline before and after blending. For the preparation of each mixture of the first series, GGBFS, fine aggregate and weighted was put into the mixer then nano materials (NMK and NS) was added with the solution and mixed for 5 minutes. GGBFS, fine aggregate and weighted coarse, was put into the mixer for the preparation of each mixture of the first series then a solution of nanomaterials (NMK and NS) was added and mixed for.

2.3. Curing Method of the Geopolymer Concrete.

Following the concrete production, the surfaces of casted specimens were coated by polyethylene film for the prevention of water evaporation and minimization of the carbonation impact. After that, the specimens were hardened for 24 h at the room temperature. Afterward, the samples were demolded and stored before conducting the test in an ambient temperature curing room accompanied by a controlled temperature of 27 to 30°C. Three identical specimens were formed for each test, and the average results of the corresponding test were determined.

2.4. Test Procedures.

The hardened state experiment was conducted for analyzing the impact of NS and SF combination on the geopolymer concrete mechanical performance (flexural, splitting tensile, and compressive strength). At curing of 7 and 28 days, a compressive strength experiment was conducted on 100 × 100 × 100 mm cube dimensions according to ASTM C39 standard. However, the flexural strength (10 × 10 × 50) and the splitting tensile (10 × 20 cm) tests were conducted on beam and cylindrical specimens, respectively, at 28 curing days. For each mix, three specimens were tested and the results which were illustrated for indirect flexural and tensile tests are the average of three samples of each mix.

3. Result and Discussion

3.1. Compressive Strength

3.1.1. Nanosilica and Nanometakaolin. Results of using nanometakaolin and nanosilica mixes individually were compared to the control GPC mixtures. Figure 4 illustrates the GPC mixtures' compressive strength during 28 and 7 days accompanied by incorporating nanometakaolin

TABLE 4: Geopolymer mix proportions in kg/m³.

Mixture	Slag binder (Kg/m ³)	Na ₂ SiO ₃ (L)	NaOH (L)	CA (Kg/m ³)	FA (Kg/m ³)	Molarity	SP (%)	SF1	SF2	NS	NMK
C0	500	187.5	62.5	907	790	12	3	0	0	0	0
CSFH0.5	500	187.5	62.5	907	790	12	3	0.5	0	0	0
CSFH1	500	187.5	62.5	907	790	12	3	1	0	0	0
CSFH1.5	500	187.5	62.5	907	790	12	3	1.5	0	0	0
CSFC0.5	500	187.5	62.5	907	790	12	3	0	0.5	0	0
CSFC1	500	187.5	62.5	907	790	12	3	0	1	0	0
CSFC1.5	500	187.5	62.5	907	790	12	3	0	1.5	0	0
CNS2	500	187.5	62.5	907	790	12	3	0	0	2	0
CNS4	500	187.5	62.5	907	790	12	3	0	0	4	0
CNS6	500	187.5	62.5	907	790	12	3	0	0	6	0
CNS8	500	187.5	62.5	907	790	12	3	0	0	8	0
CNMK2	500	187.5	62.5	907	790	12	3	0	0	0	2
CNMK4	500	187.5	62.5	907	790	12	3	0	0	0	4
CNMK6	500	187.5	62.5	907	790	12	3	0	0	0	6
CNMK8	500	187.5	62.5	907	790	12	3	0	0	0	8
CSFH0.5 + CNS4	500	187.5	62.5	907	790	12	3	0.5	0	4	0
CSFH1 + CNS4	500	187.5	62.5	907	790	12	3	1	0	4	0
CSFH1.5 + CNS4	500	187.5	62.5	907	790	12	3	1.5	0	4	0
CSFH0.5 + CNMK6	500	187.5	62.5	907	790	12	3	0.5	0	0	6
CSFH1 + CNMK6	500	187.5	62.5	907	790	12	3	1	0	0	6
CSFH1.5 + CNMK6	500	187.5	62.5	907	790	12	3	1.5	0	0	6
CSFC0.5 + CNS4	500	187.5	62.5	907	790	12	3	0	0.5	4	0
CSFC1 + CNS4	500	187.5	62.5	907	790	12	3	0	1	4	0
CSFC1.5 + CNS4	500	187.5	62.5	907	790	12	3	0	1.5	4	0
CSFC0.5 + CNMK6	500	187.5	62.5	907	790	12	3	0	0.5	0	6
CSFC1 + CNMK6	500	187.5	62.5	907	790	12	3	0	1	0	6
CSFC1.5 + CNMK6	500	187.5	62.5	907	790	12	3	0	1.5	0	6

CA: coarse aggregate; SF1: steel fiber with hooked end; NMK: nanometakaolin; FA: fine aggregate; SF2: crimped steel fiber; SP: superplasticizer; NS: nanosilica.

