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# Application of Self-Compacting Steel Fiber Reinforced Concrete for Pervious Frames Used for River Revetment

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**Abstract:** Aimed at improving the production efficiency of tetrahedron-like pervious frames for the river revetment, self-compacting steel fiber reinforced concrete (SFRC) was applied to strengthen the tensile resistance of concrete to remove conventional steel bars used as reinforcement. The workability and mechanical properties of self-compacting SFRC were experimentally studied with the volume fraction of steel fiber changed from 0.4% to 1.2%, and the rational volume fraction of 0.8% was determined for producing the pervious frames. Based on the flow-induced orientation of the steel fibers in the fresh mix, the casting process of self-compacting SFRC was optimal from one inclined rod to other two inclined rods and the horizontal rods of the pervious frame. The loading capacities of pervious frames during lifting and stacking were respectively detected by the simulation tests on the testing machine, which ensure the safety of pervious frames lifted six layers together and stacked for nineteen layers. By testing groups of pervious frames throwed in and then salvaged from the river, the quality of pervious frames without any damage was observed. Finally, the pervious frames were successfully applied in an engineering project for the river revetment.

**Keywords:** self-compacting SFRC; pervious frame; river revetment; workability; mechanical property; loading capacity



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## 1. Introduction

In the field of water conservancy, the protection of embankments, shorelines and wading structures in rivers, lakes, and coastal zones is very important for flood control and shipping safety. Traditional techniques for river revetment include solid revetment and current reduction revetment. The solid revetment is an engineering facility on the riverbed to prevent riverbank erosion by water flow. It mainly includes riprap, masonry, sinking rows, geotechnical pillows, concrete mold bags and reinforced concrete hinge rows. However, the foundation of a solid revetment is easily washed away, resulting in an obvious drawback of structural instability [1,2]. The current reduction revetment aims to reduce the flow velocity to block sediment loss to lighten the washing of the river bank. In this area, the pervious frame and I-shaped block, especially the tetrahedron-like pervious frames, are widely applied. According to the hydraulic test results, the tetrahedron-like pervious frames play an important role in dispersing water flow, dissipating scour energy and blocking sediment. This makes it widely used in ecological waterway construction projects as a new protective structure. In recent years in China, tetrahedron-like pervious frames have been used for the repair and maintenance of erosion damage at the edge of the built beach protection zone, the protection of the edge of a rockfill dam head, and the promotion of siltation and consolidation of the beach body [2,3].

The initial tetrahedron-like pervious frame consists of six precast reinforced concrete rods connected to each other to form a triangular tetrahedral structure. The length of rods is equal to about 600–1000 mm based on practical usage, and the cross-section is 100 mm $\times$ 100 mm. A steel bar with 10 mm diameter is placed in the axis of each rod, and extends 150 mm out of the ends. Three rods as a group are welded or tied together at one end by the exposed steel bars, and their other end is linked with a rod to compose a trigonal pyramidal structure [4–6]. In practical engineering application, it is found that the exposed steel bars at the ends are easily corroded and lose their connection function, which reduces the service life of pervious frames. Therefore, by improving the production techniques, the integral pervious frame with a welded steel skeleton embedded in concrete rods was developed [3,7]. This increases the production steps of the welding of steel bar skeleton, the compositing of the steel formwork, the positioning of the welded steel bar skeleton and the one-step forming of fresh concrete. As a result, the construction complexity was increased and the production efficiency was reduced [3,8].

The self-compacting steel fiber reinforced concrete (SFRC) is a kind of composite high-performance concrete, which is produced by adding steel fibers in the self-compacting concrete matrix [9–11]. Although the addition of steel fiber could bring down the workability of fresh SFRC, and even lead to an unsatisfactory flowability if the fiber content exceeds a certain value, the strengthening of tensile properties and bending toughness of hardened SFRC is remarkable [12–15]. Except for excellent mechanical properties and durability including high tensile and flexural strengths, better resistance to impact and erosion, and lower shrinkage, the self-compaction of the fresh mix is also favorable for the convenient production of the pervious frame [14–17]. At the same time, the flow-induced orientation of steel fibers along the axis of the rods benefits the cracking resistance and loading capacity of pervious frames during lifting for storage and stacking in service life. This provides the possibility of partially or completely replacing steel bars with steel fibers in self-compacting SFRC. Meanwhile, the advantage of self-compaction of the fresh mix also contributes to the economic production of the pervious frame, including the reduction of noise due to the elimination of concrete vibration, the improvement of the construction environment with no steel bars welded, and the speeding up of the production with a simplified process.

On the above technical review, the self-compacting SFRC is adaptable to the application of producing pervious frames [18–22]. However, there are some issues to be further studied. The mix proportion of self-compacting SFRC should be determined to achieve rational workability of fresh mix and the tensile strength of hardened SFRC. The production process, especially the casting method of self-compacting SFRC to form the pervious frame, should be investigated to realize the axial orientation of steel fibers in the rods. The loading performance of the pervious frames should be ensured for safety while lifting and stacking during production and in service life. Therefore, combined with the pervious frames applied in a river revetment project [23,24], the above issues were experimentally investigated in this study. Good results were obtained to provide a valuable reference for similar engineering production and application of self-compacting SFRC.

