

## Research Article

# Experimental Study of High-Strength Steel Fiber Lightweight Aggregate Concrete on Mechanical Properties and Toughness Index

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In this paper, three different kinds of steel fibers, being micro (M), end-hooked (H), and corrugated (C), commonly used in engineering applications, are added to high-strength lightweight aggregate concrete (HLAC) to study the effects of steel fiber and volume content ratio of fiber on the compressive, splitting tensile, and flexural strength of HLAC. The range of steel fiber volume content fraction studied is 0.5% to 2.0%. The research shows that different types of steel fiber have different effects on the mechanical properties and toughness of HLAC. M steel fibers have the best reinforcing performance on the mechanical properties. The study also shows that the toughness of M steel fibers is the best with the same fiber content. The toughening effect of H and C steel fibers can only reach 2/3 and 1/2 of M steel fibers, respectively. At the end of this paper, the unified strength formula and toughness index of these three kinds of high-strength steel fiber lightweight aggregate concrete (HSLAC) with different fiber contents are given to provide a reference for engineering practice and design.

## 1. Introduction

With the development of high-rise buildings, as well as of large-span and large-scale engineering systems, more and more high-performance structural concrete is required in the construction industry to cope with complex and diverse engineering demands. A significant amount of recent research [1–5], therefore, has focused on light-weight, high-strength, high-toughness, energy-saving, and environment-friendly concrete materials. Among them, the lightweight aggregate structural concrete (LAC) uses high-strength lightweight aggregate instead of natural stone; this change of raw materials makes it different from ordinary concrete in many aspects: its density is below 2000 kg/m<sup>3</sup> while that of normal-weight concrete (NC) is 2400 kg/m<sup>3</sup> [6]; besides, compared to NC, its strength/weight ratio is higher. LAC has numerous advantages over NC. For instance, it reduces the self-weight and dimensions of the structural members; it saves the dead load for structural design and foundation; it

lowers the risk of earthquake damage to a structure; it shows good performance in tensile strain capacity; and it has lower coefficient of thermal expansion and better durability [6–8]. However, the higher brittleness and lower mechanical properties of LAC compared to NC at the same compressive strength have limited its popularization and application in construction. Various short fibers are often used to reduce the brittleness of concrete [9]. Some researchers have proved that steel fibers impart good strengthening, toughening, and crack resistance to both NC and LAC materials, and such steel fiber reinforced concrete would have a direct effect on the deformation and seismic performance of the whole structure [10–18]. In practical application, with the increase of fiber content, the dispersion of steel fiber will become more and more difficult, increasing the bulk density of materials. However, due to the advantages of steel fiber in low costs, remarkable improvement of substrate performance and relatively convenient construction, it is still widely used in practical projects.

With the development of LAC, high-strength lightweight aggregate concrete (HLAC) with the compressive strength about 40–80 MPa has been produced [19]. The increase in strength causes further brittleness of the compression and tension of concrete, especially in the case of LAC [20]. Researchers [21–27] evenly introduced a certain proportion of steel fiber into newly mixed HLAC to improve its mechanical properties and toughness by taking advantage of the bonding and crack-bridging effects of steel fibers. Campione et al. [21] showed that steel fibers increased the compressive strength of expanded clay and ceramsite concrete by about 30%, but had no effect on the compressive strength of pumice LAC. Thus, they drew the conclusion that the effect of steel fibers on the compressive strength of LAC mainly depends on the aggregate type. Ma et al. [22] showed that when the 13 mm micro-steel fiber was added to three different aggregate concretes, the compressive strength increased by 19%, 40%, and 42%, respectively, while the flexural strength increased by 108%, 92%, and 78%. The aggregate type has a greater influence on the pressure-strengthening effect of steel fibers. Liu et al. [23] also confirmed that the steel fiber has a significant improvement effect on the strength and toughness of HLAC and that the reinforcing effect on HLAC is better than that on ordinary concrete. Previous studies have also shown that different types of steel fibers have different strength enhancement effect on the concrete because of size effect [24]. In summary, the improvement effect of steel fibers on HLAC is greatly affected by steel fiber type and size parameters, as well as aggregate type and size effect. Therefore, it is necessary to adopt a unified method to further study the strengthening and toughening effects, as well as the mechanism of different steel fibers on HLAC.

Considering that there are many kinds of steel fibers in the market, with different test methods and different sizes of specimens used in research, the number of systematic research results is insufficient. Therefore, it is necessary to select representative products of different types of steel fibers to study and compare the strengthening and toughening effects on HLAC and thereby to provide a general experimental and theoretical basis for HSLAC.

In this paper, high-strength shale ceramsite concrete was selected as the base material, and the commonly used steel fibers, being micro (M), end-hooked (H), and corrugated (C), were added to explore their influence on the strength and toughness of HLAC. The experimental results of this paper could help provide some reference for the design of HSLAC structures.

