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Quality Evaluation Tests for Tensile Strength of Reactive Powder Concrete

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This study presents a comparison between different testing procedures to determine the tensile strength of reactive powder concrete (RPC). The tensile strength test methods include a direct tensile test and two indirect tensile tests, the splitting test and the double punch test (DPT). In this study, the RPC was designed to obtain a nominal compressive strength of 100 MPa at the age of 28 days. Macro steel fibers were used to reinforce the RPC by volumetric percentages of 0, 1, 2, and 3%. Mechanical properties of RPC were obtained at 28 days such as compressive, tensile, and flexural strengths; compressive stress-strain relationship; and tensile stress-strain behavior. By comparing the experimental results of the two indirect tensile tests with the uniaxial direct tensile test (DTT), it was shown that the DPT presents more accurate results of the RPC tensile strength than the splitting test. The experimental results were verified with the existing model to predict the tensile strength of the RPC. In addition, considering the low cost and the ease of conducting the DPT, this test can be used as an alternative to the DTT to obtain the tensile strength of the RPC.

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Abstract

The current study presents a comparison between different testing procedures to determine the tensile strength of the Reactive Powder Concrete (RPC). The tensile strength test methods include a direct tensile test and two indirect tensile tests, the splitting test and the double punch test. In this study, the RPC was designed to obtain a nominal compressive strength of 100 MPa at the age of 28 days. Macro-steel fibers were used to reinforce the RPC by volumetric percentages of 0%, 1%, 2% and 3%. Mechanical properties of RPC were obtained at 28 days such as compressive, tensile, and flexural strengths; compressive stress-strain relationship; and tensile stress-strain behavior. By comparing the experimental results of the two indirect tensile tests with the uniaxial Direct Tensile Test (DTT), it was shown that the

Double Punch Test (DPT) presents more accurate results of the RPC tensile strength than the splitting test. The experimental results were verified with existing model to predict the tensile strength of the RPC. In addition, considering the low cost and the ease of conducting the DPT, this test can be used as an alternative to the DTT to obtain the tensile strength of the RPC.

Keywords: splitting; double punch; direct tensile; Reactive Powder Concrete.

Introduction

Reactive Powder Concrete (RPC) is a composite material that consists of fine powder (Portland cement, silica fume and fine sand) with very low water to binder (Portland cement and silica fume) ratio. A superplasticizer must be used to ensure the desired workability of this type of concrete. The RPC is a type of Ultra-High Performance Concrete (UHPC) that is characterized by its high strength and ductility. This high ductility and energy absorption are due to the presence of a significant amount of steel fiber within the composition of the RPC (Richard and Cheyrezy 1995). The tensile strength and ductility of the RPC are highly affected by the type, shape and volume fraction of the fiber. A few studies have been conducted to experimentally investigate the effect of these factors on the tensile behavior of the RPC, such as Behloul et al. (1996); Park et al. (2012); Li and Liu (2016) and Kang et al. (2016).

The tensile strength of RPC can be determined directly or indirectly with different test procedures which have been used for normal concrete. There are some impediments with the performance of the Direct Tensile Test (DTT) of concrete. These impediments include slippage between gripping apparatus and concrete specimen, concentration of stresses at the gripping apparatus and misalignment of the gripping apparatus (Swaddiwudhipong et al.

2003; Choi et al. 2014 and Wee and Lu 2016). On the other hand, the splitting test or Brazilian test which is an indirect tensile test of concrete was adopted by many standards such as ASTM C496 (2004) and Australian Standard (AS) 1012.10 (2000). According to Hannant et al. (1973), the splitting test is easier to conduct than the DTT and generally shows an acceptable prediction of normal concrete tensile strength (5-12% higher than the DTT). Olesen et al. (2006), however, stated that for normal concrete the splitting strength is 10-40% higher than the direct tensile strength the tensile strength. In addition, Olesen et al. (2006) stated that the splitting strength test should not be used to determine the tensile strength of Steel Fiber Reinforced Concrete (SFRC). This is because of the ductile behavior of SFRC due to the implication of steel fiber within the mix of concrete.

The Double Punch Test (DPT) or Barcelona test was firstly suggested by Chen (1970) as a substitutional indirect test approach to evaluate the tensile strength of normal concrete. A few experimental and analytical studies were conducted to assess the DPT method such as Chen and Yuan (1980); Marti (1989); Molins et al. (2009) and Carmona et al. (2013). According to previous studies, the DPT showed more accurate results of the tensile strength than the splitting test and much easier to perform than the splitting (Chen 1970; Chen and Yuan 1980; Marti 1989; Molins et al. 2009 and Carmona et al. 2013).

Chao et al. (2011) stated the DPT can be used efficiently to evaluate the tensile behavior of SFRC. The test results of the DPT on SFRC showed an acceptable coefficient of variation of less than 12% (Chao et al. 2011). For the tensile strength of SFRC, the DPT showed a lower coefficient of variation than other test methods of the tensile strength (Molins et al. 2009). The DPT also has the advantages of easy preparation of samples and simple performance of test procedure (Chen 1970).

The existing studies in the literature only used DPT to evaluate the tensile strength of normal concrete and SFRC. This study was conducted to investigate the viability of extending the

DPT to reliably evaluate the tensile strength of the RPC. Also, none of the previous studies compared different test methods to determine the tensile strength of the RPC. To this end, this paper aims to compare the tensile strengths of RPC obtained from the splitting test and DPT with those obtained from DTT. The study includes four different percentages of steel fiber 0%, 1%, 2% and 3% that were added to the RPC with a nominal compressive strength of 100 MPa.

Experimental Program

The experimental program of this study consisted of 48 concrete cylinder specimens that were cast and tested to determine the 28-day compressive strength, compressive stress-strain relationship, splitting tensile strength and double punch tensile strength of the RPC. In addition, 24 concrete prism specimens were also cast and tested to determine the direct tensile strength, tensile stress-strain behavior and flexural strength of the RPC. The experimental program was performed in the High Bay Laboratory of the School of Civil, Mining and Environmental Engineering at the University of Wollongong, Australia.