## 2. Materials and Methods

### 2.1. Raw Materials

Raw materials were selected in this study based on the principles of wide supply in the local market, and the rational preparation of concrete at strength grade C20. Grade 32.5 pozzolana silicate cement was used with the physical and mechanical properties shown in Table 1. Class II fly ash was used as a mineral admixture with a density of 2342 kg/m$^3$, a specific surface area of 406 m$^2$/kg, a water demand of 84.0%, and a strength activity index of 73.3%. Table 2 presents the chemical compositions of the cement and fly ash.

**Table 1.** Basic physical properties of cement.

| Density (kg/m$^3$) | Consistency (%) | Setting Time (min) | | Triage Residue (%) | | Flexural Strength (MPa) | | Compressive Strength (MPa) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Initial | Final | 45 μm | 80 μm | 3 d | 28 d | 3 d | 28 d |
| 3034 | 30.0 | 290 | 390 | 13.8 | 4.9 | 4.3 | 6.0 | 20.7 | 37.5 |

**Table 2.** Chemical composition of cement and fly ash.

| % | CaO | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $SO_3$ | MgO | Loss |
|---|---|---|---|---|---|---|---|
| Cement | 66.0 | 18.3 | 3.6 | 6.7 | 3.8 | 2.9 | 3.8 |
| Fly ash | 6.6 | 55.9 | 17.3 | 5.9 | 1.9 | 3.8 | 2.6 |

The fine aggregate was natural river sand, and the coarse aggregate was continuously graded crushed limestone with a particle size of 5–10 mm. The basic physical properties are presented in Table 3.

**Table 3.** Basic physical properties of coarse and fine aggregates.

| Aggreagte | Density (kg/m$^3$) | | | Water Absorption at 24 h (%) | Silt Content (%) | Fineness Modulus |
|---|---|---|---|---|---|---|
| | Apparent | Bulk | Compacted | | | |
| Crushed limestone | 2713 | 1412 | 1561 | 2.60 | 2.86 | - |
| River sand | 2613 | 1501 | 1601 | 1.33 | 2.74 | 2.77 |

The polycarboxylic acid superplasticizer with a water-reducing rate of 30% and a density of 1020 kg/m$^3$, and tap water were used. The mill steel fiber was 0.8 mm in diameter and 32 mm long, as shown in Figure 1, which is 4545 steel fibers per kilogram.


**Figure 1.** Mill steel fiber.

### *2.2. Mix Proportion of Self-Compacting SFRC*

The absolute volume method was adopted for the mix proportion design of the self-compacting SFRC, in which the coarse aggregate was substituted with an equal volume of steel fiber [9,11]. The target cubic compressive strength is 25 MPa for concrete at a strength grade C20 [25]. Referenced with previous studies [23,24], four mix proportions designed in this study are listed in Table 4, which took into account the changes of the volume fraction of steel fiber at 0%, 0.4%, 0.8%, and 1.2%, respectively, with the expectedly uniform distribution of steel fibers and the flowability of fresh self-compacting SFRC. The fly ash ratio was the mass percent of fly ash to binders of cement and fly ash.

**Table 4.** Mix proportion of self-compacting SFRC.

| Mix ID | SCF00 | SCF04 | SCF08 | SCF12 |
|---|---|---|---|---|
| Water to binder ratio $w/b$ | 0.35 | 0.35 | 0.35 | 0.35 |
| Sand ratio $\beta_s$ (%) | 53 | 54 | 55 | 56 |
| Fly ash ratio $\beta_f$ (%) | 20 | 20 | 20 | 20 |
| Water reducer ratio $\beta_a$ (%) | 1.4 | 1.4 | 1.4 | 1.5 |
| Volume fraction of steel fiber $v_f$ (%) | 0 | 0.4 | 0.8 | 1.2 |
| Water (kg/m$^3$) | 195.9 | 195.9 | 195.9 | 195.9 |
| Cement (kg/m$^3$) | 447.8 | 447.8 | 447.8 | 447.8 |
| Fly ash (kg/m$^3$) | 112.0 | 112.0 | 112.0 | 112.0 |
| Sand (kg/m$^3$) | 795.4 | 806.1 | 816.8 | 827.5 |
| Gravel (kg/m$^3$) | 705.4 | 683.5 | 661.5 | 639.6 |
| Steel fiber (kg/m$^3$) | 0 | 31.4 | 62.8 | 94.2 |
| Water reducer (kg/m$^3$) | 7.8 | 7.8 | 7.8 | 8.4 |

### *2.3. Manufacture of Pervious Frames*

#### 2.3.1. Composite Steel Mold

The pervious frame was manufactured with a composite steel mold which consists of an internal mold and an external mold. As shown in Figure 2, the steel plates are welded to form the internal mold to form the inside surfaces of the inclined and horizontal rods, and the shaped steels are welded to form the external mold to form the outside surfaces of the inclined rods, and the bottom and side surfaces of the horizontal rods. Before casting the self-compacting SFRC, the internal mold is embedded in the external mold, and fixed by three hasps. After formed the pervious frame by casting the self-compacting SFRC cured for certain periods, the three hasps are unlocked, the internal mold is first demolished, and the pervious frame is turned over to remove the external mold.