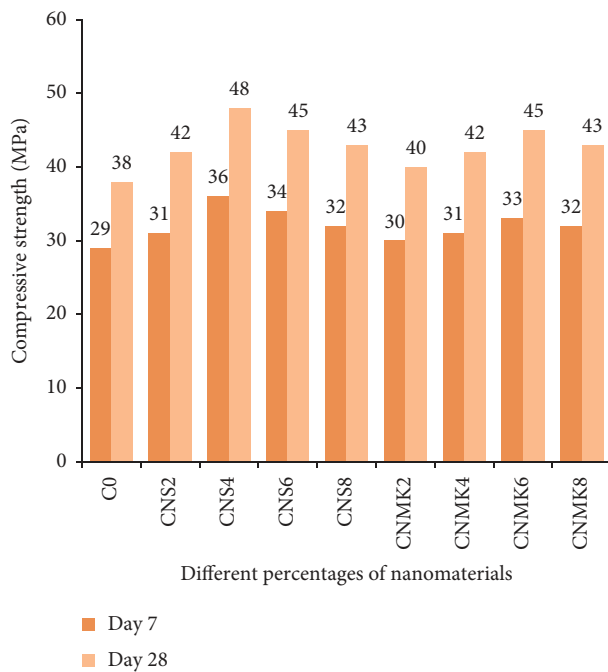


FIGURE 4: Effect of NS and NMK on compressive strength.

(NMK) and nanosilica (NS). An enhancement in the compressive strength of GPC with nanosilica was observed from 7 to 28 days through the usage of 6% nanometakaolin and 4% nanosilica by weight of the

cementitious content which is considered as the optimum used quantity. The percentage of improved compressive strength was achieved around 18.42% (CNMK6) and 26.31% (CNS4) compared to the control mixtures. Such results were predictable according to the previous studies due to nanoparticles addition that formed harder binder materials [27, 31]. The development of harder binder materials was explained as a result for the enhancement of the interfacial transition zone between the aggregates and the hydrated geopolymer paste. Thus, a reduction in the porosity and an increment in the compactness of specimens were detected because of the small dimensions and the high specific surface area of these mixtures in regard to geopolymer paste [32, 33]. Nevertheless, high quantities of these two pozzolan types result in an enhancement in compressive strength till a certain value; after that, a reduction in compressive strength was observed that could be explained due to the incomplete hydration reaction (e.g., 6% nanometakaolin and 4% nanosilica in the current research). As the two pozzolan types are characterized by a high level of water absorption, the achieved results through this experiment illustrated that the nanosilica has a higher impact on the compressive strength compared to nanometakaolin. The enhancement in the compressive strength of specimens that contain pozzolan could be explained as a result of the pozzolanic reaction. Nanosilica is characterized by strong pozzolanic reaction in comparison with nanometakaolin.

3.1.2. Hooked-End and Crimped Type Steel Fiber. Figure 5 demonstrates a slight enhancement in the compression-resistant capacities due to the integration of two various types of SF in GPC. The highest values were recognized at a volume proportion of 1% for all concrete types manufactured in this research. However, Aydın and Baradan [34] found that the optimum results for compressive strength in geopolymer mortar were achieved through the usage of 2% SF content. The improved percentage of compressive strength was achieved around 5.3% (CSFC1) and 8% (CSFH1) compared to the control mixes. Generally, the improvement in fiber reinforced concrete compressive strength was associated to the capability of fibers to hinder and postpone the propagation of crack and to minimize the stress concentration extent at the crack tip [35]. The hooked-end steel fibers handle the existence of several microcracks in the concrete body in a better way due to the cracks' microdimension as well as having smaller size in comparison with the crimped steel fibers. So, the hooked-end steel fibers were recognized to impact the enhancement of the efficiency in bridging microcracks and thus improving the compressive strength. Nevertheless, the crimped steel fibers were observed for not taking an effective role in load carrying till the peak loading point was accomplished due to their greater length and macroscale. After the achievement of peak loading point and near the moment of sample failure, crimped steel fibers were recognized to participate in enhancing the ductility and prohibiting further microcracks and crack propagation. Examining the difference between the outcomes of the control geopolymer concrete and the fiber reinforced concrete specimens illustrated a decrement in the compressive strength through the usage of fibers in high volume fractions, which was considered as a result of pore formation and fiber clumping in the fiber reinforced concrete.