Materials

The RPC used in this study was a part of a PhD study to investigate the behavior of RPC columns. For this reason, the RPC was designed to have a nominal compressive strength of 100 MPa due to the limitation of the loading capacity of the testing machine. Four RPC mixes were produced with general purpose cement 800 kg/m^3, fine sand (with range of particle size from 150 µm to 600 µm) 1050 kg/m^3, densified silica fume 250 kg/m^3, water 180 kg/m^3 and superplasticizer 60 kg/m^3. The steel fiber was added by weight of 0 kg/m^3, 80 kg/m^3, 160 kg/m^3 and 240 kg/m^3 for 0%, 1%, 2% and 3% by volume of the RPC, respectively. These percentages of the steel fiber were used in this study because a number of previous studies such as Richard and Cheyrezy (1995); Dugat et al. (1996); Zhang et al. (2012) have reported the optimum percentage of steel fiber is 2-3% by volume of concrete. However, Tai et al. (2011) reported an optimum steel fiber percentage of 2% by volume of concrete showed the highest compressive strength. The superplasticizer Sika-Viscocrete (2016) was used in this study and complied with the specifications ASTM C494 (2015). The steel fibers were provided by Ganzhou Daye Metallic Fibers (2015), having the dimensions of 13 mm in length and 0.2 mm in diameter with a maximum tensile strength of 2500 MPa. For the purposes of this study, each RPC mix was recognized with an acronym. Mixes RPC0, RPC1, RPC2 and RPC3 refer to RPC mix reinforced with 0, 1, 2 and 3 volumetric percentage of steel fiber, respectively.

Mixing, casting and curing of specimens

An electronic balance was used to weigh all the dry materials that were mixed in a laboratory mixer of 0.1 m^3 capacity. First, all dry materials (cement, fine sand and densified silica fume) were mixed together for 5 minutes. Then, the water and the superplasticizer were added to the dry mixture. After a period of 10 minutes of mixing, the full amount of steel fiber was added and the desired flowability (Flow table test > 120 mm) was obtained in accordance with ASTM C230 (2014).

Test setup and procedure

Compressive stress-strain behavior

The compressive stress-strain behavior tests were carried out using a Denison universal testing machine with a loading capacity of 5000 kN, as shown in Figure 1. Three RPC cylinders (150 mm diameter × 300 mm height) of each RPC mix were tested to determine the compressive stress-strain response. One Linear Variable Differential Transformer (LVDT) was used to measure the axial deformation of the mid-height region of 115 mm. In addition, two LVDTs were attached to the lower loading head of the machine to measure the total axial deformation of the specimens. Under displacement control loading, all specimens were axially loaded up to failure with a displacement rate of 0.3 mm/minute.

Flexural test

The flexural strength test was conducted in accordance with the AS 1012.11 (1985). Three prisms with a cross-section of 100 mm × 100 mm and a length of 500 were tested under four-point loading. The flexural strength was calculated according to the AS 1012.11 (1985) using Equation (1):

$$f_{\mathrm{ct.f}} = \frac{PL\,(1000)}{BD^2} \tag{1}$$

where $f_{\mathrm{ct.f}}$ is the flexural strength in MPa, P is the maximum applied load in kN**,** L is the span length in mm**,** B is the width of the specimen at the point of failure in mm**,** D is the depth of specimen at the point of failure in mm.

Splitting Test (ST)

The splitting tests were conducted according to the AS 1012.10 (2000). Three cylinders (150 mm diameter × 300 mm height) of each RPC mix were tested to determine the average splitting strength. Two timber strips having the dimensions of 400 mm in length, 25 mm in width and 5 mm in thickness were located between the loading heads and the specimen as bearing strips. A compression testing machine was used to conduct the test at a loading rate of 1.5 MPa/min according to the AS 1012.10 (2000). Equation (2) was used to calculate the splitting tensile strength according to the AS 1012.10 (2000):

$$ST = \frac{2000P}{\pi LD} \quad (2)$$

where ST is the splitting tensile strength in MPa, P is the maximum applied load in kN, L is the length of specimen in mm, and D is the diameter of the specimen in mm.

Double Punch Test (DPT)

The test procedure of the DPT in Chen (1970) was adopted to perform the DPT in this study. Three cylinders with a diameter of 150 mm and a height of 150 mm were tested in a compression testing machine to determine the average DPT tensile strength of each RPC mix, see Figure 2. Two steel punches were used to transfer the load from the testing machine to the concrete specimen, as shown in Figure 2. Each cylindrical punch had a diameter of 37.5 mm and a height of 25 mm, according to Chen (1970). A loading rate of 1.4 MPa/min was used to test the specimens according to Chen (1970). Equation (3), suggested by Chen (1970), was used to calculate the DPT tensile strength:

$$DPT = \frac{P}{\pi(0.6dh - 0.25x^2)} \quad (3)$$

where, DPT is the double punch tensile strength in MPa, P is the maximum applied load in kN, d is the diameter of specimen in mm, h is the height of specimen in mm, and x is the diameter of steel punch in mm.

Direct Tensile Test (DTT)

The instrumentation of the DTT used in this study was firstly proposed by Alhussainy et al. (2016). Each DTT test was conducted using a concrete prism with a cross-sectional area of 100 mm × 100 mm and a total length of 500 mm. The formwork of the specimens was made of a timber. To ensure a mid-span failure, the cross-sectional area of the concrete prism was reduced in the middle of the specimen. The tensile force was applied on the specimen by using a steel gripping claw on both ends of the specimen, as show in Figure 3. The gripping claws were made of threaded steel bar with a diameter of 20 mm. To provide sufficient anchorage between the claws and the concrete, four pins made of steel were welded to the threaded bar.

The claws were fastened to the timber formwork by a nut and a washer from the outside and a washer from the inside of the formwork, to ensure an adequate alignment between the two gripping claws, as shown in Figure 3. To avoid the misalignment between the jaws of the testing machine during the test, two universal joints, as can be seen in Figure 4, were used to grip the ends of the specimen and to provide free movement at the ends of the specimen as shown in Figure 5. Specimens were loaded up to failure with a displacement of 0.1 mm/min and the data were recorded at every two seconds. Also, a strain gauge with 100 mm length was attached to the middle of the prism to measure the concrete strain within the specimens.

Results and Discussion

Compressive properties

Compressive strength

Table 1 shows the mechanical properties of the RPC mixes at the age of 28 days. The compressive strength test of RPC was conducted according to the AS 1012.9 (2014). The average 28-day compressive strength of the four RPC mixes ranged from 73 MPa to 113 MPa. The highest compressive strength of the RPC was achieved with 3% of steel fiber content. Compared to Mix RPC0, the compressive strength of Mixes RPC1, RPC2 and RPC3 was increased by 8.4%, 43.6% and 53.5%, respectively. As mentioned above, some of the previous studies reported that the optimum percentage of steel fiber in RPC mixes was in range of 2% to 3% by volume of concrete, although Tai et al. (2011) stated that 2% of steel fiber showed higher compressive strength than 3%.

Compressive stress-strain behavior

Figure 6 shows the typical compressive stress-strain curves of Mixes RPC0, RPC1, RPC2 and RPC3. Compared to Mix RPC0, the presence of steel fiber in Mixes RPC1, RPC2 and RPC3 have a marginal effect on the stress-strain behavior before the peak stress. Mix RPC0 showed a softening stress-strain response of nearly 10% of the maximum stress followed by a sudden drop of the compressive stress accompanied with the explosive failure mode. Whereas Mixes RPC1, RPC2 and RPC3 experienced a strain softening stress-strain behavior in the post-cracking stress extended to nearly 50% of the maximum stress due to the effect of interaction between concrete matrix and steel fiber. The best ductile stress-strain behavior was achieved by Mix RPC3 which had the highest volume content of steel fiber, as shown in Figure 6.