## 2. Test Overview

**2.1. Raw Materials.** The cement was the P·O42.5-grade ordinary Portland cement with an apparent density of the cement 3100 kg/m<sup>3</sup>. Coarse aggregate was the 800-grade crushed shale ceramsite, which has a cylindrical compressive strength of 6.2 MPa, particle size of 5–16 mm, bulk density of 750 kg/m<sup>3</sup>, apparent density 1360 kg/m<sup>3</sup>, and water absorption of 3.2% (in one hour) or 3.8% (in 24 hours). Fine aggregate was ordinary river sand, which had a good

gradation, a fineness modulus of 2.6, and an apparent density of 2600 kg/m<sup>3</sup>. The grain grading curve of sand is shown in Figure 1, and the basic properties of sand are shown in Table 1. Mineral admixtures included fly ash with a density of 2600 kg/m<sup>3</sup> and micro-silicon powder with a density of 2200 kg/m<sup>3</sup>. The polycarboxylic acid superplasticizer with water reducing rate of 25%–27% was selected. Three kinds of commonly used steel fibers with different characteristic parameters and external shapes are as shown in Table 2 and Figure 2. In Table 2, MSF0213 denotes micro-steel fibers, abbreviated as M; HSF0512 denotes end-hooked steel fibers, abbreviated as H; and CSF0830 denotes corrugated steel fibers, abbreviated as C.

**2.2. Test Mix Ratio.** The absolute volume method was used in the mix design of the benchmark HLAC. Table 3 gives the mix ratio of HLAC of strength grade LC50 according to the Chinese Code [25].

According to the mix ratio shown in Table 3, the slump and expansion of reference lightweight aggregate concrete mixture are 244 mm and 680 mm, respectively, which has good fluidity and better workability. The three kinds of steel fibers, as shown in Table 2, were mixed with the freshly mixed benchmark material LC50, according to 0.5%, 1.0%, 1.5%, and 2.0% of the volume content ratio, respectively. For convenience, the benchmark HLAC is abbreviated as P, and different kinds of HSLAC materials are abbreviated as the simplified symbol of each kind of steel fibers (M\H\C). They are followed with the percentage of steel fiber content as M0.5, M1.0, M1.5, M2.0, H0.5, H1.0, H1.5, H2.0, C0.5, C1.0, C1.5, and C2.0.

**2.3. Test Method.** The mechanical properties of specimens were tested according to the method given in [26]. The size of the specimens tested for cube compressive strength and splitting tensile strength was 100 × 100 × 100 mm, with the dimensional conversion coefficients of 0.95 and 0.85, respectively. The size of the bending test specimens was 100 × 100 × 400 mm and the size conversion factor was 0.85. Each test group included three identical specimens. The test was carried out on a 1000 kN universal testing machine. The loading speeds of the compression and splitting tensile tests were 8 kN/s and 0.8 kN/s, respectively. The three-point bending test was loaded with displacement control at a loading speed of 0.1 mm/min. The bending test device is shown in Figure 3.

## 3. Test Results and Analysis

The test results are shown in Table 4. Figures 4(a)–4(c) are the cube compressive strength, splitting tensile strength, bending strength, and corresponding fitting curves of different-volume fractions of each kind of HSLAC.

**3.1. Cube Compressive Strength.** From Table 4 and Figure 4(a), it can be seen that the cube compressive strength of HLAC was improved by all three kinds of steel fibers, but

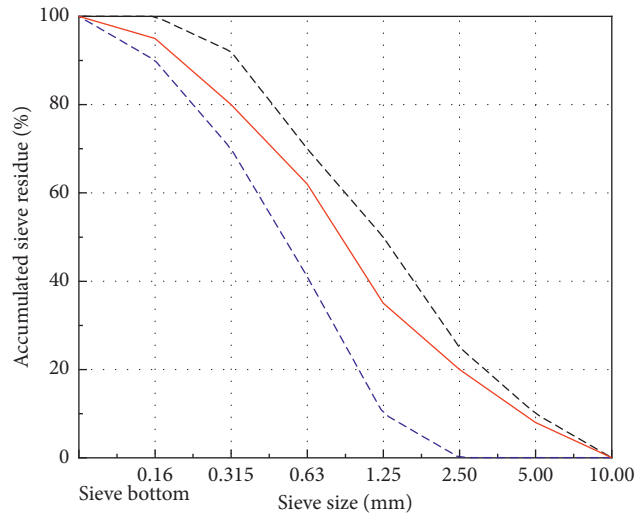


FIGURE 1: The grain grading curve of sand.

TABLE 1: The basic properties of sand.

Fine aggregate	Fineness modulus	Bulk density (kg/m <sup>3</sup> )	Apparent density (kg/m <sup>3</sup> )	Maximum particle size (mm)	Sediment percentage (%)	Moisture content (%)
Medium sand	2.6	1520	2600	4	2.1	0.3

TABLE 2: Characteristic parameters of steel fibers.

