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Experimental Study on the Effect of Volume Ratio of Steel Fiber on Mechanical Properties of Ceramsite Concrete

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Abstract

In this paper, the mix proportion design of Steel Fiber Ceramsite Concrete is carried out by combining the total calculation method with the absolute volume method. The mechanical properties of SFRLAC with steel fiber volume fraction (V_f) 0% - 2% and matrix strength of LC30, LC40 and LC50 were tested. The relationship between the volume fraction of steel fiber and the increase of compressive strength, flexural strength and splitting tensile strength was analyzed. The test results show that, with the increase of steel fiber volume fraction, the compressive strength, flexural strength and splitting tensile strength of SFRLAC are improved to varying degrees, but the flexural strength and splitting tensile strength increase greatly.

Subject Areas

Civil Engineering

Keywords

Steel Fiber Ceramsite Concrete, Mixture Ratio, Mechanical Properties

1. Introduction

Concrete is one of the most widely used building materials in the world. In recent years, with the development of China's social economy, there are more and more infrastructures such as buildings, structures, highways and railways, and the demand for concrete is also increasing. The increasing demand for concrete has brought new requirements for its performance. At the same time, the requirements of environmental protection and energy conservation also put forward higher requirements for concrete. The lightweight, composite performance and environmental friendliness of concrete structures are important directions for their development. Compared with ordinary concrete, lightweight aggregate concrete has the properties of heat preservation, heat insulation and sound insulation, and the concrete quality and engineering cost will be reduced under the same strength.

Ceramsite concrete, also known as Lightweight Aggregate Concrete (LAC), has always been attached great importance to its research and application. Compared with ordinary concrete, LAC has no stone, and it replaces coarse aggregate stone with artificial or natural lightweight aggregate, which has the advantages of lightweight, heat insulation, impermeability, frost resistance and seismic resistance. It can not only meet the use function of buildings, but also has high economic and technical benefits, which is conducive to promoting sustainable development and is of great significance to the field of engineering construction [1] [2] [3] [4]. At the same time, the brittleness of LAC increases with the increase of strength, and it is easy to crack. Steel Fiber Reinforced Lightweight Aggregate Concrete (SFRLAC) is formed by adding steel fiber into ceramsite concrete. The incorporation of steel fibers effectively restricts the propagation of microcracks in the matrix, which makes the tensile, bending, shear, punching and durability of LAC significantly improved. Based on this, this paper takes LC30, LC40 and LC50 ceramsite concrete as reference concrete, carries out the mechanical properties test of steel fiber ceramsite concrete, and studies the influence of steel fiber volume ratio on the mechanical properties of ceramsite concrete. SFRLC has the advantages of lightweight aggregate concrete and steel fiber concrete. On the one hand, the toughening and crack resistance of steel fiber improve the ductility of concrete, and lightweight ceramsite solves the self-weight of concrete. On the other hand, ceramsite and steel fiber can also complement each other, so that concrete can give full play to their advantages in different stress stages and improve the corresponding mechanical properties of concrete [5] [6] [7] [8].

The research on steel fiber ceramsite concrete has been continuous. R. Mutsuddy and V. Bindiganavile *et al.* [9] used expansive shale lightweight coarse aggregate, granular raw rubber, Portland cement, silica fume and metakaolin as cementing admixtures, and added hook-end steel fiber to prepare lightweight steel fiber-reinforced concrete at a volume rate of 1%; the response and elastic modulus of the fiber under quasi-static compression were measured: the results showed that the flexural strength and fracture toughness of the fiber reinforced concrete were significantly enhanced. M. Hassanpour and P. Shafigh *et al.* [10] studied the processing performance, compressive strength, stress-strain characteristics, tensile strength, elastic modulus, compression and flexural toughness of lightweight aggregate concrete with different types of fibers. The results show that the mechanical properties of lightweight aggregate concrete containing fibers, such as single or mixed forms, will be improved, and its toughness, ductility and energy absorption will be significantly increased. However, steel fibers will reduce its workability, especially when steel fibers are used in concrete mixtures. F. Altun and B. Aktas [11] studied the mechanical properties of SFRLAC beams under four-point loading, and also measured the apparent density. The results show that the addition of steel fiber increases the toughness and ductility of the beam, and the ductility increases by 64% to 98%. At the same time, compared with ordinary reinforced concrete beams, the self-weight of SFRLAC beams decreased significantly, with a decrease of 42% in the test. E. Güneyisi and M. Gesoglu [12] studied the compressive strength, splitting tensile strength and flexural strength of steel fiber volume fraction 0.35%, 0.70% and 1.00% SFRLAC. The test results show that the incorporation of steel fiber mainly improves the splitting tensile and flexural strength, but does not significantly affect the compressive strength.