3.1.3. Hooked-End and Crimped Type Steel Fiber with Optimum Percentage of NS and NMK. As shown in Figures 6 and 7, a higher compressive strength was achieved through the usage of the geopolymer mixes including various percentages of two types of steel fiber (hooked end and crimped type) (0.5, 1 and 1.5%) with optimal percentage of 6% NMK and 4% NS. The average ratio of improvement due to the usage of CSFH1 + CNS4 and CSFH1 + CNMK6 was found to be 10.14 and 9.0% for concrete, respectively, compared to GPC control samples. On the other hand, the average ratio of improvement due to the usage of CSFC1 + CNS4 and CSFC1 + CNMK6 was found to be 8.3 and 6.2% for concrete, respectively, compared to GPC control samples. The enhancement in compressive strength was because of the NS efficiency in enhancing the products of geopolymerization reaction in the matrix [36].

As shown in Figure 6, the usage of nanometakaolin as well as nanosilica with high percentages led to a brittle or very brittle fracture in the concrete samples characterized by lacking fibers; however, the existence of fibers in pozzolanic concrete caused a ductile fracture.

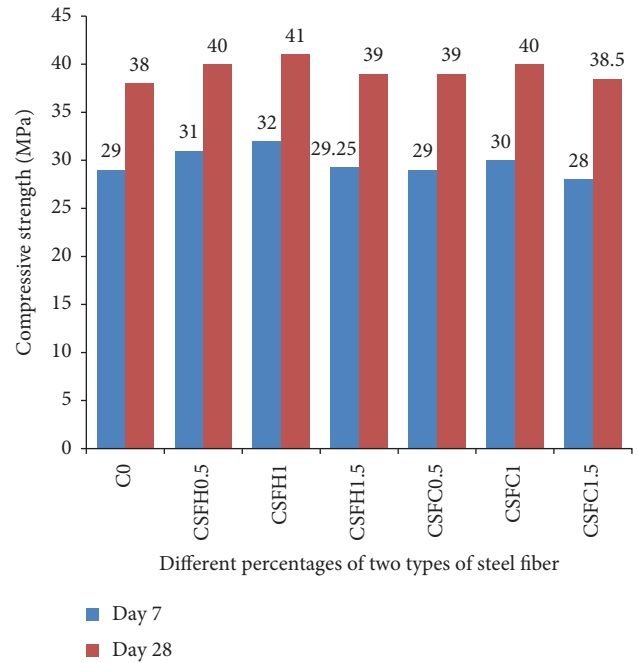


FIGURE 5: Effect of two types of steel fiber (hooked end and crimped) on compressive strength.

3.2. Splitting Tensile Strength. The test results of the splitting tensile strength for the samples including nanometakaolin and nanosilica, the ones including different fibers, and those including fiber-pozzolan combination are illustrated in Figure 8. The outcomes of the fiber reinforced concrete illustrated that the usage of steel fibers particularly caused a decrement in crack width which subsequently enhanced the splitting tensile strength due to their existence in the brittle GPC matrix. As shown in Figure 8(a), the tensile strength of the concrete samples accompanied by 0.5, 1, and 1.5% hooked end steel fibers demonstrated an increase of 8.14, 14.81, and 11.11%, respectively, compared to GPC control samples. Also, the specimens' tensile strength containing 0.5 and 1% crimped steel fibers was enhanced compared to the plain concrete by 7 and 9.63%, respectively, while the concrete samples that possess 1.5% crimped steel fibers illustrated a decrement in splitting tensile strength compared to the reference mix without additions by 8%.

The above outcomes illustrate that the usage of hooked-end steel fibers efficiently enhances the concrete splitting tensile strength compared to crimped steel fibers. In case of using hooked-end steel fiber, a strong bond was formed through the matrix of concrete under tensile stresses due to the hooked shape for the end of hooked-end steel fiber. Besides, the propagation of the postcracking was prevented by the hooked-end steel fibers which are characterized by high splitting tensile strength and length which led to the significant improvement in the tensile strength. In case of using crimped steel fibers, the formation of microcracks during the initial stages was prevented effectively through the usage of crimped steel fibers which possess lower tensile strength and longer length in comparison with the hooked-end fibers. Nevertheless, following the specimen cracking operation, the crimped steel fibers were found to be not taking a complete