Flexural strength

Table 1 shows the average flexural strength results of Mixes RPC0, RPC1, RPC2 and RPC3. The test results show that the flexural strength was increased by the increase of volume fraction of steel fiber within the mix of RPC. Compared to Mix RPC0, the flexural strength of

Mixes RPC1, RPC2 and RPC3 were increased by 18%, 62% and 76%, respectively. It can be seen from these results that the flexural strength of the RPC was improved more than the compressive strength by increasing the steel fiber content from 0% to 3% by volume of concrete.

Tensile properties

Tensile strength

Three different test methods were used to determine the tensile strength of the RPC with different percentages of steel fiber. An experimental evaluation was carried out to compare the test results of these methods.

Splitting Test

The typical failure modes of Mixes RPC0, RPC1, RPC2 and RPC3 are shown in Figure 7. In Figure 7a, Mix RPC0 showed one failure surface at the centre of the cylinder and along the line of the loading strip. Mix RPC0 experienced a sudden and brittle failure mode. However, for Mixes RPC1, RPC2 and RPC3, the failure was not brittle and the specimens remained nearly intact after the failure. The incomplete splitting failure was because the steel fibers distributed the applied stresses through the failure surface. In addition, a compressive zone can be seen under the bearing bar which unevenly distributed the load along the direction of the load due to the effect of the steel fibers.

Table 1 and Figure 8 present the test results of the average tensile strength of Mixes RPC0, RPC1, RPC2 and RPC3. The average splitting tensile strength of Mixes RPC1, RPC2 and RPC3 was increased by 47%, 108% and 180%, respectively, compared to Mix RPC0. The highest splitting tensile strength (17.4 MPa) was achieved by Mix RPC3, which had the highest compressive strength and 3% of steel fiber by volume of the RPC.

Double Punch Test

Figure 9 shows the typical failure modes of Mixes RPC0, RPC1, RPC2 and RPC3 tested under DPT. Mixes RPC0, RPC1 and RPC2 failed in four radial cracks which have been reported as an ideal failure mode (Chen (1970); Chen and Yuan (1980); Marti (1989); Molins et al. (2009) and Carmona et al. (2013)). Mix RPC3, however, failed in five radial cracks due to the increase of steel fiber volume fraction, as shown in Figure 9d. The typical failure mode of Mix RPC0 is presented in Figure 9a. Four radial failure surfaces were observed at an angle of nearly 30º between each two close failure surfaces. By increasing the percentage of the steel fiber into the concrete mixture, the failure surfaces were observed at an equal angle of nearly 90º, as shown in Figure 9b, 9c and 9d. This behavior could be due to the effect of steel fiber that distributes the stress in the RPC specimen during the test.

Table 1 and Figure 8 show the test results of the DPT of all mixes. The average tensile strength of Mixes RPC1, RPC2 and RPC3 was increased by 26%, 65% and 106%, respectively, compared to Mix RPC0. Mix RPC3 was achieved the highest DPT tensile strength of 10.2 MPa, where the highest content of steel fiber was used.

Direct Tensile Test

The typical failure modes of the DTT for Mixes RPC0, RPC1, RPC2 and RPC3 are shown in Figure 10. For Mixes RPC0 and RPC1 tested under direct tensile load, only one failure crack surface was observed at the middle of the specimens, as shown in Figures 10a, b. Different failure modes, however, were observed in Figures 10c, d where two and three failure crack surfaces were seen for Mixes RPC2 and RPC3, respectively. No claw slippage was observed at the ends of all specimens, which indicated that adequate alignment was provided to the specimens under the DTT.

Table 1 and Figure 8 present the test results of Mixes RPC0, RPC1, RPC2 and RPC3 test under DTT. The minimum tensile strength of 4.5 MPa was obtained by Mix RPC0 and the maximum tensile strength value of 9.8 MPa was achieved by Mix RPC3 which has 3% of steel fiber by volume of RPC. The test results also show that the average direct tensile strength of Mixes RPC1, RPC2 and RPC3 increased by 30%, 74% and 120%, respectively, compared to RPC0.

Comparison of tensile test methods

Table 1 and Figure 11 compare the results of the tensile strength of different test methods. Figure 11 showed that the splitting test overestimates the tensile strength of the RPC when compared with the results of the DTT. In addition, by increasing the steel fiber content, the overestimation of the tensile strength was increased. Table 1, shows that the splitting tensile strength of Mixes RPC0, RPC1, RPC2 and RPC3 was 39%, 57%, 66% and 77% higher than the direct tensile strength, respectively. This is due to the ductile conduct of the RPC with steel fiber that composes a wide compressive area under the bearing bar during the test, as can be seen in Figure 7b, 7c and 7d. Basically, the value of the splitting tensile strength is calculated using Equation 2 assuming that the concrete specimen splits into two halves by one primary surface failure along the vertical diameter of the specimen. By introducing steel fiber to the RPC mixes, however, the horizontal tensile stress distributes along one primary surface failure and more than one secondary surface failure which creates a vertical failure zone instead of a surface failure, as can be seen in Figure 12. Thus, a higher result of tensile strength can be expected than the actual one.

According to the results shown in Figure 11, the tensile strengths of the DPT were close to those obtained from the DTT. The DPT tensile strength of Mixes RPC0, RPC1, RPC2 and RPC3 was within 11% higher than the direct tensile strength, as shown in Table 1. Chen (1970) reported that the precision of the DPT enhanced as the number of radial cracks increased. The higher number of failure surfaces, the more uniform distribution of the stresses in the specimen. Using of steel fiber within the RPC mixes can also result in more uniform distribution of the stress in the specimen under DPT, as can be seen in Figure 9d.

The tensile strength test methods used in this study have differences in the shape and the dimensions and between each other. The effect of specimens' size has been extensively investigated by a number of previous studies, such as Melhotra (1970); Melis et al. (1985); Rossi et al. (1996) and Kadleček et al. (2002). Rossi et al. (1996) stated that the effect of specimen's size on the tensile strength is marginal when very high strength concrete is used. This is because of the fact that the size effect is highly depends on the ratio of maximum aggregate size to the specimen size and this ratio is very small for the RPC mixes due to the very fine materials composition.

Based on the results discussed above, the DPT showed more accurate tensile strength than the splitting test when compared with the DTT for the RPC.

