Hindawi
Advances in Civil Engineering
Volume 2024, Article ID 6616375, 14 pages
https://doi.org/10.1155/2024/6616375

Research Article

Effect of Steel Fiber Type and Curing Regimen on the Mechanical Properties of Reactive Powder Concrete

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Received 21 November 2023; Revised 16 December 2023; Accepted 9 January 2024; Published 30 January 2024

Academic Editor: Afaq Ahmad

Reactive powder concrete (RPC) can provide enhanced mechanical properties and durability compared to conventional concrete. RPC has been developed in this study using locally available materials. Six types of steel fibers and three curing regimens were considered to examine their effect on the mechanical properties of RPC. Steel fibers were incorporated by 1% and 2% of the total volume of mixtures. Generally, the experimental results showed that 1% steel fibers enhanced the compressive, flexural, and splitting tensile strengths by 23.6%, 65.1%, and 72.7%, respectively, compared to control mixtures (no fibers). On the other hand, the 2% of fibers improved the compressive, flexural, and tensile strengths by 39.2 %, 155.0%, and 191.7%, respectively. The curing regimen, which consisted of 2 days at 60°C and 3 days at 90°C, followed by 21 days of moist curing at 21°C, indicated the ultimate enhancement of the mechanical properties of RPC. Also, hooked fibers appeared to enhance flexural strength and tensile strength compared to other types of fibers.

1. Introduction

There is a great tendency to develop concrete materials with desirable engineering properties such as compressive strength, elastic modulus, and durability. Due to the increasing demand for building materials with exceptional mechanical properties and enhanced durability, there was a need to develop high-performance concrete. Therefore, reactive powder concrete (RPC) has been introduced to satisfy such enhanced properties.

Typically, RPC is a cement composite with a high amount of cementitious materials: ordinary Portland cement, silica fume, and other supplementary cementitious materials. Ultra-fine sand (150–600 μm) and superplasticizer are normally used with RPC; superplasticizer is necessary with RPC since the water/binder ratio is extremely low ~0.2 [1–3]. The low water/binder ratio is essential to achieve the required compressive strength (approximately $\leq$120 MPa). Steel fibers are usually used with RPC to increase the ductility of the concrete since the composite is very brittle. A ratio of 2%–3% by fraction volume is typically used to avoid the sudden failure of the concrete [4]. The matrix of RPC is very dense due to the use of a high amount of supplementary cementitious materials and ultra-fine sand, and accordingly, the packing density of the matrix is high; this is responsible for the high strength and durability of RPC [5–7]. Most of the developed RPCs in the literature did not contain any coarse aggregate since the interfacial transition zone between the binder matrix and the coarse aggregate is the weakest phase of the concrete microstructure. Based on what is stated in the literature, the following recommendations are listed to develop RPC with enhanced mechanical properties [8, 9].

(i) Excluding the coarse aggregate to develop a homogenous matrix and minimize the effect of the interfacial transition zone.
(ii) Adding steel fibers to increase the ductility of the matrix.
(iii) Ultra-fine sand is used to increase the packing density of the matrix.
(iv) Using superplasticizers to overcome the low water/binder ratio and achieve the desired workability and strength.

(v) Using a heat or steam curing regimen to achieve high early strength.

(vi) Using a high amount of supplementary cementitious materials, especially silica fume. Silica fume reacts with calcium hydroxide from cement hydration to form a new calcium silicate hydrate, which is responsible for the strength.

In short, constituent materials should be thoroughly chosen, and advanced technical procedures should be used to obtain the required mechanical properties.

A number of studies have examined the effect of steel fibers and different curing regimens on the mechanical properties of RPC. Al-Hassani et al. [10] investigated the properties of RPC containing different types of steel fibers and silica fume. They found that increasing the silica fume content from 0% to 30% had little effect on tensile strength, while there was a significant increase in compressive strength. It was also observed that the use of fibers significantly increased the tensile strength, while the improvement in tensile strength was very little. Also, the increase in steel fiber and silica fume improved the load–deflection curve. Marzoq and Borhan [11] were able to manufacture RPC using locally available materials, and the results showed that RPC concrete could be achieved with compressive strength, modulus of rupture, and splitting tensile strength of 111, 15.29, and 13.326 MPa, respectively. These results were attained using ambient temperature and standard moist curing conditions. Sarika and Elson [12] presented an experimental study on the properties of RPC. The results showed that it is possible to obtain concrete with a compressive strength of up to 130 MPa at 28 days of age under standard curing conditions, and 70% of the total strength was gained at the age of 7 days.

Cwirzen [13] investigated the effect of the curing regimen on the properties of the RPC. Nine methods of curing were examined. The results indicated that the long periods (28 days) of heat curing increased the heat of hydration, enhanced the microstructure of the concrete, and consequently increased the compressive strength. On the other hand, curing too late or too early after casting results in decreased hydration and a less long-term improvement in compressive strength. Abd el Raheem et al. [14] studied the properties of RPC with different ratios of water/binder, silica fume, and steel fiber. They found that changing the content of silica fume from 30% to 35% decreased the strength by 11.6%. Also, they stated that using a water/binder ratio of 0.19 yielded the highest compressive strength compared to water/binder ratios of 0.17 and 0.21. Also, increased steel fiber from 0% to 1%, 2%, and 3% led to an improvement in compressive strength by 20%, 26%, and 41%, respectively. Jing et al. [15] conducted a study on different factors that affect RPC made of locally available materials. They indicated that the highest strength is achieved using 30% and 25% replacement of silica fume and slag, respectively, of the total binder content. Also, the optimal ratio of sand to binder was 1.4. When the volume of steel fibers was 1%–3%, the compressive strength of the samples increased with the increase of the water/binder ratio by a certain amount, and then it began to decrease gradually. It was found that the optimal water/binder ratio was 0.2, which showed outstanding mechanical properties.

Gamal et al. [16] studied the properties of RPC using economical and locally available materials. The study found that developing RPC with a compressive strength of 121 MPa was feasible at 28 days of age under standard curing conditions: water at a temperature of 25°C. This result was achieved using 25% silica fume of the total binder content, 2% steel fibers by the total volume, and a water/binder ratio of 0.25. It was also stated that the strength improves with an increase in the temperature of the curing, reaching 149.1 MPa at a temperature of 90°C for 24 hr of curing. Xikang and Jiapeng [17] examined the effect of temperature and steel fiber type on strength. The study found that the strength increased as the curing temperature increased; the highest compressive was obtained at a temperature of 90°C. The researchers also concluded that the use of thin steel fibers in the RPC leads to an improvement in mechanical properties more than coarse steel fibers. Saloma et al. [18] studied the properties of RPC using different curing temperatures: 27, 60, 90, and 120°C. It was found that the optimal treatment was 90°C; the achieved compressive strength, tensile strength, flexural strength, and modulus of elasticity were 111.43, 6.19, 10.82, and 51,400 MPa, respectively. Ola et al. [19] studied the effect of the different curing regimens on compressive strength. It was concluded that the treatment method affects the strength considerably; autoclave curing showed better performance compared to the stream curing regimen, especially for the mixtures that contained lower cement. Mingyang and Wenzhong [20] cast 58 RPC mixtures with different mixture proportions and examined the effect on compressive strength. They found the use of fly ash and nano-silica enhanced the compressive strength, and the percentage of silica foam ranges from 0.15% to 0.3%. Chkheiwer and Kadim [21] studied the effect of silica fume ratio, steel fiber percentage, curing, and sand gradation on the properties of RPC made with locally available materials. It was found that the optimum percentage of silica fume was 25% of the total weight of the binder. They also found that using sand with a maximum size of 0.3 mm increased the strength by 39% compared to the mixtures that contained natural gradation sand. The heat curing, which consisted of 2 days at 60°C, followed by 3 days at 80°C, achieved the highest compressive strength. Also, increasing the steel fibers to a ratio greater than 1.5% led to changing the concrete into ultra-high-performance concrete (UHPC), and therefore, the impact of the steel fibers was significant on the mechanical properties. Abdulamir and Hussein [22] investigated the effect of heat curing and steel fiber content on the mechanical properties of RPC. It was found that it is possible to obtain concrete with a strength of 119 MPa at 7 days of age when using 7 days of continuous heat curing at 60°C. It was found that increasing the steel fibers from (2% to 2.4%) by volume increased the compressive strength by 34.4% and also increased the splitting and flexural strength by 60% and 33.8%, respectively. They also stated that RPC with silica fume needed more time (91 days) to achieve the same strength as RPC, which did not contain any silica fume.

