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Article

Influence of Fiber Shape and Volume Content on the Performance of Reactive Powder Concrete (RPC)

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Abstract: This research studied the influence of three types of open (short-straight, long-straight, semicircular) and three different shapes of closed steel fibers (triangular, rectangular, circular) with different fiber contents by volume (0, 0.5%, 1%, 1.5%, and 2%) on the working and mechanical performance of reactive powder concrete (RPC). The results indicated that (1) the number of steel fibers and the enclosed area formed by closed steel fibers would remarkably impact the performance of RPC; (2) the semicircular fiber improves RPC's strength the most among the three open shapes; (3) the short-straight fiber works more effectively than the closed steel fibers; (4) the circular fiber works the most efficiently in improving RPC's mechanical performance while the triangular ones have the least effect among the three closed steel fibers; (5) both the closed and open steel fibers improve their compressive strength more than their flexural strength; (6) the closed steel fiber works more efficiently in improving the flexural strength but less efficiently in improving the compressive strength; (7) the open steel fibers enhance the mechanical performance of RPC via their anchoring performance while the closed steel fibers work by confining the concrete; (8) the hybrid utilization of steel fibers improves RPC's mechanical performance to a higher level via combing the advantages of open and closed steel fibers.

Keywords: steel-fiber-reinforced RPC; open steel fiber; closed steel fiber; improvement mechanism; fiber hybrid

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1. Introduction

Concrete, as one of the most widely used building materials, consumes large amounts of raw materials and generates high levels of carbon emission. Therefore, the development of concrete with high mechanical performance and superior durability is of great necessity [1]. The addition of steel fibers in reactive powder concrete (RPC) or ultra-high-performance concrete (UHPC) is a common method to improve its strength, toughness, energy absorption capacity and ductility after crack formation [2–9]. On the other hand, the adding of steel fibers may introduce a negative impact on the workability by increasing the air content of the concrete [6]. RPC or UHPC is a type of construction material made of a high content of cementitious materials and fine aggregate with a low water/binder ratio [2]. Steel fibers can not only improve the mechanical performance of RPC but can also effectively restrain the development of cracks and provide post-cracking strength and toughness, thus increasing the service life [10,11]. Al-Baghdadi et al. [12] found that the steel fiber can advance the brittleness ratio of concrete. Furthermore, Lau et al. [13] pointed out that the fatigue life of concrete can be improved by at least 135% with the addition of fibers at 0.5% volume content. Steel fibers present with varying geometrical forms, lengths, and sizes. The commonest shapes include round-straight, crimped, dumbbell, end-hooked, and twisted.

The addition of steel fiber greatly increases the properties of RPC, especially the ductility and energy dissipation [14–17]. The cracks in the concrete reinforced with steel fiber can be restrained due to the bridging effect at the crack locations [18,19]. Therefore, the residual bond strength of concrete is improved via the addition of steel fibers [16]. Furthermore, the steel fibers can restrain shear cracks and delay or even prevent shear failure [17]. Therefore, the specimens reinforced with enough steel fiber can have large deformation and large amount of energy dissipation even under a strong shear effect [18]. The specimen reinforced with steel fiber can stay intact after failure, with only few and small cracks in the concrete [14], thus greatly improving the ductility of RPC. Furthermore, the steel fibers help to dissipate energy during progressive damage, fracture, and steel fiber pullout [20]. The work of both Kravchuk et al. [20] and Landis et al. [21] found that fiber pullout dissipates much more energy than concrete matrix cracking. Based on the above literature, the addition of steel fiber in the concrete is highly beneficial in improving the seismic performance of concrete structures.

It was reported that the properties were greatly influenced by the aspect ratio [22,23], tensile strength [23], shape [24–27], and volume content [28–30] of steel fibers, and the shape and volume content are the two most frequently studied factors. Generally, the strength of RPC or UHPC improves gradually with the increase of steel fiber content [31–38]. Some research reported that the strength of UHPC improved gradually in proportional to fiber content up to 3% [39]. Wu et al. [40] found that the compressive strength was improved by 8–32% by adding 1–3% straight steel fibers into the UHPC. However, a high steel fiber fraction of over 3% may impair the properties of UHPC [41,42]. High fiber content may bring too much air into the concrete, thus reducing the workability and mechanical performance of concrete. Therefore, the maximum steel fiber content is usually 3% by taking the cost, working performance, and mechanical performance into consideration [39]. However, the maximum steel fiber content varies in different conditions. Lehner et al. [43] pointed out that the threshold of the fiber fraction is 1.4% for steel-fiber-reinforced concrete in a chloride environment as high fiber content increases the diffusion coefficient.

In addition to the volume content, previous research has found out that the shape of the steel fibers has a significant influence on the properties of the concrete [33,44–46]. Deformed steel fiber is more effective than round-straight steel fiber in terms of improving the mechanical properties of concrete [46], with a much higher pullout strength due to the bridging effect [47–49]. Previous research has concluded that the tensile strength of UHPC varies from 5% decrease [3,50] up to 40% increase [50,51] compared with that for straight fibers. Kim et al. [51] found that about 20–40% improvement in tensile strength of concrete can be obtained by using three different deformed steel fibers compared with only straight steel fibers. However, some other research has reported that deformed steel fiber can provide more than three times greater fiber–matrix bond strength than that of straight fibers [44,52]. Katzer et al. [53] used crimped steel fiber to create high-performance concrete based on a mix of waste and natural aggregates, which was proved to be practicable and efficient. Wu et al. [40] applied three different shaped steel fibers, i.e., straight, corrugate, and hooked, with volume content ranging from 0 to 3%. The results showed that the steel-fiber-reinforced UHPC presented the best performance with the hooked shape at a volume fraction of 2%. However, Zhang et al. [26] found a different result. In the work of Zhang et al., the corrugated steel fiber had the best reinforced effect on the strength of concrete. Therefore, there is still a debate on the influence of steel fiber shape on the concrete.

In addition to fiber content and fiber shape, Wu et al. [44] pointed out that the hybrid use of two types of deformed fibers is more effective compared to the utilization of only straight fibers. Meng and Khayat [47] suggested that a hybrid combination of steel fibers is more effective in improving UHPC's strength than increasing the fiber content. The combination of longer and hooked-end fibers is the most common hybrid combination of steel fibers [47,54]. The steel fiber hybrid can not only be created with fibers of different shapes but also with those of different types, lengths, and aspect ratios. Therefore, there are many possible schemes for fiber hybrids. Though many studies have approved that the fiber hybrid is a favorable method to improve the mechanical performance of concrete, controversial debates still exist, and other researchers demonstrated that hybrid steel fibers might lower the strength of UHPC [55,56].

