Research Article

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Mechanical and fracture properties of steel fiber-reinforced geopolymer concrete

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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, CO$_2$ [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 CO$_2$. The amount of CO$_2$ produced during the production of concrete accounts for 7–10% of the total global CO$_2$ 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...
subsequently form a three-dimensional polymeric chain and a ring structure [8–10]. The empirical formula [11] of a geopolymer is as follows:

$$X_{q}[\text{(SiO}_{2}\text{)}_{a} - \text{AlO}_{2}]_{q} \cdot n\text{H}_{2}\text{O},$$

where $X$ represents a metal cation ($\text{Ca}^{2+}$, $\text{K}^+$, or $\text{Na}^+$); $a$ 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/cm$^3$, 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 Chenzxing Industry Co. Ltd, Shijiazhuang, with an average grain diameter of 1.2µm. 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
was 6.6. The chloride (Cl\textsuperscript{−}) and sulfate (SO\textsubscript{4}\textsuperscript{2−}) contents were 160.58 and 231.56 mg/L, respectively.

The alkaline activator used in this study was a mixture of sodium silicates (Na\textsubscript{2}SO\textsubscript{3}) and sodium hydroxide (NaOH). It was prepared by mixing Na\textsubscript{2}SO\textsubscript{3}, NaOH, and ordinary tap water. NaOH solid flakes of 99% purity were employed. The Na\textsubscript{2}SO\textsubscript{3} solution was from Longxiang Ceramic Co. Ltd, Zhengzhou, Henan Province, China, with a special gravity of 1.41 g/cm\textsuperscript{3}. The solid ratio of the Na\textsubscript{2}SO\textsubscript{3} 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 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 1: Chemical composition of fly ash

| Chemical composition | SiO\textsubscript{2} | Al\textsubscript{2}O\textsubscript{3} | Fe\textsubscript{2}O\textsubscript{3} | CaO | MgO | f-CaO | SO\textsubscript{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\textsubscript{2} | Al\textsubscript{2}O\textsubscript{3} | Fe\textsubscript{2}O\textsubscript{3} | CaO + MgO | K\textsubscript{2}O + Na\textsubscript{2}O |
|----------------------|---------------------|-----------------------------|----------------|---------------|----------------|
| Mass ratio (%)       | 54 ± 2              | 43 ± 2                      | ≤1.3           | ≤0.8          | ≤0.7           |

![Figure 1: Patterns of steel fibers.](image-url)


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:

\[ E_c = \frac{F_a - F_0}{A} \times \frac{L}{\varepsilon_{\Delta}} \]  

(2)

where \( E_c \) is the compressive elastic modulus (MPa); \( F_a \) is the load when the compressive strength reaches one-third of 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 \( \varepsilon_{\Delta} \) 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:

\[ \varepsilon_{\Delta} = \varepsilon_a - \varepsilon_0, \]

(3)

where \( \varepsilon_a \) is the average deformation between both sides of the specimen when the load reaches \( F_a \) (mm) and \( \varepsilon_0 \) 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 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/m³) |
|---------------------|-------------|----------------|----------------------|-----------------|---------------------------------|----------------------|-----------------|
| Results (average)   | 2.5         | 0.35           | 40                   | 38              | ≥800                            | ≥200                 | 7,850           |

Table 4: Mixture proportions of geopolymer concrete

| Specimen number | Metakaolin (kg/m³) | Fly ash (kg/m³) | Alkaline activator Na₂SO₃ (kg/m³) | NaOH (kg/m³) | Water (kg/m³) | River sand (kg/m³) | Gravel (kg/m³) | Steel fiber (%)¹ | Water reducer (kg/m³) |
|-----------------|--------------------|----------------|----------------------------------|---------------|---------------|--------------------|---------------|-----------------|----------------------|
| 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.

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      |
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:

\[ f_t = \frac{F_t l}{b h^2}, \]

where \( f_t \) is the flexural strength (MPa); \( F_t \) 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.