Type of steel fibers	Average length (mm)	Equivalent diameter (mm)	Aspect ratio
MSF0213	13	0.2	65
HSF0525	25	0.5	50
CSF0830	30	0.8	38

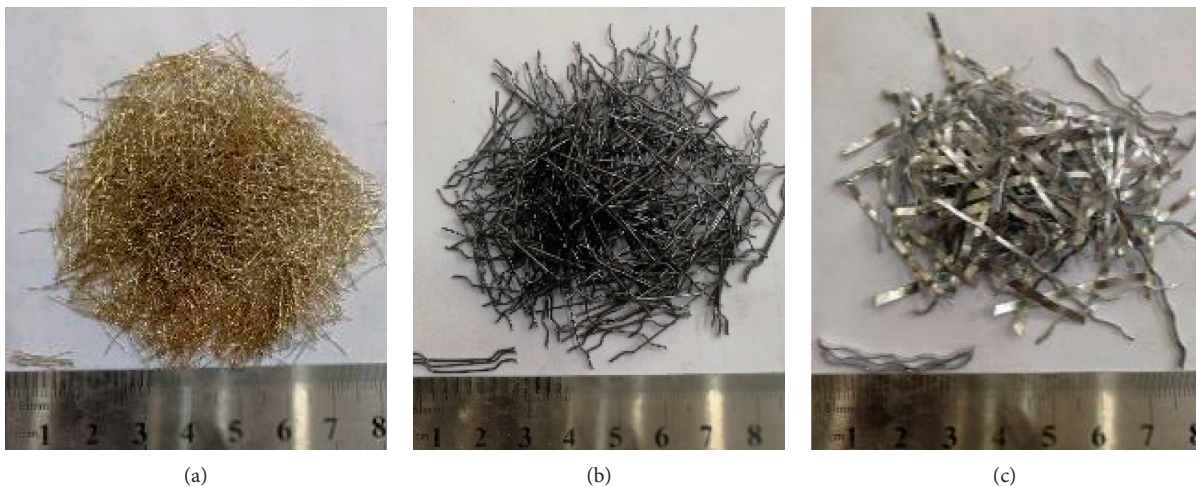


FIGURE 2: The appearance of steel fibers. (a) MSF0213. (b) HSF0525. (c) CSF0830.

TABLE 3: Mix proportion of benchmark HLAC (kg/m<sup>3</sup>).

Cement	Water	Fly ash	Silica fume	Shale ceramicsite	Sand	Water reducer
440	165	82.5	27.5	511	753	4.4



FIGURE 3: Bending toughness test device.

TABLE 4: Mechanical performance test results of HSLAC.

Code	Density (kg/m <sup>3</sup> )	Compressive strength (MPa)	Tensile strength (MPa)	First-crack flexural strength (MPa)	Flexural strength (MPa)	Ratio of tensile to compressive	Ratio of flexural to compressive
P	1822	55.3	3.66	5.26	5.26	0.066	0.095
M0.5	1879	61.6	5.12	5.45	6.11	0.083	0.099
M1.0	1905	67.9	6.44	5.97	6.94	0.095	0.102
M1.5	1931	73.4	7.25	6.68	7.65	0.099	0.104
M2.0	1997	81.3	8.67	7.15	8.52	0.107	0.105
H0.5	1854	58.0	4.46	5.37	5.60	0.077	0.097
H1.0	1892	61.5	5.67	5.42	6.59	0.092	0.107
H1.5	1935	65.8	6.28	6.31	7.80	0.095	0.119
H2.0	1969	67.7	7.08	6.53	8.18	0.105	0.121
C0.5	1838	54.6	4.04	5.13	5.19	0.074	0.095
C1.0	1879	58.9	4.54	5.14	5.46	0.077	0.093
C1.5	1900	62.0	4.85	5.35	5.82	0.078	0.094
C2.0	1911	60.8	4.73	5.06	5.27	0.078	0.087

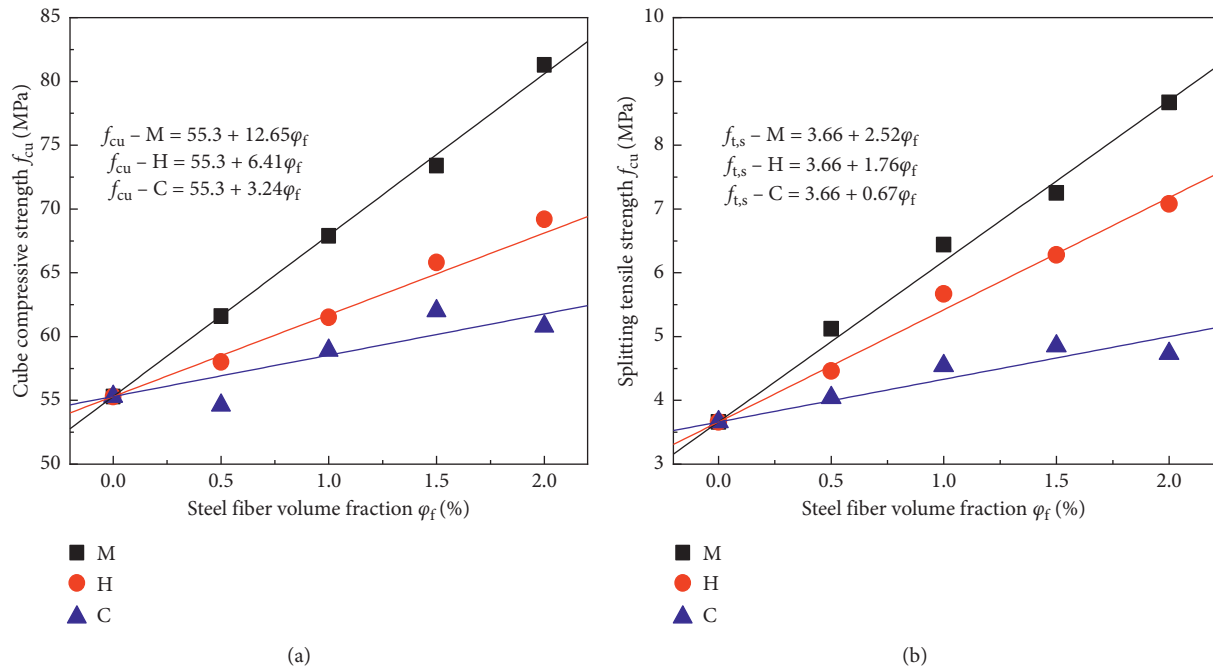


FIGURE 4: Continued.

