Research Article

Peng Zhang, Jia Wang, Qingfu Li*, Jinyi Wan, and Yifeng Ling

Mechanical and fracture properties of steel fiber-reinforced geopolymer concrete

<https://doi.org/10.1515/secm-2021-0030>

received March 06, 2021; accepted June 02, 2021

Abstract: In this study, the effects of steel fibers on the mechanical properties of the geopolymer concrete – compressive, splitting tensile, and flexural strength; compressive elastic modulus; and fracture properties – were evaluated. Milling steel fibers were incorporated into the geopolymer concrete, and the volume fraction of the steel fibers was varied from 0 to 2.5%. Fly ash and metakaolin were chosen as the geopolymer precursors. Fracture parameters – critical effective crack length, initial fracture toughness, and unstable fracture toughness – were measured by a three-point bending test. The results indicated that all the mechanical properties of the geopolymer concrete are remarkably improved by the steel fibers with the optimum dosage. When the steel fiber content was under 2%, the cubic and axial compressive strength and the compressive elastic modulus increased. The inclusion of 2% steel fibers enhanced the cubic and axial compressive strength and the compressive elastic modulus by 27.6, 23.7, and 47.7%, respectively. When the steel fiber content exceeded 2%, the cubic and axial compressive strength and the compressive elastic modulus decreased, having values still higher than those of the geopolymer concrete without steel fibers. The splitting tensile strength and flexural strength of the concrete were enhanced with increasing steel fiber content. When the steel fiber content was 2.5%, the increment of the splitting tensile strength was 39.8%, whereas that of the flexural strength was 134.6%. The addition of steel

fibers effectively improved the fracture toughness of the geopolymer concrete. With 2.5% steel fibers, the initial fracture toughness had an increase of 27.8%, and the unstable fracture toughness increased by 12.74 times compared to that of the geopolymer concrete without the steel fibers.

Keywords: geopolymer concrete, fly ash, metakaolin, steel fiber, mechanical properties, fracture properties

1 Introduction

Cement concrete has been extensively used in construction worldwide because it is a low-cost raw material and can be formed into any shape or size. Moreover, cement concrete has excellent mechanical properties, durability, and continuity after curing, which are the key for its prominence. Ordinary Portland cement, as one of the major raw materials of cement concrete, requires various natural sources and substantial energy, and will produce massive amounts of greenhouse gases during the production. Based on studies, producing 1 ton of cement requires approximately 1.6 ton of raw materials; it also utilizes approximately 1,300 kW h of embodied energy and releases approximately 0.8 ton of the greenhouse gas, CO₂ [1–4]. Producing cement concrete requires not only cement but also river sands, gravels, and other natural resources, which will consume additional energy and release more CO₂. The amount of CO₂ produced during the production of concrete accounts for 7–10% of the total global CO₂ emission in accordance with the studies [5]. It is in conflict with the concept of sustainable development to abuse cement concrete. Considering the above factors, it is imperative to identify other construction materials for replacing cement concrete.

Geopolymers were first proposed in the 1980s by Joseph Davidovits [6]. They are produced by the activation of an aluminosilicate source material by an alkaline solution [7]. When the alkaline solution is mixed with such materials containing alumina and silica, aluminum (Al) and silicon (Si) will rapidly dissolve in it and

* **Corresponding author: Qingfu Li**, School of Water Conservancy Engineering, Zhengzhou University, No. 100, Science Avenue, Zhengzhou, Henan Province, Zhengzhou 450001, People's Republic of China, e-mail: lqfch@zzu.edu.cn

Peng Zhang, Jia Wang: School of Water Conservancy Engineering, Zhengzhou University, No. 100, Science Avenue, Zhengzhou, Henan Province, Zhengzhou 450001, People's Republic of China

Jinyi Wan: Yellow River Engineering Consulting Co., Ltd., Zhengzhou 450003, People's Republic of China

Yifeng Ling: Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA 50011, United States

subsequently form a three-dimensional polymeric chain and a ring structure [8–10]. The empirical formula [11] of a geopolymer is as follows:

where X represents a metal cation (Ca^{2+} , K^+ , or Na^+); a represents the Si-to-Al ratio, and it can be chosen as 1, 2, or 3; q represents the polycondensation degree; and n is the number of chemically bound water molecules.

In recent years, geopolymer concrete has drawn the attention of researchers. Geopolymer concrete is a new, innovative, and sustainable engineering material formed of a geopolymer binder, coarse aggregates, and fine aggregates. Because it does not contain cement and there is no much water in the geopolymerization process, geopolymer concrete can be considered as the environment-friendly material [12]. In addition, it can utilize solid wastes, such as fly ash and blast furnace slag, as the raw material to produce geopolymer concrete [13,14], leading to the saving of natural resources and the reduction of the land used to cover solid wastes [15]. Furthermore, geopolymer concrete presents similar or better mechanical performance than ordinary cement concrete [16–18]. Considering these advantages, recently, geopolymer concrete has been used as a substitute for ordinary cement concrete as construction materials [10,19]. However, geopolymer concrete exhibits a more brittle nature and possesses a lower elastic modulus compared with ordinary cement concrete [20,21]. To improve the mechanical performance of geopolymer concrete, fibers can be used. Generally, some types of fibers are commonly used, such as steel fibers, polyvinyl alcohol fibers, polypropylene fibers, nylon fibers, carbon fibers, glass fibers, and natural fibers [22–27]. Among the abovementioned fibers, steel fibers have been preferred by researchers because of their high elastic modulus and fracture strain [28,29]. So far, numerous research results have been reported on steel fiber-reinforced geopolymer concrete. Studies conducted by Gomes *et al.* [30] obtained crack mouth opening displacement, stored energy rate, and other fracture factors by a three-point bending test. They reported that mixing steel fibers with a geopolymer concrete is effective in decreasing crack propagation and preventing brittle fractures in concrete composites. Farhan *et al.* [31] studied the behavior of a geopolymer concrete with diverse types of steel fibers under axial and flexural loads. It was concluded that the steel fiber-reinforced geopolymer concrete presents better performance than the plain geopolymer concrete under axial and flexural loads, and that adding hybrid steel fibers offers the maximum benefit. Liu *et al.* [32] studied the compressive strength and

flexural behavior of an ultra-high-performance geopolymer concrete (UHPGC) incorporating steel fibers in disparate ratios and of different shapes. They found that increasing the fiber content and decreasing the fiber diameter improved the mechanical strength of the UHPGC.

At present, there are some studies on the fabrication and strength of steel fiber-reinforced geopolymer concrete. However, a systemic study on their mechanical and fracture properties cannot be found in the current literature, which are of great significance in the further study and application of steel fiber-reinforced geopolymer concrete. Considering this gap in the literature, in this study, a series of systematic investigations were conducted on the mechanical and fracture properties of a geopolymer concrete reinforced with different volume fractions of steel fibers. The following mechanical properties were analyzed and are discussed in this article: compressive strength, flexural strength, and compressive elastic modulus. In addition, the fracture performance – the initial fracture load, unstable fracture load, critical effective crack length, initial fracture toughness, and unstable fracture toughness – were also measured and evaluated by a three-point bending test.