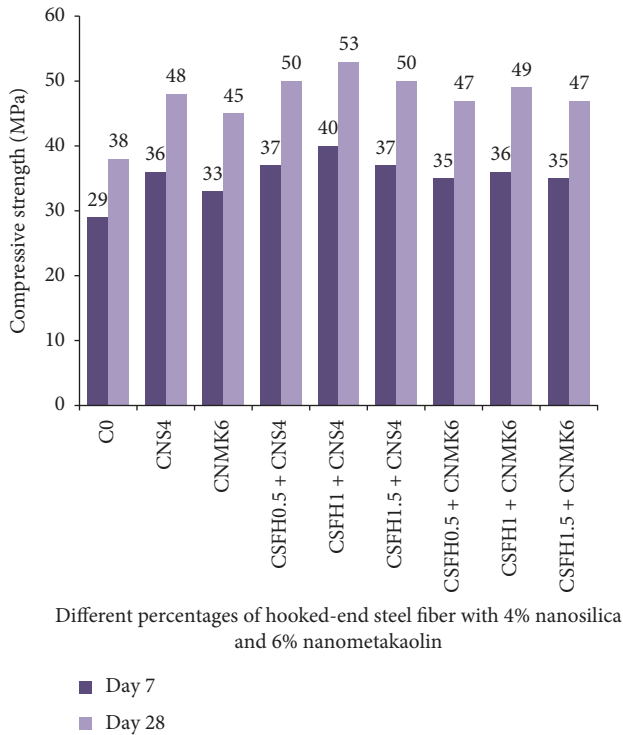


FIGURE 6: Using different % of hooked-end steel fiber with 4% NS and 6% NMK on compressive strength.

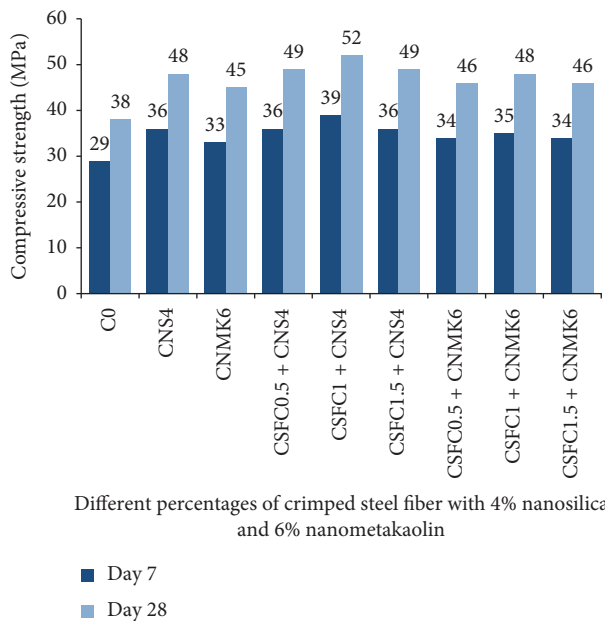


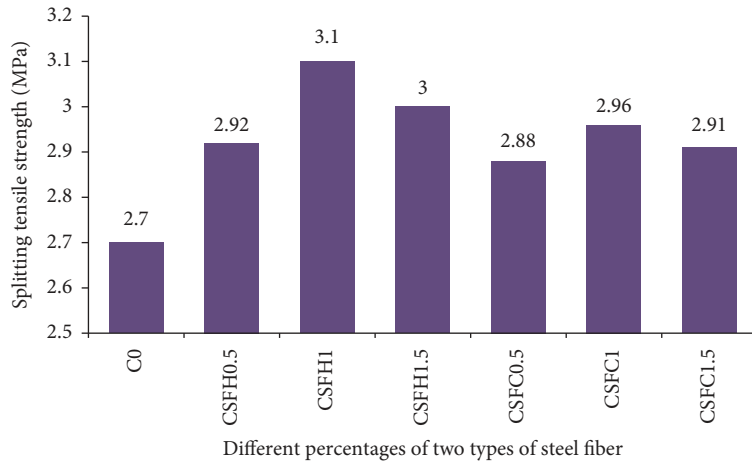
FIGURE 7: Using different % of crimped steel fiber with 4% NS and 6% NMK on compressive strength.

role in opposing the tensile stress. Thus, up to volume content of 1%, microcracks were opposed by the crimped steel fibers which enhanced the tensile strength. However, once the threshold was overcome through the volume fraction of crimped, a slight reduction in the tensile strength was observed due to the formation of the pores by fiber agglomeration.