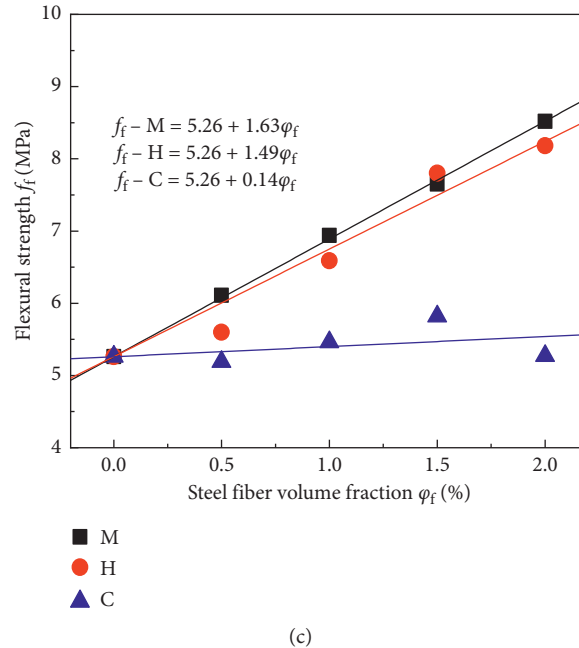


FIGURE 4: Relationship between strengths and steel fiber volume fraction. (a) Cube compressive strength. (b) Splitting tensile strength. (c) Flexural strength.

the influence was rather different. As the volume content ratio of each type of steel fibers increased from 0.5% to 2%, the compressive strength of each HSLAC specimen also increased, but the increment was different with different steel fibers. With a fiber content ratio of 2%, compared with the benchmark HLAC LC50, the cube compressive strength of M, H, and C HSLAC increased by about 47%, 22%, and 12%, respectively. By comparing the data and fitting curves in Figure 4(a), it can be seen that M steel fibers had the most significant effect in improving the compressive strength. The reasons are as follows: it is easy to disperse uniformly; it shows better cementation performance with hardened cement; and it has stronger deformation binding force on the benchmark HLAC. By combining with Table 2, it is easy to conclude that the effect of steel fibers on compressive strength decreases with the increase of fiber size and decrease of fiber aspect ratio. The compressive strength of HLAC increased by 23.8% and 30% after 2.0% volume fraction of fine steel fibers was added [23, 27], coinciding with the test results of this paper. Based on the above analysis, it can be concluded that the effect of M steel fibers on the compressive strength of HLAC is better than that of other large-diameter coarse steel fibers.

With the addition of steel fibers, the workability of the new mixture worsened. When the volume ratio of these three kinds of steel fibers changed between 0.5% and 1.5%, the slump and expansion of the mixture were basically altered between 190 mm~240 mm and 410 mm~650 mm. As the volume ratio of steel fibers raised to 2.0%, the fluidity of the mixture dropped sharply; the slump and expansion of the mixture were 96 mm and 190 mm. The fluidity of freshly mixed concrete manifested that when the volume ratio of M steel fibers was more than 1.5%; more cement paste would be

used due to the large surface area of this type of steel fiber. Based on this fact, the dosage of steel fibers should not be too large, especially for fine steel fibers. Previous research [24] showed that when the volume fraction of steel fibers in ordinary concrete reached 2.0%, the compressive strength increased by only about 10%. The compressive strength even slightly decreased when using C steel fibers. Compared with the test results of an earlier study [24], the compressive strength increase of HLAC with the same volume ratio of the same type of steel fibers was better than that of the steel fiber reinforced concrete. The reason may be that the coarse aggregates of LAC are generally weaker with larger deformation, while the steel fibers mixed in the matrix show miscellaneous phase distribution, giving good lateral restraint, decomposing the vertical force from the matrix, and thereby alleviating the fragmentation of aggregate to a certain extent. The effect of C steel fibers on compressive strength is not ideal, especially when it is lower (0.5%) or higher (2%); the strength would even be reduced. This is mainly due to the small contact area between corrugated steel fibers and cement colloids; the large deformation of the fibers themselves would not provide enough restraint for the aggregate. Therefore, in order to ensure the compressive strengthening effect of steel fibers on HLAC, fine steel fibers with larger lengths and diameter ratios, like M steel fibers, should be used appropriately. The surface of the fibers should be rough to strengthen the bond between fibers and cement colloids. In addition, the stiffness of fibers themselves should not be too small.