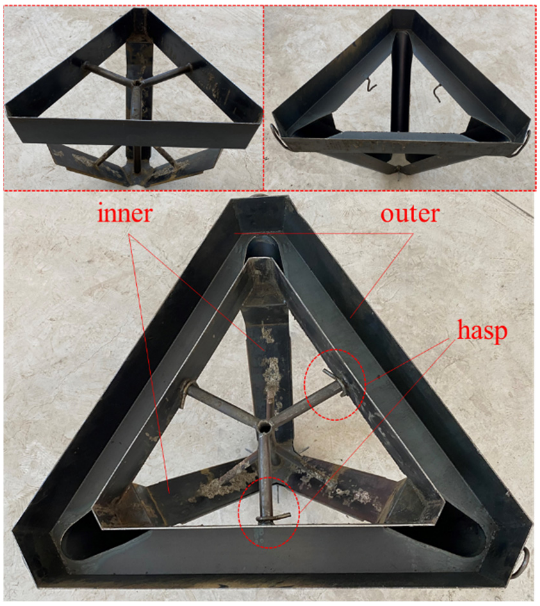



**Figure 2.** Composite steel mold of pervious frame.

#### 2.3.2. Casting Process

A horizontal-shaft force mixer was used for the mixing. The coarse and fine aggregates and the cementitious materials were added and mixed for 1 min, then the mixing water and the water reducing agent were added and mixed for 3 min, finally the steel fiber was sprinkled in and mixed for 2 min. With the flowability of self-compaction, the steel fibers uniformly oriented along the flowing direction.

As presented in Figure 3, the pervious frame is produced in the following order: (1) the internal and external molds were firstly brushed with a release agent, and then composited and fixed by the locks. (2) The self-compacting SFRC was poured into one of the inclined rods and filled the other two by passing through the top connection. When the three inclined rods were completely filled up, the self-compacting SFRC began to flow in the horizontal mold until full. (3) The surface of horizontal rods was plastered, and covered with plastic film for 5 h, then the internal mold was demolished. (4) When a certain strength of the self-compacting SFRC of the pervious frame had been achieved after curing for 24 h, the outer mold was removed. After continuously cured by spraying water for 48 h, the pervious frames were moved and piled up in the store site for natural curing until engineering application.

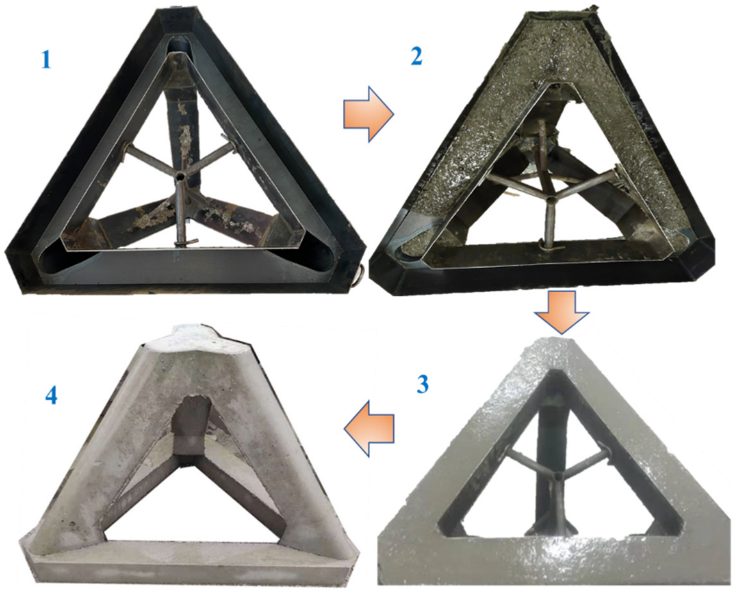



**Figure 3.** Casting process of pervious frame.

### 2.4. Test Method of Loading Test on Pervious Frames

Two kinds of tests were carried out on the pervious frames to simulate lifting for storage after production and stacking during service life. The first takes place during the layered lifting of pervious frames from the manufacturing plant to a storage area. The latter happens in the layered stack of pervious frames at the store area.

As presented in Figure 4a, the loading device used to simulate the lifting of pervious frames was composed of a hydraulic testing machine, a load sensor, a loading steel frame, and two layers of tested pervious frames supported on a steel prop. The lifting load was exerted on the top connection by the testing machine through the loading steel frame on the three inclined rods of the pervious frames and detected with the load sensor step-by-step according to the loading process. The steel prop was used to simulate the suspension of layered pervious frames.

As presented in Figure 4b, the loading device used to simulate stacking was composed of a hydraulic testing machine, a load sensor, a loading steel frame, and two layers of tested pervious frames. The stacking load was exerted by the testing machine through the loading steel frame on the three inclined rods of the pervious frames and detected with the load sensor step-by-step according to the loading process. The main difference between the two test methods is the placement of the layered pervious frames. The first was supported on a steel prop, and the second was directly placed on the bottom plate of the testing machine.