2 Experimental materials

Fly ash and metakaolin were chosen as the geopolymer precursors. The properties of fly ash have great influence on properties of geopolymer [33]. Fly ash produced by the Luoyang Power Station, with density and average bulk density of 2.16 and 0.77 g/cm³, respectively, was used. The average water absorbing capacity of the fly ash was 105%. The standard consistency of the fly ash was 47.1%, which implies that if the consistency reaches the standard value, the ratio of water to fly ash is 47.1% by mass. The metakaolin used in this study was from Chenxing Industry Co. Ltd, Shijiazhuang, with an average grain diameter of 1.2 μm. The whiteness of the metakaolin was 70–80%, and the loss of ignition was 0.5%. The chemical compositions of the fly ash and the metakaolin are listed in Tables 1 and 2.

Two different types of aggregates were used in this study, which were obtained from a quarry in Nanyang, Henan Province, China. A graded gravel was adopted as the coarse aggregate, and the total grain size range varied from 5 to 20 mm. Natural river sand with a final fineness modulus of 2.7 was chosen as the fine aggregate.

Ordinary tap water was used to prepare the alkaline liquid and the geopolymer concrete. The pH of water

Table 1: Chemical composition of fly ash

Chemical composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	f-CaO	SO ₂	Others
Mass ratio (%)	60.98	24.47	6.70	4.90	0.68	0.58	0.52	1.17

Table 2: Chemical composition of metakaolin

Chemical composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO + MgO	K ₂ O + Na ₂ O
Mass ratio (%)	54 ± 2	43 ± 2	≤1.3	≤0.8	≤0.7

was 6.6. The chloride (Cl⁻) and sulfate (SO₄²⁻) contents were 160.58 and 231.56 mg/L, respectively.

The alkaline activator used in this study was a mixture of sodium silicates (Na₂SiO₃) and sodium hydroxide (NaOH). It was prepared by mixing Na₂SiO₃, NaOH, and ordinary tap water. NaOH solid flakes of 99% purity were employed. The Na₂SiO₃ solution was from Longxiang Ceramic Co. Ltd, Zhengzhou, Henan Province, China, with a special gravity of 1.41 g/cm³. The solid ratio of the Na₂SiO₃ solution was 40%, and its modulus was 3.2 M.

Milling steel fibers were produced by Henan Yujian Steel Fiber Co. Ltd. The patterns and main physical properties of the steel fibers are shown in Figure 1 and listed in Table 3, respectively.

A water-reducing agent from Zhongyi Chemical Engineering Co. Ltd was used to improve the workability of the fresh concrete and promote the final strength of the geopolymer concrete specimens. The pH value of the water-reducing agent was 6–8, and its water reducing rate was 25–40%.

3 Experimental methods

3.1 Mixture design of geopolymer concrete

In this study, mixture proportions of each material were chosen according to a Chinese standard (JCJ55-2011) and by trial and error. The water–binder ratio was fixed as 0.4. The total water content comprised the water in the alkaline activator solution and the additional water added during the mixing progress. The aggregate–binder ratio was 3. The mass ratio of fly ash to metakaolin was 2:3. The concentration of the alkaline activator was 1.3 M, and the mass ratio of sodium oxide was 16.8%, which was chosen as the optimum ratio after several attempts. To

Figure 1: Patterns of steel fibers.

investigate the content effect of the steel fibers on the properties of the geopolymer concrete, their volume fractions were chosen as 0, 0.5, 1.0, 1.5, 2.0, and 2.5% [26,34]. The mixture without any steel fibers was the control group, and the other mixtures were the test groups. In addition, considering that steel fibers are heavier than aggregates, the latter were replaced by steel fibers by mass. Details of the mixture proportions are listed in Table 4.

3.2 Preparation of specimens

First, the steel fibers, binder, and aggregates were mixed together and subsequently were stirred for 2 min. Second, the alkali solution was poured, and the mixture was stirred for another 2 min. The NaOH solution was prepared 12 h in advance because the dissolution of NaOH flakes in water releases heat. After uniform mixing, the fresh concrete was poured into molds. The sizes of all the specimens are listed in Table 5. After a 24 h curing at ambient temperature, the specimens were demolded and moved into a standard curing room. After 28 days of curing, the hardened pieces were removed and moved into a room with relatively lower moisture for another 3 days of curing. Finally, the mechanical properties of each steel fiber-reinforced geopolymer concrete were tested.

Table 3: Physical properties of steel fibers

Physical properties	Length (mm)	Thickness (mm)	Standard length (mm)	The aspect ratio	Splitting tensile strength (MPa)	Elastic modulus (GPa)	Gravity (kg/m ³)
Results (average)	2.5	0.35	40	38	≥800	≥200	7,850

3.3 Compressive and splitting tensile strength test

The cubic and axial compressive strength and the splitting tensile strength were measured in accordance with the Chinese standard (GB50081-2002). An electro-hydraulic servo pressure testing machine (2,000 kN) was used for measuring the cubic and axial compressive strength and the splitting tensile strength. The loading speeds for the cubic and axial compressive strength tests and the splitting tensile strength tests were controlled at 0.5, 0.5, and 0.07 MPa/s, respectively.

3.4 Compressive elastic modulus test

Compressive elastic modulus tests were conducted in accordance with the Chinese standard (GB50081-2002). The test machine used for the axial compressive strength test was employed. The loading speed was maintained at 0.5 MPa/s until the specimen was damaged. The compressive elastic modulus test apparatus is shown in Figure 2.

The elastic modulus was calculated as follows:

$$E_c = \frac{F_a - F_0}{A} \times \frac{L}{\varepsilon_\Delta}, \quad (2)$$

where E_c is the compressive elastic modulus (MPa); F_a is the load when the compressive strength reaches one-third of

Table 5: Sizes of specimens in various tests

Test	Size (mm)	Amounts
Compressive strength test	150 × 150 × 150	18
Splitting tensile strength test	150 × 150 × 150	18
Flexural strength test	100 × 100 × 400	18
Compressive elastic modulus test	150 × 150 × 300	36
Three-point bending test	100 × 100 × 400	30

the axial compressive strength (N); F_0 represents the beginning load when the compressive strength reaches 0.5 MPa (N); A is the compression area of the specimen (mm²); L is the test distance (mm); and ε_Δ is the average deformation between both sides of the specimen when the load increases from F_0 to F_a (mm), which is calculated as follows:

$$\varepsilon_\Delta = \varepsilon_a - \varepsilon_0, \quad (3)$$

where ε_a is the average deformation between both sides of the specimen when the load reaches F_a (mm) and ε_0 is the average deformation between both sides of the specimen when the load reaches F_0 (mm).

3.5 Flexural strength test

For flexural strength of structure, the span-depth is an important influence factor [35–40]. With the same depth, the structure with longer span will be more likely to fail [41].

