Experimental Study on Compressive and Splitting Tensile Strength of Layer Hybrid Steel Fiber Recycled Aggregate Concrete

Yuying Wang¹, Jiajun Tang²*, Jie Hu² and Silong An²

¹School of Engineering, the Tourism College of Changchun University, Changchun, Jilin, 130607, China
²School of Civil Engineering, Changchun Institute of Technology, Changchun, Jilin, 130012, China

*Corresponding author’s e-mail: tangjiajun@ccit.edu.cn

Abstract. In order to improve the mechanical properties of recycled aggregate concrete, hybrid steel fiber layers were added to recycled aggregate concrete. By changing the number of layers and contents of hybrid steel fibers, compressive and splitting tensile strength tests were carried out on 10 groups of 60 recycled aggregate concrete blocks. The results show that with the increase of the number of layers of hybrid steel fibers, the overall change of compressive strength is not significant, the splitting tensile strength gradually shows an upward trend, and the change of tension-compression ratio is not obvious, but the tension-compression ratio generally increases compared with group RC. With the increase of hybrid steel fiber contents, the compressive strength first increases and then decreases, the splitting tensile strength gradually increases, and the tension-compression ratio first decreases and then increases. After adding hybrid steel fiber layers, the failure of recycled aggregate concrete changes from brittleness to plasticity.

1. Introduction

At present, the basic consensus has been reached on the reduction of strength, toughness and crack resistance of recycled concrete after adding recycled aggregate [1-3]. In recent years, a large number of experimental results show that the mechanical properties of recycled concrete can be improved by adding steel fiber. The test results of Yang Fen et al. [4] show that the cube compressive strength, axial compressive strength, splitting tensile strength, flexural strength and compressive elastic modulus of recycled concrete with steel fiber are increased by 1.3%~11.5%, 1.0%~13.4%, 7.1%~26.0%, 2.1%~15.1% and 0.3%~10.4% respectively. However, the high cost of steel fiber reinforced recycled concrete (large amount of steel fiber) and the difficulty of construction (steel fiber is not easy to mix evenly and the slump of steel fiber reinforced concrete is small) limit its development to a certain extent [5]. In the case of layered steel fiber reinforced recycled concrete structure (that is to say, a certain amount of steel fiber is evenly distributed in the structural member layer by layer to form the reinforcing layer of steel fiber and recycled concrete), a small amount of steel fiber can improve its tensile strength, flexural strength and toughness. This not only saves the cost, but also reduces the construction difficulty, so it has good social and economic benefits and application prospects [6].

Based on this, in the previous study [7, 8], the optimal steel fiber mixing ratio (the mass ratio of primary and secondary end hook steel fiber is 3:1) is selected to study the influence of the hybrid steel
fiber on the cube compressive strength, splitting tensile strength, tension compression ratio and failure mode of the test block by changing the layer number and content of hybrid steel fiber, which provides a reference for the practical application of hybrid steel fiber reinforced recycled concrete. The theoretical basis is provided for the application of the program.

2. Test overview

2.1. Raw material
Cement: P·O 42.5 ordinary portland cement with density of 3150 kg/m³. Fly ash: Class F grade I fly ash, with density of 2180 kg/m³, fineness of 10.4%, water demand ratio of 84%, loss on ignition of 0.36%, water content of 0.1%, sulfur trioxide of 0.18% and free calcium oxide of 0.06%. Silicon powder: silicon powder, density is 700 kg/m³, loss on ignition is 1.1%, pH is neutral. Mixing water: ordinary tap water. Water reducing agent: polycarboxylate high performance water reducing agent, water reducing rate of 20%. Fine aggregate: ordinary river sand with fineness modulus of 2.56 and moisture content of 2.1%. Natural coarse aggregate: local crushed stone in Yanji City, with particle size of 5-20 mm and moisture content of 2.5%. Recycled coarse aggregate: the waste test block of Yanbian University structural laboratory is crushed by pressure testing machine, broken by jaw crusher and screened manually. The particle size is 5-20 mm and the water absorption is 3.61%. Steel fiber: the primary end hook steel fiber produced by Hebei Hengshui Shengze building materials Co., Ltd. and the secondary end hook steel fiber made by the laboratory are 50 mm in length, 60 in length diameter ratio, and 834 MPa in tensile strength. The shape of steel fiber is shown in Figure 1.