So far, all the research was carried out on the open steel fibers, such as the straight, crimped, hooked, etc. The authors proposed a new type of steel fiber, i.e., the closed steel fiber, which is a potential fiber that can be applied in RPC and UHPC. However, the authors have searched and found that there is still a lack of study on the performance of RPC with closed steel fibers. The shape of closed steel fibers is totally different from that of the existing fibers, and the ring of closed steel fibers affects the workability and performance of RPC via not only confining but also friction. Therefore, the closed steel fiber may produce a different improvement in the RPC. The existing research does not provide references for the closed steel fibers. In order to realize the properties of RPC reinforced with closed steel fibers, experiments on this topic should be carried out. The objective of this research is to investigate the effects of three different shaped closed steel fibers (circular, triangular, and rectangular) with different fiber contents (0, 0.5%, 1%, 1.5%, and 2%) on the working and mechanical performance of RPC. The improvement mechanism of closed steel fiber was also developed. Furthermore, the properties of RPC reinforced with three different shaped open steel fibers (short-straight, long-straight, and semicircular) with different fiber contents (0, 1%, 1.5%, and 2%) were compared.

2. Theoretical Hypothesis

According to the literature review, the fiber content, geometrical difference (shape, length, and aspect ratio), distribution, and orientation of steel fibers has a significant influence on the mechanical properties of concrete. The more distorted and twisted the shape of the steel fibers, the more remarkable the enhancement of strength and crack suppression on concrete. In the literature review, the research was carried out mainly on the open and straight steel fiber, and great improvement was found. Therefore, the authors propose that if the straight steel fiber was replaced with closed steel fiber, a much greater improvement in the performance of RPC will be realized. In this study, a hypothesis that the increase of the closure degree of steel fiber improves the restrain effect of steel fibers on concrete was proposed, as shown in Figure 1. When the shape of the steel fibers is closed, then the concrete enclosed by the steel ring will play an essential role in the RPC's mechanical performance. Research on concrete filled in a steel tube reported that the performance of the concrete was enhanced remarkably [57,58]. The effect of rectangular and triangular fibers was also studied to compare with the circular ones in this research.

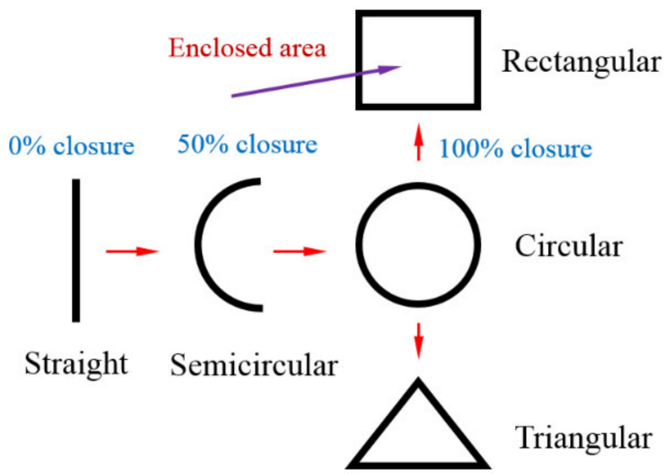


Figure 1. Hypothesis of steel fibers from open to closed.

As aforementioned, the concrete enclosed by the closed steel fiber affects the performance of concrete. As presented in Figure 1, the concrete enclosed by rectangular steel fiber and circular steel fiber is 1.71 and 1.69 times of the concrete enclosed by triangular steel fiber. Therefore, it can be confirmed that the influence of triangular steel fiber on the RPC will be obviously smaller than that of the rectangular and circular steel fibers.

Figure 2 shows the improvement mechanism on the mechanical performance of concrete with different shapes of steel fibers. The figure clearly illustrates that the straight steel fiber restrains the development of cracks of RPC mainly through friction. The steel fiber can be easily pulled out under low tensile force. When the steel fiber is bent into a semicircular shape, the arc fiber not only produces friction with the concrete when it is pulled out but also produces an extrusion effect on the concrete. Therefore, the combined action of friction and extrusion produces a greater pullout force. When the steel fiber is totally closed, the circular steel fibers will provide more significant extrusion and restriction. The concrete enclosed by the closed steel fiber will present a higher performance. Therefore, the mechanical performance of RPC will be improved remarkably. To prove this hypothesis, experimental tests on RPC reinforced with different shaped steel fibers with different volume contents were carried out.

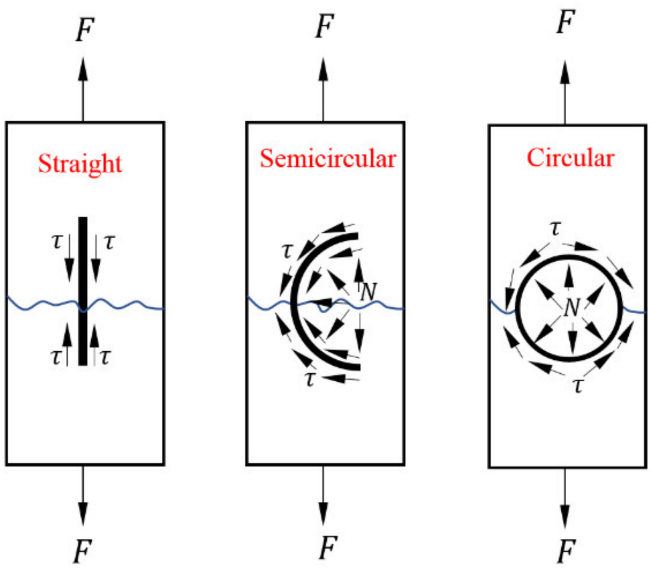


Figure 2. Working mechanism of open and closed steel fiber–reinforced RPC.

3. Experimental Verification

3.1. Raw Materials

Portland Cement P.O 42.5R was selected for the test, grade I fly ash was used, and a silica fume with a diameter of 1.3 μm was applied. The main chemical compositions of the cement, fly ash, and silica fume are listed in Table 1. River sand with a particle size of 0.6–1.18 mm was used as the fine aggregate. A polycarboxylate superplasticizer (SP) with a solid content of 15% was used as the water reducer. All the materials are shown in Figure 3.

Table 1. Chemical composition of cement, silica fume, and fly ash (%).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
Cement	21.83	3.59	6.3	57.8	2.61	0.84	0.23
Silica fume	92.18	0.23	0.09	0.99	1.83	0.31	0.05
Fly ash	46.44	38.01	3.12	7.5	0.23	0.88	0.33