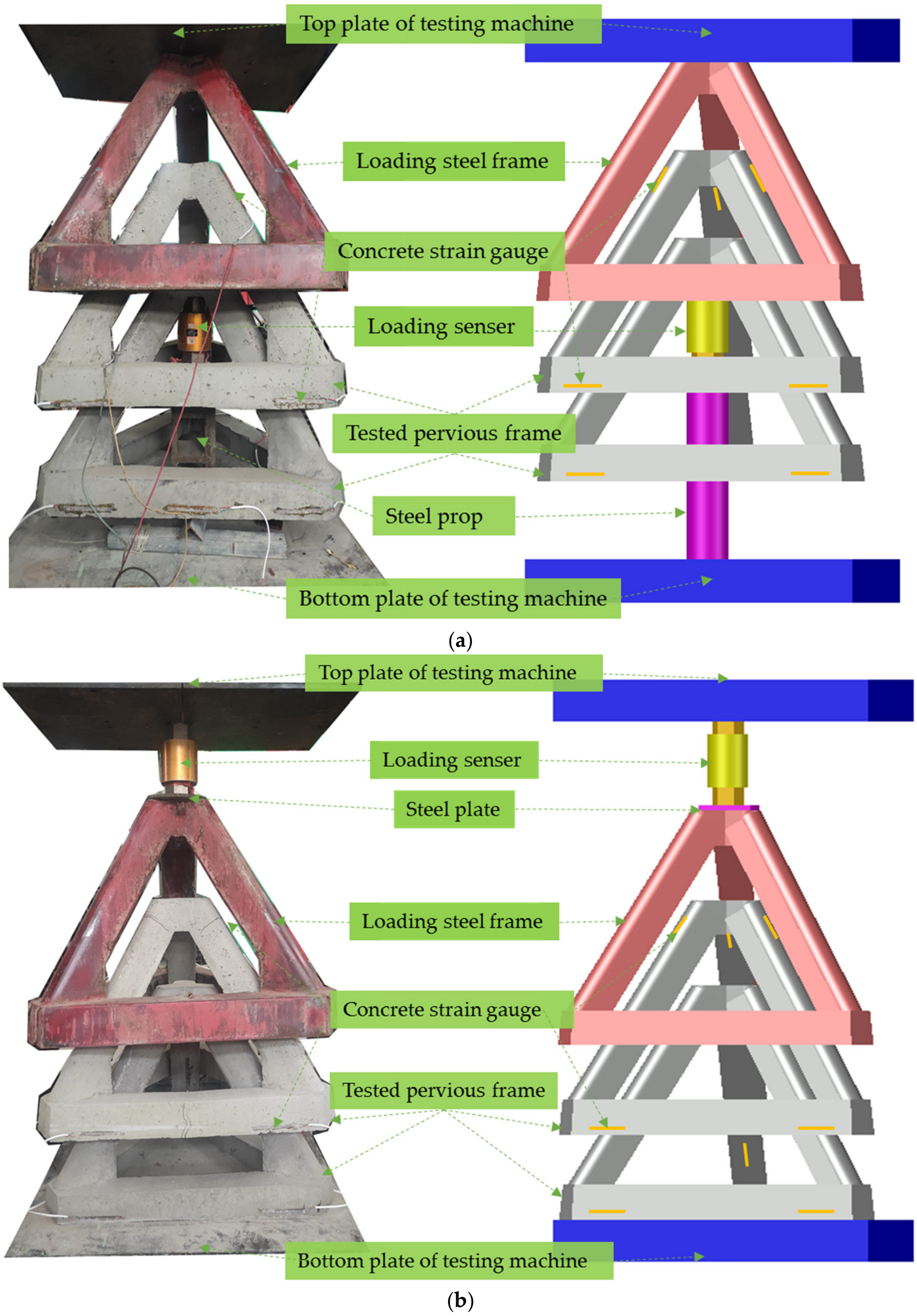



**Figure 4.** Test methods for pervious frames: (**a**) Lifting; (**b**) Stacking.

As presented in Figure 5, three sets of concrete strain gauges were bonded on the surfaces of the rods near the connections. Set1 consists of three gauges to measure the strains on the inclined rods near the top connection. Set2 consists of three gauges to measure the strain on the internal surfaces near the connections of the inclined and horizontal rods. Set3 consists of six gauges to measure the strains on the side surfaces of the horizontal rods near the connections of the inclined and horizontal rods. In addition, the limit load corresponding to the cracking resistance of the pervious frame was also determined.

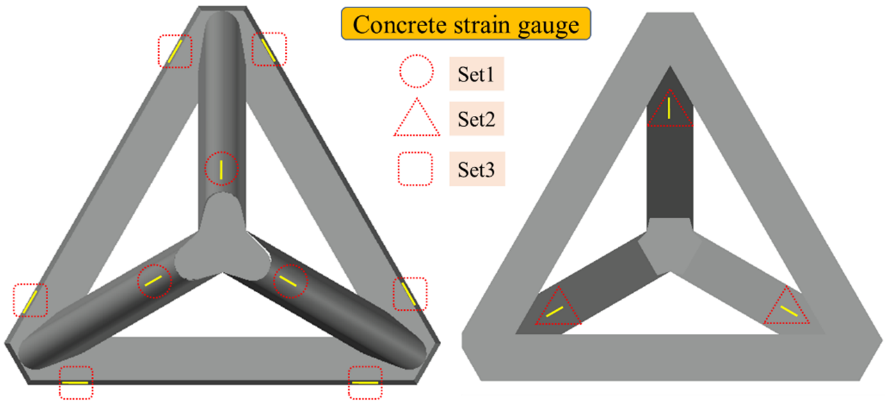



**Figure 5.** Arrangement of strain gauges bonded on surface of pervious frames.

## 3. Results and Discussion

### *3.1. Workability of Fresh Self-Compacting SFRC*

Following the China codes JG/T472 and JGJ/T283 [25,26], and the modification of the China code CECS13 for the details of test operation [10,27], the workability of fresh self-compacting SFRC was evaluated by the slump flow $D$, the flow time $T_{500}$, the J-ring flow $D_{J}$, and the static segregation test. Results are shown in Figure 6.