The following equation is the fitting unified relationship between different types of steel fiber content  $\phi_f$ , the aspect ratio ( $l_f/d_f$ ) of each kind of steel fibers, and compressive strength of HLAC:

$$f_{f_{cu}} = f_{cu} \left( 1 + \frac{\alpha_{cu} \varphi_f l_f}{d_f} \right), \quad (1)$$

where  $\alpha_{cu}$  is the compressive strength enhancement coefficient of HSLAC. The values of  $\alpha_{cu}$  for M, H, and C steel fibers are 0.352, 0.232, and 0.154, respectively.

**3.2. Splitting Tensile Strength.** From Table 4 and Figure 4(b), it can be seen that the splitting tensile strength of HLAC was also improved by these three types of steel fibers. As the volume fraction of fibers was increased from 0.5% to 2%, the splitting tensile strength of M, H, and C HSLAC could be increased by 93%, 45%, and 37%, respectively. The performance parameters of H steel fibers in this paper were basically the same as those in [23]. The strengthening effect of H steel fibers on the tensile strength of HLAC was also basically the same as that shown in the previous study [19]. To a certain extent, it illustrates that the steel fiber with a similar aspect ratio has a similar strengthening effect on the splitting tensile strength. From Table 2, it can be seen that fine steel fibers combined with larger length and diameter could increase the bond between steel fibers and the matrix. The results of the study on the tensile strength of steel fiber reinforced ordinary high-strength concrete [28] were in agreement with the experimental results of this paper; they both show that the strengthening effect of steel fibers on the tensile strength of base materials is mainly due to the bonding force, which is produced by the fibers around the cracks and restraining the development of cement colloidal cracks. The steel fiber with finer and stronger tensile strength should be selected to improve the tensile properties of HLAC without decreasing the workability. In Table 4, the tension-compression ratios of all kinds of HSLAC also increased with the increase of fiber volume content. The tension-compression ratio of HLAC without steel fibers was 0.066. When the volume fraction increased from 0.5% to 2%, the tensile-compressive ratios of M, H, and C HSLAC were between 0.083 and 0.107; 0.077 and 0.105; and 0.074 and 0.078, respectively. The improvement effect of these three kinds of steel fibers on the brittleness of HLAC decreased in turn, and the influence of volume content of C steel fibers on the tension-compression ratio is insignificant.

The fitting relationship between different types of steel fiber volume content ratio  $\varphi_f$ , the aspect ratio of steel fiber  $l_f/d_f$ , and the splitting tensile strength  $f_{t,s}$  of HLAC is shown in the following equation:

$$f_{f_{t,s}} = f_{t,s} \left( 1 + \frac{\alpha_{t,s} \varphi_f l_f}{d_f} \right), \quad (2)$$

where  $\alpha_{t,s}$  is the tensile strength enhancement coefficient of HSLAC.  $\alpha_{t,s}$  of M, H, and C steel fibers is 1.060, 0.960, and 0.477, respectively.

**3.3. Initial Crack Resistance and Ultimate Flexural Strength.** From Figure 4(c), it can be seen that the influence of these three kinds of steel fibers on the ultimate flexural strength of HLAC is also quite different. When the volume content ratio

of steel fiber was 0.5%–2%, M, H, and C steel fibers increased the flexural strength of HLAC up to 62%, 56%, and 11%, respectively. M and H steel fibers only made little difference in the flexural strength of HLAC, indicating that the end hook of H steel fibers can provide effective anchorage effect with the matrix. Under the same volume content, C steel fibers with less quantity, larger size, and smaller aspect ratio caused insufficient bonding with the matrix. Moreover, C steel fibers were more difficult to disperse uniformly than the other two kinds of steel fibers, resulting in the decrease of compactness of C HSLAC and the easy debonding with cement colloids. Meanwhile, the corrugated shape of the C steel fiber made it easier to produce large deformation under stress and reduce the bridging effect on cracks. Thus, it had little contribution to the flexural strength of HLAC. Previous study [24] indicates that when different types of steel fibers with a 2.0% volume content ratio are added to ordinary high-strength concrete, the flexural strength of nonstandard specimens could be increased by about 50%, which is consistent with the experimental data in this paper. This means that the strengthening effect of steel fibers on bending strength is mainly affected by the fiber performance.

From the comparative analysis of the data in Table 4, it can be seen that although the strengthening effect of M and H steel fibers on the flexural strength of HLAC is basically the same, the strengthening mechanism of these two kinds of fibers is slightly different. With the volume content ratio of fibers studied in this paper, the initial crack strength of M and H HSLAC increased by 36% and 24%, respectively, while the ultimate bending strength increased by 19% and 25%. This shows that the M steel fiber has a stronger ability to resist the initial cracking of HLAC, while the H steel fiber is weaker to resist this cracking but has stronger ability after cracking. On the contrary, the C steel fiber has little effect on the flexural-compressive ratio of HLAC.

The fitting relationship between different types of steel fiber volume content ratio  $\varphi_f$ , the aspect ratio of steel fiber  $l_f/d_f$ , and the splitting tensile strength  $f_{f_{tm}}$  of HLAC is shown in the following equation:

$$f_{f_{tm}} = f_{tm} \left( 1 + \frac{\alpha_{tm} \varphi_f l_f}{d_f} \right), \quad (3)$$

where  $\alpha_{tm}$  is the tensile strength enhancement coefficient of HSLAC.  $\alpha_{tm}$  of M, H, and C steel fibers is 0.476, 0.565, and 0.070, respectively.