Table 4: Mixture proportions of geopolymer concrete

Specimen number	Metakaolin (kg/m ³)	Fly ash (kg/m ³)	Alkaline activator			River sand (kg/m ³)	Gravel (kg/m ³)	Steel fiber (% ¹)	Water reducer (kg/m ³)
			Na ₂ SO ₃ (kg/m ³)	NaOH (kg/m ³)	Water (kg/m ³)				
C	274.8	195.0	286.3	53.2	66.5	577.4	1072.4	0	2.0
S1	274.8	195.0	286.3	53.2	66.5	563.7	1046.9	0.5	2.0
S2	274.8	195.0	286.3	53.2	66.5	549.9	1021.4	1.0	2.25
S3	274.8	195.0	286.3	53.2	66.5	536.2	995.9	1.5	2.5
S4	274.8	195.0	286.3	53.2	66.5	522.5	970.3	2.0	2.75
S5	274.8	195.0	286.3	53.2	66.5	508.7	944.8	2.5	3.0

¹The volume fraction.

Figure 2: Compressive elastic modulus test apparatus: (a) raster displacement sensor and (b) test machine.

In this literature, flexural strength tests were conducted according to the Chinese standard (GB50081-2002) to evaluate the effect of steel fiber better. In order to obtain accurate test results, a four-point bending test was adopted as shown in Figure 3. The samples were tested using a 300 kN electro-hydraulic servo universal testing machine. The loading speed was set as 0.08 MPa/s.

Subsequently, the flexural strength of the geopolymer concrete specimens were determined as follows:

$$f_t = \frac{F_f l}{bh^2}, \quad (4)$$

where f_t is the flexural strength (MPa); F_f represents the broken load in the flexural strength test (N); l is the distance between the supports, which was 300 mm in this study; and b , h represent the height and length of the cross section, respectively, both of which are 100 mm in this study.

Figure 3: Four-point bending test (GB50081-2002).

3.6 Fracture tests

Fracture tests were performed in accordance with a Chinese standard (DL/T 5332-2005). A three-point bending test was conducted to evaluate the fracture performance of each geopolymer concrete specimen. The sizes of the samples and the initial notch are shown in Figure 4. The testing machine used in the flexural strength test was employed to determine the fracture parameter. A continuous and uniform loading method was adopted in this study, and the loading rate was maintained at 100 N/s. The crack mouth opening displacement was measured using clamp-type extended instruments, and the load was measured by a load transducer having a maximum range of 30 kN and an accuracy of 1 N. The crack mouth opening displacements and the loads were recorded using a static strain tester. The experimental instrument is shown in Figure 5.

In this study, the double-K fracture model was adopted to evaluate the fracture properties of the geopolymer concrete based on a Chinese standard (DL/T5332-2005) and previous research [42–46]. The double-K fracture criterion can be described as follows: when $K_I = K_{IC}^Q$, cracks begin to appear; when $K_{IC}^Q \leq K_I \leq K_{IC}^S$, cracks increase steadily; and when $K_I > K_{IC}^S$, cracks increase at an unstable speed. In the above criteria, K_I is the fracture toughness, K_{IC}^Q is the initial fracture toughness, which depends on two factors – initial fracture load F_Q and initial crack length a_0 , K_{IC}^S is the unstable fracture toughness, which is determined by two factors – unstable fracture load F_{max} and critical effective crack length a_c . The related fracture parameters are as follows:

Figure 4: Sizes of specimen for fracture test (DL/T 5332-2005).

Figure 5: Experimental instrument for three-point bending test.

(1) Initial fracture load F_Q

In this study, the initial fracture load, F_Q , was obtained from load–displacement curves. The point representing the load–displacement curve changing from linearity to nonlinearity was chosen, and the corresponding load at this point is the initial fracture load, F_Q .

(2) Critical effective crack length a_c

Critical effective crack length a_c was calculated using equation (5).

$$a_c = \frac{2}{\pi}(h + h_0) \arctan \sqrt{\frac{tEV_c}{32.6F_{\max}}} - 0.1135 - h_0, \quad (5)$$

where a_c represents the critical effective crack length (mm); h is the length of the specimen (mm), which is 0.1 m in this study; h_0 is the distance between the location of the clip-type extensometer and the bottom of the specimen, which is 0.02 m here; t is the thickness of the specimen, and it is 0.1 m in this study; V_c is the critical value of the crack mouth opening displacement (μm), and it is obtained when the load reaches

unstable fracture load $F_{\max}$ (kN); and E is the elastic modulus (GPa), which is calculated as follows:

$$E = \frac{1}{tc_i} \left[3.7 + 32.6 \tan^2 \left(\frac{\pi}{2} \frac{a_0 + h_0}{h + h_0} \right) \right], \quad (6)$$

where c_i is the initial value of $\frac{V}{F}$ ($\mu\text{m}/\text{kN}$) and a_0 is the initial crack length, which is 0.03 mm in this study.

(3) Initial fracture toughness K_{IC}^Q

Initial fracture toughness K_{IC}^Q is obtained by the following equation, provided the structural performance is still within the elastic range when the experimental load reaches initial fracture load F_Q :

$$K_{IC}^Q = \frac{1.5 \left(F_Q + \frac{mg}{2} \times 10^{-2} \right) \times 10^{-3} S \sqrt{a_0}}{th^2} f(\alpha_0), \quad (7)$$

$$f(\alpha_0) = \frac{1.99 - \alpha_0(1 - \alpha_0)(2.15 - 3.93\alpha_0 + 2.7\alpha_0^2)}{(1 + 2\alpha_0)(1 - \alpha_0)^{\frac{3}{2}}}, \quad (8)$$

where K_{IC}^Q represents the initial fracture toughness ($\text{MPa m}^{\frac{1}{2}}$); F_Q represents the initial fracture load (kN); m is the total mass comprising mass m_1 of the loading plate and mass m_2 of the specimen between the supports, m_1 is 6.102 kg, and m_2 is 3/4 of the specimen mass; and S represents the distance between two supports, which was set as 0.3 m in this study.

(4) Unstable fracture toughness K_{IC}^S

It can be assumed that when a structure suffers instability failure, the unstable fracture toughness, K_{IC}^S , can still be calculated based on the linear elasticity assumption as follows:

$$K_{IC}^S = \frac{1.5 \left(F_{\max} + \frac{mg}{2} \times 10^{-2} \right) \times 10^{-3} S \sqrt{a_c}}{th^2} f(\alpha_c), \quad (9)$$

$$f(\alpha_c) = \frac{1.99 - \alpha_c(1 - \alpha_c)(2.15 - 3.93\alpha_c + 2.7\alpha_c^2)}{(1 + 2\alpha_c)(1 - \alpha_c)^{\frac{3}{2}}}, \quad (10)$$

$$\alpha_c = \frac{a_0}{h}, \quad (11)$$

where K_{IC}^S is the unstable fracture toughness ($\text{MPa m}^{\frac{1}{2}}$) and $F_{\max}$ is the unstable fracture load (kN).