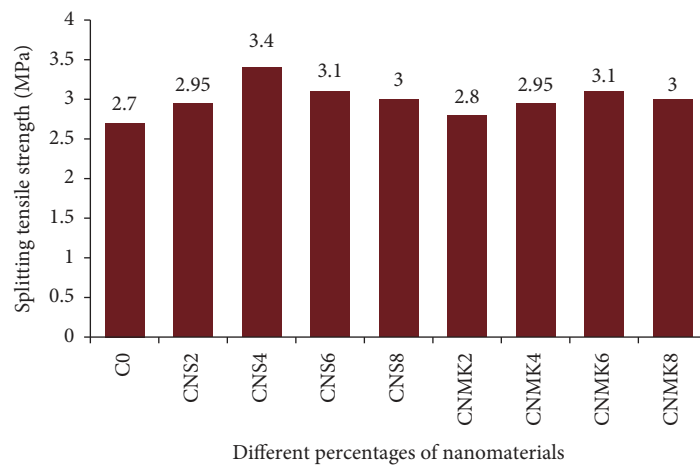
According to Jiang et al. [37], basalt fibers were utilized with the lengths of 12 and 22 mm and the results demonstrated that basalt fibers accompanied by a longer length led to a higher tensile strength enhancement. The explanation for the results of Jiang et al. was a stronger force demanded for withdrawing them out as well as a more effective bridging impact across the crack width. According to Figure 8(b), an improvement was demonstrated in the splitting tensile strength in comparison with the control of GPC due to the nanosilica and nanometakaolin addition to the GPC. An improvement in the specimens' splitting tensile strength including 2, 4, 6, and 8% of nanosilica was observed to accomplish 9.25, 26, 15, and 11.11%, respectively, compared to the control GPC. On the other hand, the specimens including 2, 4, 6, and 8% nanometakaolin demonstrated 4, 9.25, 15, and 11.11% improvement in splitting tensile strength relative to plain concrete. The recognized enhancement in the tensile strength could be associated with the improvement in the bond between the aggregates and the hydrated cement matrix. The nanosilica particles have a more momentous impact on the splitting tensile strength compared to the nanometakaolin particles because of the reason that nanosilica is more amorphous than nanometakaolin and silicon dioxide (SiO₂) percentage in nanosilica is higher than that in metakaolin.

According to Figures 8(c) and 8(d), it could be recognized that blending 0.5, 1 and 1.5% hooked-end and crimped steel fiber with optimal nanometakaolin and nanosilica percentage led to an increment in the concrete tensile strength in comparison with that of the concrete containing optimum percentage of either one of them. The mix which was composed of 1% hooked-end steel fibers accompanied by 4% nanosilica and 6% nanometakaolin illustrated the highest positive impact on the splitting tensile strength of the concrete samples. As the observed enhancement in the tensile strength fiber reinforced concrete (CSFH1 + CNS4, CSFH1 + CNMK6, CSFC1 + CNS4, and CSFC1 + CNMK6) compared to with the control GPC was 37, 26, 33, and 26% respectively. The majority of the different dosages of silicon oxide nanoparticles and nanometakaolin utilized in the fiber-lacking concrete samples resulted in either severe or very severe cracking, indicating the formation of brittle or very brittle fracture. However, the existence of fibers in the pozzolanic and nonpozzolanic samples resulted in a ductile failure. This trend was also recognized previously in the compressive tests.

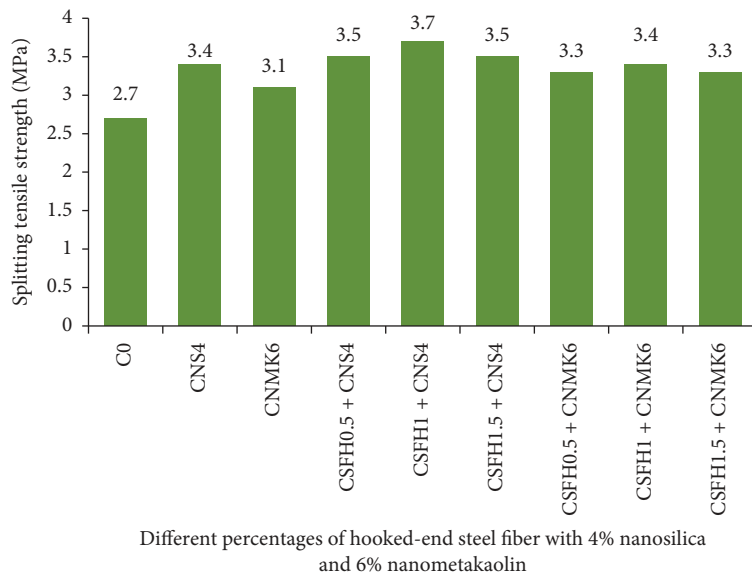
3.3. Flexural Strength. As shown in Figure 9, the flexural strength of the various concrete mixes was enhanced because of the addition of 4% NS, 6% NMK, 1% hooked-end steel fiber, 1% crimped steel fiber, 1% hooked-end steel fiber with 4% NS, 1% hooked-end steel fiber with 6% NMK, 1% crimped steel fiber with 4% NS, and 1% crimped steel fiber with 6% NMK in mixtures (CNS, CNMK, CSFH1, CSFC1, CSFH1 + CNS4, CSFH1 + CNMK6, CSFC1 + CNS4, and CSFC1 + CNMK6) with values of 30.43%, 24%, 22, 15.22, 39.13, 30.43, 35, and 24%, respectively, compared to GPC control sample. In all concrete mixes, an increment in the



