Effect of Modified Deformed Steel Fiber on Mechanical Properties of Artificial Granite

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Received 29 May 2020; Revised 25 August 2020; Accepted 18 March 2021; Published 2 April 2021

1. Introduction

Precision machine tools, ultraprecision machine tools, and precision measuring instruments are the cutting-edge equipment of advanced manufacturing industry, and they are the core force of a country’s development, with high requirements for basic components. At present, artificial granite (also known as resin concrete) has made great progress in replacing traditional cast iron materials with its excellent dynamic, static, and thermal properties in machine tool foundation parts [1–4]. Artificial granite is made of granite aggregate with different gradations, which is cast into shape by special epoxy resin binder at room temperature and atmospheric pressure, and a certain amount of filler should be added in the mixing process [5–7]. However, the compressive strength, bending strength, and tensile strength of artificial granite are insufficient, so how to improve the mechanical properties of artificial granite has become the focus of scholars.

In order to improve the mechanical properties of matrix, some scholars have done a lot of research and think that adding different fibers (steel fiber, plant fiber, basalt fiber, polypropylene fiber, carbon fiber, glass fiber, etc.) can improve the strength of matrix [8–14]. Some scholars used the fractal design program to design, manufacture, and test the matrix reinforced fiber and achieved good results [15]. Some scholars choose two kinds of binders and combine the excellent properties of the two kinds of binders to maintain the sufficient strength of the materials in the process of degradation [16]. Ai et al. [17] used numerical method to analyze the influence of aggregate shape and distribution on the strength and fracture behavior of polyurethane polymer concrete (PPC).

Many scholars have done a lot of research on steel fiber and added steel fiber to the matrix to enhance the matrix strength [18–29]. Under external loading, steel fiber can effectively prevent the formation and expansion of cracks in artificial granite matrix. The load is transferred to steel fiber through the interface between resin and fiber, and steel fiber and resin matrix deform at the same time. However, the elastic modulus and toughness of steel fiber are much higher than those of resin matrix, which can restrain the deformation of matrix and improve the mechanical properties of artificial granite. Steel fiber becomes the reinforcing element of artificial granite, and its mass fraction, size, distribution, shape, surface treatment, and other factors have an
important influence on the mechanical properties of artificial granite [19–22, 30–35]. The influencing factors of steel fiber in artificial granite matrix have also been studied at home and abroad. When the mass fraction of steel fiber is 0.5% ~ 2.0%, the tensile strength, bending strength, and compressive strength of the material increase gradually, and the tensile strength and bending strength change more obviously than the compressive strength [23]. When the fiber mass fraction reaches 1.5%, the tensile strength of corragated steel fiber reinforced resin concrete is 1.6 times higher than that of straight steel fiber reinforced resin concrete [36]. Peng et al. [24], through the tensile and bending experiments of UHPC with profiled steel fiber, found that the effect of corrugated steel fiber is better than that of end hook steel fiber at the same mass fraction; Kim et al. [25], through the drawing experiment of single steel fiber, found that the corrugated steel fiber has the maximum drawing resistance, followed by the end hook and straight steel fiber; Shen et al. [26] used the ring experiment to obtain that the double end hook steel fiber can effectively reduce the free shrinkage and residual stress of high strength concrete; Tao et al. [27] verified the influence of fiber shape on ultrahigh performance concrete by drawing experiment and obtained that the drawing power of copper-plated single fold end hook steel fiber is greater than that of copper-plated double hook, wave, and straight steel fiber; Callens et al. [28] treated the stainless steel fiber with silane coupling agent, and the transverse three-point bending strength increased by 50%; Zhong and Fu [29] treated the surface of copper coated steel fiber with silane coupling agent γ-methylacryloxypropyltrimethoxysilane (MPS) containing carboxyl group and γ-mercaptopropyltrimethoxysilane (MPTS) containing mercapto SH group. The roughness, corrosion resistance, and drawing power of the steel fiber were greatly improved. However, there are few researches on the influence of the shape of steel fiber and the surface modification of steel fiber on the mechanical properties of artificial granite, and the mechanical properties of materials are insufficient.

In this paper, the influence mechanism of the shape of steel fiber (W-shape, L-shape, V-shape, and I-shape steel fiber) and the steel fiber before and after the modification of KH-550 on the mechanical properties of artificial granite has been studied by means of theoretical and experimental research, so as to further enhance the mechanical properties of artificial granite. This study provides a reference for the application of precision and ultraprecision machine tools and precision measuring instruments.