Because nonstandard specimens were used in this experiment, their toughness were transformed into that of the standard specimen based on the Weibull theory as follows:

$$K_{IC}^{st} = \left(\frac{V_{\text{nonst}}}{V_{st}} \right)^{\frac{1}{\alpha}} \times \left(\frac{h_{st}}{h_{\text{nonst}}} \right)^{\frac{1}{2}} \times K_{IC}^{\text{nonst}}, \quad (12)$$

where K_{IC}^{st} and K_{IC}^{nonst} are the toughness of the standard and nonstandard specimens, respectively ($\text{MPa m}^{\frac{1}{2}}$); V_{st} and V_{nonst} are the volumes of the standard and nonstandard specimens, respectively (m^3); h_{st} and h_{nonst} are the heights of the standard and nonstandard specimens, respectively (m), and the value of h should be less than 750 mm; and α is the Weibull parameter, which is 10 in this study.

4 Results and discussion

4.1 Compressive strength

The variation in the cubic compressive strength of the reinforced geopolymer concrete with the steel fiber content is shown in Figure 6, and it can be described by the following formula:

Figure 6: Cubic compressive strength.

$$y = -3.6x^4 + 16.7x^3 - 24.1x^2 + 16.0x + 43.3, \quad (13)$$

$$R^2 = 0.96.$$

It can be inferred that the geopolymer concrete specimens incorporated with steel fibers have higher cubic compressive strength than ordinary geopolymer concrete. The cubic compressive strength of the geopolymer concrete is increased by 8.1, 12.7, 16.8, 27.6, and 23.5% with the increases in the steel fiber content of 0.5, 1.0, 1.5, 2.0, and 2.5%, respectively, compared to that of the ordinary geopolymer concrete. The cubic compressive strength increases till the volume fraction of the steel fibers is 2.0%, following which it decreases. The lowest cubic compressive strength is 46.9 MPa, which is still higher than that of the geopolymer concrete without steel fibers.

The damage patterns of specimens after the cubic compressive tests are shown in Figure 7. The specimen with 2.5% steel fibers presents a complete pattern, with only some small cracks and few spalls on the surface, whereas that with 1.5% steel fibers has more spalls but with the whole structure intact. Compared to steel fiber-reinforced geopolymer concrete specimens, the ordinary geopolymer concrete presents serious breakage. Numerous fragments are seen to fall from it, and the inner concrete is broken. It can be concluded that the integrity of specimens after failure has a consistent relation with the cubic compressive strength. The specimens with a higher cubic compressive strength are more complete. The addition of the steel fibers assists in maintaining the integrity of specimens, and when their volume fraction is 2.0%, they have the maximum effect on the integrity of the geopolymer concrete.

The results of the axial compressive strength test are presented in Figure 8. The axial compressive strength is increased by 4.4, 9.8, 13.3, 23.7, and 20.5% as the steel fiber content increases from 0.5, 1.0, 1.5, 2.0, to 2.5%, respectively, compared to that of the ordinary geopolymer concrete. From Figure 9, it could be found that the changes in the axial and cubic compressive strength are similar. They both increase when the fiber content is less than 2% and decrease when the fiber content increases from 2 to 2.5%. The relationship between axial and cubic compressive strength can be expressed by the following formula:

$$y = 0.78x + 3.8, \quad R^2 = 0.98. \quad (14)$$

There is a good correlation between the axial and cubic compressive strength as shown in Figure 10.

There are several factors contributing to the increase in the compressive strength of the steel fiber-reinforced geopolymer concrete. First, the incorporation of the steel fibers increases the density of the geopolymer concrete,

Figure 7: Damage patterns of specimens after cubic compressive strength test: (a) C, (b) S3, and (c) S5.

which is beneficial for the compressive performance of the geopolymer [47]. Second, steel fibers incorporated into the geopolymer concrete can effectively prevent the appearance and propagation of cracks by the bridge effect [20]. Another important factor is the high elastic modulus of the steel fibers, which helps to disperse and withstand the stress [48]. When the addition of steel fibers exceeds 2.0%, the compressive strength of the geopolymer concrete decreases. This may be because excessive fibers are dispersed nonuniformly in the matrix, which has an adverse effect on the interior structure of the geopolymer concrete specimen. Furthermore, excessive steel fibers introduce additional air into the concrete during the mixing process, thus increasing the porosity of the specimen [49,50]. Nonuniformly distributed fibers and high porosity reduce the compressive strength. Previous research studies [16,28] have drawn the same conclusion in that an appropriate content of steel fibers has a

remarkable positive influence on the compressive strength of a geopolymer concrete. However, Shi *et al.* [51] found that adding fibers does not have a significant impact on the compressive strength improvement of cement concrete. That may be because a geopolymer concrete has better adhesive properties than ordinary cement concrete, and the shape of the fibers has a significant impact on the strength enhancement [52,53].

4.2 Compressive elastic modulus

The change in the compressive elastic modulus is presented in Figure 11. The increments of the compressive elastic modulus are 25.9, 25.0, 30.9, 47.7, and 42.1%, with the steel fiber contents of 0.5, 1.0, 1.5, 2.0, and 2.5%, respectively, compared to that of the ordinary

Figure 8: Axial compressive strength.

Figure 9: Compression of axial and cubic compressive strength.

Figure 10: Relation between axial and cubic compressive strength.

geopolymer concrete. It causes a remarkable increase in the compressive elastic modulus, with the largest value being 27.0 GPa. The steel fibers are effective in improving the compressive elastic modulus of the geopolymer concrete. This may be on account of steel fibers' high elastic modulus and the strong bond between the fibers and the matrix [54,55]. However, in previous studies [56–58], the conclusion was different in that the compressive elastic modulus of a geopolymer concrete is improved slightly by the addition of steel fibers or other fibers. The difference between this study and the previous ones can be attributed to the shape of the fibers incorporated into the geopolymer concrete. Milling steel fibers with more hooks have better bond strength with concrete than that of straight steel fibers and one-hooked-end fibers.

Figure 11: Compressive elastic modulus.

The correlation between the compressive elastic modulus and the compressive strength was also established and is shown in Figure 12. It can be seen that there is a strong correlation between the two properties from the following formula:

$$R^2 = 0.67x - 9.9, R^2 = 0.92. \quad (15)$$

The strong correlation was confirmed in the studies by Liu et al. [6] and Raza et al. [55]. They also found that the relation between the compressive elastic modulus and the compressive strength does not depend on the type of fibers used. The same conclusion – the compressive strength has a good relationship with the compressive elastic modulus – is also found for steel fiber-reinforced concrete [59].

4.3 Splitting tensile strength

Figure 13 presents the results of the splitting tensile strength test. It can be inferred that the splitting tensile strength increases with the increase in the steel fiber content. The incremental ratios of the splitting tensile strength are 5.7, 11.1, 15.0, 23.1, and 39.8% when the steel fiber volume fractions are 0.5, 1.0, 1.5, 2.0, and 2.5%, respectively. The highest splitting tensile strength is 3.69 MPa when the steel fiber content is 2.5%, and the lowest is 2.79 MPa at 0.5% content, which is still higher than that of the geopolymer concrete without steel fibers. The splitting tensile strength test results can be described by the following equation:

$$y = 0.13x^2 + 0.068x + 2.7, R^2 = 0.96. \quad (16)$$

Figure 12: Relation between compressive elastic modulus and cubic compressive strength.