Table 1: Chemical properties of cement.

Components	Contents (%)	Limits of ASTM C150-04 [24]
CaO	63.71	—
SiO_2	20.3	—
Al_2O_3	5.01	—
Fe_2O_3	4.2	—
MgO	2.11	6.0 (max)
SO_3	2.23	—
Loss on ignition (LOI)	2.19	3.0 (max)
Na_2O	0.26	—
K_2O	0.54	—
Insoluble residue	0.49	0.75 (max)
Potential compounds		
C3S	53.8	—
C2S	18.1	—
C3A	2.61	3.0 (max)
C4AF	12.8	25.0 (max)

Table 2: Physical properties of cement.

Physical properties	Test result	Limits of ASTM C150-04 [24]
Specific surface area (Blaine method) (m^2/kg)	305	Not less than 280
Setting time (Vicat method) (min)		
Initial setting time	145	More than 45
Final setting time	285	Less than 375
Compressive strength (MPa)		
3 days	16.8	More than 12
7 days	24.8	More than 19
Specific gravity (g/cm^3)	3.15	—
Color	Light gray	—

Sultan et al. [23] used 8 mm crushed dolomite with 2 mm quartz sand to produce RPC. The obtained results were compared with the RPC values containing aggregate with a maximum size of 0.6 mm. It has been found that the use of crushed dolomite improves the mechanical properties of RPC, modifies the mixing process, facilitates homogenization of the mixture, and reduces the mixing time. The results also showed that it is possible to obtain RPC from locally available materials with compressive strength, splitting strength, and flexural strength of 134.3, 11.95, and 27.75 MPa, respectively.

2. Experimental Work

2.1. Materials. In this study, the binder content consists of ordinary Portland cement (Type I), Mabrouka type, which is produced locally in Iraq. The physical and chemical properties of cement are shown in Tables 1 and 2, which meet the requirements of ASTM C150 [24], and densified microsilica (silica fume), which fills the voids in the RPC mixture due to its small size. It also adds additional binders to the mixture as a result of its interaction with the mixture; the physical and chemical properties of silica foam are shown in Table 3, which meets the requirements of ASTM C1240 [25].

The fine aggregate used in this study is sand grains that are available locally in the Safwan area in the Basra Governorate, with a specific gravity of 2.65 and a sulfate content of 0.2%; the sulfate content of the sand conforms to the requirements of the Iraqi Standard Specification No. 45/1984 [26]. The natural gradation is sieved to obtain ultra-fine sand. Particles that passed through a No. 30 sieve (600 μm) and particles retained in a No. 100 sieve (150 μm) were used (Figure 1). The sieve analysis of sand particles is shown in Figure 2.

The steel fibers in the RPC matrix improve the properties of concrete, and according to previous research [8, 14, 15, 19], it has been shown that the optimal percentage ranges between 1% and 3% of the mixture volume to design an economical and practical mixture, and that increasing the percentage to more than 3% becomes the mixture uneconomical and not workable.

Six types of steel fibers were used in this study, as shown in Figure 3; they were incorporated by 0%, 1%, and 2% of the total volume of the mixture. The properties of steel fibers are

Table 3: Chemical and physical properties of silica fume.

Item	Description	Limits of ASTM C1240-20 [25]
Chemical		
CaO	0.26%	—
SiO_2	96.2%	85 (min)
Al_2O_3	0.61%	—
Fe_2O_3	0.59%	—
MgO	0.43%	—
SO_3	0.23%	—
Loss on ignition (LOI)	1.84%	6.0 (max)
Na_2O	—	—
K_2O	0.21%	—
Physical		
Percent retained on 45 μm sieve (no. 325)	4.5%	10 (max)
Density (specific gravity)	2.25	—
Bulk density	695 kg/m^3	—
Specific surface area	18.5 m^2/g	15 (min)
Accelerated pozzolanic activity index with Portland cement at 7 days, percent of control	115%	105 (min)
Color	Dark gray	—

Figure 1: Sieves of fine sand.

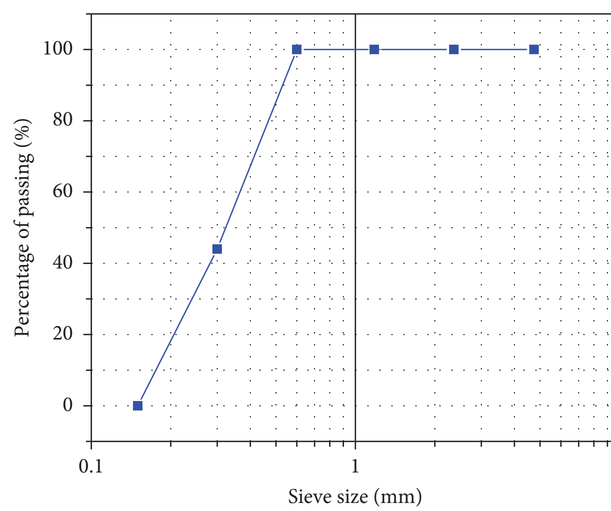


Figure 2: Gradation of the sands used.

summarized in Table 4. The superplasticizer used in this study is Sika ViscoCrete F180G, which is used at a ratio of (500–1,000) g/100 kg of the total weight of the binder per the recommendation of the manufacturer. Superplasticizer complies with ASTM C494/C494M-19 [27] specifications.

2.2. Testing Program. To investigate the mechanical properties of RPC (compressive strength, splitting tensile strength, and flexural strength), 13 mixtures of locally available RPC were developed. The mixture proportions are summarized in Table 5. Three curing regimens were used to cure the concrete. Curing regimen I consisted of curing the concrete at 100% relative humidity for 3 days at 90°C followed by 2 days at 60°C. Curing regimen II consisted of curing the concrete at 100% relative humidity for 3 days at 90°C followed by 2 days at 60°C and then curing the concrete for 23 days in water at 20°C. Finally, curing regimen III, which is standard curing for 28 days at 20°C, is shown in Figure 4. The current work relied on the mixed ratios that were suggested from previous research [28–32] for the purpose of achieving a compressive strength greater than 100 MPa underwater treatment conditions. All mixtures have the same binder content (1,132 kg/m^3), silica fume %, *w/b*, and fine aggregate content. The variables studied are the types of fiber, its content %, and curing methods.