2. Survey of Experiments on SFRLAC

2.1. Test Raw Materials

1) Cement: P.O42.5R ordinary Portland cement, density 3200 kg/m^3, provided by Concrete Mixing Station in HanDan. Mixing water is Handan tap water, PH value is about 7.

2) Medium sand: concrete mixing station provides apparent density of 1570 kg/m^3, fineness modulus of 2.5, maximum particle size of 5 mm continuous gradation.

3) Steel fiber: milling steel fiber, length 32 mm, diameter 0.8, aspect ratio 40mm, tensile strength greater than 600 MPa, as shown in **Figure 1**.

4) Crushed ceramsite, bulk density is 760 kg/m^3, an hour water absorption 3.4%, 5 mm ~ 25 mm continuous gradation, as shown in **Figure 2**.

Figure 1. Steel fiber.

Figure 2. Ceramsite.

5) Water reducing agent is high efficient liquid polycarboxylate water reducing agent, water reducing rate is 25%, fly ash of grade II, apparent density of 2200 kg/m^3 provided by concrete mixing station.

2.2. SFRLC Proportion Design

In order to understand the mechanical properties of SFRLAC with different strength grades and different steel fiber volume fractions, three concrete strength grades of LC30, LC40 and LC50 were set in this experiment. The strength grades are 0, 0.5%, 1%, and 2% of steel fiber volume fraction. The new design method of mix proportion of ceramsite concrete is obtained by combining the total calculation method of ordinary concrete and the absolute volume method. A total of 12 groups of dosage, the dosage of steel fiber ceramsite concrete is shown in Table 1. The volume fraction of steel fiber is calculated at 78 Kg corresponding to 1% absolute volume method. V_f in the table represents steel fiber volume fraction.

3. Preparation of Concrete Specimen

3.1. Feeding and Mixing

First of all, the raw materials are weighed according to the electronic weighing with the accuracy of 0.001 Kg. First, cement, fly ash and dry sand are put into the horizontal axis forced concrete mixer (Figure 3) for about 2 minutes, and then the pre-wetted ceramsite is put into the mixing for about 2 minutes after the shutdown. Secondly, water and water reducing agent are added to mix and stir to give full play to the role of water reducing agent and ensure the uniformity of the mixture [13]. Then steel fiber is evenly dispersed into the mixture under stirring and continues to stir for 2 - 3 minutes until steel fiber is evenly distributed

Table 1. SFRLAC concrete mix proportion (Kg/m^3).

Specimen number	Cement	Ceramsite	Medium sand	Flyash	Water reducer	Steel fiber	Water
LC30V_{0}	360	460	780	130	6	0	200
LC30$V_{0.5}$	360	460	780	130	6	39	200
LC30$V_{1.0}$	360	460	780	130	6	78	200
LC30$V_{2.0}$	360	460	780	130	6	156	200
LC40V_{0}	390	490	740	140	9	0	186
LC40$V_{0.5}$	390	490	740	140	9	39	186
LC40$V_{1.0}$	390	490	740	140	9	78	186
LC40$V_{2.0}$	390	490	740	140	9	156	186
LC50V_{0}	460	510	700	150	14	0	165
LC50$V_{0.5}$	460	510	700	150	14	39	165
LC50$V_{1.0}$	460	510	700	150	14	78	165
LC50$V_{2.0}$	460	510	700	150	14	156	165

Figure 3. The horizontal axis forced concrete mixer.

in the mixture.