Figure 1. The structural diagram of LSFRAC beams

Figure 2. Location of steel fiber

2.2. Mix proportion
In the test, the water binder ratio is 0.25, sand ratio is 0.45, 20% fly ash and 10% silica fume (mass percentage in cementitious body) are used to replace part of cement, 30% recycled coarse aggregate (mass percentage in total coarse aggregate) is used to replace part of natural coarse aggregate [9], and the dosage of water reducing agent is 0.8%. The same mix proportion is used in all test groups. The mix proportion design of recycled concrete is shown in Table 1.

Table 1. Mix design of recycled concrete

| Materials             | Consumption(kg/m³) | Materials             | Consumption(kg/m³) |
|-----------------------|--------------------|-----------------------|--------------------|
| Natural coarse aggregate | 561                | Cement                | 448                |
| Recycled coarse aggregate | 240                | Fly ash               | 128                |
| Sand                  | 655                | Silica fume           | 64                 |
| Water                 | 141                | Water reducing agent  | 5.12               |

2.3. Test method
Firstly, the natural coarse aggregate, recycled coarse aggregate, sand, cement, fly ash and silica fume are poured into the blender in sequence, and mixed for 30 s. Then, the water reducer is added into the
water and mixed evenly, and then poured into the blender together, and mixed for 3 min. After the concrete is well mixed, pave 20 mm thick concrete at the bottom of the trial formwork. After the concrete is self-flowing and dense, manually spread the first layer of steel fiber (make the steel fiber evenly distributed as far as possible), continue to add the second layer of concrete and steel fiber, and repeat the operation to the required number of layers. The location of hybrid steel fiber layer is shown in Figure 2.

In this experiment, 10 groups of 60 150 mm×150 mm×150 mm concrete cube standard test blocks were made. After curing for 28 days under standard conditions, YAD-2000 microcomputer controlled electro-hydraulic servo pressure testing machine was used to carry out compressive and splitting tensile strength tests. According to the standard of test methods for mechanical properties of ordinary concrete (GB/T 50081-2002) [10], the loading rate is 0.8 MPa/s in compression test and 0.08 MPa/s in splitting tensile test.

3. Feasibility analysis

The results of cube compressive strength ($f_{cu,k}$) and splitting tensile strength ($f_s$) of 10 groups of recycled concrete blocks are shown in Table 2.

| Specimen number | $f_{cu,k}$/MPa | $f_s$/MPa | Specimen number | $f_{cu,k}$/MPa | $f_s$/MPa |
|-----------------|---------------|-----------|-----------------|---------------|-----------|
| RC              | 76.1          | 4.16      | B5              | 75.6          | 4.27      |
| B1              | 74.0          | 4.27      | B6              | 78.0          | 4.53      |
| B2              | 74.2          | 4.10      | B7              | 78.4          | 5.66      |
| B3              | 74.5          | 4.15      | A4              | 73.9          | 4.01      |
| B4              | 77.6          | 4.17      | C4              | 76.5          | 4.90      |

Note: RC represents ordinary recycled concrete test group; A, B and C represent hybrid steel fiber content of 1.0 kg/m$^2$, 1.5 kg/m$^2$ and 2.0 kg/m$^2$ respectively; 1-7 represent hybrid steel fiber spreading layers.

3.1. Analysis of compressive strength

Figure 3 and figure 4 show the change of compressive strength with the layer number and content of hybrid steel fiber. It can be seen from Figure 3 that when the number of hybrid steel fiber layers is less (1-3 layers), the compressive strength is lower than that of RC group. When the number of hybrid steel fiber layers is 1, the compressive strength reaches the minimum, which is 2.8% lower than that of RC group. This is because after adding the hybrid steel fiber layer, the internal porosity of concrete becomes larger, and when the steel fiber content is small, the reinforcement effect is not obvious, resulting in the reduction of compressive strength [11]. When the number of hybrid steel fiber layers is 4 or more, the compressive strength is higher than that of RC group. When the number of hybrid steel fiber layers is 7, the compressive strength reaches the maximum, which is 3.0% higher than that of RC group. This is because steel fiber can reduce the stress concentration at the end of micro cracks in the concrete matrix, and absorb a lot of energy in the process of concrete loading, so as to inhibit the expansion of cracks and improve the compressive strength of recycled concrete [12]. On the whole, with the increase of hybrid steel fiber layers, the compressive strength has little change.