(a)



(b)



(c)

FIGURE 8: Continued.

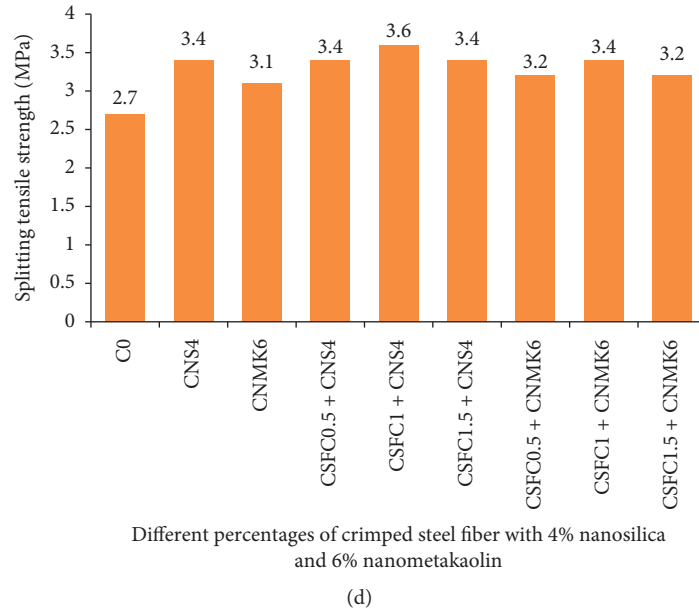


FIGURE 8: Splitting tensile strength for (a) GPC containing nanosilica, (b) GPC containing nanometakaolin, (c) different % of hooked-end steel fiber reinforced GPC containing 4% nanosilica, and (d) different % of hooked-end steel fiber reinforced GPC containing 6% nanometakaolin.