2. Material Preparation

2.1. Composition of Steel Fiber Reinforced Artificial Granite Material. Steel fiber reinforced artificial granite is composed of binder system, aggregate system, steel fiber, and filler. The material of each component is shown in Figure 1, and the mass fractions of each component are 11%, 80%, 1.9%, and 7.1%, respectively.

In the binder system, the binder is bisphenol A epoxy resin E44. The curing agent is 650 polyamide resin; AGE as diluent; DBP as toughener (appropriate addition); the ratio of binder, curing agent, and diluent is 15:7:4 [37].

The aggregate system is Jinan green granite aggregate; its main composition and mass fraction are shown in Table 1. According to “Horsfield most dense filling principle [38],” combined with “Beret method [39],” the aggregate is divided into five different specifications. According to A. H. M. Andreasen formula, the experimental index is 0.44, and the mass fractions of five different specifications of aggregate are as follows: 0 mm–0.11 mm accounting for 13.75%; 0.11 mm–0.52 mm accounting for 13.48%; 0.52 mm–2.36 mm accounting for 25.75%; 2.36 mm–4.75 mm accounting for 19.09%; 4.75 mm–10 mm accounting for 27.93%.

The filler is MgSO₄ and mica powder, and their mass fraction ratio is 1:2.

A. H. M. Andreasen [38] formula is

$$U_1 = 100 \left( \frac{d}{D} \right)^q,$$

where

- $U_1$ is mass fraction of particle size at all levels (%)
- $D$ is maximum aggregate size (mm)
- $d$ is sieve size (mm)
- $q$ is experimental index

2.2. The Establishment of Theoretical Model of Steel Fiber Drawing with Different Shapes. Different shapes of steel fibers used in the experiment were produced by Zhengzhou Yujian Steel Fiber Co., Ltd. W, L, V, and I steel fibers have the same parameters except for shape. The main physical performance parameters of steel fiber are shown in Table 2, and the actual steel fiber is shown in Figure 2.

The length of each small section after bending of W-shape, L-shape, V-shape, and I-shape steel fiber is equal. The length of bending section of W-shape steel fiber is $L_W$; the length of bending section of L-shaped steel fiber is $L_L$; the length of bending section of V-shaped steel fiber is $L_V$; the length of bending section of I-shaped steel fiber is $L_I$. Under the condition that the resin matrix meets the strength requirements, four kinds of steel fiber drawing theoretical models are established, as shown in Figure 3.

2.3. Maximum Drawing Load of Steel Fiber with Different Shapes. The length of steel fibers with different shapes embedded in resin matrix is equal. Theoretically, under the action of the maximum drawing force $P_{max}$, steel fiber will overcome the bonding force $P_b$ at the interface between resin and steel fiber, the deformation force $P_d$ when fiber is pulled out, and the friction force $P_f$ between fiber and resin. The maximum drawing force of steel fiber embedded in resin matrix is calculated by

$$P_{max} = P_b + P_d + P_f.$$
The interfacial adhesion $P_b$ of steel fiber resin is calculated by

$$P_b = \tau \pi d L,$$  \hspace{1cm} (3)

where

- $\tau$ is bond strength between steel fiber and resin
- $d$ is steel fiber diameter
- $L$ is total length of steel fiber embedded in resin matrix

The deformation force $P_d$ of steel fiber is calculated by

$$P_d = \frac{W\sigma_s}{L_i} \tan \alpha,$$  \hspace{1cm} (4)

where

- $W$ is bending section modulus of steel fiber; $\sigma_s$ is yield strength of steel fiber; $L_i$ is length of bending section of steel fiber.
- $\alpha$ is angle between drawing force direction and fiber bending section.

The friction force $P_f$ between steel fiber and resin is calculated by

$$P_f = \mu P_g = \mu \times 2P_d \sin \frac{\alpha}{2} = \mu \frac{2W\sigma_s}{L_i} \tan \alpha \sin \frac{\alpha}{2},$$  \hspace{1cm} (5)

where $\mu$ is friction coefficient between steel fiber and resin matrix and $P_g$ is the resultant force of correction force and deformation force.