3.2. Forming and Maintenance of Concrete Specimen

When pouring the model, the concrete mixture should be rammed into the mold layer by layer with steel bars in three layers. At the same time, the filler should be slightly higher than the top of the mold. Secondly, it should be vibrated and compacted on the shaking table. When the surface of the test block is flooded, the vibration should be stopped. Then, the surface of the test block after molding should be smoothed. A plastic film should be covered on the surface of the mold after pouring. After standing for 24 h under the natural environment, the demoulding machine should be used for demoulding treatment. Then, the finished test block should be labeled and numbered. Finally, the test block should be placed in a standard room with a temperature of about 20˚C and a relative humidity of more than 95%, and maintained for 28 days.

3.3. Test Methods

Three strength grades of LC30, LC40 and LC50 were set in the test. The volume rates of steel fiber in each strength grade were 0, 1%, 2% and 3%, a total of 12 groups of specimens. After the curing age reached 28 d, the mechanical properties of the specimens were tested. The compressive strength, flexural strength and splitting tensile strength were tested on a 200t microcomputer controlled automatic pressure testing machine. In this test, the size of cube compressive and splitting tensile specimens is 100 mm × 100 mm × 100 mm, and the size of flexural strength specimen is 40 mm × 40 mm × 160 mm. The number of corresponding mechanical properties of each group is three. The final test result is the arithmetic average of the three. The loading method used in this test is stress control. The stress loading rate of compressive strength test is about 1.2 MPa/s, the stress loading rate of tensile test is about 0.1 MPa/s, and the stress loading rate of splitting tensile test is about 0.08 MPa/s.

4. Test Phenomena and Failure Characteristics

4.1. Compressive Strength Test

The failure mode of cube specimen under compression is shown in Figure 4. It can be seen from Figure 4 that the compressive failure mode of matrix ceramsite

(a) (b)

Figure 4. Compression failure mode. (a) The specimen without steel fiber; (b) The specimen with steel fiber.

concrete is obviously different from that of steel fiber ceramsite concrete in the loading failure process. At the initial loading stage of the matrix ceramsite concrete specimen, there was no significant change in the outer surface of the specimen. With the increase of loading pressure, there are more vertical cracks in the loading side of the specimen, and the cracks continue to develop, and gradually penetrate the loading surface of the specimen. There are local fragments falling off the side of the specimen. When the peak load is reached, the specimen emits a slight crack sound, and the concrete on the loading side is crushed. The loading failure of the concrete specimen shows great brittleness. With the increase of loading pressure, there are few vertical cracks on the side of the specimen loaded with steel fiber. With the slow development of cracks, steel fiber is pulled out from the crack surface and is not broken. When the peak load is reached, there is a slight tearing noise and the test block is damaged, but the integrity is good. The ceramsite concrete specimen mixed with steel fiber is bonded.

4.2. Break Strength

The flexural failure state of the cuboid specimen under loading is shown in Figure 5. It can be seen from Figure 5 that the flexural failure mode of matrix ceramsite concrete is quite different from that of steel fiber ceramsite concrete in the loading failure process. It was found in the bending test that during the loading process, when the specimen without steel fiber ceramsite concrete reached the ultimate load of bending capacity, the tensile zone suddenly broke in the three-point, and the loading failure of the matrix ceramsite concrete specimen was a typical brittle failure mode. In the test process of ceramsite concrete specimen mixed with steel fiber, the cracks of the specimen first appear in the middle span, and then there are more small cracks gradually, and develop to the vertical direction of the specimen. When the peak load is reached, some fine cracks in the middle part of the span gradually develop into larger cracks, and the specimen is finally destroyed. The observation section found that the specimen was not completely broken, because only a small amount of fiber was broken, most of the steel fiber was not pulled out of the concrete on both sides of the crack.

(a) (b)

Figure 5. Fracture-resistant form. (a) The specimen without steel fiber; (b) The specimen with steel fiber.

4.3. Split Tensile Test

The splitting tensile failure state of cube specimens under loading is shown in Figure 6. During the loading test, when the specimen without steel fiber ceramsite reaches the ultimate load of splitting tensile bearing capacity, the specimen is directly split into two halves completely separated, and the concrete specimen is brittle fracture. During the splitting process of ceramisite concrete specimens mixed with steel fiber, several fine cracks were generated in the initial stage along the splitting direction. With the increase of load, the cracks widened continuously. When the peak load is reached, the splitting tensile failure of the test block is divided into two parts. Because the steel fiber on both sides of the crack connects the ceramsite concrete test block, it maintains a complete state.