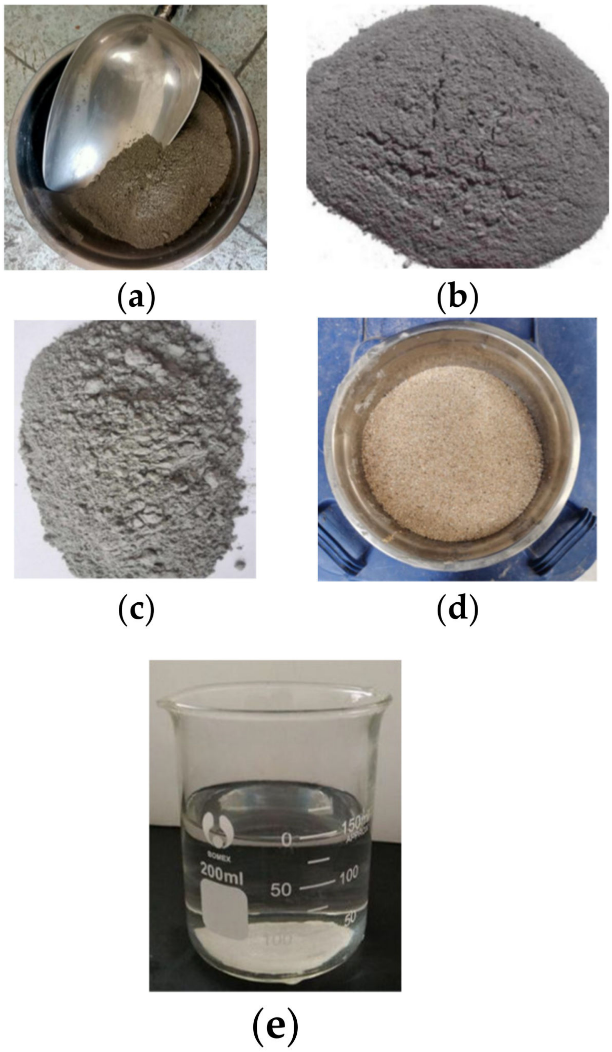


Figure 3. Materials: (**a**) cement; (**b**) silica fume; (**c**) fly ash; (**d**) sand; (**e**) SP.

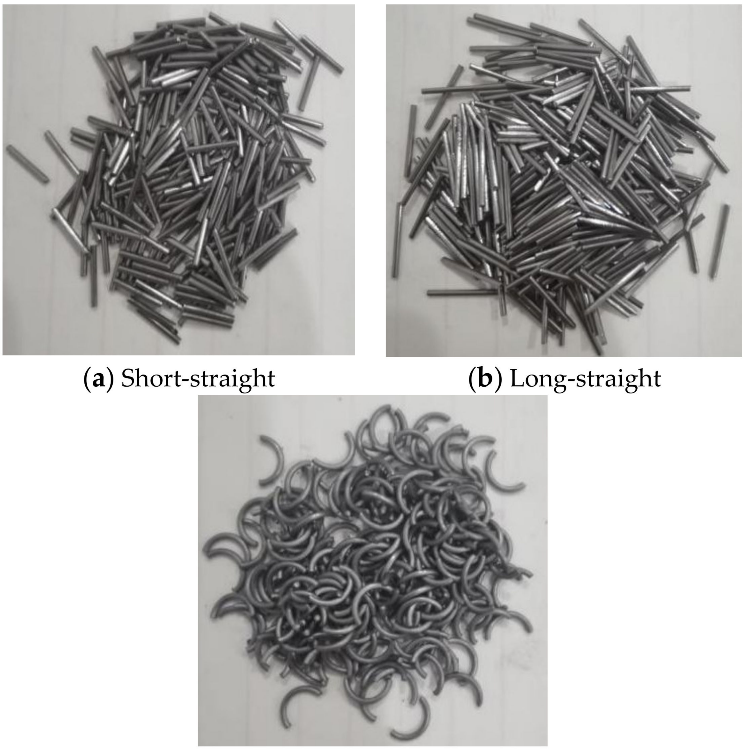
3.2. Steel Fiber

Two groups of steel fibers were studied in this research, and each group contains three different shapes. The open steel fibers included short-straight, long-straight, and semicircular fibers, which are displayed in Figure 4. The closed steel fibers included circular, triangular, and rectangular ones, which are shown in Figure 5. All steel fibers were made of 304 stainless steel with a density of 7.93 g/cm^3. The tensile strength of steel fibers is greater than 1025 MPa. The detailed parameters of each type of steel fibers are summarized in Table 2. It should be noted that the number before the letters represents the volume content, and the capital letters represent the shape of the steel fiber.

Table 2. The detailed parameters of each type of steel fiber.

	Short-Straight	**Long-Straight**	**Semicircular**	**Circular**	**Triangular**	**Rectangular**
Length (mm)	10	15	15	31.4	30	40
Diameter (mm)	1.2	1.2	1.2	1.2	1.2	1.2

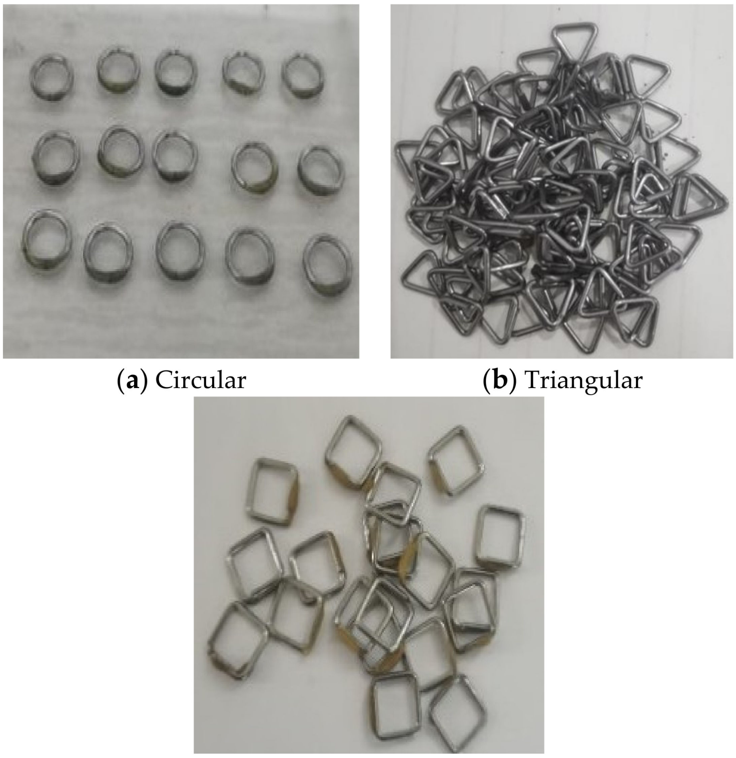
To study the influence of the steel fiber shape on RPC, the total number of steel fibers and the enclosed area formed by closed steel fibers in each specimen were calculated and are listed in Table 3.



(**a**) Short-straight (**b**) Long-straight

(**c**) Semicircular

Figure 4. The shapes of open steel fiber.



(**a**) Circular (**b**) Triangular

(**c**) Rectangular

Figure 5. The shapes of closed steel fiber.

Table 3. The number of steel fibers and the closed area in each specimen.