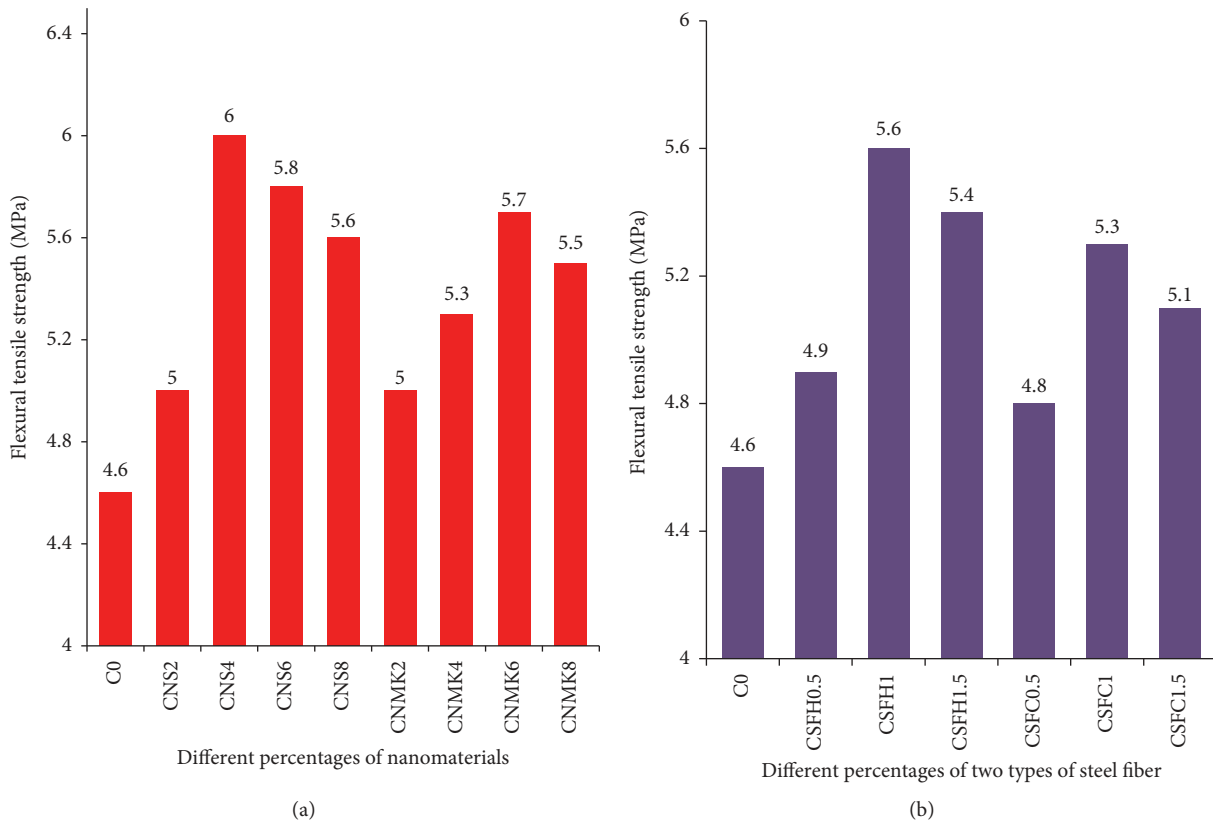


FIGURE 9: Continued.

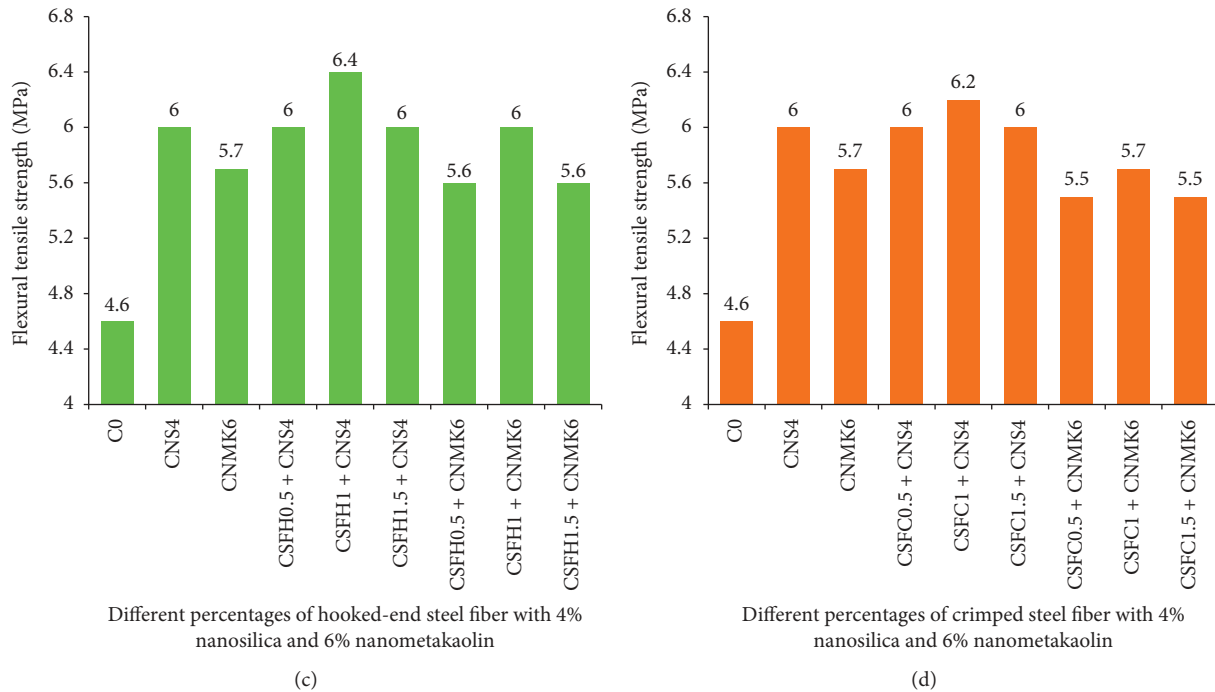


FIGURE 9: Flexural strength for (a) GPC containing nanosilica, (b) GPC containing nanometakaolin, (c) different % of hooked-end steel fiber reinforced GPC containing 4% nanosilica, and (d) different % of hooked-end steel fiber reinforced GPC containing 6% nanometakaolin.

flexural tensile was observed through increasing nano-material content, mix steel fiber, and steel fibers accompanied by nanomaterials till achieving optimum value of the used materials; after that, a reduction in flexural tensile strength was recognized. The compact and refined micro-structure caused an improvement in the flexural tensile strength. In addition, the fibers and matrix have strong bonding that increase the force of fiber bridging which correspondingly improves the strength. Same results were noticed in other research studies [38, 39]. According to the test results of flexural tensile strength, the optimal quantity of crimped steel and hooked-end fiber should be 1% because CSFC1 CSFH1 specimens showed high ductility and strength. However, the usage of 1% crimped steel and hooked-end fiber accompanied by 6% NMK and 4% NS illustrated the highest ductility and strength in comparison with the control GPC.