**3.4. Flexural Toughness.** The load-displacement curves of different types of HSLAC with different volume content ratios were obtained by collecting and sorting out the data obtained from bending tests as shown in Figure 5.

Figures 5(a)–5(c) are load-displacement curves of the M, H, and C HSLAC in three-point bending tests.

From Figures 5(a)–5(c), the load-displacement curves of the specimens under bending tests are upward with the increase of volume fraction of all kinds of steel fibers. Figure 5(a) shows that the load-displacement relationship curves of the M HSLAC become extremely full and smooth when the content ratio of steel fiber is 0.5%~2.0%. This

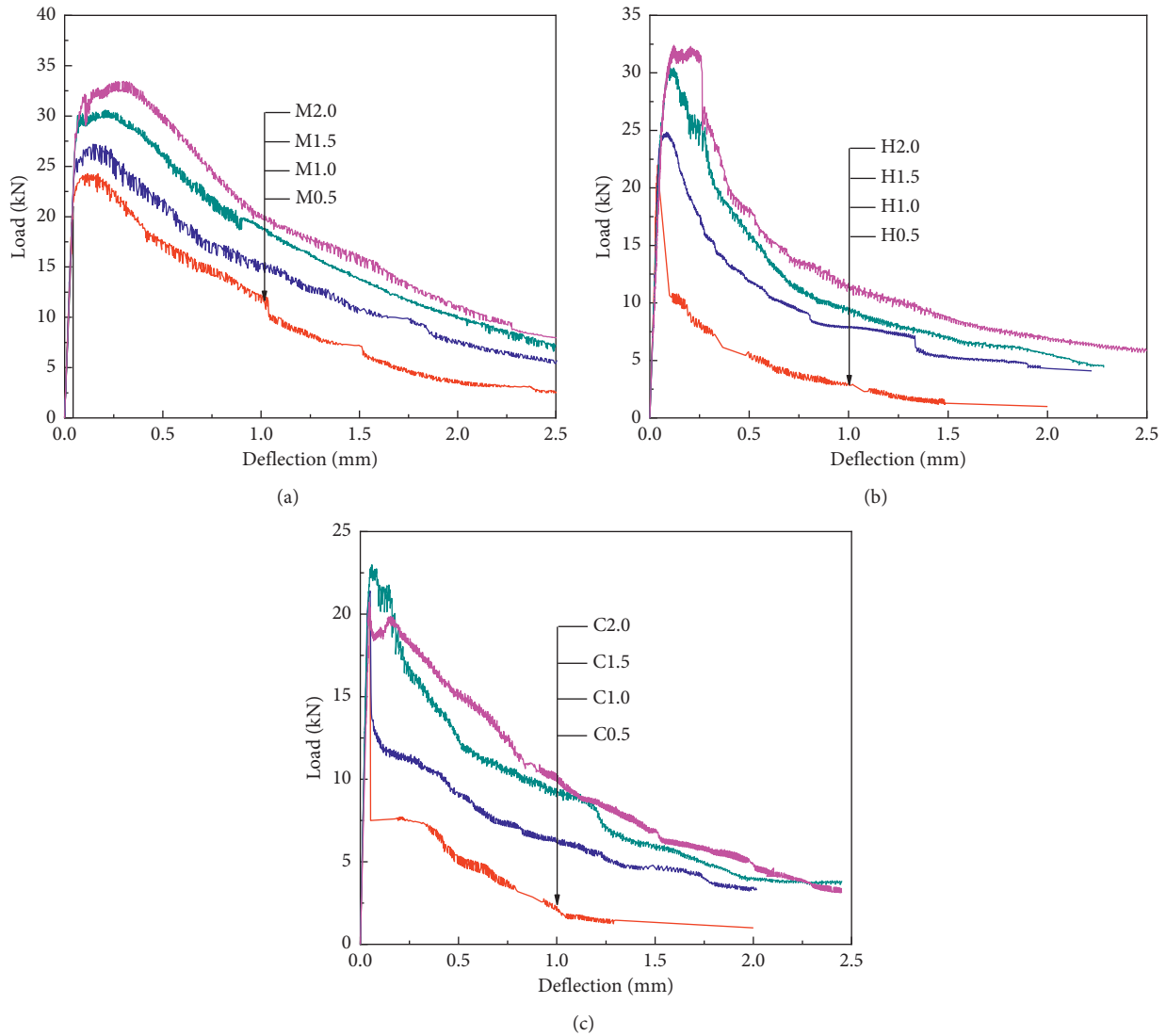


FIGURE 5: The load-displacement curve of three-point bending test. (a) M steel fibers. (b) H steel fibers. (c) C steel fibers.

shows significant toughening effect, and the curve basically shows a linear decrease after the peak load, suggesting the deformation load holding capacity. The load-displacement curves of H HSLAC are also very full and smooth at the beginning but decrease rapidly after reaching the peak value. This shows that H HSLAC is severely debonded after the crack developing to a certain degree and that the bonding and biting effect of H steel fibers with cement colloids becomes worse. When the content of C steel fibers is lower, the curve suddenly declines; as the number of fibers at the cracking interface is small and the bonding performance is poor, the HSLAC shows great brittleness. When the content of C steel fibers is larger, the area around the load-displacement curve and the abscissa coordinate slightly increases; besides, the toughening effect is not ideal. It is suggested that the content of the C steel fibers should be controlled between 1.0% and 1.5%.