Specimen	The Shape of Steel Fiber	Volume Content (%)	Number	Enclosed Area (mm^2)
Control	No steel fiber	0.0	0	0
1.0% SS	Short-straight	1.0.	680	0
1.5% SS		1.5	1020	0
2.0% SS		2.0	1360	0
1.0% LS	Long-straight	1.0	455	0
1.5% LS		1.5	680	0
2.0% LS		2.0	910	0
1.0% SC1	Semicircular	1.0	455	0
1.5% SC		1.5	680	0
2.0% SC		2.0	910	0
0.5% CC	Circular	0.5	107	8400
1.0% CC		1.0	215	16,878
1.5% CC		1.5	325	25,513
2.0% CC		2.0	432	33,912
0.5% TA	Triangular	0.5	115	4980
1.0% TA		1.0	230	9959
1.5% TA		1.5	345	14,939
2.0% TA		2.0	460	19,918
0.5% RT	Rectangular	0.5	85	8500
1.0% RT		1.0	170	17,000
1.5% RT		1.5	255	25,500
2.0% RT		2.0	340	34,000
1.0% CC + 0.5% SS	Circular + short-straight	1.0 + 0.5	215 + 340	16,878
0.5% CC + 1.0% SS	Circular + short-straight	0.5 + 1.0	105 + 170	8243

3.3. Preparation of RPC

The material mix ratio used in this research is shown in Table 4. It should be noted that the mass of cementitious material was the sum of the mass of cement, silica fume, and fly ash, and the total water added into the sample included the water from SP. The water–binder ratio was 0.21, and the solid content of SP was 15%.

Table 4. Mixing proportion of RPC (kg/m^3).

Cement	Silica Fume	Fly Ash	Sand	Water	SP
553	166	111	1245	132	50

The cement, silica fume, and fly ash were weighed first and then poured into the mixer together. After mixing for 2 min, the river sand was evenly poured into the mixer, and mixing was continued for 2 min. During this period, the weighed water and SP were mixed and stirred, then slowly poured into the dry materials within 30 s. The mixer was then changed to the fast mixing mode and continued mixing for 3 min. Steel fibers were added into the mixer within 30 s after the concrete slurry showed a plastic flow state, and mixing continued for 1 min. When the RPC mixtures were ready to cast, the slurry was poured into a 40 mm × 40 mm × 160 mm mold and vibrated for 1 min. The specimens with molds were kept in a room at 20 °C and covered with plastic sheets for 24 h. After that, specimens were demolded and cured in 90 °C hot water for 7 d.

3.4. Test Methods

3.4.1. Test of Fluidity

The fluidity was determined according to the Chinese code "Test method for the fluidity of cement mortar" [59]. The mixtures were cast into the cone mold, and then the mold was lifted vertically. The jolting table was started to jump 25 times, then the average diameter of the RPC slurry paved on the table was measured.

3.4.2. Pullout Bond Test

The pullout bond test was carried out on an eight-shaped mold with a length of 78 mm and 22.5 mm × 22.2 mm in the midsection, which is displayed in Figure 6. The mold was cleaned first and then oil was evenly applied on the surface of the mold. A cardboard of 0.5 mm thickness was placed at the minimum section of the mold. Oil was also applied on both sides of the cardboard to avoid adhesion. Then the fibers must be placed in the cardboard before the casting. The casting should be carried out carefully in order to keep the fibers in the original position. The specimens were moved to a standard curing box and demolded after 24 h. After that, the specimens were moved to a steaming environment with 90 °C for 72 h. The pullout test of the specimens was then carried out by a microcomputer-controlled universal testing machine provided by WANCE. Five specimens were tested for each group.

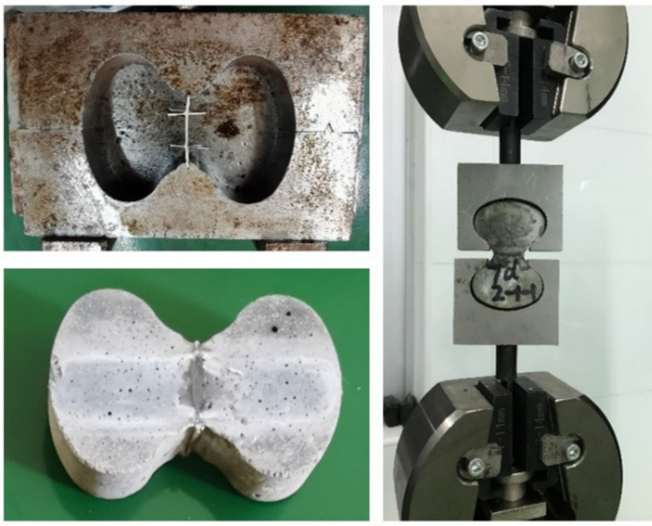
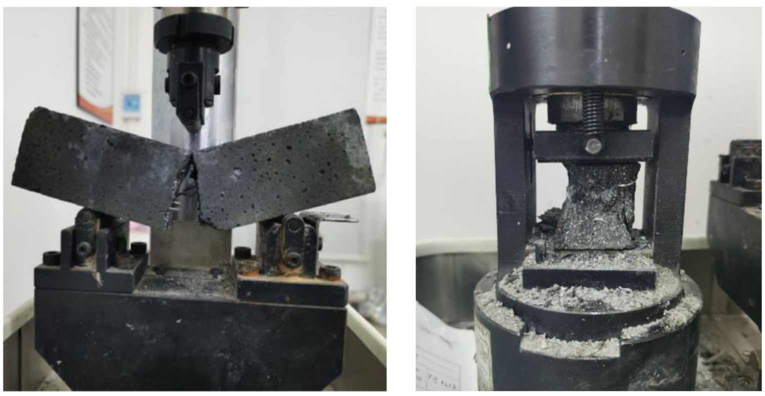


Figure 6. Eight-shaped mold and test method for pullout bond test.

3.4.3. Test of Flexural Strength

The flexural strength of steel-fiber-reinforced RPC was determined according to the Chinese code "Method of testing cements—Determination of strength" [60], which was carried out on prism specimens of 40 mm × 40 mm × 160 mm, with three specimens in each group, and the average value of three specimens was taken as the flexural strength of RPC. The loading speed of 50 N/s was applied. The test device is shown in Figure 7a.



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

Figure 7. Strength test: (**a**) flexural strength test; (**b**) compressive strength test.

3.4.4. Test of Compressive Strength

The compressive strength test of steel-fiber-reinforced RPC was carried out on the broken prism specimens after the flexural strength test. The test was conducted based on the Chinese code "Method of testing cements—Determination of strength" [60]. The broken prism was placed in the test device shown in Figure 7b. When placing the half prism, the center of the test specimen must be aligned with the compression center of the press plate. The loading speed of the compressive test was 2.4 kN/s until failure. Each group contained six specimens, and the average compressive strength of the six specimens was taken as the final result. If there was a specimen whose compressive strength difference surpassed the average value by 10%, then this specimen was excluded, and the average value of the rest five specimens was taken as the final result.

4. Experimental Results and Analysis

4.1. The Influence of Closed Steel Fiber on RPC's Fluidity

Figure 8 shows the variation curves of the fluidity of triangular, circular, and rectangular steel fiber–reinforced RPC at different volume contents. The curves show that the increase of steel fiber content decreases the fluidity, and the shape of the fiber has a different influence on the fluidity of the RPC. In detail, the figure demonstrates that the circular steel fiber affects the fluidity to the greatest extent, followed by the rectangular fiber while the triangular fiber affects it least at the same volume content of steel fiber. According to Table 3, the number of steel fibers and the enclosed area formed by steel fibers is different under the same volume content. Therefore, it is assumed that the internal reason that influences the fluidity is the number of steel fibers and the enclosed area formed by steel fibers in the RPC. The steel fibers distributed in the matrix acted as a skeleton and prevented the flow of concrete [2]. Therefore, a greater number of steel fibers provides more friction effect between fibers and the concrete slurry.