RPC-1 is considered the control mixture as it does not contain any steel fibers. Steel fibers are incorporated at three percentages: 0%, 1%, and 2%. A small lab shear mixer (20-quart pan mixer) was used to mix the RPC mixtures; shear

Figure 3: Represents the types of steel fibers.

Table 4: Properties of steel fibers.

Steel fiber type	Symbol	Shape	Length (mm)	Aspect ratio (L/D)	Tensile strength (MPa)
Microfiber with copper-coated	S12.5	Straight	12.5	50	2,850
Crimped fibers	C30	Waved	30	55	≥700
Hooked fibers I	H60	Hooked ends and straight middle	60	80	≥1,000
Hooked fibers II	H50	Hooked ends and straight middle	50	55	≥1,000
Hooked fibers III	H30	Hooked ends and straight middle	30	60	≥1,000
Glued hooked fibers	H35	Hooked ends and straight middle	35	64	1,650

Table 5: Mixture proportions.

Mixture	Total binder (kg/m^3)	Silica fume (%)	w/b[1]	Fine sand (kg/m^3)	Steel fiber type	Steel fiber (%)	S.P. (kg/m^3)
RPC-1	1,132	20	0.14	906	—	0	45.3
RPC-2	1,132	20	0.14	906	S 12.5	1	45.3
RPC-3	1,132	20	0.14	906	S 12.5	2	45.3
RPC-4	1,132	20	0.14	906	C30	1	45.3
RPC-5	1,132	20	0.14	906	C30	2	45.3
RPC-6	1,132	20	0.14	906	H 60	1	45.3
RPC-7	1,132	20	0.14	906	H 60	2	45.3
RPC-8	1,132	20	0.14	906	H 50	1	45.3
RPC-9	1,132	20	0.14	906	H 50	2	45.3
RPC-10	1,132	20	0.14	906	H 30	1	45.3
RPC-11	1,132	20	0.14	906	H 30	2	45.3
RPC-12	1,132	20	0.14	906	H 35	1	45.3
RPC-13	1,132	20	0.14	906	H 35	2	45.3

[1] w/b does not account for the water in the superplasticizers.

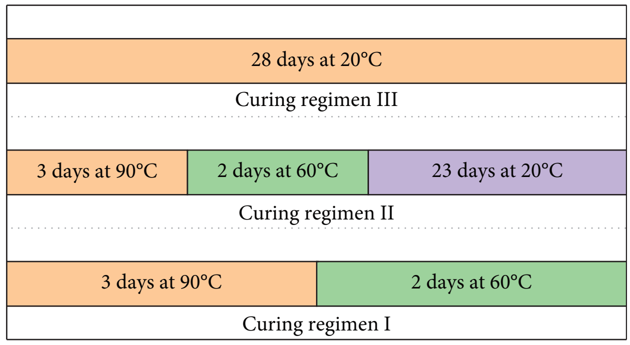


Figure 4: Represents the curing regimen time and its temperature.

Figure 5: Mixing procedure and casting of RPC.

mixers are necessary to overcome the low water/binder ratio and minimize the time to mix the RPC. All the dry materials were mixed first, and then approximately 75% of the water (water plus superplasticizer) was added and mixed for 5 min. The remaining water was added gradually and mixed for another 5 min. After obtaining a homogeneous mixture, the steel fibers were added and mixed for 5 min; the total mixing time was approximately 15 min. To evaluate the compressive strength of the concrete, nine cubes (100 x 100 x 100) mm were cast, and the cubes were tested according to BS EN 122390 -03 [33] specifications, with three cubes for each curing regimen. Six prisms were cast (350 x 100 x 100) mm to evaluate the flexural strength (modulus of rupture); flexural strength was tested according to ASTM C293 [34] specifications. Six cylinders (100 m diameter and 200 mm height) were used to evaluate the splitting tensile strength; splitting strength was tested according to ASTM C496 [35] specifications. The molds were covered with polyethylene sheets for 48 hr after casting to prevent moisture loss. Then, the samples were kept and cured until the day of testing. Figure 5 shows the mixture procedures and molds used in this experiment.

3. Results and Discussions

Compressive, splitting tensile, and flexural strength were conducted to evaluate the effect of steel fiber type, ratio, and curing regimen on the properties of RPC.

3.1. Compressive Strength. The results of the compressive strength are summarized in Table 6. Each compressive strength value presented in the table is an average of three samples. Figures 6(a) and 6(b) demonstrate the effect of six types of steel fibers on the compressive strength of RPC, which were added by 1% and 2% of the volume of mixtures, respectively. For a given curing regimen, RPC-2 showed the highest compressive strength compared to other mixtures; RPC-2 included steel fibers type of S 12.5. For mixtures with 1% of steel fibers, RPC-2 showed an average increase in strength (for all curing) of 6.3%, 3.6%, 8.3%, 12.2%, and 15.3% compared to RPC-4, RPC-6, RPC-8, RPC-10, and RPC-12, respectively. On the other hand, all mixtures containing 1% steel fibers were examined and gave higher compressive strength compared to RPC-1, which did not include any type of steel fibers; this is because steel fibers reduce brittleness and increase the ductility of concrete. The enhancement in strength is also

Table 6: Compressive strength results.

Mixture	Compressive strength (MPa)		
	Curing I	Curing II	Curing III
RPC-1	74.8	81.1	52.1
RPC-2	98.5	102.3	75.2
RPC-3	115.7	121.2	94.6
RPC-4	94.1	96.2	69.3
RPC-5	105.2	107.8	83.2
RPC-6	95.8	98.5	72.2
RPC-7	106.5	108.9	87.7
RPC-8	92.1	94.9	67.9
RPC-9	101.1	105.9	80.2
RPC-10	87.1	93.5	65.4
RPC-11	94.6	96.8	71.2
RPC-12	84.2	91.8	63.4
RPC-13	92.2	94.8	69.2