Tensile stress-strain behavior

The typical tensile stress-strain curves of all RPC mixes are shown in Figure 13. Table 2, also shows the test results of the ultimate tensile stress and the corresponding strain of specimens under DTT. For all mixes, linear axial stress-strain behavior up to the maximum stress was observed. As can be observed in Figure 13, the axial stress dropped to zero immediately after reaching the maximum stress in Mix RPC0. As expected, only one major crack was observed at the mid-length of Mix RPC0, see Figure 10a. The post-peak behavior, however, changed by including 1%, 2% and 3% steel fiber by volume of the RPC. For Mix RPC1, the axial tensile stress dropped to nearly one-third of the maximum load followed by a descending axial stress-strain curve. The axial tensile strain corresponding to the maximum tensile stress of Mix RPC1 was increased by 20% compared to that of Mix RPC0, according to the results presented in Table 2. Mix RPC1 also failed with one major crack located in the middle of the specimen, as shown in Figure 10b. By increasing the steel fiber to 2% in Mix RPC2, the post-peak stress-strain curve experienced a softening behavior but without a sudden drop in the axial tensile stress. The axial tensile strain corresponding to the maximum tensile stress of Mix RPC2 was increased by 52% compared to that of Mix RPC0, as shown in Table 2. Two major cracks were observed in the failure mode of Mix RPC2, as shown in Figure 10c. For Mix RPC3, however, the post-peak stress-strain curve showed a tensile strain hardening behavior with three peaks of tensile stress and the axial tensile strain corresponding to the maximum tensile stress of Mix RPC3 was increased by nearly 120% compared to that of Mix RPC0, as shown in Table 2. Mix RPC3 failed with three major cracks, as illustrated in Figure 10d. The maximum axial tensile stress of the RPC specimens increased due to the influence of an increase in the content of steel fiber, as can be seen in Figure 13. Thus, DTT results showed that the tensile strength of the RPC can be enhanced by increasing the content of steel fibers in the RPC mix and the tensile strain hardening can be achieved with 3% of steel fiber by volume of RPC.

Relationship between the tensile strength and the compressive strength

The tensile strength f_t is an important material property in the design of structures. Most of the international design codes present an equation to predict the value of the tensile strength from the compressive strength f_c. The ratio between these two parameters is affected by the type and strength of concrete. Several studies were conducted to obtain simple and accurate models to predict the tensile strength of different types of concrete, a list of these studies are presented below:

The FIB model code for concrete structures CEB-FIB (1991) adopted Equation (4) in the structural design to predict the tensile strength of concrete from the compressive strength as below:

$$f_t = 0.3 f_c^{2/3} \tag{4}$$

The American Concrete Institute of high strength concrete ACI 363R-92 (1992) suggested the following equation to predict the tensile strength of concrete with a compressive strength from 21 MPa to 83 MPa, as shown in Equation (6) below:

$$f_t = 0.59 f_c^{0.5} \tag{5}$$

Ashour and Faisal (1993) proposed a model to predict the tensile strength of steel fiber concrete, considering the properties of the used steel fiber, see Equation (6) below:

$$f_t = \frac{f_c}{20 - \sqrt{FRI}} + 0.7 + \sqrt{FRI} \tag{6}$$

where, *FRI* is the fiber reinforcement index, $FRI = V_f \times \frac{l}{d}$, V_f is the volume fraction of fiber, *l* is the length of fiber and *d* is the diameter of fiber.

Zain et al. (2002) proposed a relation between the tensile strength and the compressive strength of high performance concrete with compressive strength more than 40 MPa, as shown in Equation (7) below:

$$f_t = \frac{f_c}{0.1 f_c + 7.11} \tag{7}$$

Based on wide range of experimental data, Arioglu et al. (2006) suggested Equation (8) below to predict the tensile strength of concrete with compressive strength ranging from 4 MPa to 120 MPa, Equation (8) is given as:

$$f_t = 0.321 f_c^{0.66} \quad (8)$$

In this study, the models presented above were used to verify the experimental results of the tensile strength of the RPC mixes. The predicted results obtained from the existing models and the experimental results of the four RPC mixes were then compared to each other using statistical measures. Only models that cover a range of tensile strength from 70 MPa to 120 MPa were selected.

To evaluate the predicted results of the tensile strength for the RPC mixes, the slope of regression line between the experimental and the predicted results, the correlation factor (R^2) and the Average Absolute error (AAE) were used in this study, as can be seen in Table 3. The AAE was calculated according to Equation (9).

$$AAE = \frac{\sum_1^N \left| \frac{pre_i - exp_i}{exp_i} \right|}{N} \quad (9)$$

where, N is the number of the specimens, pre_i is the predicted value of the model, exp_i is the experimental test result.

According to the results illustrated in Table 3, all the values of the slope of regression line were < 1 which means all the selected models are conservative. The results also showed that the predicted values of f_t were closer to the experimental f_t results of the RPC for the DTT and the DPT than the f_t results of the splitting test, as presented in Table 3. Ashour and Faisal (1993) proposed Equation (6) for steel fiber reinforced concrete and they included the effect of steel fiber (FRI) in this equation. Equation (6) obtained the highest values of slope of regression line and correlation factor between the experimental and predicted values of the f_t

compared to other equations. Equation (6) also obtained the lowest value of AAE of 40%, 13% and 7% for the splitting test, the DPT and the DTT, respectively. For this reasons, it can be concluded that Equation (6) yielded the most accurate prediction of f_t among other equations.

Conclusions

Three different test methods were used to experimentally evaluate the tensile strength of the RPC. According to the results of this study, the following findings are summarized below:

- Based on the experimental results of this study, the DTT procedure developed by Alhussainy et al. (2016) can be efficiently used to determine the tensile strength of the RPC.
- The splitting test procedure was found to be ineffective to determine the tensile strength of the RPC. For the splitting tensile strength of RPC with 0% of steel fiber, an overestimation of 39% of the tensile strength was found compared to the tensile strength of the DTT. In addition, by increasing the steel fiber content, the overestimation of the tensile strength was increased.
- For the RPC mixes with steel fiber of volume fraction of 0%, 1%, 2% and 3%, the DPT was capable to detect the tensile strength of the RPC within a range of 11% higher than the direct tensile strength. The DPT also showed more accurate tensile strength of the RPC than the splitting test when compared with the DTT.
- Based on the outcomes of the experimental program, the DPT test can be considered as an alternative to the DTT to obtain the tensile strength of the RPC. This is because of the low cost and the easy performance of the DPT.

- More research is needed to develop a model that can precisely predict the tensile strength of the RPC. According to the results of this study, the existing models that can be used to predict the tensile strength of the RPC yield more accurate results for the DPT and the DTT than the splitting test.