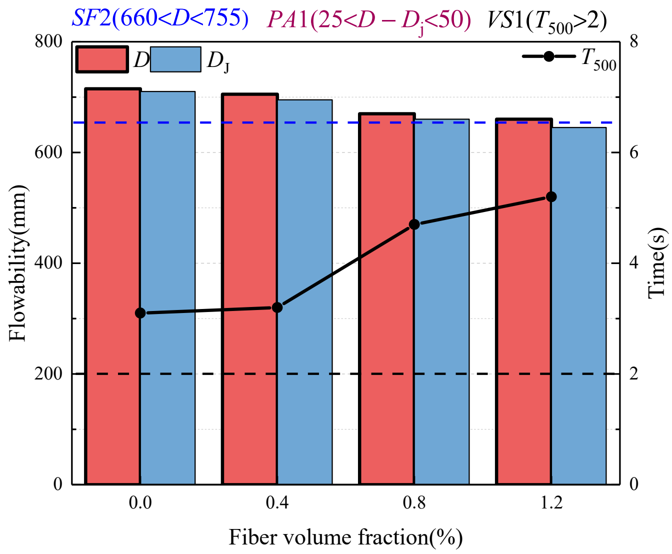



**Figure 6.** Workability of fresh self-compacting SFRC.

No segregation and bleeding occurred in the fresh self-compacting SFRC. The slump flow, the J-ring flow, and the flow time $T_{500}$ decreased with the increase of steel fiber content. This is consistent with the previous studies on the workability of self-compacting SFRC affected by the presence of steel fibers [10,16]. The flowability of the fresh mix was reduced due to the demand for binder paste wrapping the steel fibers and the linkage of steel fibers to the aggregates. With the slump flow larger than 600 mm, the difference between slump flow and J-ring flow less than 50 mm, and the flow time $T_{500}$ longer than 2 s, the fresh self-compacting SFRC had a filling ability at grade *SF*2/*VS*1 and a passing ability at grade *PA*1 [26]. Therefore, the fresh mixes met the requirement of self-compacting SFRC to be used for casting the pervious frames.

### *3.2. Mechanical Properties of Self-Compacting SFRC*

The mechanical properties of hardened self-compacting SFRC were measured by the tests in accordance with the China code JG/T472 and CECS13 [25,27]. Cubes with a dimension of 150 mm were made to determine the cubic compressive strength ($f_{fcu}$) and the splitting tensile strength ($f_{fts}$), cylinders with a 150 mm diameter and 300 mm height were made to measure the axial compressive strength ($f_{fc}$) and modulus of elasticity ($E_c$), and beams of 100 mm × 100 mm × 400 mm were made to determine the flexural strength ($f_{ff}$). Each trial had three specimens, and a total of sixty specimens were prepared. After forming in steel molds for 24 h, the specimens were demolded and placed in the standard curing room for another 27 days. Then, the specimens were taken out of the curing room to wipe up the surface moisture and tested for corresponding mechanical properties. Test results are presented in Figure 7.