Figure 13: Splitting tensile strength.

The incorporated steel fibers effectively modify the tensile behavior of the geopolymer concrete. This can be attributed to the bridging effect of the steel fibers, which reduces the coalescence of cracks in the geopolymer concrete, causing the failure mode of the geopolymer concrete to change from brittle failure to ductile failure [60–63]. Concurrently, the milling steel fibers used in this study have a high bond strength with the geopolymer concrete, delaying the pull-out of the steel fibers [52]. The positive influence of steel fibers on the splitting tensile strength was confirmed in previous studies. Athiyamaan and Ganesh [64] concluded that the steel fiber content is directly related to the splitting tensile strength of concrete, and the latter increases with increasing steel fiber content. Moreover, the concretes containing steel fibers did not present a brittle failure. The enhancing effect of steel fibers on the splitting tensile strength of concrete was also verified in the studies by Syamsir *et al.* [65] and Mehdipour *et al.* [66]. The damage

patterns of the specimens after the tests are shown in Figure 14. The specimen without steel fibers produces a fracture in the middle, whereas the specimens mixed with the steel fibers only have a few cracks in the center.

4.4 Flexural strength

The flexural strength is shown in Figure 15, and it can be expressed by the following equation:

$$y = 2.1x + 4.3, R^2 = 0.98. \quad (17)$$

Because nonstandard specimens with dimension of 100 mm × 100 mm × 400 mm were used in this study, the calculated results should be multiplied by a conversion factor of 0.82. The flexural strength of the steel fiber-reinforced geopolymer concrete increases with the increase in the steel fiber content. The incremental ratios of the flexural strength were 37.1, 47.5, 77.0, 101.7, and 134.6% compared to that of the geopolymer concrete without steel fibers. The highest and lowest flexural strength of the geopolymer concrete are 9.80 and 5.7 MPa when the steel fiber contents are 2.5 and 0.5%, respectively.

There are several factors contributing to the improvement in the flexural strength of the geopolymer concrete. An important reason is that steel fibers improve the post-crack behavior of a geopolymer concrete [57,67]. Another key factor is the strong adhesion force between the steel fibers and geopolymer concrete [56], which is stronger than that in fiber-reinforced cement concretes [67]. Gao *et al.* [61] found that short steel fibers inhibit the evolution of microcracks at the early age, whereas long steel fibers are effective in preventing the development of macro cracks through bridging and bonding before the load exceeds their bearing capacity. This mechanism of

Figure 14: Damage patterns of specimens after splitting tensile strength test: (a) C, (b) S1, and (c) S4.

Figure 15: Flexural strength.

the steel fibers is similar to that in the cement concrete system. Bhutta et al. [68] concluded that steel fibers can promote the flexural strength of geopolymer concrete by the bridging effect, facilitating the stress redistribution, and delaying the spread of cracks. They also stated that

the shapes of the fibers have a clear effect on the flexural strength. Length-deformed steel fibers possess a high bearing resistance. This bearing resistance combined with good adhesion between the geopolymer concrete and the fibers can produce a high bond strength, thus increasing the flexural strength. Figure 16 shows the damage patterns of the specimens after the flexural test. It is observed that there are only a few cracks at the bottom of the steel fiber-reinforced geopolymer concrete specimen, whereas the ordinary geopolymer concrete specimen is broken.

4.5 Fracture properties

The fracture parameters were calculated and are listed in Table 6, and the changes in the fracture toughness are shown in Figure 17. According to the current research results, fracture toughness was frequently used as the appropriate parameter to evaluate fracture properties of concrete materials [68–73]. It can be seen that the initial fracture toughness increases by 20.6, 25.2, 26.9, and

Figure 16: Damage patterns of specimens after cubic compressive strength test: (a) C, (b) S2, and (c) S4.

Table 6: Parameters of fracture properties

Specimen number	Volume fraction (%)	F_Q^1 (kN)	F_{max}^2 (kN)	a_c^3 (mm)	K_{IC}^{Q4} (MPa m $^{1/2}$)	K_{IC}^{Q5}	K_{IC}^{S6} (MPa m $^{1/2}$)	K_{IC}^{S7}
C	0	2.17	2.81	47.43	0.35	1.00	0.69	1.00
S1	0.5	2.03	3.64	64.37	0.33	0.95	1.57	2.27
S2	1.0	2.76	5.45	74.21	0.42	1.21	3.63	5.27
S3	1.5	2.88	6.37	79.04	0.44	1.25	5.72	8.30
S4	2.0	2.94	7.91	79.36	0.44	1.27	7.14	10.34
S5	2.5	2.96	9.70	79.63	0.45	1.28	8.79	12.74

¹The initial fracture load; ²the unstable fracture load; ³the critical effective crack length; ⁴the initial fracture toughness; ⁵the relative initial fracture toughness; ⁶the unstable fracture toughness; ⁷the relative unstable fracture toughness.

Figure 17: Effect of steel fiber content on fracture toughness. (a) Initial fracture toughness and (b) unstable fracture toughness.

27.8% compared to that of the ordinary geopolymer concrete when the mixing proportions of the steel fibers are 1.0, 1.5, 2.0, and 2.5%, respectively. There is a slight decrease when the addition ratio varies from 0 to 0.5%. When the steel fiber contents are 0.5, 1.0, 1.5, 2.0, and 2.5%, the unstable fracture toughness of the steel fiber-reinforced geopolymer concrete is 2.27, 5.27, 8.30, 10.34, and 12.74 times as that of the geopolymer concrete without the steel fibers.

The initial and unstable fracture toughness of the steel fiber-reinforced geopolymer concrete are improved compared to those of the ordinary geopolymer concrete, which are consistent with previous research studies [61,74]. This may owe to the good adhesion between fibers and the geopolymer matrix, producing a material with increased toughness [75]. Moreover, the large difference in the increased values of the initial and unstable fracture

toughness may be because that only when the crack's width is above a certain length that steel fibers can be activated and their strength capacity can be utilized fully [57,76]. This suggests that although steel fibers play a crucial role in arresting the development and propagation of macro cracks, they have little positive impact in reducing the evolution of microcracks [75]. Therefore, the addition of steel fibers mainly improves the behavior in the later stage of the fracture process of the geopolymer concrete, instead of that in the early stage. Owing to the high elastic modulus of the steel fibers, the load can be absorbed and transferred to another matrix, which can improve the plasticity of the geopolymer concrete [20,30].