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 \( K_i = K_{IC}^0 \), cracks begin to appear; when \( K_{IC}^0 \leq K_i \leq K_{IC}^S \), 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, \( K_{IC}^0 \) is the initial fracture toughness, which depends on two factors – initial fracture load \( F_0 \) 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:

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

**Figure 3:** Four-point bending test (GB50081-2002).
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, $F_Q$.

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

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

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

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

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

Initial fracture toughness $K_{IC}^0$ is obtained by the following equation, provided the structural performance is still within the elastic range when the experimental load reaches initial fracture load $F_Q$:

$$K_{IC}^0 = \frac{1.5(F_Q + \frac{mg}{2} \times 10^{-2}) \times 10^{-3}S\sqrt{a_0} f(a_0)}{th^2}, \quad (7)$$

$$f(a_0) = \frac{1.99 - a_0(1 - a_0)(2.15 - 3.93a_0 + 2.7a_0^2)}{(1 + 2a_0)(1 - a_0)^2}, \quad (8)$$

where $K_{IC}^0$ represents the initial fracture toughness (MPa m$^{1/2}$); $F_Q$ 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.

Unstable fracture toughness $K_{IC}$ can still be calculated based on the linear elasticity assumption as follows:

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

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

Figure 5: Experimental instrument for three-point bending test.
\[ f(a_c) = \frac{1.99 - a_c(1 - a_c)(2.15 - 3.93a_c + 2.7a_c^2)}{(1 + 2a_c)(1 - a_c)^{\frac{3}{2}}} \] (10)

\[ a_c = \frac{a_0}{h} \] (11)

where \( K_{IC}^S \) is the unstable fracture toughness (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:

\[ K_{IC}^{st} = \left( \frac{V_{nonst}}{V_{st}} \right)^{\frac{1}{2}} \times \left( \frac{h_{st}}{h_{nonst}} \right)^{\frac{1}{2}} \times K_{IC}^{nonst} \] (12)

where \( K_{IC}^{st} \) and \( K_{IC}^{nonst} \) are the toughness of the standard and nonstandard specimens, respectively (MPa m^{\frac{1}{2}}); \( V_{st} \) and \( V_{nonst} \) are the volumes of the standard and nonstandard specimens, respectively (m³); \( h_{st} \) 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 \( \alpha \) 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:

\[ y = -3.6x^4 + 16.7x^3 - 24.1x^2 + 16.0x + 43.3, \] \( R^2 = 0.96 \) (13)

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:

\[ y = 0.78x + 3.8, \] \( R^2 = 0.98 \) (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,
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
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 accounted for by the 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.

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:

\[
R^2 = 0.67x - 9.9, R^2 = 0.92.
\]  

(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:

\[
y = 0.13x^2 + 0.068x + 2.7, R^2 = 0.96.
\]  

(16)
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:

$$ y = 2.1x + 4.3, R^2 = 0.98. $$

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
the steel fibers is similar to that in the cement concrete system. Bhutta et al. \cite{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 \cite{68–73}. It can be seen that the initial fracture toughness increases by 20.6, 25.2, 26.9, and

![Image](image_url)

**Figure 15:** Flexural strength.

![Image](image_url)

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

| Specimen number | Volume fraction (%) | $F_0^1$ (kN) | $F_{\max}^2$ (kN) | $a_c^3$ (mm) | $K_{IC}^{0.4}$ (MPa m$^{1/2}$) | $K_{IC}^{0.5}$ | $K_{IC}^{0.6}$ (MPa m$^{1/2}$) | $K_{IC}^{0.7}$ |
|-----------------|---------------------|--------------|-------------------|-------------|----------------------------|--------------|----------------------------|--------------|
| 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        |

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

**Table 6:** Parameters of fracture properties
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.
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 MPa·m \(^{1/2}\) and the maximum unstable fracture toughness was 8.79 MPa·m \(^{1/2}\), which was 12.74 times than that of the ordinary geopolymer concrete.

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