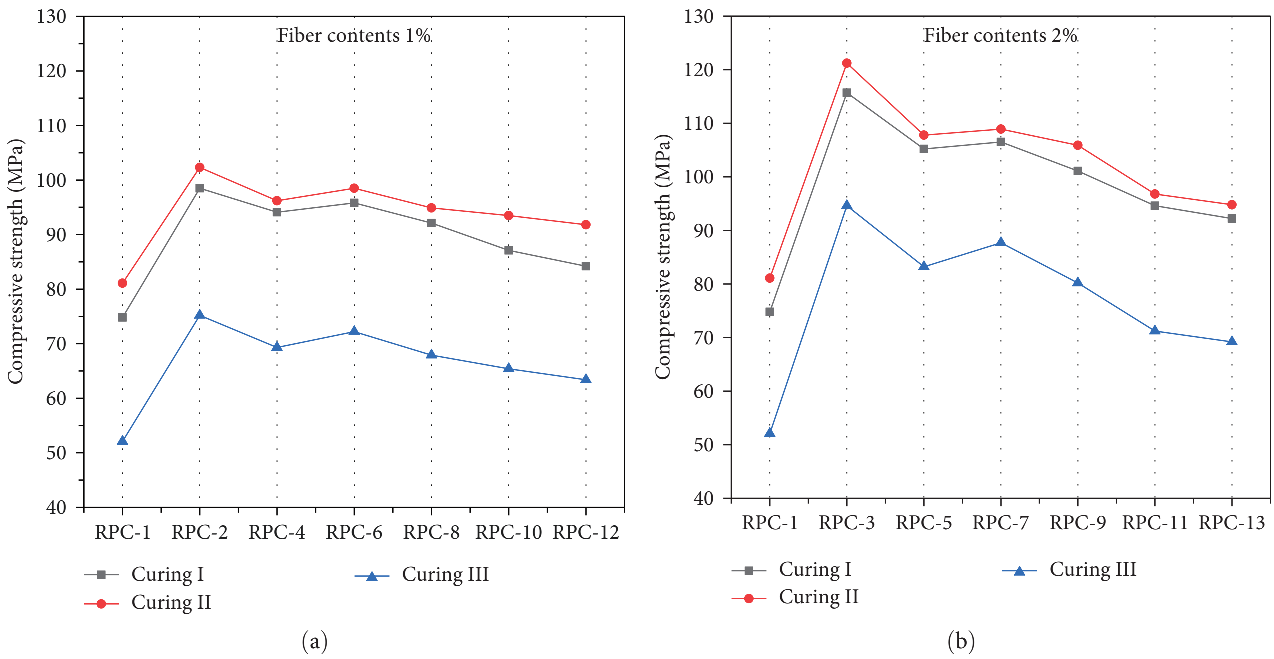


Figure 6: Effect of type of steel fibers on compressive strength: (a) 1% incorporation and (b) 2% incorporation.

attributed to the fact that the fiber efficiently delays the development and spread of cracks when concrete is subjected to compressive or tensile stresses, preventing sudden shattering failure of the cubes, as shown in Figure 7(a).

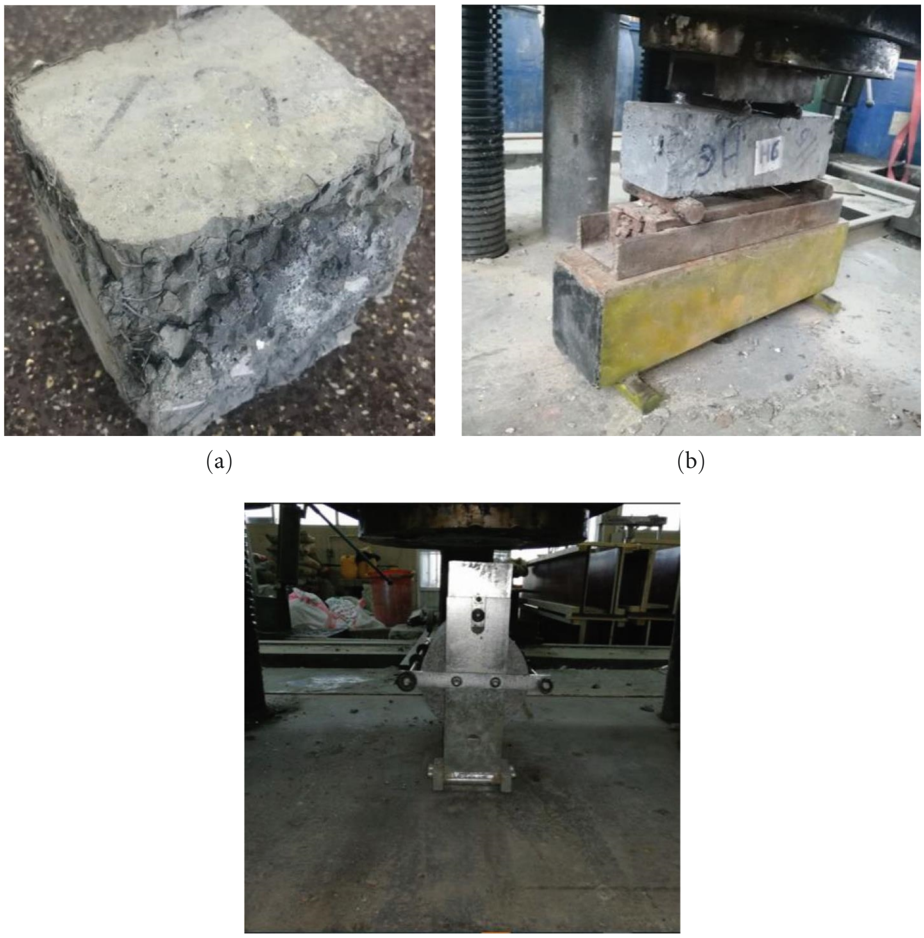
Similarly, RPC-3, which included steel fibers type S12.5, showed the highest strength when fibers were incorporated by 2% of the total volume of the mixture; RPC-3 showed an average increase in strength of 11.9%, 9.4%, 15.4%, 26.2%, and 29.4% compared to RPC-5, RPC-7, RPC-9, RPC-11, and RPC-13, respectively. It is stated that many factors can affect the strength of concrete that contains steel fibers, such as the width-to-length ratio, the size of fibers, and their distribution within the concrete. The possible reason that mixtures contained steel fibers type S 12.5 showed the highest strength can be attributed to these fibers are straight and short in length which makes them easy to mix with the other constituent materials. Curing regimens can influence the mechanical properties of RPC or UHPC significantly, as stated in the previous studies; heat curing regimens may be desired for some cases when high early strength is needed, such as prestressed concrete. As shown in Figure 4, curing regimen II, which consisted of curing the concrete at 100% relative humidity for 3 days at 90°C, followed by 2 days at 60°C and then curing the concrete for an additional 23 days in water at 20°C, yielded the highest compressive strength.

Figures 8(a) and 8(b) demonstrate the effect of the curing regimen on the compressive strength of RPC for a given type of steel fibers and 1% incorporation; curing regimen II showed an average increase in strength of 4.6% and 39.6% compared to curing regimens I and III, respectively. On the other hand, for a given type of steel fibers and 2% incorporation, curing regimen II showed an average increase in strength of 3.3% and 30.7% compared to curing regimens I and III, respectively. For RPC-1, which had no steel fibers, curing regimen II showed 8.4% and 55.7% higher compressive strength compared to curing regimens I and III, respectively. These results indicate that heat curing regimens (I and II) accelerated the hydration process of the binder materials and, therefore, possibly the ultimate strength of the concrete was achieved. Also, the additional curing for 23 days at 20°C after the heat curing was still effective to increase the gain of the strength.

For curing I, RPC-2–RPC-13 showed an average increase in strength of 30.0% compared to RPC-1. For curing II, RPC-2–RPC-13 showed an average increase in strength of 24.6% compared to RPC-1. On the other hand, for curing III, RPC-2–RPC-13 showed an average increase in strength of 43.9% compared to RPC-1.

Figure 9 demonstrates the effect of steel fibers for all mixtures and all curing regimens; each value in the column chart represents the average of the curing regimen (I, II, and III). It can be noticed that RPC-1, which has 0% of steel fibers, showed the lowest compressive strength compared to all other mixtures (RPC-2–RPC-13), which had steel fibers regardless of the curing regimen type. It was also observed that increasing fibers from 0% to 1% and 2% leads to an increase in the average compressive strength, regardless of fiber type and treatment, by 23.6% and 39.2%, respectively. Also found that an increase in steel fiber from 1% to 2% increased the compressive strength by 12.8%.