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List of Tables

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Table 1 Mechanical Properties of the RPC mixes at the age of 28 days

Mix Label	Compressive Strength (MPa)		Flexural Strength (MPa)		Splitting Strength (ST) (MPa)		Double Punch Strength (DPT) (MPa)		Direct Tensile Strength (DTT) (MPa)		ST/DTT	DPT/DTT
	Single	Average	Single	Average	Single	Average	Single	Average	Single	Average		
	70.63		14.06		5.82		4.86		4.19			
RPC0	75.18	73.41	12.29	12.63	5.89	6.26	4.98	4.97	4.40	4.46	1.39	1.11
	74.42		11.54		7.07		4.98		4.79			
	76.60		15.33		9.52		6.19		5.52			
RPC1	81.33	79.62	14.81	14.94	9.08	9.10	6.38	6.29	5.84	5.78	1.57	1.09
	80.93		14.68		8.70		6.31		5.98			
	108.25		19.60		11.93		7.97		7.58			
RPC2	105.07	105.52	22.85	20.47	14.55	12.94	9.10	8.21	7.91	7.78	1.66	1.06
	103.24		18.96		12.34		7.56		7.85			
	116.14		21.43		17.30		10.32		9.70			
RPC3	109.48	112.71	20.71	22.24	15.56	17.42	9.51	10.23	9.96	9.81	1.77	1.04
	112.51		24.58		19.40		10.86		9.77			

Table 2 Test results of the Direct Tensile Test

Mix Label	Maximum Tensile Stress (MPa)		Corresponding Strain (%)		Maximum Tensile Load (kN)		Corresponding Elongation (mm)	
	Single	Average	Single	Average	Single	Average	Single	Average
RPC0	4.19	4.46	0.089	0.095	33.52	35.68	1.84	1.98
	4.40		0.095		35.20		1.97	
	4.79		0.103		38.32		2.13	
RPC1	5.52	5.78	0.109	0.116	44.16	46.24	2.34	2.49
	5.84		0.117		46.72		2.51	
	5.98		0.122		47.84		2.62	
RPC2	7.58	7.78	0.141	0.144	60.64	62.24	3.03	3.10
	7.91		0.146		63.28		3.14	
	7.85		0.146		62.80		3.14	
RPC3	9.70	9.81	0.203	0.209	77.60	78.48	4.19	4.32
	9.96		0.218		79.68		4.50	
	9.77		0.207		78.16		4.27	

Table 3 Validation of existing equations to predict the tensile strength of the RPC

Equation No.	Source	Slope of regression line			R^2			AAE %		
		ST	DPT	DTT	ST	DPT	DTT	ST	DPT	DTT
(4)	CEB-FIB (1991)	0.161	0.357	0.384	0.866	0.898	0.920	41	17	16
(5)	ACI 363R-92 (1992)	0.10	0.230	0.250	0.865	0.897	0.922	44	21	20
(6)	Ashour and Faisal (1993)	0.330	0.675	0.710	0.895	0.922	0.948	40	13	7
(7)	Zain et al. (2002)	0.10	0.210	0.210	0.860	0.892	0.920	44	21	21
(8)	Arioglu et al. (2006)	0.133	0.217	0.290	0.866	0.898	0.922	38	16	15

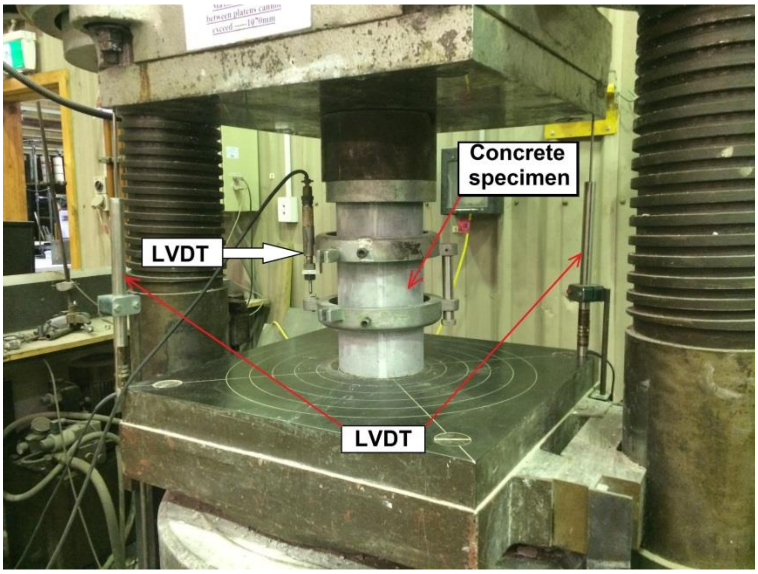

Figure 1 Test setup for compression stress-strain test

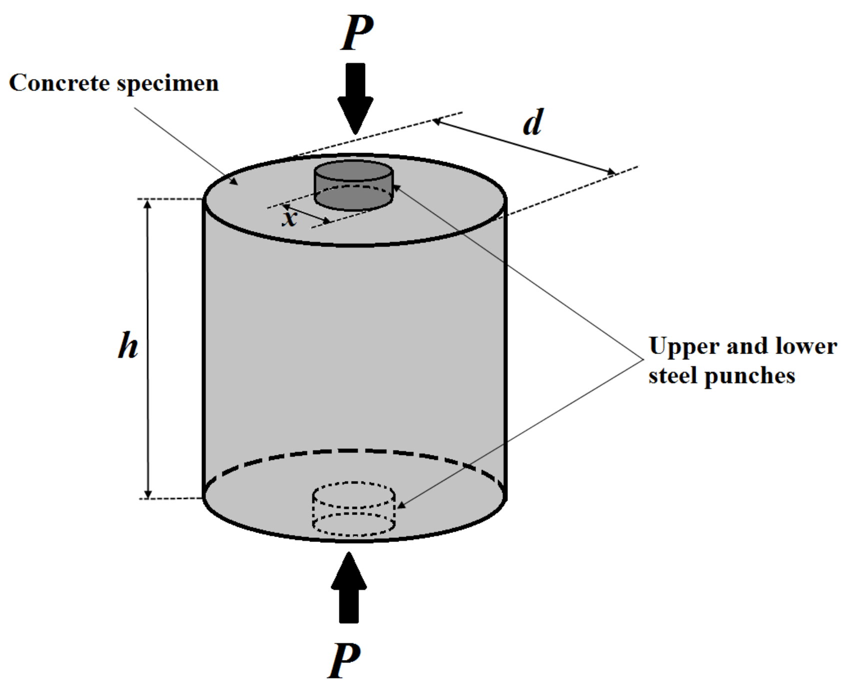

Figure 2 Test setup for DPT

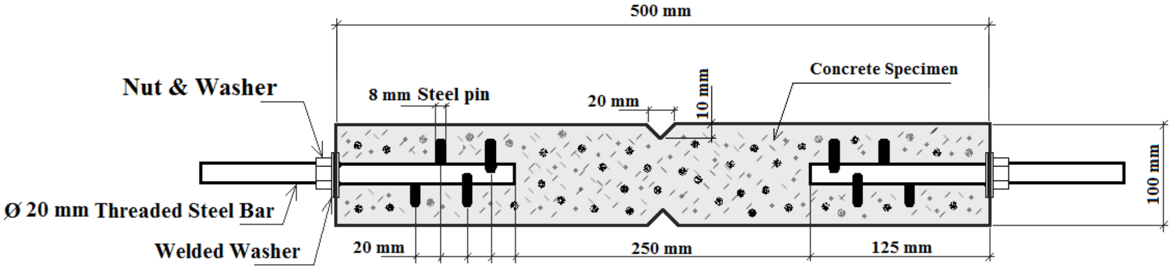

Figure 3 Dimensions of specimens for the DTT (Adopted from Alhussainy et al. 2016)