This can also be explained by the energy theory. Steel fibers substantially enhance the energy absorption ability of the geopolymer concrete, particularly in the post-crack stage. A large amount of energy is consumed in the slow pull-out process and the rupturing process of randomly distributed steel fibers, which significantly improves the maximum unstable fracture toughness of geopolymer composites [75,77,78]. Figure 18 presents the load–displacement curves of the specimens with different volume fractions of steel fibers. The area under the load–displacement curve of a geopolymer concrete represents the absorbed energy, and a large area implies that the geopolymer concrete has a better energy-absorbing property. As shown in Figure 18, the geopolymer concrete with a steel fiber content of 2.5% has the largest area under the curve, which presents that it has the best energy-absorbing ability.

Figure 18: Effect of steel fiber content on load–displacement curve.

5 Conclusion

In this study, the effect of steel fibers on geopolymer concrete was studied. The compressive, splitting tensile, and flexural strength; compressive elastic modulus; and fracture properties were investigated. The following conclusions were drawn from this study:

- (1) The addition of steel fibers increased the cubic and axial compressive strength and compressive elastic modulus of the geopolymer concrete. The three properties increased when the volume fraction of steel fibers was under 2.0% and decreased when it exceeded 2.0%. When the volume fraction of the steel fibers was 2.0%, the cubic and axial compressive strength were 55.4 and 46.9 MPa, respectively, and the compressive elastic modulus was 27 GPa.
- (2) The incorporation of steel fibers significantly improved the splitting tensile strength and flexural strength. These properties exhibited the same trends with the addition of the steel fibers. Both strengths increased as the volume fraction of the steel fibers increased and reached the maximum values when the content of the steel fibers was 2.5%. The highest splitting tensile strength was 3.69 MPa, and the highest value of flexural strength was 9.80 MPa.
- (3) The steel fibers are effective in improving the fracture properties of the geopolymer concrete, particularly on the unstable fracture toughness. When the volume fraction of the steel fibers is between 0 and 2.5%, the initial fracture toughness decreased and subsequently increased. The unstable fracture toughness significantly increased with the addition of steel fibers. When the content of the steel fibers was 2.5%, the maximum value of the initial fracture toughness was $0.45 \text{ MPa} \cdot \text{m}^{\frac{1}{2}}$ and the maximum unstable fracture toughness was $8.79 \text{ MPa} \cdot \text{m}^{\frac{1}{2}}$, which was 12.74 times than that of the ordinary geopolymer concrete.

Acknowledgments: The authors would like to acknowledge the financial support received from the National Natural Science Foundation of China (Grant No. 51979251, U2040224), the Natural Science Foundation of Henan (Grant No. 212300410018), and the Program for Innovative Research Team (in Science and Technology) in University of Henan Province of China (Grant No. 20IRTSTHN009).

Funding information: National Natural Science Foundation of China (Grant No. 51979251, U2040224), Natural Science Foundation of Henan (Grant No. 212300410018), and

Program for Innovative Research Team (in Science and Technology) in University of Henan Province of China (Grant No. 20IRTSTHN009).

Author contributions: Peng Zhang: Funding acquisition, Investigation, Formal analysis, Data curation, Writing - Original Draft; Jia Wang: Methodology, Resources, Supervision, Validation, Writing - Original Draft; Qingfu Li: Conceptualization, Investigation, Supervision, Project administration, Writing - Review & Editing; Jinyi Wan: Validation, Investigation, Methodology; Yifeng Ling: Writing - Review & Editing.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: All data presented in this study are available upon request.

References

- [1] Bouaissi A, Li LY, Abdullah MMA, Bui QB. Mechanical properties and microstructure analysis of FA-GGBS-HMNS based geopolymer concrete. *Constr Build Mater.* 2019;210:198–209.
- [2] Lee WH, Wang JH, Ding YC, Cheng TW. A study on the characteristics and microstructures of GGBS/FA based geopolymer paste and concrete. *Constr Build Mater.* 2019;211:807–13.
- [3] Rajini B, Sashidhar C. Prediction mechanical properties of GGBS based on geopolymer concrete by using analytical method. *Mater Today Proc.* 2019;19:536–40.
- [4] Amran YHM, Alyousef R, Alabduljabbar H, El-Zeadani M. Clean production and properties of geopolymer concrete; a review. *J Clean Prod.* 2020;251:119679.
- [5] Moradikhah AB, Esparham A, Avanaki MJ. Physical & mechanical properties of fiber reinforced metakaolin-based geopolymer concrete. *Constr Build Mater.* 2020;251:118965.
- [6] Davidovits J. Geopolymers-and-geopolymeric-materials. *J Therm Anal.* 1989;35(2):429–41.
- [7] Zhang HY, Qiu GH, Kodur V, Yuan ZS. Spalling behavior of metakaolin-fly ash based geopolymer concrete under elevated temperature exposure. *Cem Concr Compos.* 2020;106:103483.
- [8] Ng C, Alengaram UJ, Wong LS, Mo KH, Jumaat MZ, Ramesh S. A review on microstructural study and compressive strength of geopolymer mortar, paste and concrete. *Constr Build Mater.* 2018;186:550–76.
- [9] Noushini A, Hastings M, Castel A, Aslani F. Mechanical and flexural performance of synthetic fibre reinforced geopolymer concrete. *Constr Build Mater.* 2018;186:454–75.
- [10] Sandanayake M, Gunasekara C, Law D, Zhang G, Setunge S. Greenhouse gas emissions of different fly ash based geopolymer concretes in building construction. *J Clean Prod.* 2018;204:399–408.
- [11] Top S, Vapur H, Altiner M, Kaya D, Ekicibil A. Properties of fly ash-based lightweight geopolymer concrete prepared using