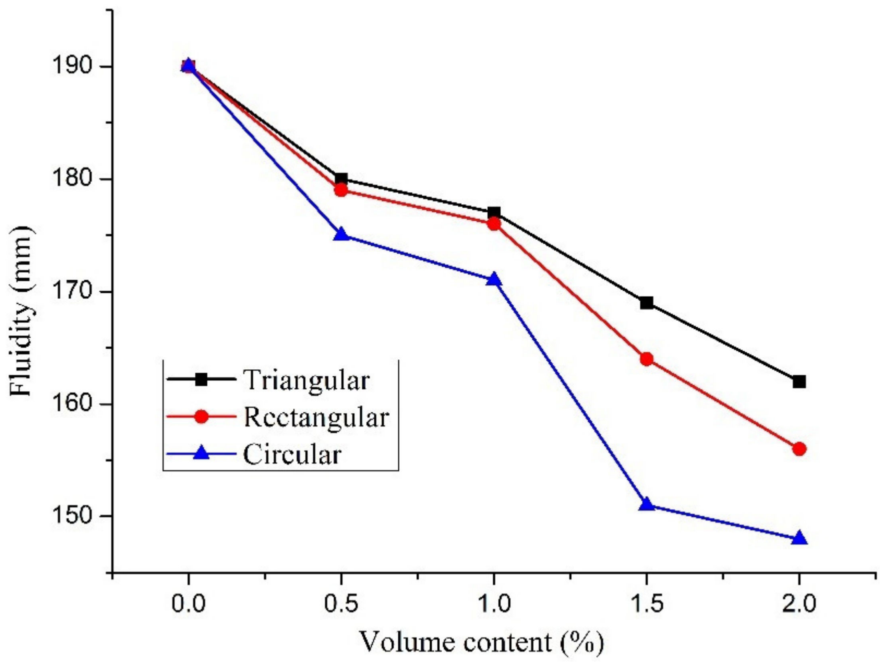


Figure 8. Influence curves of closed steel fiber content on the flowability.

Moreover, the concrete enclosed inside of the steel ring cannot flow freely, thus reducing the fluidity of the RPC. Under the same volume content, take 2% for example, the numbers of steel fibers poured into the specimens were 430, 460, and 340 for circular, triangular, and rectangular, respectively, while the enclosed area formed by the closed fiber is 33,900 mm^2, 20,000 mm^2 and 34,000 mm^2, respectively. It can be concluded that the enclosed area formed by steel fiber dominates the fluidity as a greater enclosed area decreases the fluidity more, which is the reason why the fluidity of the RPC reinforced with triangular steel fibers was the greatest. However, if the enclosed area formed by the steel fiber is similar, then the number of steel fibers will affect the fluidity. The number of circular fibers is greater than that of the rectangular fibers, which can cause circular fibers to form a more compact fiber skeleton, resulting in worse fluidity.

4.2. The Influence of Steel Fiber's Shape on the Bond Strength

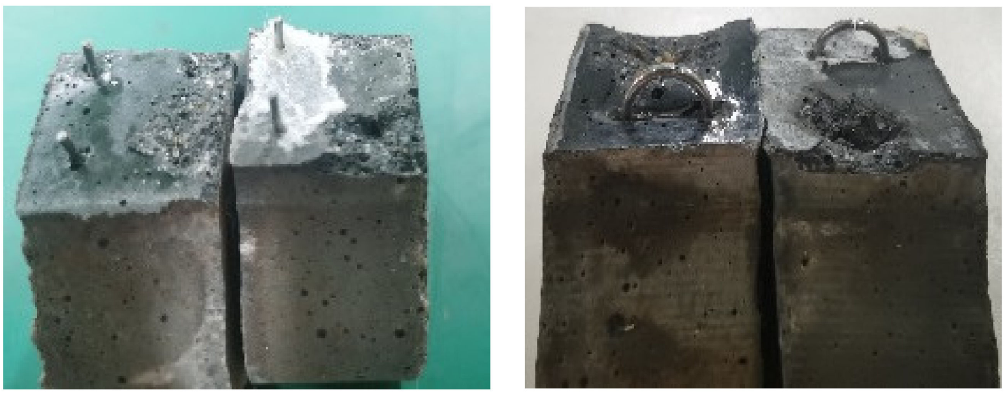
The pullout test force of each specimen is listed in Table 5. According to the table, the closed steel fiber provides greater bond strength than the open type in terms of a single steel fiber. Among the three types of open steel fibers, the long-straight fiber provides the greatest bond force. The reason is that the longer the fiber, the greater the friction produced between the steel fiber and the concrete. In terms of shapes of closed steel fibers, the rectangular steel fiber provides the largest pullout force. The reason is that the concrete enclosed by the rectangular shape is the most, which helps to confine more concrete.

Table 5. Pullout test results.

Specimen	Pullout Force per Fiber (kN)	Standard Error (kN)	Length (mm)	Pullout Force per mm (N/mm)
SS	0.149	0.0093	10	14.9
LS	0.187	0.0056	15	12.5
SC	0.157	0.0044	15	10.5
CC	0.276	0.0137	31.4	8.8
RT	0.403	0.0204	40	10.1
TA	0.249	0.0171	30	8.3

However, if the length or volume of each fiber is taken into consideration, the test results leads to a different conclusion. The table shows that the pullout force per mm of the RPC reinforced with the short-straight fiber was the largest among the three types of open steel fibers. For the closed steel fibers, the pullout force per mm of the RPC reinforced with rectangular fiber was the greatest, while the triangular one was the smallest.

Though Table 5 shows that the bond strength provided by the closed steel fibers was smaller compared with that of the open steel fibers, the closed steel fiber still provided a better anchorage and restriction in RPC. Figure 9a displays that the straight steel fibers were directly pulled out while Figure 9b shows that the concrete around the anchorage end was cracked and pulled out, which means the closed steel fibers provide a better anchorage performance in RPC.



(**a**) Straight steel fiber (**b**) Circular steel fiber

Figure 9. Failure mode of pullout test.

4.3. The Influence of Steel Fiber's Shape on the Flexural Strength of RPC

4.3.1. Influence of Open Steel Fiber on RPC's Flexural Strength

Figure 10 shows the influence of open steel fiber on RPC's flexural strength. It can be seen from the figure that all three different shapes of steel fiber improved the flexural strength of PRC, and the greater the volume content, the higher was the flexural strength. The steel fiber helps to delay the formation and propagation of cracks, thus improving the flexural strength of RPC [61]. At low volume content, the long-straight fiber improves RPC's flexural strength more than the short-straight fiber. However, when the volume content was increased to 2%, the flexural strength of RPC improves 20.1% and 17.5% for short-straight and long-straight, respectively, which indicates that the short-straight fibers start to work more efficiently at a high volume of content. Fibers with a smaller geometry provide a greater number of steel fibers than those with large geometry at the same volume content. The greater number of smaller fibers forms a denser skeleton in the RPC, which controls the development of microcracks more efficiently [49]. Furthermore, the semicircular steel fiber works the most efficiently in improving RPC's flexural strength at any content.