3.2. Flexural Strength. The effect of flexural strength is summarized in Table 7. Each value represents the average of the two samples examined. Figures 10(a) and 10(b) show the



(a) (b)

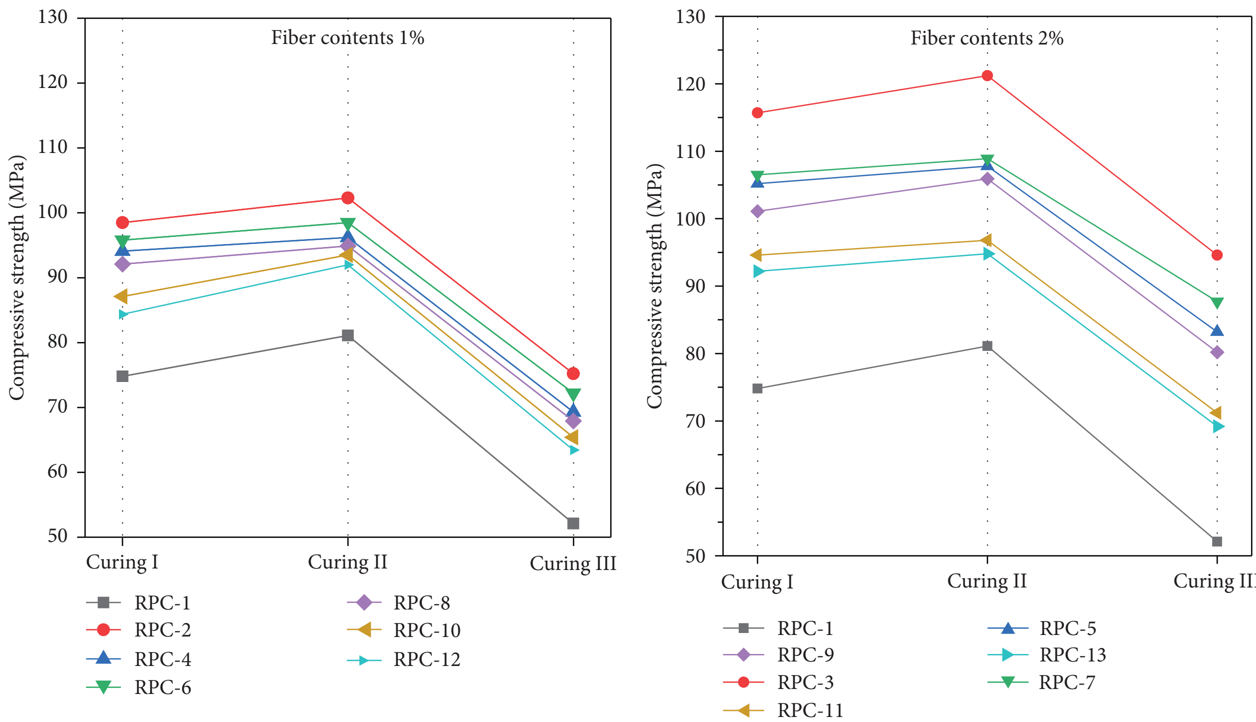
(c)

Figure 7: (a) Failure of cube samples with steel fibers, (b and c) sample setup for flexural and splitting testing.

effect of six types of steel fibers on the flexural strength of RPC, which were added at rates of 1% and 2% of the volume of the mixtures, respectively. For 1% steel fibers incorporation and for all curing regimens, the RPC-6 showed the highest flexural strength compared to the other mixtures; RPC-6 contained steel fibers type H60. RPC-6 mixture showed an average increase of 27.4%, 41.7%, 13.6%, 34.6%, and 21.2% compared to RPC-2, RPC-4, RPC-8, RPC-10, and RPC-12, respectively. Additionally, all mixtures with 1% steel fibers showed higher flexural strength compared to RPC-1 (0% steel fibers). This is due to the fact that steel fibers increase the tensile strength of the concrete and enhance the ductility of the concrete. On the other hand, from Figure 10(b), RPC-7 showed the highest flexural strength compared to other mixtures that contained 2% of steel fibers of different types. RPC-7 showed an average increase in flexural strength of 25.3%, 60.8%, 8.0%, 32.2%, and 15.6% compared to mixtures RPC-3, RPC-5, RPC-9, RPC-11, and RPC-13, respectively. In flexural strength, which is an indirect way to estimate the tensile strength of concrete, steel fibers type can affect the strength significantly. RPC-6 and RPC-7 contained steel fibers type H60; these fibers are hooked in shape and long (length of 60 mm), which increases the energy required to pull the fibers from the matrix, thus preventing crack growth and leading to increased flexural strength. Figure 6(b) represents the sample setup in the flexural test. Figures 11(a) and 11(b) also demonstrate the effect of the curing regimen on flexural strength. For a given type of steel fibers and incorporation of 1%, curing regimen II showed an average increase in flexural strength by 10.7% and 36.3% compared to curing regimens I and III, respectively. On the other hand, for a given type of fibers and 2% incorporation, curing regimen II showed an average increase in strength of 7.7% and 16.5% compared to curing regimens I and III, respectively. For RPC-1, which had no fibers, curing regimen II still yielded the highest flexural strength; curing II showed 16.7% and 71.1% higher strength compared to curing I and curing III, respectively.

Also, from Figures 11(a) and 11(b) for curing I, RPC-2–RPC-13 showed an average increase in strength of 101.5% compared to RPC-1. For curing II, RPC-2–RPC-13 showed an average increase in strength of 88.1% compared to RPC-1. On the other hand, for curing III, RPC-2– RPC-13 showed an average increase in strength of 160.0% compared to RPC-1.

Figure 12 shows the effect of increasing the incorporation ratio of steel from 1% to 2% for all curing regimens; each



(a) (b)

FIGURE 8: Effect of curing regimen on compressive strength (a and b).

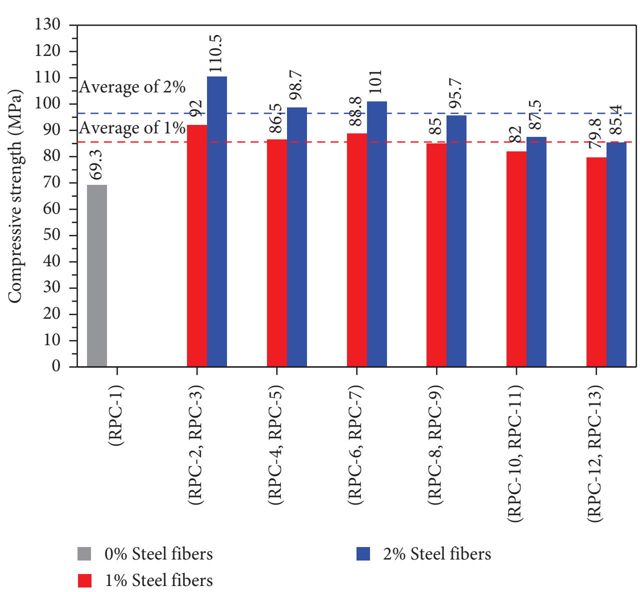


FIGURE 9: Effect of steel fiber on compressive strength.

TABLE 7: Flexural strength results.

Mixture	Flexural strength (MPa)		
	Curing I	Curing II	Curing III
RPC-1	6.6	7.7	4.5
RPC-2	10.1	11.4	8.1
RPC-3	15.3	16.8	14.1
RPC-4	9.1	10.3	7.2
RPC-5	12.1	13.1	10.8
RPC-6	12.9	13.7	11.1
RPC-7	19.7	20.4	17.8
RPC-8	11.5	12.4	9.3
RPC-9	17.9	18.9	16.8
RPC-10	9.6	10.9	7.5
RPC-11	14.5	15.9	13.4
RPC-12	10.6	11.9	8.6
RPC-13	16.3	18.1	15.7

value in the column chart represents the average of the curing regimen (I, II, and III). Mixtures with 2% of steel fibers showed an average increase in flexural strength of 54.5% compared to mixtures with 1% of steel fibers. Also, it can be observed that RPC-1, which has 0% of steel fibers, showed the lowest flexural strength compared to all other mixtures (RPC-2–RPC-13), which had steel fibers regardless of the curing regimen type.