- pumice and expanded perlite as aggregates. *J Mol Structure*. 2020;1202:127236.
- [12] Jindal BB. Investigations on the properties of geopolymer mortar and concrete with mineral admixtures: a review. *Constr Build Mater*. 2019;227:116644.
  - [13] Pilehvar S, Cao VD, Szczotok AM, Carmona M, Valentini L, Lanzon M, et al. Physical and mechanical properties of fly ash and slag geopolymer concrete containing different types of micro-encapsulated phase change materials. *Constr Build Mater*. 2018;173:28–39.
  - [14] Assi LN, Carter K, Deaver E, Ziehl P. Review of availability of source materials for geopolymer/sustainable concrete. *J Clean Prod*. 2020;263:121477.
  - [15] Jena S, Panigrahi R. Performance assessment of geopolymer concrete with partial replacement of ferrochrome slag as coarse aggregate. *Constr Build Mater*. 2019;220:525–37.
  - [16] Their JM, Ozakca M. Developing geopolymer concrete by using cold-bonded fly ash aggregate, nano-silica, and steel fiber. *Constr Build Mater*. 2018;180:12–22.
  - [17] Liu Y, Shi C, Zhang Z, Li N, Shi D. Mechanical and fracture properties of ultra-high performance geopolymer concrete: effects of steel fiber and silica fume. *Cem Concr Compos*. 2020;112:103665.
  - [18] Rashid K, Li XD, Xie Y, Deng J, Zhang FJ. Cracking behavior of geopolymer concrete beams reinforced with steel and fiber reinforced polymer bars under flexural load. *Compos Part B-Eng*. 2020;186:107777.
  - [19] Gulsan ME, Alzebaree R, Rasheed AA, Nis A, Kurtoglu AE. Development of fly ash/slag based self-compacting geopolymer concrete using nano-silica and steel fiber. *Constr Build Mater*. 2019;211:271–83.
  - [20] Ding Y, Bai YL. Fracture properties and softening curves of steel fiber-reinforced slag-based geopolymer mortar and concrete. *Materials*. 2018;11(8):1445.
  - [21] Zhang P, Wang KX, Wang J, Guo JJ, Hu SW, Ling YF. Mechanical properties and prediction of fracture parameters of geopolymer/alkali-activated mortar modified with PVA fiber and nano-SiO₂. *Ceram Int*. 2020;46(12):20027–37.
  - [22] Wang L, He TS, Zhou YX, Tang SW, Tan JJ, Liu ZT, et al. The influence of fiber type and length on the cracking resistance, durability and pore structure of face slab concrete. *Constr Build Mater*. 2021;282:122706.
  - [23] Qin Y, Zhang XW, Chai JR, Xu ZG, Li S. Experimental study of compressive behavior of polypropylene-fiber-reinforced and polypropylene-fiber-fabric-reinforced concrete. *Constr Build Mater*. 2019;194:216–25.
  - [24] Wang L, Guo FX, Yang H, Wang, Tang SW. Comparison of fly ash, PVA fiber, MgO and shrinkage-reducing admixture on the frost resistance of face slab concrete via pore structural and fractal analysis. *Fractals*. 2020;29(2):2140002. doi: 10.1142/S0218348X21400028.
  - [25] Qin Y, Li M, Li YL, Ma WL, Xu ZG, Chai JR, et al. Effects of nylon fiber and nylon fiber fabric on the permeability of cracked concrete. *Constr Build Mater*. 2021;274:121786.
  - [26] Zhang P, Li Q, Chen Y, Shi Y, Ling YF. Durability of steel fiber-reinforced concrete containing SiO₂ nano-particles. *Materials*. 2019;12(13):2184.
  - [27] Qin Y, Zhang XW, Chai JR. Damage performance and compressive behavior of early-age green concrete with recycled nylon fiber fabric under an axial load. *Constr Build Mater*. 2019;209:105–14.
  - [28] Shaikh FUA, Hosan A. Mechanical properties of steel fibre reinforced geopolymer concretes at elevated temperatures. *Constr Build Mater*. 2016;114:15–28.
  - [29] Ahmed HQ, Jaf DK, Yaseen SA. Flexural capacity and behaviour of geopolymer concrete beams reinforced with glass fibre-reinforced polymer bars. *Int J Concr Struct Mater*. 2020;14(1):14.
  - [30] Gomes RF, Dias DP, Silva FD. Determination of the fracture parameters of steel fiber-reinforced geopolymer concrete. *Theor Appl Fract Mech*. 2020;107:102568.
  - [31] Farhan NA, Sheikh MN, Hadi MNS. Behaviour of ambient cured steel fibre reinforced geopolymer concrete columns under axial and flexural loads. *Structures*. 2018;15:184–95.
  - [32] Liu Y, Zhang Z, Shi C, Zhu D, Li N, Deng Y. Development of ultra-high performance geopolymer concrete (UHPGC): influence of steel fiber on mechanical properties. *Cem Concr Compos*. 2020;112:103670.
  - [33] Wang L, Jin MM, Guo FX, Wang Y, Tang SW. Pore structural and fractal analysis of the influence of fly ash and silica fume on the mechanical property and abrasion resistance of concrete. *Fractals*. 2021;22(9):2140003.
  - [34] Ozkiliç YO, Aksoylu C, Arslan MH. Experimental and numerical investigations of steel fiber reinforced concrete dapped-end purlins. *J Build Eng*. 2021;36:102119.
  - [35] Gemi L, Aksoylu C, Yazman S, Ozkiliç YO, Arslan MH. Experimental investigation of shear capacity and damage analysis of thinned end prefabricated concrete purlins strengthened by CFRP composite. *Comp Struct*. 2019;229:111399.
  - [36] Aksoylu C, Yazman S, Ozkiliç YO, Gemi L, Arslan MH. Experimental analysis of reinforced concrete shear deficient beams with circular web openings strengthened by CFRP composite. *Comp Struct*. 2020;249:112561.
  - [37] Ozkiliç YO, Yazman S, Aksoylu C, Arslan MH, Gemi L. Numerical investigation of the parameters influencing the behavior of dapped end prefabricated concrete purlins with and without CFRP strengthening. *Constr Build Mater*. 2021;275:122173.
  - [38] Gemi L, Köroğlu MA. Çekme Bölgesi Lifli Beton Olan Cam Fiber Takviyeli Polimer (GFRP) ve Çelik Donatılı Etriyesiz Kirişlerin Eğilme Etkisi Altındaki Davranışı ve Hasar. *Selçuk Univ J Eng Sci Technol*. 2018;6(4):654–67.
  - [39] Gemi L, Madenci E, Özkiliç YO. Çelik, cam FRP ve Hibrit Donatılı Betonarme Kirişlerin Eğilme Performansının İncelenmesi. *Düzce Üniver Bilim ve Teknol Derg*. 2020;8:1470–83.
  - [40] Aksoylu C, Özkiliç YO, Yazman Ş, Gemi L, Arslan MH. İnceltilmiş Uçlu Önüretimli Aşık Kirişlerinin Yük Taşıma Kapasitelerinin Deneysel ve Numerik Olarak İrdelenmesi ve Çözüm Önerileri. *Teknik Dergi*. 2021;32(3):667066.
  - [41] Aksoylu C, Ozkiliç YO, Arslan MH. Damages on prefabricated concrete dapped-end purlins due to snow loads and a novel reinforcement detail. *Eng Struct*. 2020;225:111225.
  - [42] Xu SL, Zhao GF. Double-k fracture criterion of crack propagation in concrete structures. *J Civ Eng China*. 1992;25(2):32–8.
  - [43] Xu SL, Zhang XF, Zheng S. Experimental measurement of double-k fracture parameters of concrete with small-size aggregates. *J Hydro Eng*. 2006;37(5):543–53.
  - [44] Guan JF, Yuan P, Li LL, Yao XH, Zhang YL, Meng W. Rock fracture with statistical determination of fictitious crack growth. *Theor Appl Fract Mech*. 2021;112:102859.
  - [45] Guan JF, Yuan P, Hu XZ, Qing LB, Yao XH. Statistical analysis of concrete fracture using normal distribution pertinent to maximum aggregate size. *Theor Appl Fract Mech*. 2019;101:236–53.