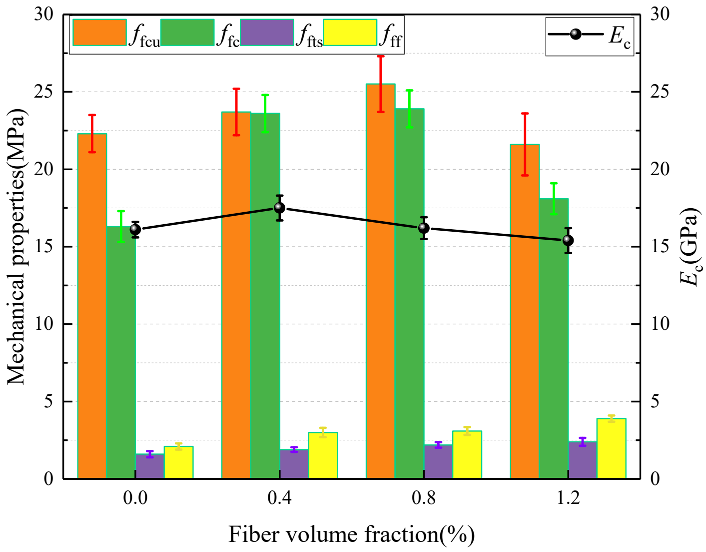


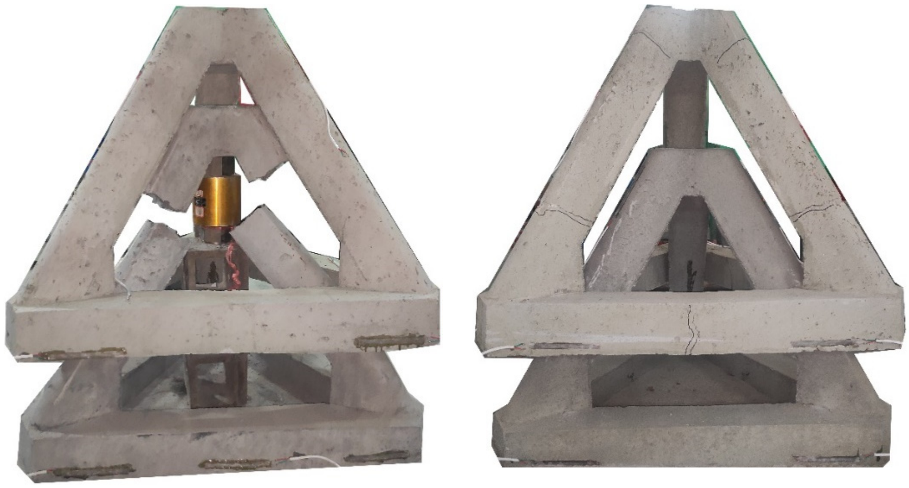

**Figure 7.** Mechanical properties of self-compacting SFRC.

Compared with self-compacting concrete SCF00 without steel fiber, as shown in Figure 7, the cube compressive strength of the self-compacting SFRC increased by 6.3% and 14.3% when the volume fraction of steel fiber was 0.4% and 0.8%, and decreased by 3.1% when the volume fraction of steel fiber was 1.2%. The axial compressive strength increased by 44.7%, 46.6% and 11.0%, respectively corresponding to the three volume fractions of steel fiber. The splitting tensile strength increased by 23.5%, 38.2%, and 51.0%, and the flexural strength increased by 42.8%, 47.6%, and 85.7%, respectively. The elastic modulus increased by 8.9% and 0.8% when the volume fraction of steel fiber was 0.4% and 0.8%, and decreased by 4.1% when the volume fraction of steel fiber was 1.2%. This once again demonstrates that the reinforcement effect of steel fiber is mainly on the mechanical properties which directly associates with the tensile performance of self-compacting SFRC [16,18,19]. Due to the trend of steel fiber orientation along the flow direction of a fresh mix, the flexural strength of self-compacting SFRC presents a higher increment with the oriented steel fibers parallel to the tensile direction at the tensile zone of beam specimens. Meanwhile, due to the confinement of steel fibers to the transversal deformation of the cylinder under axial compression, the axial compressive strength of self-compacting SFRC presented an increase with the presence of steel fibers. Relatively, less transversal deformation occurred on cubic specimens under compression, and less axial deformation of cylinders under compression was detected. This indicates a less influence of steel fiber on the cubic compression strength and the modulus of elasticity of self-compacting SFRC.

According to the test results of the self-compacting SFRC, SCF08 was selected for the production of the pervious frames. That is, the volume fraction of 0.8% is rational for self-compacting SFRC.

### *3.3. Failure Characteristics of Pervious Frames*

The statuses of the tested pervious frames after the loading tests are presented in Figure 8. In the lifting study, as shown in Figure 8a, the lower-layer frame exhibited heavier damage than the upper-layer frame. The lower-layer frame broke at the inclined rods, while the upper-layer frame basically maintained an entirety without fracture of the inclined rods. This indicates that apart from the load exerted by the testing machine on the upper-layer frame, the weights of the testing steel frame and the upper pervious frame contribute to the tensile strain leading to the fracture of the inclined rods of the lower frame. Meanwhile, the self-weight of the lower pervious frame also contributed to the tensile strain of the inclined rods, due to the hinge of the pervious frame on the steel prop. At the broken section of the inclined rods, steel fibers were stretched out of the concrete matrix. This shows a higher strength of concrete can be used to improve the bond of steel fiber to the concrete matrix to promote the usage of the steel fibers' strength [16,28].



(**a**) (**b**)

**Figure 8.** Status of pervious frames after loading test: (**a**) Broken of inclined rods in lifting test; (**b**) Cracking of rods in stacking test.

In the stacking study, as shown in Figure 8b, no breakage of rods took place on the two layers of pervious frames, although a serious cracking of the SFRC was detected on the inclined rods of the upper-layer pervious frame. Cracks appeared at the section of the inclined rods near the connections of the inclined rods to the horizontal rods, due to the load being transferred from the testing steel frame to the contact points of the pervious frame. Meanwhile, cracks also appeared at the mid-section of horizontal rods, due to the tensile strain caused by the elongation of the horizontal rods under the horizontal component of the loads on the contact points of the pervious frame. This shows that the loading condition is better during stacking due to the lower-layer frame located on the bottom plate of the testing machine.

Generally, the risk of pervious frame failure will transfer from the lower-layer during lifting to the upper-layer frame during stacking. This should be concerned during the manufacturing process and storage before engineering application.

### *3.4. Strains*

The relationship of the axial tensile strength and splitting tensile strength for SFRC can be expressed as [28,29],

$$\frac{f_{\mathrm{ft}}}{f_{\mathrm{fts}}} = 0.9(1 - 0.27\lambda_{\mathrm{f}}) \quad (1)$$

where, $f_{\mathrm{ft}}$ is the axial tensile strength of SFRC, $f_{\mathrm{fts}}$ is the splitting tensile strength of SFRC, $\lambda_{\mathrm{f}}$ is the factor of steel fiber obtained by multiplying the aspect ratio with the volume fraction of steel fiber.

With the measured splitting tensile strength of self-compacting SFRC (SCF08 group) at 2.17 MPa, the axial tensile strength is 1.78 MPa calculated by Formula (1).

In this study, the peak tensile strain $\varepsilon_{t,r}$ on the rods of the pervious frame is the limit of SFRC cracking, which can be calculated by the formula as follows [29,30],

$$\varepsilon_{t,r} = f_{ft}^{0.54} \times 65 \times 10^{-6} \tag{2}$$

By the Formulas (1) and (2), the peak tensile strain of self-compacting SFRC (SCF08 group) is 88.7 $\times$ $10^{-6}$.