According to formulas (2)–(5), the maximum drawing force $P_{w_{\text{max}}}$ of W-shape steel fiber is obtained as follows:

$$P_{w_{\text{max}}} = \tau \pi d L + 56 \left(1 + 2\mu \sin \frac{\alpha}{2}\right) \frac{W\sigma_s}{L_i} \tan \alpha.$$  \hspace{1cm} (6)

The maximum drawing force $P_{l_{\text{max}}}$ of L-shape steel fiber is

$$P_{l_{\text{max}}} = \tau \pi d L + 16 \left(1 + 2\mu \sin \frac{\alpha}{2}\right) \frac{W\sigma_s}{L_i} \tan \alpha,$$  \hspace{1cm} (7)

The maximum drawing force $P_{v_{\text{max}}}$ of V-shape steel fiber is

$$P_{v_{\text{max}}} = \tau \pi d L + 32 \left(1 + 2\mu \sin \frac{\alpha}{2}\right) \frac{W\sigma_s}{L_i} \tan \alpha,$$  \hspace{1cm} (8)

The maximum drawing force $P_{i_{\text{max}}}$ of I-shape steel fiber is

$$P_{i_{\text{max}}} = \tau \pi d L.$$  \hspace{1cm} (9)

The results show that $P_{w_{\text{max}}} > P_{v_{\text{max}}} > P_{l_{\text{max}}} > P_{i_{\text{max}}}$.

2.4. Steel Fiber Modification. After treatment with silane coupling agent, the surface free energy of steel fiber increases, which improves the wettability of steel fiber surface, and facilitates the wettability of epoxy resin on steel fiber surface; the bond strength between steel fiber and resin is improved. In addition, the silicon functional group in the coupling agent can be combined with the chemical bond on the surface of the steel fiber through the hydrolysis condensation reaction to form the functional group containing nitrogen Y and carbon R, and this functional group can be bonded by the chemical reaction epoxy resin to effectively enhance the bond strength of the steel fiber resin interface.

The silane coupling agent used in the experiment is $\gamma$-aminopropytriethoxysilane (KH-550), which is produced in Nanjing Shuguang Chemical Industry Group. It is soluble in water and alkaline. Its main physical properties are shown in Table 3.

The modification of steel fiber is carried out according to the following process: ① perform ultrasonic cleaning of steel fiber with distilled water and ethanol; ② dry the cleaned steel fiber; ③ mix ethanol and silane coupling agent KH-550 in proportion, and the mass fraction of silane coupling agent KH-550 after mixing is 5%; ④ add acetic acid to adjust the pH value of mixed solution to 4; ⑤ add the steel fiber treated by ③ into the mixed solution with pH value of 4; ⑥ heat the water bath to 60°C, keep constant temperature, and stir for 1 h; ⑦ after washing with distilled water and ethanol and drying, the silane coupling agent KH-550 modified steel fiber was obtained. The experimental process is shown in Figure 4.
2.5. Experimental Design. The steel fibers with different shapes before and after modification by KH-550 were studied. We make the experimental design table and carry out the compression and bending strength test and pull-out test. The influence mechanism of different shapes of steel fiber before and after modification by KH-550 coupling agent on mechanical properties of artificial granite material was explored. Table 4 shows the experimental design of steel fiber reinforced artificial granite with different shapes before and after modification by KH-550.

3. Preparation of Test Piece

The compressive and bending strength of steel fiber with different shapes modified by KH-550 was tested. The preparation of the test piece was carried out according to the

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**Table 2: Main physical property parameters of steel fiber.**

| Fiber type   | Diameter/mm | Length/mm | Tensile strength/MPa | Modulus of elasticity/GPa | Density/(g.cm\(^{-3}\)) |
|--------------|-------------|-----------|-----------------------|---------------------------|--------------------------|
| Steel fiber  | 0.9         | 40        | 2000                  | 210                       | 7.8                      |

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**Figure 2:** Material object of steel fibers of different shapes: (a) W-shape; (b) L-shape; (c) V-shape; (d) I-shape.

**Figure 3:** Drawing theoretical model of steel fibers with different shapes (mm): (a) W-shape; (b) L-shape; (c) V-shape; (d) I-shape.

**Table 3: Main physical properties of KH-550.**

| Types of coupling agent | Boiling point/°C | Molecular weight | Flash point/°C | Refractive index | P (25°C)/(g.cm\(^{-3}\)) |
|-------------------------|------------------|------------------|----------------|------------------|---------------------------|
| KH-550                  | 217              | 221              | 104            | ND25: 1.4205     | 0.946                     |

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following process: ① crush aggregate; ② sieve according to the size of aggregate; ③ dry the aggregate after cleaning; ④ the epoxy resin, diluent, curing agent, and toughening agent were mixed and stirred in proportion for 2 min; ⑤ the aggregate system, binder system, filler, and steel fiber with different shapes treated by coupling agent are weighed in proportion; ⑥ the treated steel fiber and aggregate system are added in proportion and stirred evenly; ⑦ the filler and binder system are added in proportion and stirred evenly; ⑧ pour ⑥ and ⑦ into the mixer and mix for 5 min; ⑨ the evenly stirred composite material is poured into the steel mold coated with release agent, vibrated and compacted, and then placed in the vibration table for 5 min; ⑩ after curing at room temperature for 48 h, the mold was removed, and the performance of the specimen was tested after 28 d. The preparation process of the test piece is shown in Figure 5, the experimental production process is shown in Figure 6, and the formed test piece is shown in Figure 7.