Figure 4 Universal joints

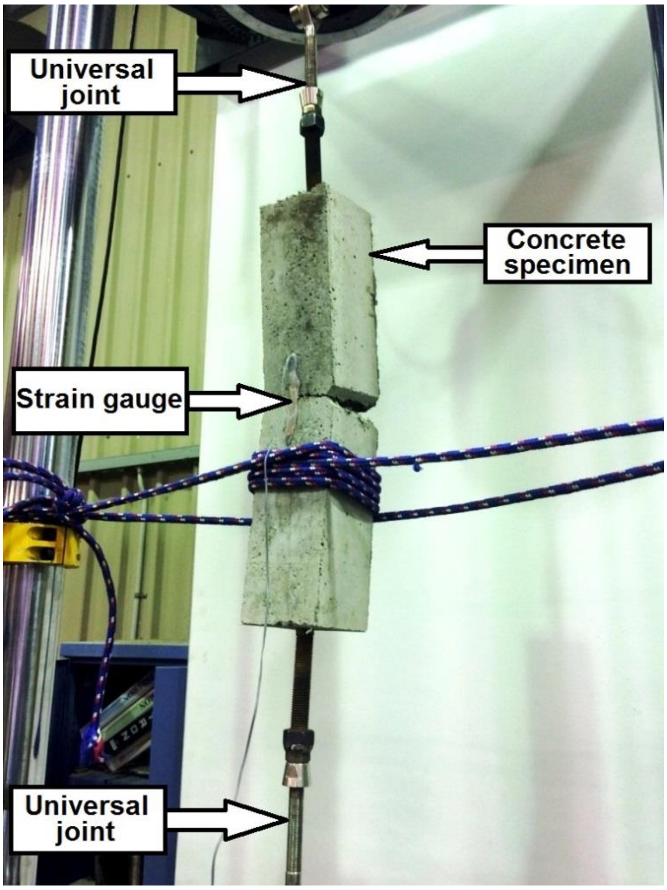

Figure 5 Test setup for the DTT

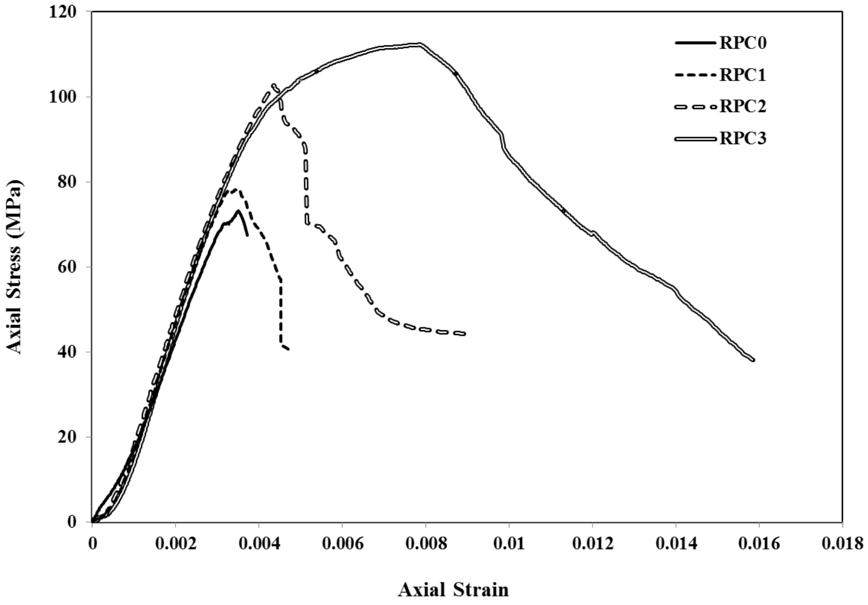

Figure 6 Typical axial compressive stress-strain curves of RPC mixes

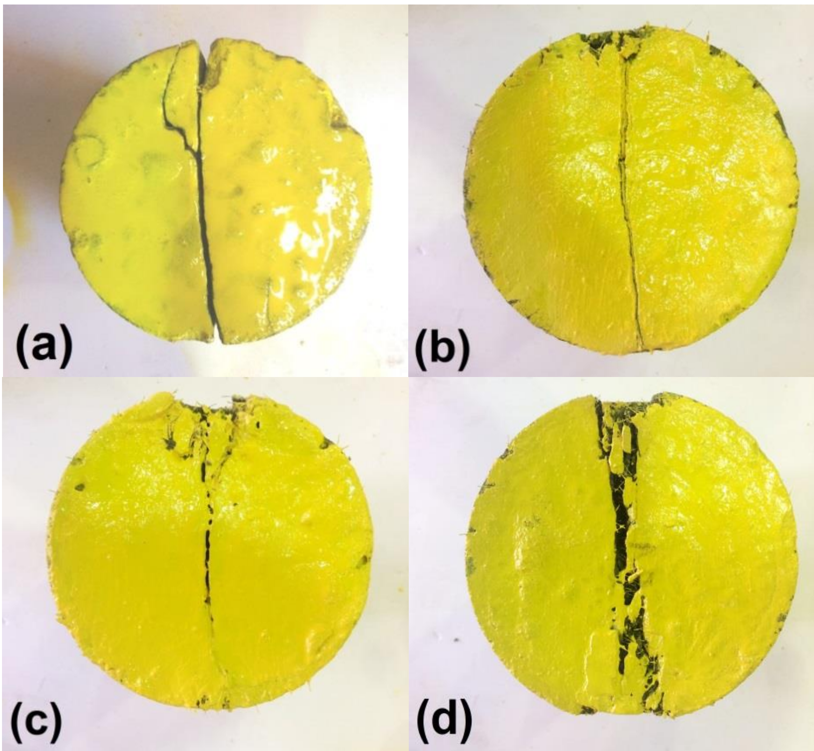

Figure 7 Typical failure mode of RPC specimens under the splitting test: (a) RPC0, (b) RPC1, (c) RPC2 and (d) RPC3