Mixtures containing 1% and 2% steel fibers (RPC-2 to RPC-13) showed an average increase in flexural strength of 65.1% and 155%, respectively, compared to mixtures without steel fibers (RPC-1). It was also found that increasing steel fibers from 1% to 2% led to an increase in flexural strength by 54.4%.

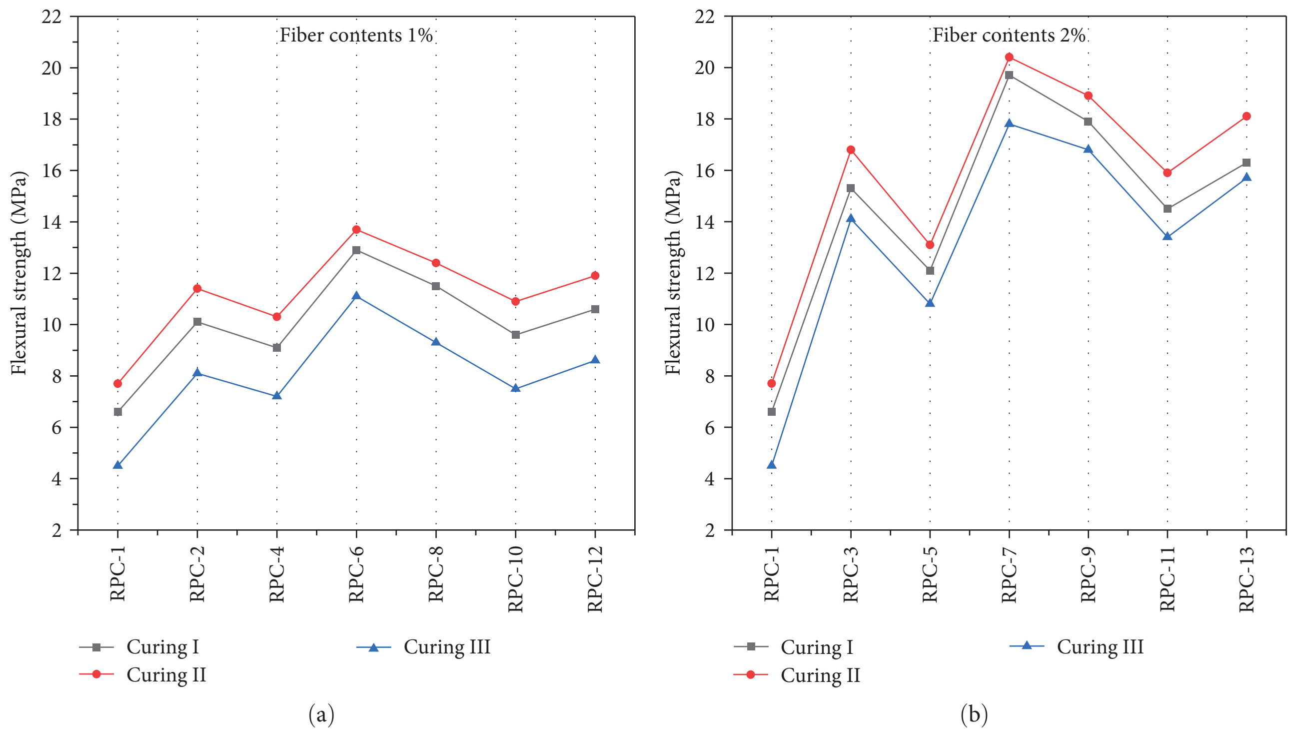


FIGURE 10: Effect of type of steel fibers on flexural strength: (a) 1% incorporation and (b) 2% incorporation.

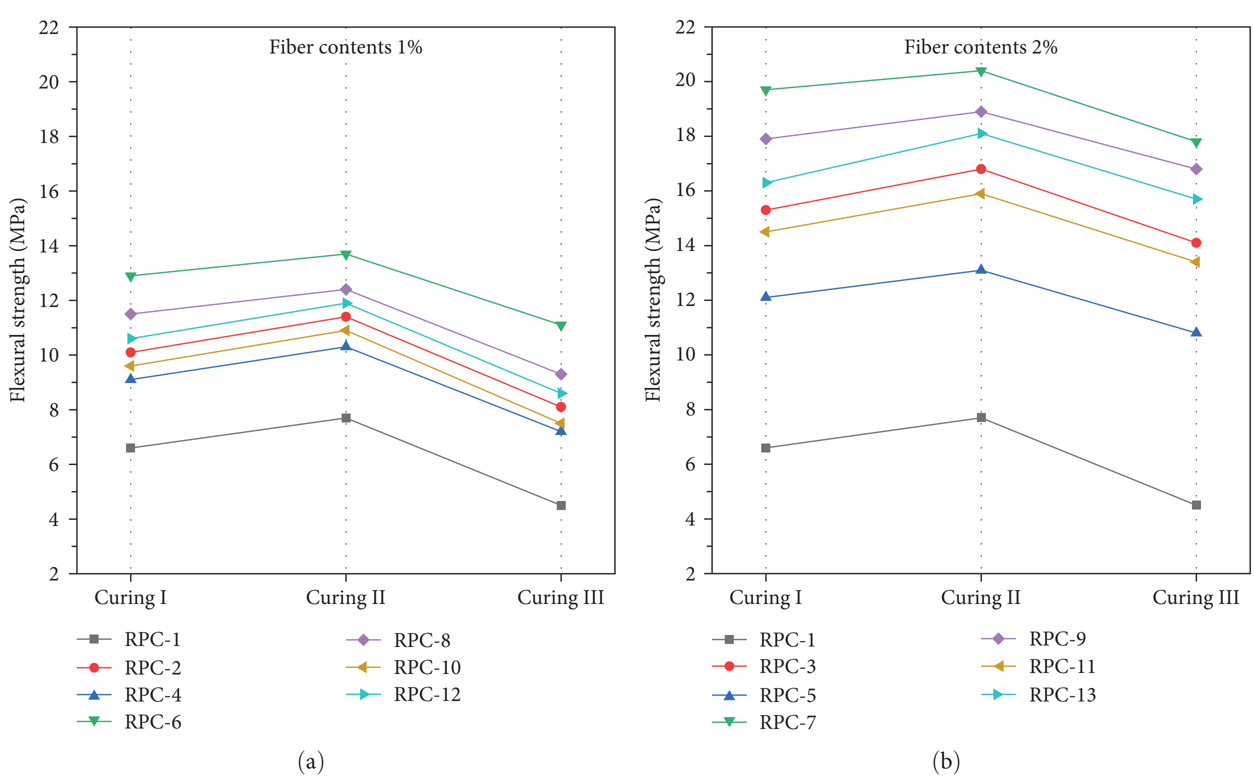


FIGURE 11: Effect of curing regimen on flexural strength (a and b).