For the drawing experiment of a single steel fiber, a special test piece needs to be prepared. The drawing end is outside the test piece, as shown in Figure 8, and the drawing fixture is shown in Figure 9.

4. Compression and Bending Test and Fiber Drawing Test

4.1. Compression and Bending Performance Test. According to GB/T 50081-2002 standard for test methods of mechanical properties of ordinary concrete [40], the compressive and bending strength tests are carried out on the...
sides of the prepared specimens with the help of universal servotesting machine.

Compression test piece size is 100 mm × 100 mm × 100 mm; bending test piece size is 100 mm × 100 mm × 400 mm.

4.1.1. Compressive Strength Test of Test Piece. During the compression test of the test piece, the compression speed is (1500 ± 100) KN/s; until the test piece is damaged, record the maximum load on the test piece. The experimental process is shown in Figure 10.

The compressive strength of the test piece is calculated by

$$f_{cc} = \frac{P_1}{A}$$

where

- $f_{cc}$ is maximum compressive strength of test piece (MPa)
- $P_1$ maximum load on test piece (N)
- $A$ load area of test piece (mm$^2$)

4.1.2. Bending Strength Test of Test Piece. During the bending test, the loading speed is 0.5 mm/min until the specimen breaks, and the maximum load borne by the specimen is recorded. The bending strength test is shown in Figure 11.

The bending strength of the test piece is calculated by

$$R_f = \frac{3P_2L}{2BH^2}$$

where

- $R_f$ is maximum bending strength of test piece (MPa)
- $P_2$ maximum load at break of test piece (N)
- $L$ is distance between two fulcrums (mm)
- $H$ is section height (mm)
- $B$ is section width (mm)

The loading mode of bending strength is shown in Figure 12.

The compressive and bending strength tests are carried out in groups of three specimens, and the average value obtained is the final compressive and bending strength. According to the above experiments, the compressive and bending strength of different shapes of steel fiber reinforced artificial granite materials before and after the coupling agent modification are obtained, as shown in Figures 13 and 14, respectively.

It can be seen from Figure 13 that the compressive strength of W-shaped steel fiber artificial granite after surface treatment is 1.49%, 0.6%, and 2.55% higher than that of L-shaped, V-shaped, and I-shaped steel fiber artificial granite. For the steel fiber without surface treatment, the compressive strength of W-shaped steel fiber artificial granite is 1.72%, 1.19%, and 4% higher than that of L-shaped, V-shaped, and I-shaped steel fiber artificial granite.

After surface treatment, the compressive strength of W-type, L-type, V-type, and I-type steel fiber artificial granite samples increased by 0.59%, 0.82%, 1.19%, and 2.07%, respectively, compared with that before modification.

Compared with the surface treatment, the shape of steel fiber before the surface treatment by KH-550 silane coupling agent has a greater impact on the compressive strength of artificial granite.

It can be seen from Figure 14 that the bending strength of W-type steel fiber artificial granite after surface treatment is 9.94%, 5.36%, and 18% higher than that of L-type, V-type, and I-type steel fiber artificial granite. For the steel fiber artificial granite without surface treatment, the bending strength of W-shaped steel fiber artificial granite is 9.52%, 5.23%, and 20.15% higher than that of L-shaped, V-shaped, and I-shaped steel fiber artificial granite.

However, the bending strength of W-type, L-type, V-type, and I-type steel fiber artificial granite samples after surface treatment is 9.94%, 9.52%, 9.8%, and 11.94% higher than that before surface treatment.

Compared with the surface treatment, the shape of steel fiber before the surface treatment by KH-550 silane coupling agent has a greater impact on the bending strength of artificial granite.

4.2. Pullout Test of Steel Fiber. The steel fiber drawing test piece before and after modification with KH-550 silane coupling agent was tested. The drawing test piece was fixed on the lower clamp end of universal servotesting machine, and the fiber clamp was fixed on the upper clamp end of universal servotesting machine. The position of the drawing test piece was adjusted to make the steel fiber coincide with the center of the fiber clamp. The universal servotesting machine was controlled to make the fiber clamp tighten the end of the steel fiber, and the embedment depth was adjusted. The drawing force is applied to the steel fiber of 40 mm, and the loading speed is controlled at 0.01 mm/s. Pull-out experiment design (a) and laboratory experiment (b) are shown in Figure 15. The drawing force-fiber displacement curve of steel fiber pulled out from the matrix before and after modification is shown in Figure 16.