Figure 9 shows that the strain on the surfaces of the rods at each measuring point of the two-layer pervious frame changed with the load in the lifting test. Set1 at the top, Set2 at the frame contact point, and Set3 at both ends of the bottom rod are shown in sequence from left to right. The strain of the first pervious frame in Set1 and Set2 increased with the increase of load and exceeded the peak tensile strain, with the corresponding load being 6.7 kN and 3.0 kN, respectively, while the strains in Set3 all exceeded the peak tensile strain. For the second-layer pervious frame, the strain increased with the increase of load, but the final three groups of measuring points did not exceed the peak tensile strain. This reflects that the cracking failure occurred in Set1 and Set2 in the first-layer frame in the lifting test, while no cracking occurred in Set3 and no cracking occurred in the second-layer frame, which is consistent with the description of the failure of inclined rods in the lifting test.

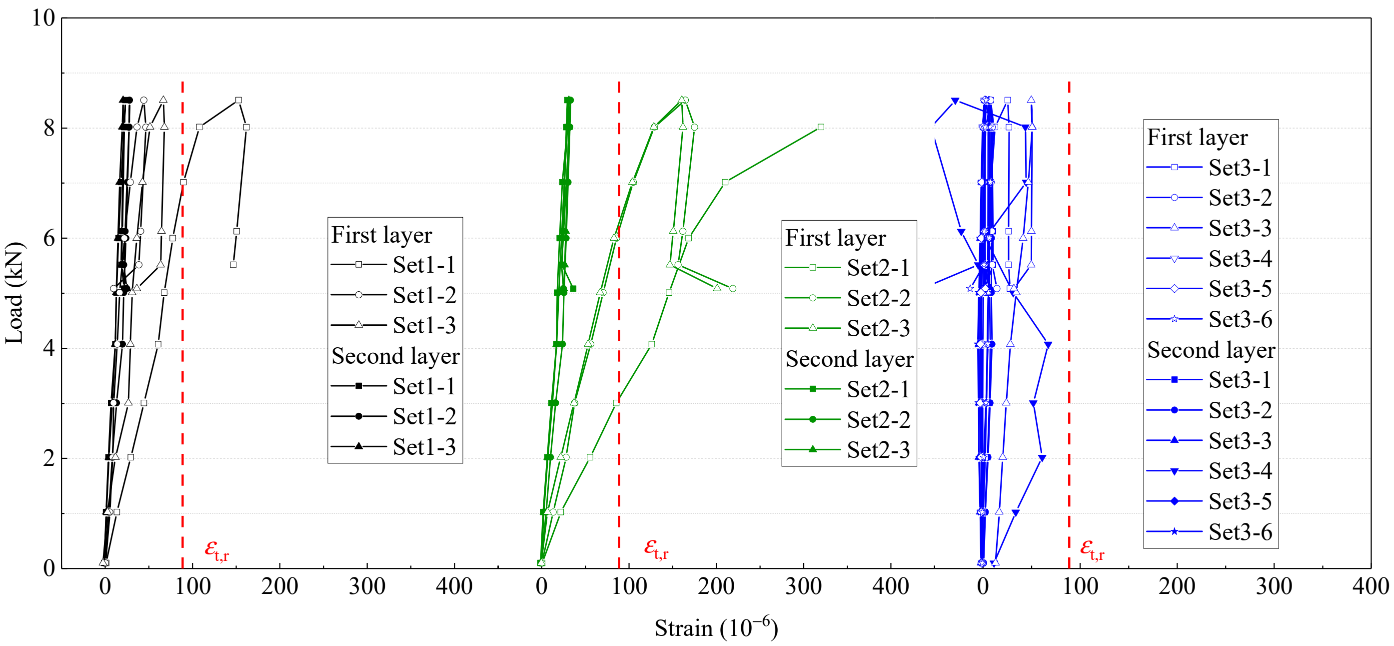



**Figure 9.** Strains on the surfaces of the rods changed with the load in the lifting test.

For the stacking load test, the strains at the three groups of measuring points of the first and second layers of the pervious frames increased with the increase of load, and finally exceeded the peak tensile strain. Before reaching the peak tensile strain, the strain growth rate from large to small was Set1, Set2, and Set3. When the strains of the three groups of measuring points of the first-layer pervious frame reached the peak tensile strain, the corresponding load was 27.5 kN, 30.0 kN, and 35.0 kN, respectively, and that of the second-layer frame was 16.5 kN, 25.0 kN, and 28.0 kN, respectively, as shown in Figure 10. The first-layer and the second-layer frames cracked with the peak tensile strain, while the second-layer frame had less loading capacity than the first-layer frame, that is, the second-layer frame cracked earlier than the first-layer frame, and was more seriously damaged than the first-layer. This is consistent with the description of the failure characteristics of the frames in the stacking test.