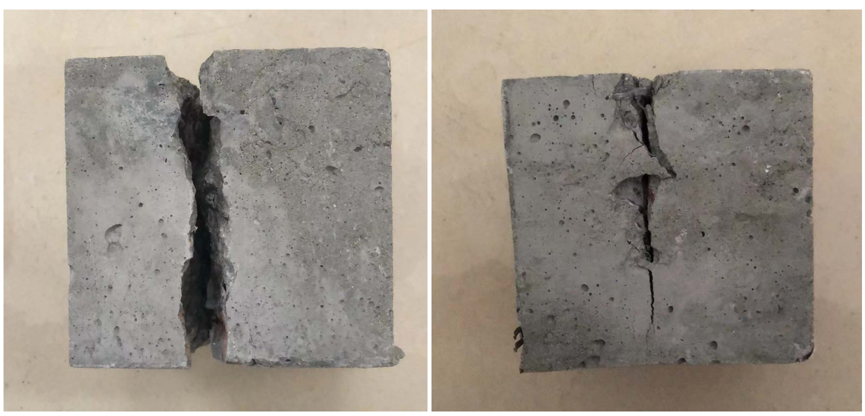
5. Experiment Results and Analysis

5.1. SFRLAC Strength Test Results

SFRLAC compressive, flexural and splitting tensile strength test results are detailed in Table 2.

5.2. Effect of Steel Fiber Volume Fraction on Mechanical Properties of SFRLAC

Table 3 shows that the compressive strength of LC30, LC40 and LC50 matrix ceramsite concrete with steel fiber increases by 11.0% ~ 31.6%, 9% ~ 25.7% and 10.7% ~ 21.5% compared with matrix ceramsite concrete with the increase of steel fiber volume fraction. When the volume ratio of steel fiber is 0.5%, the compressive strength is higher than that of matrix ceramsite concrete, and the amount of steel fiber is sensitive to the strength growth. When the volume ratios of steel fibers are 1% and 2%, the incorporation of steel fibers increases slowly on the strength. When the specimen is under compression, the random distribution of steel fiber inside the ceramsite concrete specimen has a certain constraint effect on its deformation, which changes its stress state and improves the compressive



(a) (b)

Figure 6. Splitting tensile failure mode. (a) The specimen without steel fiber; (b) The specimen with steel fiber.

Table 2. SFRLAC compressive, flexural and splitting tensile strength (MPa).

Specimen number	Compressive strength	Break off strength	Split tensile strength
$LC30V_0$	33.5	3.1	2.2
$LC30V_{0.5}$	37.2	3.5	3.7
$LC30V_{1.0}$	40.6	3.9	4.0
$LC30V_{2.0}$	44.1	4.7	5.2
$LC40V_0$	43.2	3.7	3.2
$LC40V_{0.5}$	47.1	4.2	4.9
$LC40V_{1.0}$	50.3	4.5	5.6
$LC40V_{2.0}$	54.3	5.7	7.2
$LC50V_0$	55.3	5.0	4.1
$LC50V_{0.5}$	61.2	5.7	6.5
$LC50V_{1.0}$	64.1	6.2	7.5
$LC50V_{2.0}$	67.2	7.6	8.9

Table 3. Effect of steel fiber volume ratio on compressive strength of SFRLAC.

Specimen number	Compressive strength (MPa)	The increase rate of cube compressive strength (%)
$LC30V_0$	33.5	0
$LC30V_{0.5}$	37.2	11.0%
$LC30V_{1.0}$	40.6	21.2%
$LC30V_{2.0}$	44.1	31.6%
$LC40V_0$	43.2	0
$LC40V_{0.5}$	47.1	9.0%
$LC40V_{1.0}$	50.3	16.4%
$LC40V_{2.0}$	54.3	25.7%
$LC50V_0$	55.3	0
$LC50V_{0.5}$	61.2	10.7%
$LC50V_{1.0}$	64.1	15.9%
$LC50V_{2.0}$	67.2	21.5%

strength of ceramsite concrete.

5.3. Effect of Steel Fiber Volume Fraction on Flexural Strength of SFRLAC

It can be seen from Table 4 that when steel fibers are added to LC30, LC40, and LC50 matrix ceramsite concrete, the flexural strength increases by 12.9% ~ 51.6%, 13.5% ~ 13.5% ~ 54.0%, 14.0% to 52.0%. When the volume ratio of the

Table 4. Effect of steel fiber volume ratio on compressive strength of SFRLAC.