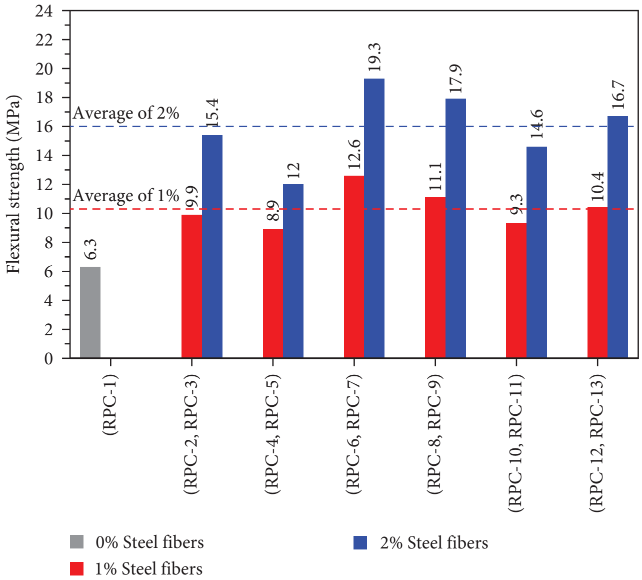


Figure 12: Effect of steel fiber on flexural strength.

Table 8: Splitting strength results.

Mixture	Splitting strength (MPa)		
	Curing I	Curing II	Curing III
RPC-1	4.8	5.3	4.1
RPC-2	8.2	8.8	6.7
RPC-3	12.9	13.5	11.4
RPC-4	7.6	8.2	5.8
RPC-5	10.6	10.9	9.2
RPC-6	9.9	10.4	8.3
RPC-7	17.8	18.2	16.5
RPC-8	8.7	9.4	7.6
RPC-9	16.6	17.2	15.7
RPC-10	8	8.6	6.4
RPC-11	11.3	11.5	9.9
RPC-12	8.4	9	7.1
RPC-13	15.6	15.9	13.8

3.3. Splitting Tensile Strength. Table 8 summarizes the results of splitting tensile strength. Each value represents the average of the two samples examined. Six types of steel fibers were examined to study the effect of fiber type on splitting strength. Figures 13(a) and 13(b) show the effect of the fiber type on the splitting tensile strength of RPC, which were added at rates of 1% and 2% of the volume of the mixtures, respectively. Mixture RPC-6 showed the highest splitting strength for mixtures compared to the other mixtures with 1% steel fiber incorporation for all curing regimens. This type of mixture contains steel fibers type H60; RPC-6 mixtures showed an average increase of 20.7%, 32.4%, 11.3%, 24.3%, and 16.7% compared to RPC-2, RPC-4, RPC-8, RPC-10, and RPC-12, respectively. On the other hand, all mixtures containing 1% steel fibers were found to have higher splitting strength than RPC-1, which does not contain steel fibers. The enhancement in strength is attributed to the fact that the steel fibers effectively delay the formation and propagation of cracks, and it also reduces brittleness and improves the ductility of concrete significantly. Figure 7(c) represents the sample setup in the splitting test.

Correspondingly, RPC-7 containing 2% fibers gave the highest splitting strength compared to the other mixtures and showed an average increase in tensile strength of 38.9%, 71.0%, 6.1%, 60.8%, and 15.9% compared to RPC-3, RPC-5, RPC9, RPC-11, and RPC-13, respectively. RPC-6 and RPC-7 contain H60-type fibers; these fibers are hocked, which leads to an increase in the energy required to pull them, and thus the splitting strength increases. Similar to compressive strength and flexural strength, the type of curing regimen has an obvious influence on the splitting tensile strength of RPC, as shown in Figures 14(a) and 14(b). For a specific type of steel fiber and incorporation of 1%, curing regimen II showed the highest strengths; it showed an average increase in splitting strength by 7.1% and 29.8% compared to curing regimens I and III, respectively. On the other hand, for a given type of steel fiber and 2% incorporation, curing regimen II showed an average increase in strength of 2.8% and 14.0% compared to treatment systems I and III, respectively. As for RPC-1, which does not contain steel fibers, curing regimen II showed a higher splitting strength ratio of 10.4% and 29.3% compared to curing regimens I and III, respectively.

Also, from Figures 14(a) and 14(b) for curing I, RPC-2–RPC-13 showed an average increase in strength of 135.4% compared to RPC-1. For curing II, RPC-2–RPC-13 showed an average increase in strength of 122.6% compared to RPC-1. On the other hand, for curing III, RPC-2– RPC-13 showed an average increase in strength of 140.7% compared to RPC-1.

Figure 15 shows the effect of the ratio of steel fibers for all mixtures and all curing regimens; each value in the column chart represents the average of the curing regimen (I, II, and III). It was reported that the RPC-1, which contains 0% fiber, gave the lowest splitting strength.

Also, the mixtures containing 1% and 2% steel fibers (RPC-2 to RPC-13) showed an average increase in splitting strength of 72.7% and 191.7%, respectively, compared to mixtures without steel fibers (RPC-1). It was also found that increasing steel fibers from 1% to 2% led to an increase in splitting strength by 68.9%.

It was also noted that the ratio between the average split strength of the mixtures (RPC-2–RPC-13) (which contain fibers) relative to the average compressive strength of the mixtures (RPC-2–RPC-13) was 11.6%, 11.7%, and 13.2% for the curing regimen I, II, and III, respectively. While the ratio between the split strength of mixture RPC-1 (which does not contain fibers) relative to the average compressive strength of the mixtures (RPC-2–RPC-13) (which contain fibers) was 4.9%, 5.2%, and 5.5% for the curing regimen I, II, and III, respectively.

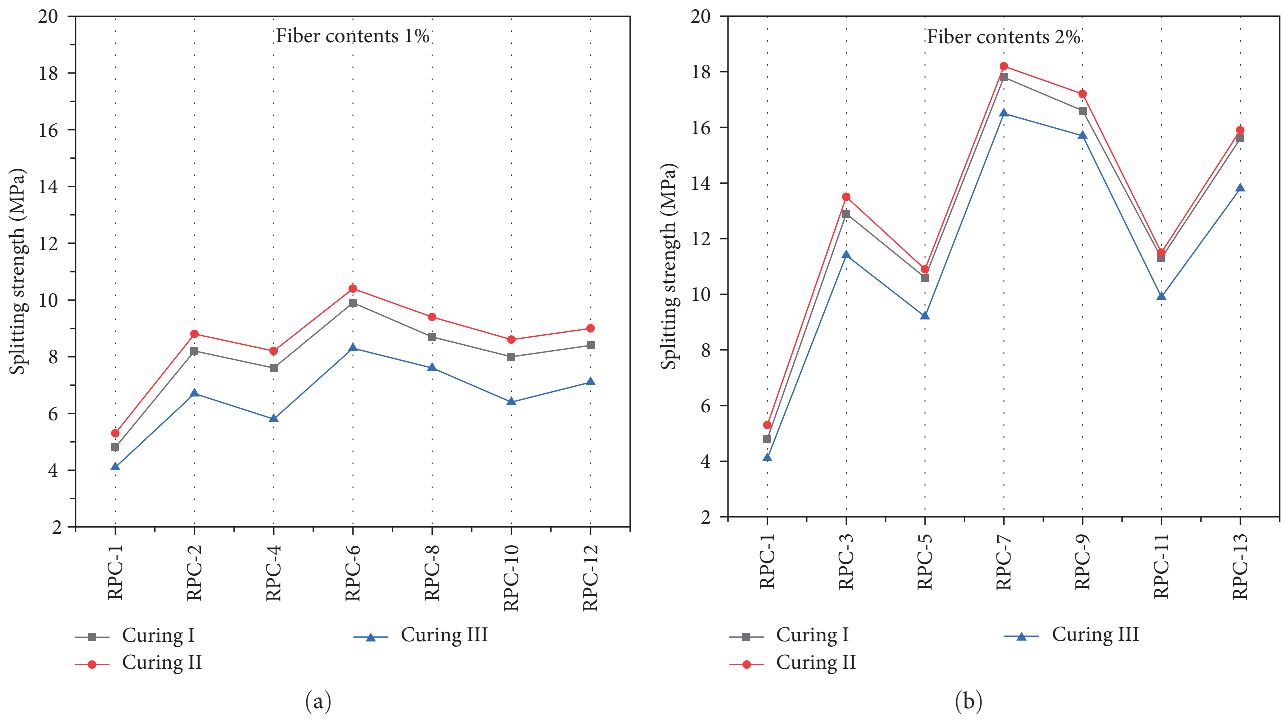


Figure 13: Effect of type of steel fibers on splitting strength: (a) 1% incorporation and (b) 2% incorporation.