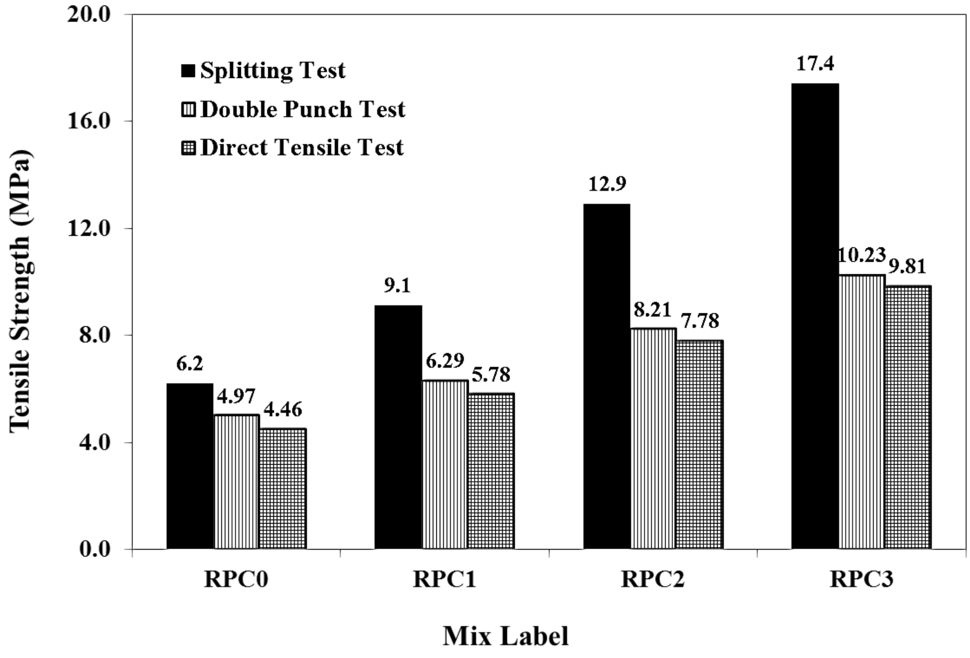

Figure 8 Average 28-day tensile strengths of RPC mixes

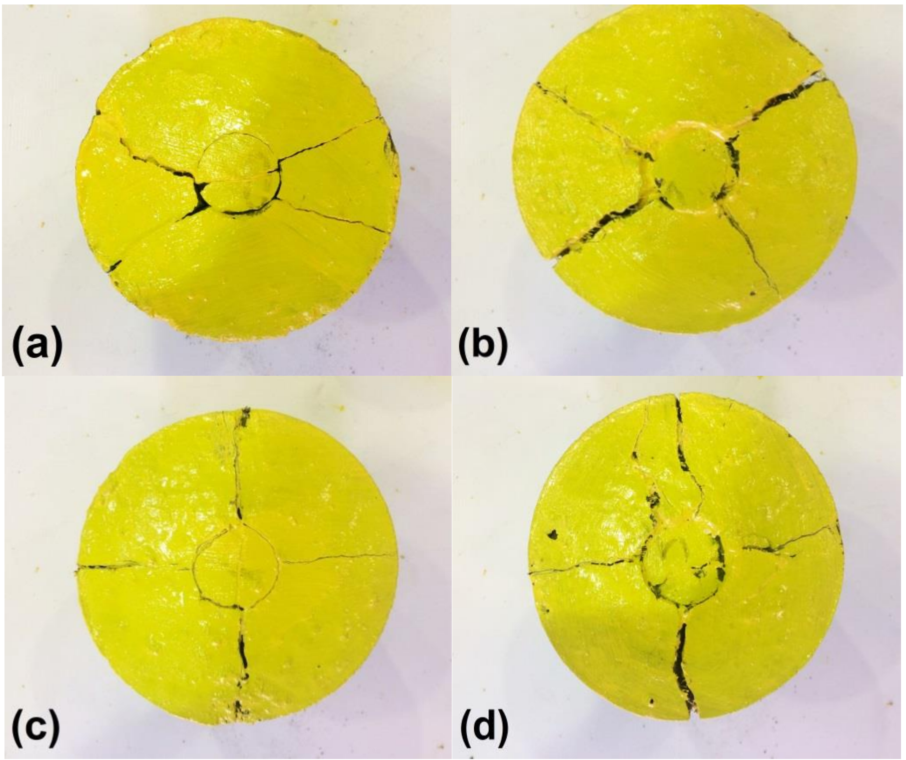

Figure 9 Typical failure mode of RPC specimens tested under the Double Punch Test (DPT): (a) RPC0, (b) RPC1, (c) RPC2 and (d) RPC3

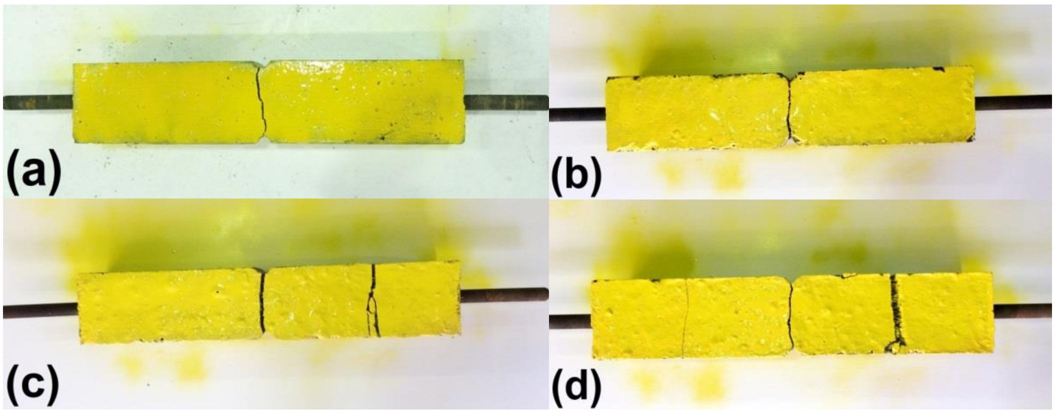

Figure 10 Typical failure mode of RPC specimens tested under the DTT: (a) RPC0, (b) RPC1, (c) RPC2 and (d) RPC3