Specimen number	Break off strength (MPa)	Increase rate of break off strength (%)
$LC30V_{0}$	3.1	0
$LC30V_{0.5}$	3.5	12.9%
$LC30V_{1.0}$	3.9	25.8%
$LC30V_{2.0}$	4.7	51.6%
$LC40V_{0}$	3.7	0
$LC40V_{0.5}$	4.2	13.5%
$LC40V_{1.0}$	4.5	21.6%
$LC40V_{2.0}$	5.7	54.0%
$LC50V_{0}$	5.0	0
$LC50V_{0.5}$	5.7	14.0%
$LC50V_{1.0}$	6.2	24.0%
$LC50V_{2.0}$	7.6	52.0%

steel fiber added is 1%, the flexural strength is higher than that of the matrix ceramsite concrete. When the volume ratio of steel fiber is 2%, the flexural strength is much higher than that of the matrix ceramsite concrete, and the amount of steel fiber added is more sensitive to the strength increase. It shows that during the loading process, when the specimen is cracked, the steel fibers that have not been pulled out at the cracks transfer the load to the concrete on both sides, which slows down the propagation speed of the cracks. The longer the time, the higher the peak tensile stress achieved.

5.4. Effect of Steel Fiber Volume Ratio on Splitting Tensile Strength of SFRLAC

Table 5 shows that the splitting tensile strength of LC30, LC40 and LC50 matrix ceramsite concrete with steel fiber increases by 68.1% ~ 136.3%, 53.1% ~ 125.0% and 58.3% ~ 117.0% compared with matrix ceramsite concrete with the increase of steel fiber volume fraction. When the volume fraction of steel fiber is 0.5%, 1% and 2% respectively, the splitting tensile strength is higher than that of matrix ceramsite concrete, which indicates that the strength increases steadily with the increase of steel fiber volume fraction. This shows that after adding steel fiber, the brittleness of matrix ceramsite concrete has been greatly improved, and the toughness has been significantly improved.

6. Conclusions

1) When the volume fraction of steel fiber increases from 0% to 2%, the compressive strength, flexural strength and splitting tensile strength of SFRLAC are all improved to varying degrees. The maximum increase rate of compressive strength is 31.6%. The increase of steel fiber increases slightly with the increase

Table 5. Effect of steel fiber volume ratio on splitting tensile strength of SFRLAC.

specimen number	split tensile strength (MPa)	Increase rate of split tensile strength (%)
$LC30V_0$	2.2	0
$LC30V_{0.5}$	3.7	68.1%
$LC30V_{1.0}$	4.0	81.8%
$LC30V_{2.0}$	5.2	136.3%
$LC40V_0$	3.2	0
$LC40V_{0.5}$	4.9	53.1%
$LC40V_{1.0}$	5.6	75.0%
$LC40V_{2.0}$	7.2	125.0%
$LC50V_0$	4.1	0
$LC50V_{0.5}$	6.5	58.3%
$LC50V_{1.0}$	7.5	82.9%
$LC50V_{2.0}$	8.9	117.0%

of concrete strength grade. The failure results of SFRLAC cube compressive strength test show that the incorporation of steel fiber can improve the brittleness of lightweight concrete and make it have a certain plastic failure mode.

2) When the volume fraction of steel fiber increases from 1% to 2%, the flexural strength of SFRLAC increases in varying degrees, and the maximum increase rate of compressive strength is 54.0%.

3) The enhancement effect of steel fiber on SFRLAC splitting tensile strength is obvious. The contribution of steel fiber to the tensile properties of LC30 with low strength grade is greater than that of LC50 with high strength grade. That is, when Vf is 0.5%, the increase of steel fiber on SFRLAC tensile strength is greater than that of SFRLAC with Vf of 1% and 2%. The splitting tensile test of SFRLAC has obvious failure signs, reflecting its good plastic characteristics. Adding steel fiber into ceramsite concrete can improve the brittleness and toughness, so the splitting tensile strength is obviously improved.

Conflicts of Interest

The author declares no conflicts of interest.

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