According to the load-displacement curve of bending specimens, the toughness indices  $I_5$ ,  $I_{10}$ , and  $I_{30}$  are

calculated using the ASTM C1018 [29] method; the toughness indices  $\eta_{m5}$ ,  $\eta_{m10}$ , and  $\eta_{m30}$  and the load-bearing capacity change coefficients  $\xi_{m,5,m}$ ,  $\xi_{m,10,m}$ , and  $\xi_{m,30,m}$  are calculated referring to the CECS13:2009 [26] method. In order to reflect the toughening effect of HSLAC more comprehensively, the toughness factor  $\sigma$  is calculated based on the toughness index T150 recommended by the Japanese standard JCI-SF4 [30]. The characteristics of the impact of the different types of steel fibers and different fiber contents on the toughness performance of HSLAC are analyzed. The toughness index T150 specified in JCI-SF4 standard is the area of load-displacement curve and abscissa when the deflection equals  $L/150$ . The average strength value of  $L/150$  is defined as the toughness factor  $\sigma$  of the specimen. Table 5 gives the flexural toughness indices calculated by the above three methods. The data in Table 5 shows that the toughness factor of HSLAC linearly increases with the increase of steel fiber content. When the volume percentage of steel fiber content increases from 0.5% to 2.0%, the toughness factors

TABLE 5: First-crack flexural strength and toughness indices.

Specimen	CECS13:2009/(ASTM C1018)						JCI-SF4	
	$\eta_{m5}/(I_5)$	$\eta_{m10}/(I_{10})$	$\eta_{m30}/(I_{30})$	$\xi_{m,5,m}$	$\xi_{m,10,m}$	$\xi_{m,30,m}$	$T_{150}$ (N-mm)	$\sigma$ (MPa)
M0.5	5.19	10.57	27.91	1.10	1.08	0.86	24.07	3.64
M1.0	5.27	10.89	28.90	1.14	1.20	0.92	31.67	4.75
M1.5	5.44	11.15	30.75	1.22	1.26	1.05	38.76	5.78
M2.0	5.58	11.56	31.42	1.23	1.28	1.20	42.63	6.42
H0.5	3.87	6.19	12.01	0.44	0.15	0.00	7.86	1.18
H1.0	5.35	10.03	20.82	1.18	1.01	0.37	19.07	2.86
H1.5	5.48	10.43	22.49	1.24	1.10	0.48	24.05	3.61
H2.0	5.76	11.38	23.96	1.38	1.31	0.58	28.08	4.21
C0.5	3.02	4.86	11.57	0.01	0.00	0.00	6.98	1.05
C1.0	3.96	6.86	17.07	0.48	0.30	0.11	13.99	2.10
C1.5	4.60	8.49	19.73	0.80	0.66	0.29	18.87	2.73
C2.0	4.82	9.64	25.78	0.91	0.92	0.71	21.78	3.27