- [46] Guan JF, Li CM, Wang, Qing LB, Song ZK, Liu ZP. Effect of polypropylene fiber content on flexural strength of lightweight foamed concrete at ambient and elevated temperatures. *Theor Appl Fract Mech.* 2019;100:114–27.
- [47] Rabiaa E, Mohamed RAS, Sofi WH, Tawfik TA. Developing geopolymer concrete properties by using nanomaterials and steel fiber. *Adv Mater Sci Eng.* 2020;2020:5186091.
- [48] Guo XL, Pan XJ. Mechanical properties and mechanisms of fiber reinforced fly ash-steel slag based geopolymer mortar. *Constr Build Mater.* 2018;179:633–41.
- [49] Hung CC, Chen YT, Yen CH. Workability, fiber distribution, and mechanical properties of UHPC with hooked end steel macro-fibers. *Constr Build Mater.* 2020;260:119944.
- [50] Wongs A, Kunthawatwong R, Naenudon S, Sata V, Chindaprasirt P. Natural fiber reinforced high calcium fly ash geopolymer mortar. *Constr Build Mater.* 2020;241:118143.
- [51] Shi XJ, Park P, Rew Y, Huang KJ, Sim C. Constitutive behaviors of steel fiber reinforced concrete under uniaxial compression and tension. *Constr Build Mater.* 2020;233:117316.
- [52] Shaikh FUA. Pullout behavior of hook end steel fibers in geopolymers. *J Mater Civ Eng.* 2019;31(6):04019068.
- [53] Rashad AM. Effect of steel fibers on geopolymer properties – the best synopsis for civil engineer. *Constr Build Mater.* 2020;246:118534.
- [54] Cui YF, Gao KK, Zhang P. Experimental and statistical study on mechanical characteristics of geopolymer concrete. *Materials.* 2020;13(7):1651.
- [55] Raza SS, Qureshi LA, Ali B, Raza A, Khan MM. Effect of different fibers (steel fibers, glass fibers, and carbon fibers) on mechanical properties of reactive powder concrete. *Struct Concr.* 2020;1–13.
- [56] Islam A, Alengaram UJ, Jumaat MZ, Ghazali NB, Yusoff S, Bashar II. Influence of steel fibers on the mechanical properties and impact resistance of lightweight geopolymer concrete. *Constr Build Mater.* 2017;152:964–77.
- [57] Khan MZN, Hao YF, Hao H, Shaikh FUA. Mechanical properties of ambient cured high strength hybrid steel and synthetic fibers reinforced geopolymer composites. *Cem Concr Compos.* 2018;85:133–52.
- [58] Isa MN, Pilakoutas K, Guadagnini M, Angelakopoulos H. Mechanical performance of affordable and eco-efficient ultra-high performance concrete (UHPC) containing recycled tyre steel fibres. *Constr Build Mater.* 2020;255:119272.
- [59] Hajforoush M, Kheyroddin A, Rezaifar O. Investigation of engineering properties of steel fiber reinforced concrete exposed to homogeneous magnetic field. *Constr Build Mater.* 2020;252:119064.
- [60] Al-Majidi MH, Lampropoulos A, Cundy AB. Steel fibre reinforced geopolymer concrete (SFRGC) with improved micro-structure and enhanced fibre-matrix interfacial properties. *Constr Build Mater.* 2017;139:286–307.
- [61] Gao X, Yu QL, Yu R, Brouwers HJH. Evaluation of hybrid steel fiber reinforcement in high performance geopolymer composites. *Mater Struct.* 2017;50(2):165.
- [62] Ameri F, de Brito J, Madhkan M, Taheri RA. Steel fibre-reinforced high-strength concrete incorporating copper slag: mechanical, gamma-ray shielding, impact resistance, and microstructural characteristics. *J Build Eng.* 2020;29:101118.
- [63] Wang Y, Aslani F, Valizadeh A. An investigation into the mechanical behaviour of fibre-reinforced geopolymer concrete incorporating NiTi shape memory alloy, steel and polypropylene fibres. *Constr Build Mater.* 2020;259:119765.
- [64] Athiyamaan V, Ganesh GM. Experimental, statistical and simulation analysis on impact of micro steel – fibres in reinforced SCC containing admixtures. *Constr Build Mater.* 2020;246:118450.
- [65] Syamsir A, Mubin SM, Nor NM, Anggraini V, Nagappan S, Sofan AM, et al. Effect of combined drink cans and steel fibers on the impact resistance and mechanical properties of concrete. *J Mech Eng Sci.* 2020;14(2):6734–42.
- [66] Mehdipour S, Nikbin IM, Dezhampahan S, Mohebbi R, Moghadam H, Charkhtab S, et al. Mechanical properties, durability and environmental evaluation of rubberized concrete incorporating steel fiber and metakaolin at elevated temperatures. *J Clean Prod.* 2020;254:120126.
- [67] Mo KH, Yeoh KH, Bashar II, Alengaram UJ, Jumaat MZ. Shear behaviour and mechanical properties of steel fibre-reinforced cement-based and geopolymer oil palm shell lightweight aggregate concrete. *Constr Build Mater.* 2017;148:369–75.
- [68] Bhutta A, Borges PHR, Zanotti C, Farooq M, Banthia N. Flexural behavior of geopolymer composites reinforced with steel and polypropylene macro fibers. *Cem Concr Compos.* 2017;80:31–40.
- [69] Golewski GL, Gil DM. Studies of fracture toughness in concretes containing fly ash and silica fume in the first 28 days of curing. *Materials.* 2021;14(2):319.
- [70] Golewski GL. Changes in the fracture toughness under Mode II loading of Low Calcium Fly Ash (LCFA) concrete depending on ages. *Materials.* 2020;13(12):5241.
- [71] Murthy AR, Ganesh P. Effect of steel fibres and nano silica on fracture properties of medium strength concrete. *Adv Concr Constr.* 2019;7(3):143–50.
- [72] Murthy AR, Ganesh P, Kumar SS, Lyer NR. Fracture energy and tension softening relation for nano-modified concrete. *Struct Eng Mech.* 2015;54(6):1201–16.
- [73] Golewski GL. Estimation of the optimum content of fly ash in concrete composite based on the analysis of fracture toughness tests using various measuring systems. *Constr Build Mater.* 2019;213:142–55.
- [74] Bhutta A, Farooq M, Zanotti C, Banthia N. Pull-out behavior of different fibers in geopolymer mortars: effects of alkaline solution concentration and curing. *Mater Struct.* 2017;50(1):80.
- [75] Asrani NP, Murali G, Abdelgader HS, Parthiban K, Haridharan MK, Karthikeyan K. Investigation on mode I fracture behavior of hybrid fiber-reinforced geopolymer composites. *Arab J Forence Eng.* 2019;44(10):8545–55.
- [76] Carvalho MR, Barros JAO, Zhang YY, Dias-da-Costa D. A computational model for simulation of steel fibre reinforced concrete with explicit fibres and cracks. *Comp Methods Appl Mech Eng.* 2020;363:112879.
- [77] Guo WN, Zhang P, Tian YP, Wang B, Ma W. Influence of the amount of steel fibers on fracture energy and drying shrinkage of HPRCC. *Adv Mater Sci Eng.* 2020;2020:8459145.
- [78] Karimipour A, Ghalehnovi M, de Brito J. Mechanical and durability properties of steel fibre-reinforced rubberised concrete. *Constr Build Mater.* 2020;257:119463.