4. Conclusion

In this research, the effect of two types of steel fibers, nanometakaolin, and nanosilica on slag-based geopolymer concrete was examined. Firstly, geopolymer concretes mixes were prepared with and without nanomaterials (nanosilica and nanometakaolin) of 0, 2%, 4%, 6%, and 8% from ground granulated blast furnace slag (GGBFS). Secondly, the role of steel fiber (hooked end and crimped) in mix preparation was studied (0, 0.5%, 1, and 1.5%). Thirdly, the usage of optimum values of nanomaterials with the optimum values of steel fiber in mix preparation was studied. According to the results, the following conclusions could be demonstrated:

- (i) The mechanical properties were enhanced as the percentage of the materials NS, NMK, and two different types of steel fibers (hooked end and crimped) which are used individually or combined in the GPC specimens increases until the optimum value of the used materials was accomplished and then a decrement in the mechanical properties was recognized.
- (ii) The highest mechanical properties were recognized through the usage of the optimum material ratios from GPC specimens as follows: of 4% NS, 6% NMK, 1% hooked-end steel fiber, 1% crimped steel fiber, 1% hooked-end steel fiber with 4% NS, 1% hooked-end steel fiber with 6% NMK, 1% crimped steel fiber with 4% NS, and 1% crimped steel fiber with 6% NMK in mixtures.
- (iii) The compressive strength of different concrete mixtures was enhanced because of the addition of 4% NS, 6% NMK, 1% hooked-end steel fiber, 1% crimped steel fiber, 1% hooked-end steel fiber with 4% NS, 1% hooked-end steel fiber with 6% NMK, 1% crimped steel fiber with 4% NS, and 1% crimped steel fiber with 6% NMK in GPC mixes with values of 26.31%, 18.42%, 8, 5.3, 10.14, 9, 8.3, and 6.2%, respectively, compared to GPC control sample.
- (iv) The splitting tensile strength of the various concrete mixtures was improved due to the addition of 4% NS, 6% NMK, 1% hooked-end steel fiber, 1% crimped steel fiber, 1% hooked-end steel fiber with

4% NS, 1% hooked-end steel fiber with 6% NMK, 1% crimped steel fiber with 4% NS, and 1% crimped steel fiber with 6% NMK in GPC mixes with values of 26%, 15%, 14.81, 9.36, 37, 26, 33, and 26%, respectively, in comparison with GPC control sample.

- (v) The flexural strength of different concrete mixtures was improved due to the addition of 4% NS, 6% NMK, 1% hooked-end steel fiber, 1% crimped steel fiber, 1% hooked-end steel fiber with 4% NS, 1% hooked-end steel fiber with 6% NMK, 1% crimped steel fiber with 4% NS, and 1% crimped steel fiber with 6% NMK in GPC mixtures with values of 30.43%, 24%, 22, 15.22, 39.13, 30.43, 35, and 24%, respectively, in comparison with GPC control sample.
- (vi) The enhancement in mechanical properties was because of the nanomaterials' efficiency in enhancing the products of geopolymerization reaction in the GPC mixes.
- (vii) The improvement in fiber reinforced concrete compressive strength was associated with the capability of fibers to hinder and postpone the propagation of crack and to minimize the stress concentration extent at the crack tip.
- (viii) The hooked-end steel fibers handle the existence of several microcracks in the concrete body in a better way due to the cracks' microdimension as well as having smaller size in comparison with the crimped steel fibers. So, the hooked-end steel fibers were recognized to impact the enhancement of the efficiency in bridging microcracks and thus improving the compressive strength.
- (ix) The usage of hooked-end steel fibers efficiently improves the concrete splitting tensile strength in comparison with crimped steel fibers. As the propagation of the postcracking was prevented by the hooked-end steel fibers due to the length and hooked end shape of the hooked-end steel fibers which led to the significant improvement in the splitting tensile strength. However, the crimped steel fibers were found to be not taking a complete role in opposing the tensile stress following the specimen cracking operation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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