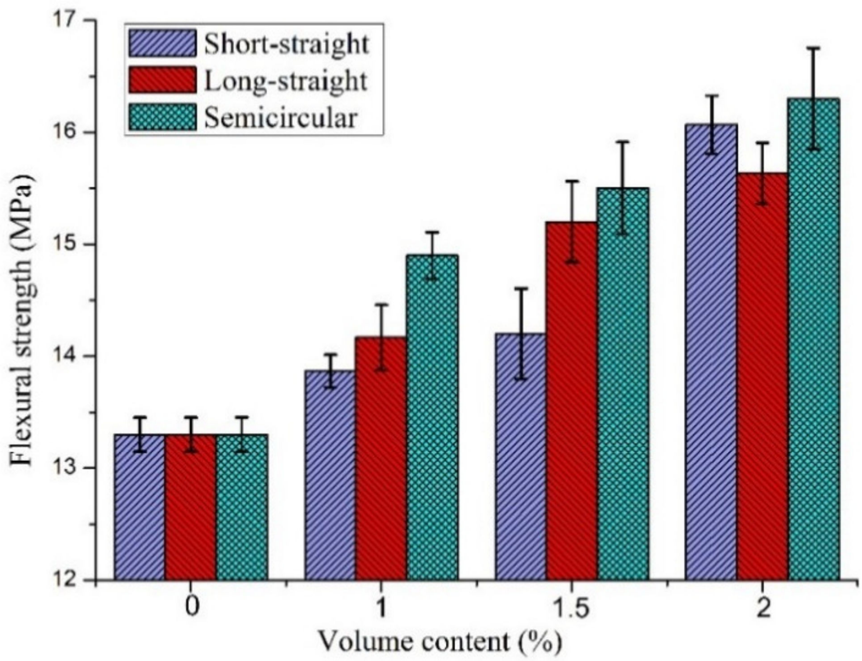


Figure 10. Influence of open steel fiber's volume content on RPC's flexural strength.

By analyzing the fracture surface morphology, the short-straight steel fiber and long-straight fiber used in this research both demonstrate similar failure modes on the failure surface, as shown in Figure 11a, i.e., the steel fiber presents a common pullout failure. In some cases, the fracture surface will be destroyed and spalled along the contact surface between the steel fiber and the concrete. Similarly, the failure of RPC with semicircular steel fibers presents similar failure modes, as displayed in Figure 11b. However, it can be seen that some of the semicircular steel fibers remain in the fracture surface, which provides confining and protection to the concrete enclosed by the fibers. Therefore, RPC reinforced with semicircular steel fibers shows a greater flexural strength.

In conclusion, the semicircular steel fiber enhances the bond between fibers and RPC through friction, mechanical interaction, and extrusion, while the straight fibers improve RPC's performance only through friction.

(**a**) Short-straight (**b**) Semicircular

Figure 11. Failure modes of RPC with open steel fiber.

4.3.2. Influence of Closed Steel Fiber

The relationship between the three types of closed steel fiber at different volume content and the RPC's flexural strength is demonstrated in Figure 12. The flexural strength of all RPC specimens with different shapes of closed steel fiber improved gradually with the increase of fiber content, and the circular shape worked the most efficiently among the three types of shape. At the volume content of 2.0%, the flexural strength of concrete with triangular, rectangular, and circular steel fibers reached the maximum value, which is 20.6%, 23.2%, and 30.6% higher than that of the control group without steel fiber. Based on the aforementioned hypothesis that the enclosed area formed by steel fibers is positively related to the mechanical performance of the RPC, similar to the conclusion made in analyzing the fluidity, the enclosed area formed by triangular fibers was the least, which results in the slightest improvement. The enclosed area and number of steel fibers in RPC with circular steel fibers were the greatest, which helps to form a more uniform and compact skeleton in RPC, thus leading to the maximum flexural strength.

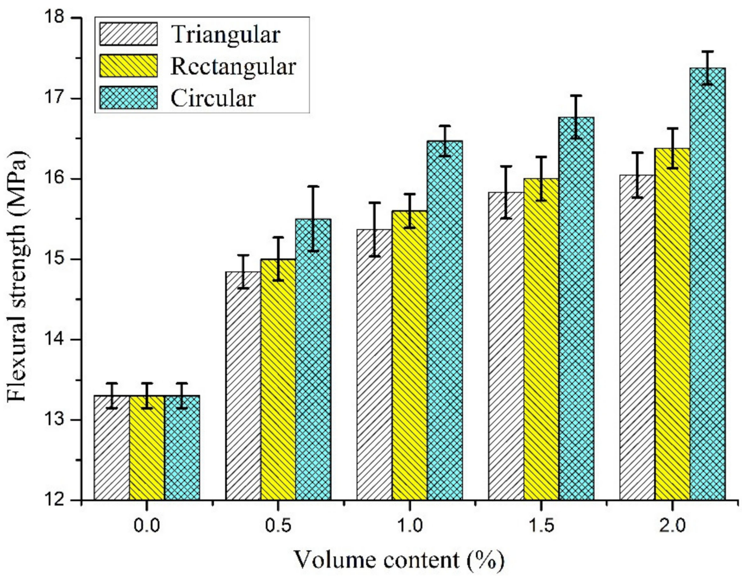


Figure 12. Flexural strength of RPC with different volume contents of steel fiber.

Furthermore, the distribution of steel fibers on the fracture surface also influences the flexural strength. Figure 13 shows that the failure of rectangular steel fiber–reinforced RPC on the fracture surface is along the contact surface between steel fibers and concrete. The concrete in the annular area is well protected. On the contrary, the contact surface between the steel fiber and the concrete becomes the weak zone to develop cracks. Therefore, the failure mode of RPC with closed steel fibers is characterized by the occurrence of cracks along the steel ring.

Figure 13. Failure mode on the fracture surface of RPC with closed steel fibers.

4.4. The Influence of Steel Fiber's Shape on the Compressive Strength of RPC

4.4.1. Influence of Open Fiber on RPC's Compressive Strength

Figure 14 displays the influence lines of open steel fibers on RPC's compressive strength. The figure shows that the RPC's compressive strength improves gradually with the increase of volume content, and the short-straight fiber works the most efficiently. At the volume content of 2%, the compressive strength of RPC with short-straight, long-straight, and semicircular reaches 138.1 MPa, 131.8 MPa, and 132.8 MPa, respectively, which is 48.1%, 41.0%, and 42.1% higher than that of the control specimen without steel fiber. The open steel fibers randomly distributed in the concrete improve the compressive strength of the RPC by restraining the formation and propagation of cracks [62]. As the RPC reinforced with short-straight steel fibers contains more fibers, the steel fiber skeleton is denser. However, when the number of long-straight and semicircular steel fiber is the same, the semicircular steel fiber provides more friction and extrusion than the long-straight steel fiber, thus slightly increasing the compressive strength of the RPC.