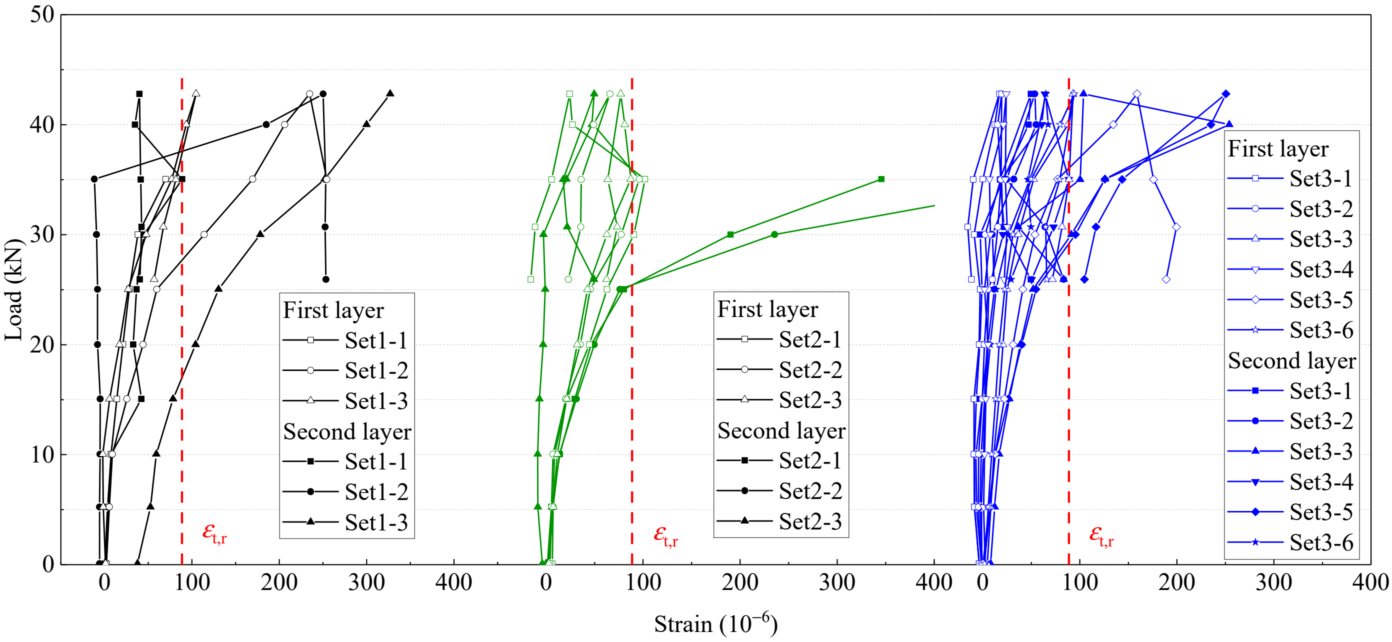



**Figure 10.** Strains on the surfaces of the rods changed with the load in the stacking test.

### 3.5. Limit Loads of Pervious Frames

The ultimate load during lifting and stacking was 8.5 kN and 42.8 kN, respectively. Considering the weights of the tested pervious frames and the loaded steel frames, 1.0 kN of a single frame and 1.2 kN of the loaded steel frame, the ultimate load during lifting and stacking should be 11.7 kN and 46 kN, respectively.

During lifting and stacking, the allowable load on the self-compacting SFRC pervious frame corresponding to the peak tensile strain at each measuring point was 6.2 kN and 19.7 kN, respectively. With the self-weight of a single frame as 1.0 kN, a maximum of six layers of pervious frames can be lifted together and a maximum of nineteen layers can be stacked. In practical engineering, three layers for lifting and six layers for stacking are needed. Therefore, the self-compacting SFRC pervious frame satisfies this requirement of application.

## 4. Engineering Application

Based on the experimental investigation and the production trial of the pervious frames in the manufacture plant, several groups of pervious frames were tested by being dropped into the river and salvaged from the river, as shown in Figure 11. After checking the status of each group of pervious frames, it was confirmed that the frames met the quality requirement of engineering application with no cracking or any other damage.

**Figure 11.** Submerged in and salvaged from the river to inspect the damage.

Finally, the pervious frames were mass-produced and then submerged in the Yangtze River waterway for the river revetment project, as shown in Figure 12. A total of 5000 self-compacting SFRC pervious frames were produced and put into the first bid section of the 6 m deep waterway revetment project. The length of the submersion channel was about 100 m, the area was about 1000 $m^2$, and the placement density was about five pervious frames per square meter.

**Figure 12.** Batch production and dropped into the river.

## 5. Conclusions

Through a series of experiments on the preparation, manufacturing and loading performance of self-compacting SFRC pervious frames, the feasibility of applying SFRC pervious frames for river revetment is finally demonstrated. The following conclusions can be drawn:

(1) The mix proportion, the workability of fresh mix, and the mechanical properties of self-compacting SFRC used for producing the pervious frames were experimentally studied with the change of the steel fiber content. The rational volume fraction of steel fiber was determined as 0.8% considering the requirement of this special application.

(2) With the good workability of self-compacting SFRC, the casting process of SFRC from an inclined rod to other inclined rods, and finally to horizontal rods leads to a conducive distribution of steel fiber along the length of the rods. This improves the mechanical properties of the pervious frame subjected to tensile forces during lifting and stacking.

(3) During lifting, the frame at the bottom layer is more likely to be damaged than that at the upper layer, which may be broken on the inclined rods. During stacking, the upper-layer frame is more prone to cracking and failure than the first-layer frame, but not including breaks in the rod. The frames allow six layers lifted together and nineteen layers stacked without any damage.

(4) The self-compacting SFRC pervious frames have been successfully applied in a river revetment project. This is a new engineering application for self-compacting SFRC.

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