It can be seen from Figure 4 that when the number of hybrid steel fiber layers is four, the compressive strength increases by 5.0% when the content of hybrid steel fiber increases from 1.0 kg/m$^2$ to 1.5 kg/m$^2$; when the content of hybrid steel fiber increases from 1.5 kg/m$^2$ to 2.0 kg/m$^2$, the compressive strength decreases by 1.4%. This is because when the content of hybrid steel fiber is too large, the fiber is not easy to be evenly distributed, and there are more pores in the bonding area between fiber and concrete to form a weak area, resulting in the reduction of compressive strength [13].
3.2. Analysis of splitting tensile strength

Figure 5 and figure 6 show the change of splitting tensile strength with the layer number and content of hybrid steel fiber. It can be seen from Figure 5 that when the number of hybrid steel fiber layers is 1, the splitting tensile strength increases by 2.6% compared with RC group; when the number of hybrid steel fiber layers increases from 2 to 7, the splitting tensile strength gradually presents an upward trend; when the number of hybrid steel fiber layers is 7, the splitting tensile strength reaches the maximum and the growth is the most significant, which increases by 36.1% compared with RC group. It can be seen from Figure 6 that with the increase of steel fiber content, the splitting tensile strength increases gradually, and the increase of C4 group is 22.2% higher than that of A4 group. This is because the hybrid steel fiber in recycled concrete is equivalent to micro reinforcement, which mainly plays the role of bridging cracks and pores, which greatly improves the splitting tensile strength of recycled concrete [14].

3.3. Analysis of tension compression ratio

Tension compression ratio (ratio of splitting tensile strength to compressive strength) is one of the indexes to characterize the brittleness of concrete. The higher the tension compression ratio, the lower the brittleness of concrete. Fig. 7 and Fig. 8 show the change of tension compression ratio with the layer number and content of hybrid steel fiber. It can be seen from Fig. 7 that after adding the hybrid steel fiber layer, the change rule of tension compression ratio with the number of layers is not obvious. Except for B4 group, the tension compression ratio decreases slightly, other groups increase, among which B7 group is the largest, which increases by 32.1% compared with RC group, and the increase range of other groups is -1.6% ~ 6.2%. The results show that the brittleness and plasticity of the recycled concrete are lower than those of the ordinary recycled concrete. It can be seen from figure 8 that when the content of hybrid steel fiber increases from 1.0 kg/m² to 2.0 kg/m², the tension
compression ratio first decreases and then increases. This shows that when the steel fiber content is large, not only the splitting tensile strength increases significantly, but also the brittleness of concrete decreases significantly.

![Figure 7. Variation of tension compression ratio with the number of layers of steel fiber](image)

![Figure 8. The change of tension compression ratio with the content of hybrid steel fiber](image)

3.4. Analysis of failure mode

Figure 9 and figure 10 show the failure modes of ordinary recycled concrete and layered hybrid steel fiber recycled concrete in compression and splitting tensile tests respectively.

In the compression test, the ordinary recycled concrete test block is damaged suddenly, accompanied by a “bang” sound, the concrete block collapses outside the body, and the test block is seriously damaged, as shown in Figure 9 (a). After adding the hybrid steel fiber layer, the explosion sound and damage degree of the concrete block are reduced, and the block is relatively complete, with multiple cracks on the surface, as shown in Figure 10 (a).

In the splitting tensile test, the ordinary recycled concrete block has brittle failure, which is divided into two parts along the splitting line, and the failure is sudden and serious, as shown in Figure 9 (b). After adding the hybrid steel fiber layer, the integrity of the concrete block is good, and it is not split into two parts, but a crack is produced along the splitting line. Before the failure, the crackle of the steel fiber can be heard, and the failure has a certain plasticity, as shown in Figure 10 (b).

![Figure 9. Failure modes of ordinary recycled concrete](image)

![Figure 10. Failure mode of layer distributed hybrid steel fiber recycled concrete](image)

4. Conclusions

(1) When the content of hybrid steel fiber is 1.5 kg/m², with the increase of the number of hybrid steel fiber layers, the compressive strength has little change; the splitting tensile strength gradually presents an upward trend, with a maximum increase of 36.1%; the tensile compression ratio has no obvious change with the number of layers, but the tensile compression ratio increases compared with the RC group, with a maximum increase of 32.1%.

(2) When the number of hybrid steel fiber layers is 4, with the increase of hybrid steel fiber content, the compressive strength first increases and then decreases; the splitting tensile strength gradually increases, when the content increases from 1.0 kg/m² to 2.0 kg/m², the splitting tensile strength increases by 22.2%; the tension compression ratio first decreases and then increases.
(3) When the number of hybrid steel fiber layers is 7 and the content is 1.5 kg/m², the mechanical properties of recycled concrete with hybrid steel fiber layers are significantly improved, and the compressive strength, splitting tensile strength and tension compression ratio are larger.

(4) It can be seen from the compressive and splitting tensile tests that the failure of recycled concrete changes from brittleness to plasticity after adding hybrid steel fiber layer.

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