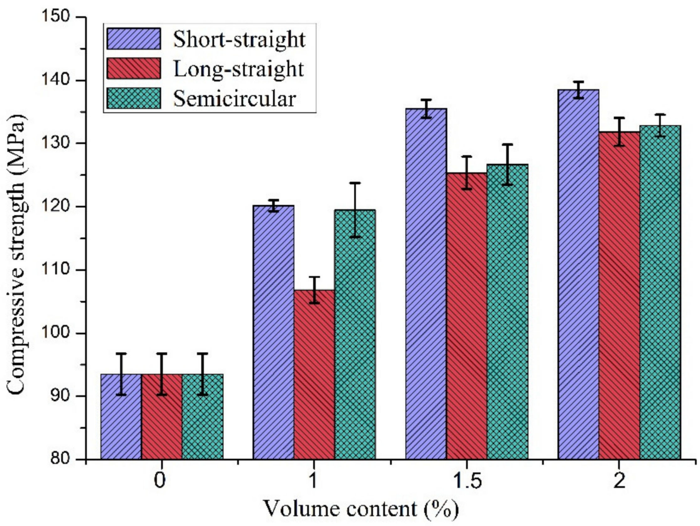


Figure 14. The compressive strength of RPC under open steel fiber volume content.

4.4.2. The Influence of Closed Steel Fiber

Figure 15 shows the comparison of the compressive strength of closed steel fiber–reinforced concrete at different volume content. It can be seen from the figure that the circular steel fiber has the best effect in improving the compressive strength of concrete, followed by rectangular fibers, and triangular fibers had the least effect. The result shows that the compressive strength of steel-fiber-reinforced RPC is highly related to the enclosed area formed by steel fibers. The greater the enclosed area formed by the closed steel fibers, the higher the compressive strength of the RPC.

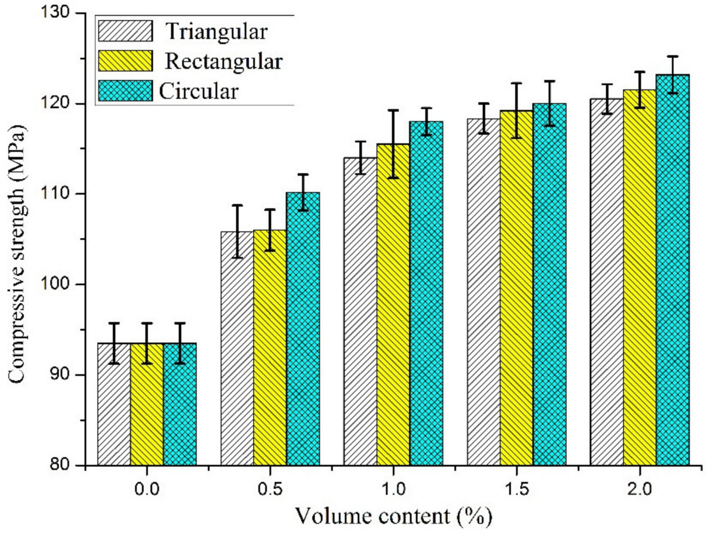


Figure 15. RPC's compressive strength under different volumes.

4.5. Comparison of Closed and Open Steel Fiber

The improvement degree of closed and open steel fiber with different volume contents on the compressive and flexural strength of RPC is listed in Table 6. It can be seen from the table that the flexural and compressive strength of RPC improves with the increase of fiber content both for the closed and open steel fibers. However, all the closed and open steel fibers improved the compressive strength of RPC more remarkably than they did the flexural strength. In terms of the improvement on flexural strength, the closed steel fiber works more efficiently. Furthermore, the circular steel fiber works the most efficiently among the three types of closed steel fibers. However, regarding the compressive strength improvement, the open steel fiber works more efficiently instead, and the short-straight steel fiber works the most efficiently among the three types of open steel fibers.

Table 6. Improvement degree of the compressive and flexural strength of RPC.

	Volume Content (%)	**Open**			**Closed**		
		SS	**LS**	**SC**	**TA**	**RT**	**CC**
Flexural strength improvement (%)	1	4.26	6.52	12.03	15.54	11.28	23.81
	1.5	6.77	14.29	16.54	19.01	18.04	26.06
	2	20.80	17.54	22.56	20.63	23.15	30.64
Compressive strength improvement (%)	1	28.52	14.26	27.81	21.93	16.04	26.20
	1.5	44.92	34.05	35.47	26.56	24.60	28.34
	2	48.13	40.99	42.07	28.88	24.96	31.73

Furthermore, Figures 11 and 13 compare the failure mode of RPC reinforced with open and closed steel fibers. It can be seen from Figure 11 that the failure mode of RPC reinforced with open steel fiber is mainly characterized by the pulling out of steel fiber, which means the open steel fibers provide friction during the pulling out, thus suppressing the propagation of cracks. Though Figure 13 shows that the failure mode of RPC reinforced with closed steel fiber is also characterized by the pulling out of the steel fiber, the concrete enclosed by the steel fiber was well protected and spalled from the concrete prism, which indicates that the closed steel fiber not only provides friction during the pulling out but also provides a constraint for the concrete.

5. The Utilization of Hybrid Fibers of Open and Closed Steel Fiber

Rambo et al. [38] found that the fiber hybridization of straight and hooked steel fibers can effectively limit the initiation and propagation of microcracks. In this research, the short-straight steel fiber can improve the strength of RPC by its support and crack resistance in the concrete matrix, and the closed steel fiber can improve the concrete strength by the protection of the closed section. Table 6 shows that the closed and open steel fibers work differently at improving the compressive and flexural strength of RPC. In addition, Figure 16 displays that the short-straight steel fiber uses its anchoring performance to connect the concrete enclosed by the circular steel fibers, thus improving the total performance of RPC. At the same time, the concrete enclosed by the circular steel fiber can also provide more stable support and anchorage for the short-straight steel fiber–reinforced RPC. Therefore, the compressive and flexural strength of the RPC can be improved by making full use of the advantages of straight and circular steel fibers, which is verified in Figure 17. The figure shows that the flexural and compressive strength of the RPC is greater when using hybrid fibers rather than when using only a single type of fiber. The figure also shows that the hybrid utilization of 0.5% short-straight fibers and 1% circular fibers works better than the hybrid application of 1% short-straight fibers and 0.5% circular fibers.