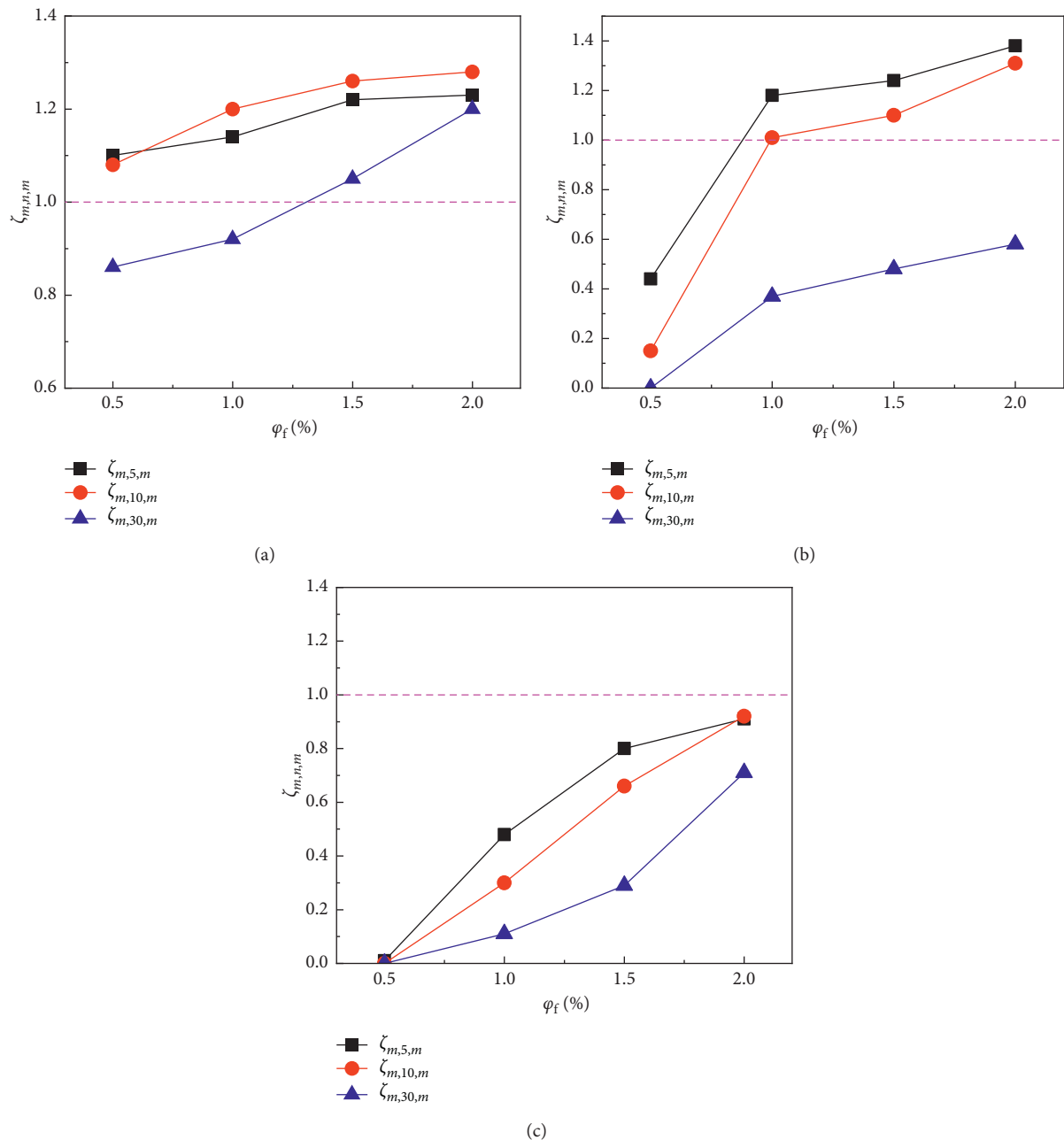


FIGURE 6: Relationship between the variation factor of flexural resistance and volume ratio of steel fibers. (a) M steel fibers. (b) H steel fibers. (c) C steel fibers.



of the specimens increase by 2.78, 3.03, and 2.22, respectively. When the volume fraction of fibers is 0.5%, the toughness factors of three kinds of HSLAC are 3.64, 1.18, and 1.05, respectively. The toughness of M HSLAC is significantly higher than the other two kinds of HSLAC. Under the same steel fiber content, the toughness of H HSLAC can reach 2/3 of M steel fibers, while that of C HSLAC is only 1/2 of M steel fibers.

Figures 6(a)–6(c) are the variation coefficients of the flexural capacity of HSLAC and their variation with the content ratio of steel fibers, respectively.

From Figures 6(a)–6(c), it can be seen that the flexural bearing capacity of HSLAC increases with the increase of steel fiber content ratio, and the flexural toughness index tends to be an ideal elastic-plastic material with the increase of fiber content. The variation coefficient of bearing capacity of M HSLAC tends to be 1.0. The M steel fiber and LAC matrix work well together and M HSLAC basically conforms to the ideal elastic-plastic material. With the addition of M steel fibers from 0.5% to 2.0%, the flexural bearing capacity of HSLAC linearly increases by about 15%. Considering the economy and workability of fresh materials, the recommended content of M steel fibers is 0.5% to 1.0%.

When the content ratio of steel fibers is 0.5%, the bearing capacity of H HSLAC deviates from the ideal elastic-plastic material because the number of fibers working as the bridge of cracks is small; thus, the toughening effect is poor. The variation coefficient of the bearing capacity decreases with the increase of displacement and  $\xi_{m,30,m}$  decreases even more. After the crack develops to a certain extent, the bond and occlusion performance between fibers and the matrix decreases and the toughness of the material is not ideal under large deformation. The load-bearing capacity change coefficient of C HSLAC is less than 1; therefore, the toughening effect of C HSLAC is extremely poor. It can also be seen from Figure 6 that C steel fibers have little toughening effect; the main reason may be that the number of this type of large-size steel fiber is less than the other two types of steel fibers. Therefore, by increasing the aspect ratio of steel fibers, reducing their diameter and setting anchorage ends at their end, the stiffness and the toughening effect of HSLAC would be ensured.

#### 4. Conclusions

- (1) The influence of different types of steel fibers on the mechanical properties of HSLAC is rather different. With the same content ratio of these three kinds of steel fibers, the reinforcement effect of M, H, and C HSLAC decreased in turn, indicating that the better reinforcement effect could be achieved by increasing the aspect ratio of steel fibers and reducing their diameter appropriately.
- (2) The mechanical indices of HSLAC linearly increase with the increase of steel fiber content. Considering the workability, mechanical properties and toughness of HSLAC, it is suggested that the volume fraction of micro-steel fibers is 0.5%–1.0% and that of large size steel fibers is 1.0%–2.0%.

- (3) The toughness factor and toughness index of HSLAC also increase with the increase of fiber content. The toughness of M steel fibers was the best with the same fiber content. The toughening effect of H and C steel fibers can only reach 2/3 and 1/2 of M steel fibers, respectively.
- (4) The unified strength formula and toughness index of all kinds of HSLAC with different fiber content are given in this paper, which would provide reference for engineering practice and design.

#### Data Availability

All data generated or analyzed during this study are included within the article.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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