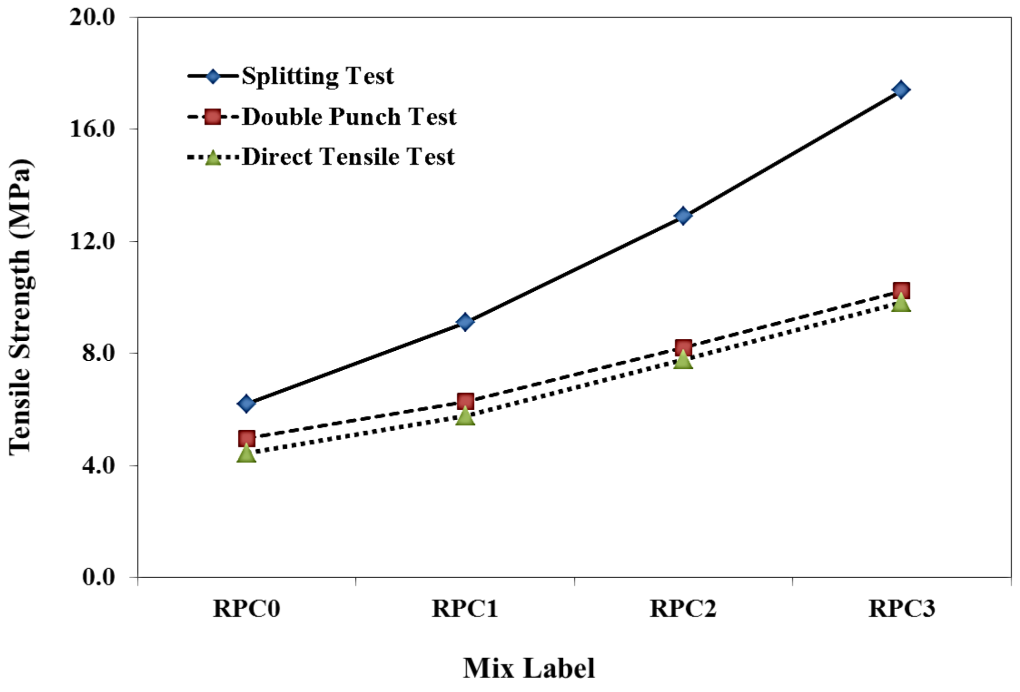

Figure 11 Comparison between the tensile strength of different test methods

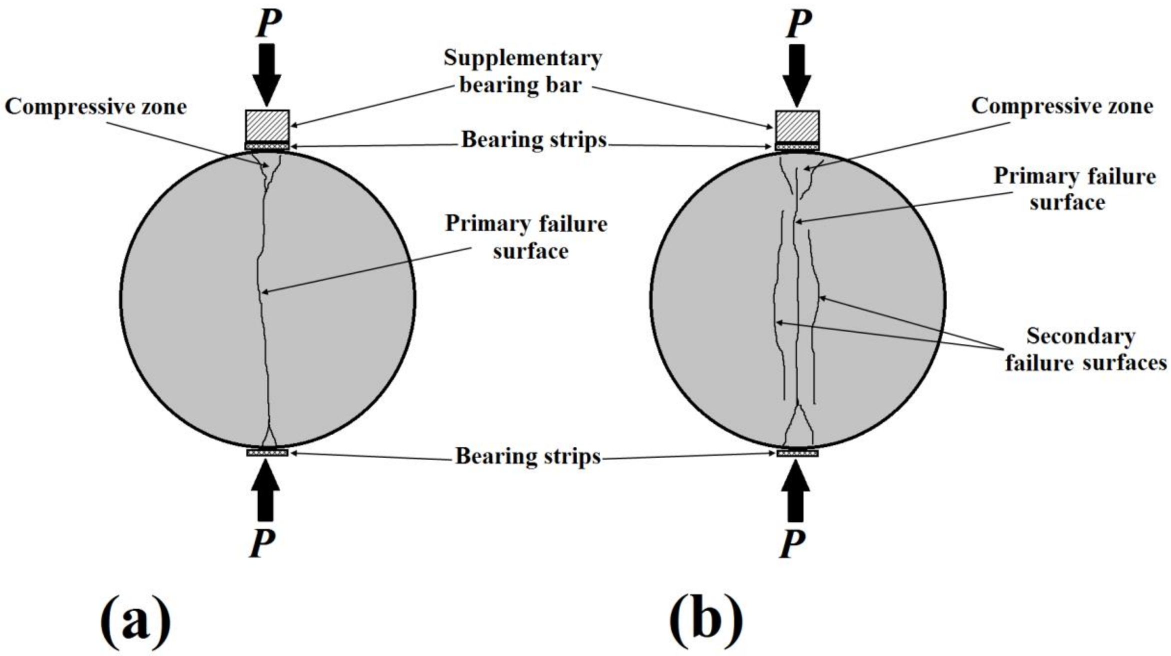

Figure 12 Crack pattern in splitting test of RPC specimens: (a) without steel fiber and (b) with steel fiber

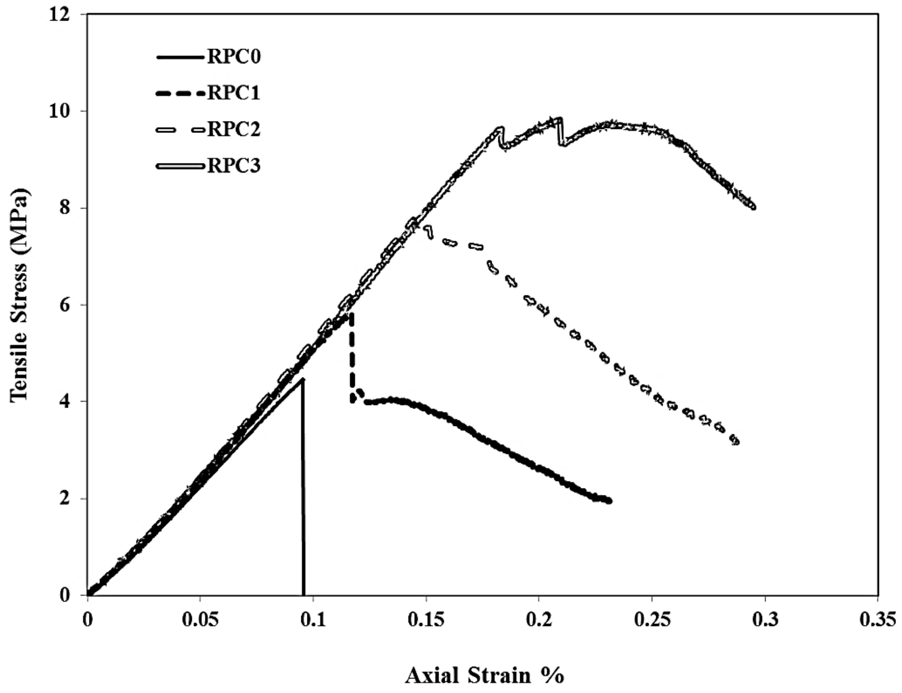

Figure 13 Typical axial tensile stress-strain curves of RPC mixes