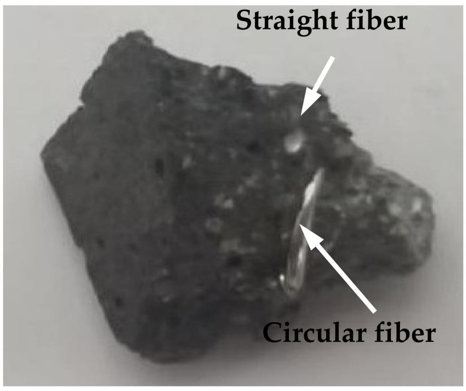


Figure 16. Working mechanism of hybrid steel fibers.

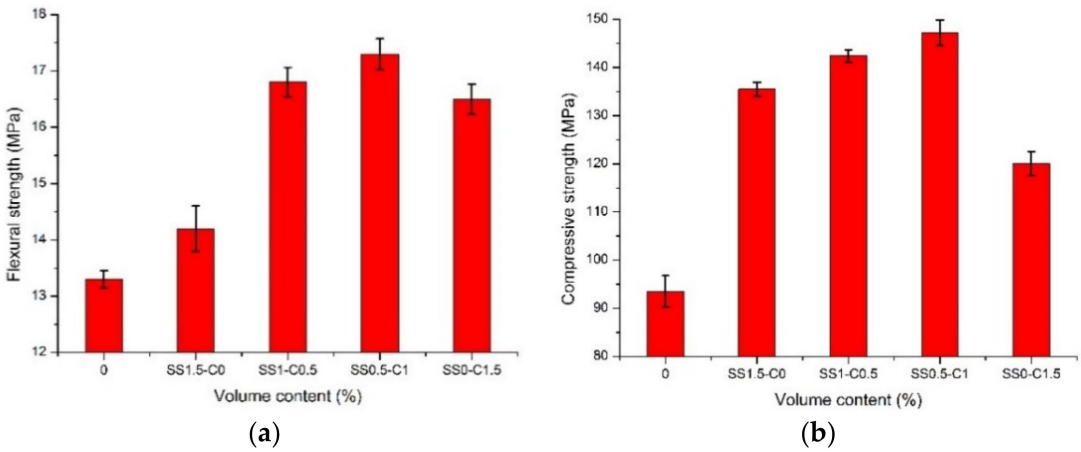


Figure 17. The mechanical performance improvement of RPC by use of hybrid steel fibers.

The working mechanism of RPC reinforced with hybrid steel fibers is illustrated in Figure 18. The circular steel fiber protects the concrete enclosed by the steel ring while the straight steel fiber connects the concrete protected by the circular steel fiber, thus forming a dumbbell shape. The dumbbell works like a huge hooked steel fiber, which has been proved effectively in enhancing the flexural and compressive strength of concrete [47]. The failure mode of the dumbbell shape can be proved by Figure 16. The circular steel fiber constrains the concrete and forms the dumbbell end, while the straight fiber works as the middle part of the dumbbell. Compared with the failure patterns of only the single steel fiber shown in Figure 18, the hybrid fibers provide more bridging effect. As displayed in Figure 19, the single type of steel fibers only protects and restrain the cracks around the fiber.

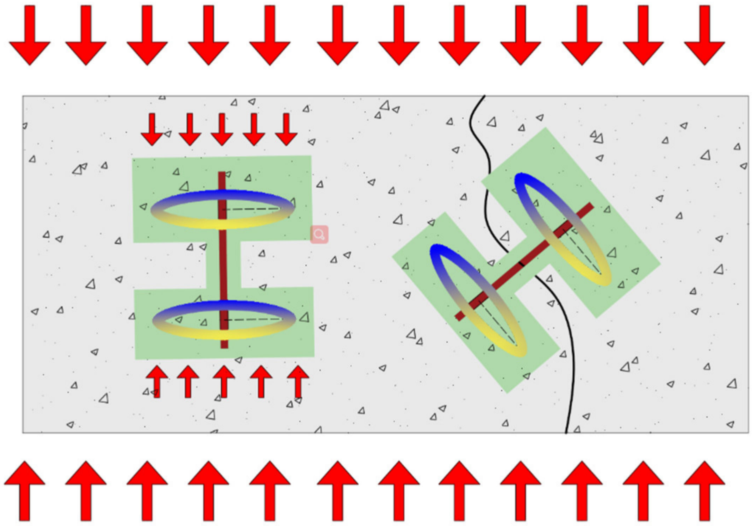
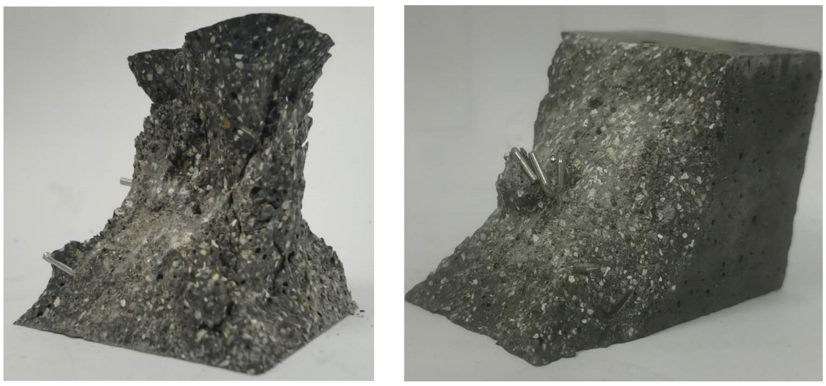


Figure 18. Mechanism of hybrid steel fiber–reinforced RPC.



(**a**) Straight fiber (**b**) Closed fiber

Figure 19. Failure pattern of steel-fiber-reinforced RPC.

6. Conclusions

In this study, an experimental investigation on the geometrical shape of steel fibers, including three different open and three different closed steel fibers, was carried out in terms of fluidity, flexural strength, pullout strength, and compressive strength. The conclusions are summarized below:

(1) The results show that the geometrical difference and the enclosed area formed by closed fibers have a significant influence on the fluidity, flexural strength, and compressive strength of RPC. The fluidity of triangular steel fiber–reinforced RPC is the best, followed by that of the rectangular fibers, and then the circular ones. However, the shape of the circular

fibers works the most efficiently at improving the flexural and compressive strength of RPC. The smaller the enclosed area formed by the closed steel fiber, the better the fluidity while the worse the mechanical performance.

(2) Among the three types of open steel fibers, the short-straight steel fiber works the most efficiently in improving the compressive strength of RPC while the semicircular steel fiber works more efficiently in improving the flexural strength of RPC.

(3) Under the same volume content, the compressive strength or RPC is improved more than its flexural strength.

(4) At the same volume content of steel fibers, the open steel fibers work more effectively than the closed steel fibers at improving the compressive strength of RPC while the closed steel fibers are good at enhancing the flexural strength of RPC.

(5) The open steel fibers enhance the mechanical performance of RPC via its anchoring performance as a result of friction, while the closed steel fibers work both by confining the RPC and providing friction to improve its strength.

(6) The hybrid of steel fibers improves RPC's mechanical performance to a higher level, and the compressive and flexural strength of RPC with 0.5% short-straight and 1.0% circular steel fiber reached 147.2 and 17.3 MPa, respectively.

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