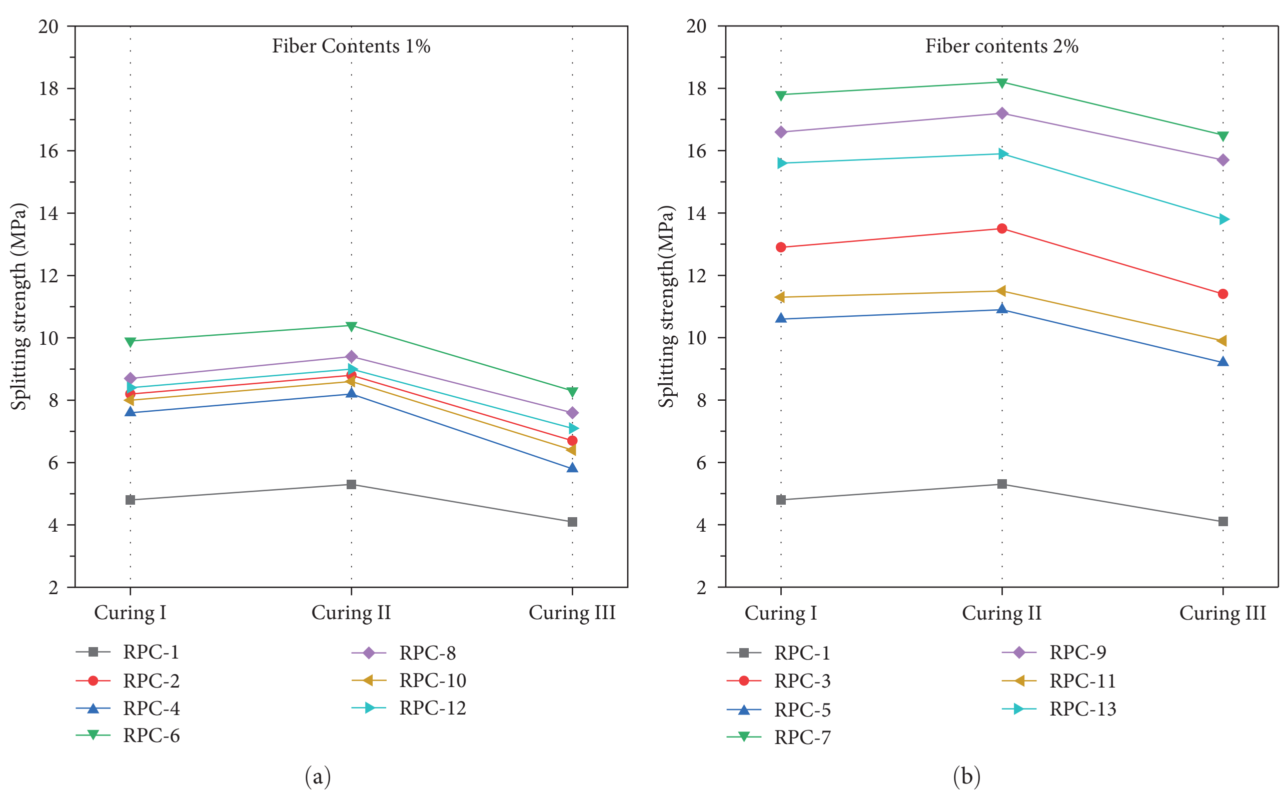


Figure 14: Effect of curing regimen on splitting strength (a and b).

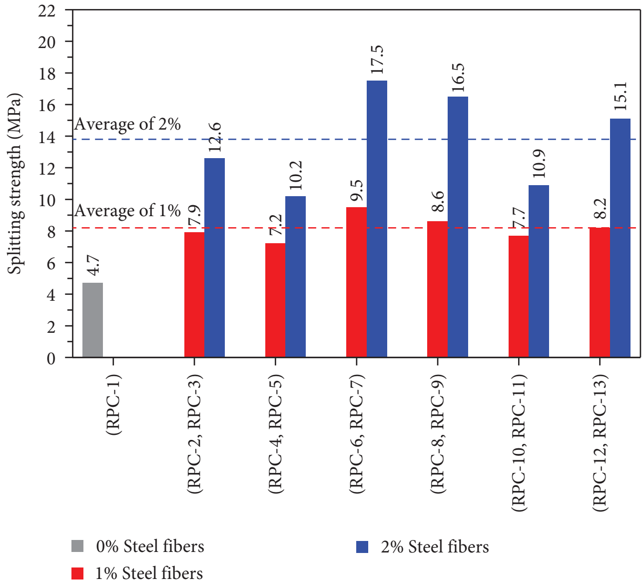


Figure 15: Effect of steel fiber on splitting strength.

4. Conclusions

Based on the experimental program, the following conclusions can be drawn:

(i) The use of steel fibers generally enhanced the compressive strength. Straight steel fiber yielded the highest compressive strength compared to other types. The average increase in compressive strength in mixtures with 1% and 2% steel fiber relative to zero-fiber mixtures is 32.7% and 59.4%, respectively.

(ii) Curing regimens can affect the mechanical properties of RPC significantly. Curing regimen II yielded the best results.

(iii) Curing II, with the incorporation of 1% of steel fibers, showed an increase in the average compressive strength of 4.6% and 39.6% compared to curing I and III, respectively. Also, with the incorporation of 2%, curing II indicated an increase of 3.3% and 30.7% compared to curing I and III, respectively.

(iv) It was found that increasing the ratio of fibers from 0% to 1% and 2% improves the average compressive strength by 23.6% and 39.2%, respectively, compared to mixtures with 0% fibers. Also improves the average flexural strength, regardless of fiber type and treatment, by 65.1% and 155.0%, respectively, and improves the average splitting strength by 72.7% and 191.7%, respectively.

(v) Hooked steel fibers (H60) demonstrated the highest flexural and splitting strength compared to other types of fibers.

(vi) The cutting regimen II, with incorporation 1% of the fibers, gave an increase in the average of flexural strength by 10.7% and 36.3% compared to curing I and III, respectively; also, with incorporation 2%, it gave an increase by 7.7% and 16.5% respectively, and gave an increase in the average of splitting strength by 7.1% and 29.8% compared to curing I and III, respectively, with incorporation 1%, also, with incorporation 2%, it gave an increase by 2.8% and 14%, respectively.

Data Availability

The experimental data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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