It can be seen from Figure 16 that the change trend of drawing force with displacement of steel fiber before and after modification is the same, and $P_{W\text{max}} > P_{V\text{max}} > P_{I\text{max}} > P_{L\text{max}}$, which is consistent with the theory. The drawing force of steel fiber after modification is higher than that before modification. The whole displacement process of steel fiber undergoes the elastic deformation process of steel fiber, as shown in the OA section in Figure 17. There is no relative sliding between steel fiber and resin matrix. The force to restrain the sliding of steel fiber is the bonding force between the matrix and fiber, and the pull-out force increases the fastest in this phase. The phase AB is the elastic deformation stage of fiber, in which the relative slippage between the fiber matrices occurs. With the gradual destruction of the bonding between the steel fiber and the resin matrix, the growth rate of the pull-out force decreases gradually. The forces restraining the slippage of the steel fiber in this stage are the bonding force between the matrix and
the fiber, the deformation force of the steel fiber, and the sliding friction force between the steel fiber and the matrix. When the pull-out force reaches the maximum in BC section, the steel fiber and resin matrix begin to debond; when the pull-out channel of the steel fiber in CD section is widened, the sliding friction force decreases, and the pull-out force drops rapidly. In DE section, the force to restrain steel fiber sliding is only affected by sliding friction, and the pull-out force is the minimum. In AC section, W-shaped steel fiber has the largest force in debonding process, so it is more difficult to pull out W-shaped steel fiber than other types of steel fiber, and it has the best effect in resin application.

When the ultimate tensile strength of steel fiber is less than the maximum pull-out load of steel fiber, the steel fiber breaks. When the ultimate tensile strength of steel fiber is greater than the maximum pull-out load of steel fiber, the steel fiber is pulled out. The SEM morphology before steel fiber modification is shown in Figure 18, and the SEM
Figure 14: Bending strength of steel fiber artificial granite specimens with different shapes before and after modification by coupling agent.

Figure 15: Pull-out experiment design (a) and laboratory experiment (b).

Figure 16: Drawing force-fiber displacement curve before and after modification. (a) Modified. (b) Unmodified.
After modification, morphology after steel fiber modification is shown in Figure 19. After modification, more epoxy resin was attached to the surface of steel fiber than before, so it was difficult to pull out.

After the surface modification of KH-550, the steel fiber will be easy to infiltrate, and the surface of steel fiber will undergo chemical changes. Firstly, the steel fiber will be oxidized and hydrolyzed in the air to form Fe(OH)$_3$. The chemical reaction between Fe(OH)$_3$ and Y-R-Si(OH)$_3$ after hydrolysis of silane coupling agent KH-550 is as follows:

$$\text{Fe(OH)}_3 + \text{Y-R-Si(OH)}_3 \rightarrow \text{Y-R-SiO}_2\text{Fe} + 3\text{H}_2\text{O}$$

Among them, Y- is a nitrogen-containing functional group and R- is a hydrocarbon functional group. This functional group will be chemically bonded with epoxy resin, and the chemical bond formed is very strong. Therefore, the steel fiber after surface modification by KH-550 silane coupling agent has better reinforcement effect on resin matrix than before.

5. Conclusions

On the basis of previous studies, this paper focuses on the influence of different shapes of steel fibers before and after modification with KH-550 silane coupling agent on the compressive and bending strength of artificial granite and draws the following conclusions:

1. Compared with L-shaped, V-shaped, and I-shaped steel fibers, W-shaped steel fibers are more difficult to pull out in artificial granite matrix, and the effect of W-shaped steel fibers in artificial granite matrix is obvious.

2. The shape of steel fiber has a great influence on the bending strength of artificial granite. The bending strength of W-shaped steel fiber is 20.15% higher than that of I-shaped steel fiber, but it has little influence on the compressive strength of artificial granite.

3. For the same shape of steel fiber, the effect of KH-550 modified steel fiber on the bending strength of artificial granite is obvious, among which the bending strength of I-shaped steel fiber after modification is 11.94% higher than that of artificial granite before modification.

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
Authors’ Contributions

Xuetao Qiao and Peng Wang were in charge of the whole trial; Peng Wang wrote the manuscript; Xuetao Qiao, Peng Wang, Cunfu Yan, Fang Li, and Long Wu assisted with sampling and laboratory analyses. All authors read and approved the final manuscript.

Acknowledgments

This work was supported by the Key Scientific and Technological Projects in Henan Province (Grant nos. 172102210586, 182102210512, and 202102210276).

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