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Statistical variations in the impact resistance and mechanical properties of polypropylene fiber reinforced self-compacting concrete

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Abstract. Extensive experimental studies on remarkable mechanical properties Polypropylene Fibre Reinforced Self-compacting Concrete (PFRSCC) have been executed, including different fibre volume fractions of Polypropylene fibers (0.25%, 0.5%, 0.75%, and 1%) and different water to cement ratios (0.21, 0.34, 0.38, and 0.41). The experimental program was carried out by using two hundred and sixteen specimens to obtain the impact resistance and mechanical properties of PFRSCC materials, considering compressive strength, splitting tensile strength, and flexural strength. Statistical and analytical studies have been mainly focused on experimental data to correlate of mechanical properties of PFRSCC materials. Statistical results revealed that compressive, splitting tensile, and flexural strengths as well as impact resistance follow the normal distribution. Moreover, to correlate mechanical properties based on acquired test results, linear and nonlinear equations were developed among mechanical properties and impact resistance of PFRSCC materials.

Keywords: mechanical properties; Polypropylene Fibre Reinforced Self-compacting Concrete (PFRSCC); statistical data analysis; probability distribution; regression analysis

1. Introduction

The main weakness of plain concrete is known to be easily cracked under low-level tensile stress due to low resistance of plain concrete under tensile loading. To enhance the tensile properties of concrete, fibres are incorporated in to concrete. Reinforcement of fibres not only improves tensile properties of concrete, but also improves other properties of concrete such as fracture toughness, impact strength, durability (Bayramov *et al*. 2004, Banthaia *et al*. 2005, Li *et*

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al. 2001, Nelson *et al*. 2002, Balendran *et al*. 2002, Balaguru *et al*. 2004). This improvement is dependent on factors such as the amount of fibre, type of fibre, mechanical properties of fibre etc. These factors are effective on both the load transfer process from the matrix to the fibre and the bridging effect across the cracks (Banthia 1987). Polypropylene (PP) fibres due to possess various geometries, nonhazardous nature, renewability, lower cost, and biodegradability, the utilization of these fibres is going to be noteworthy. However, further research is required to study the performance of this fibre as reinforcement of cementitious composites (Duzgun *et al*. 2005, Song *et al*. 2004, Koksal *et al*. 2008, Dhonde *et al*. 2007, Sahmaran *et al*. 2007, Mohammadi *et al*. 2008, ACI 363 1992). In this regard, various studies have been executed by using PP fibre to improve mechanical properties of concrete (Badr *et al*. 2006, Mohammadi *et al*. 2009, Rahmani *et al*. 2012, Ghasemi *et al*. 2014a, Sadrmomtazi *et al*. 2010). It worth stating that there are various methods to improve the mechanical properties of concrete in addition to reinforcement of concrete such as replacement of nano-particles and waste materials instead of Portland cement (Pacheco-Torgal *et al*. 2012a, Pacheco-Torgal *et al*. 2012b, Pacheco-Torgal *et al*. 2012c, Ghasemi *et al*. 2014b, Soon *et al*. 2014, Chaohua *et al*. 2014, Soon *et al*. 2013).

Fakharifar *et al*. in 2014 studied on mechanical properties of PP fibre reinforced concrete. They showed that specimens reinforced with 0.5% PP fibre have the highest rate of gaining flexural strength, while specimens with 1% and 0.5% PP fibre content showed the best performance in terms of the first crack and the ultimate impact resistance, respectively (Fakharifar *et al*. 2014). Moreover, Mindess *et al*. showed that concrete containing 0.5% volume fraction of PP fibre increased the maximum bending load by 40% and the fracture energy was approximately doubled (Mindess *et al*. 1988). In the meantime, compressive strength and tensile strength are two important indices used for characterizing concrete mechanical properties. To design structural cementitious elements, using mechanical properties of concrete is necessarily required. Therefore, various studies have been implemented to correlate the mechanical properties of different reinforced and plain concretes (ACI318 1999, CEB-FIP 1991, Arioglu *et al*. 2006, Zain *et al*. 2002, Oluokun 1991, Ahmad *et al*. 1985, Xu *et al*. 2009). According to the authors´ best knowledge, there are two studies reported in (Rahmani *et al*. 2012, Fakharifar *et al*. 2014) about correlation of the mechanical properties of PP fibre reinforced concrete. Rahmani *et al*. correlated impact resistance of PP fibre reinforced concrete specimens to compressive strength, while Fakharifar *et al*. correlated flexural strength and the impact resistance of specimens to compressive strength (Rahmani *et al*. 2012, Fakharifar *et al*. 2014). Both of implemented studies did not cover the correlation of all necessarily required mechanical properties of PP fibre reinforced concrete (Compressive, tensile, flexural, and impact).

In this regard, in the present study, mechanical properties of PP reinforced self-compacting concrete (SCC) were correlated together, including compressive strength, tensile strength, flexural strength, and impact resistance on two hundred and sixteen specimens tested experimentally and the obtained results statistically analysed. Then, the developed empirical relations among mechanical properties through various sources used for the experimental data in order to compare the available experimental data and predicted data with using the developed empirical relations. Finally, equations based on nonlinear and linear regression analysis developed to establish relationship among mechanical properties of PP fibre reinforced self-compacting concrete (SCC). Effect of fibre contents and water to cement ratios on the correlation of mechanical properties of PP fibre reinforced self-compacting concrete is not completely characterized yet. Implementation of experimental/statistical study leads to achieve a better understanding of the impact resistance and mechanical properties of PP fibre reinforced self-compacting concrete, including different

Table 1 Mixture proportions of concrete (kg/m^3)

Specimens designation	W/C	Cement	Polypropylene fiber (Vol._%)	Fine aggregate	SP
PFRSCC0	0.27 0.34 0.38 0.41	980	0	980	3
PFRSCC0.25			0.25		
PFRSCC0.5			0.5		
PFRSCC0.75			0.75		
PFRSCC1			1		

Table 2 Mechanical properties of polypropylene fibers

Length (mm)	Diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Density (kg/m^3)
12	0.018	800	10	910

fibre contents and water to cement ratios. Thus, a relatively large test matrix was developed by the authors to further investigate the correlation among mechanical properties. Two hundred and sixteen specimens total, that is significantly larger than test matrices in similar studies to provide a reliable baseline for statistical analyses, were cast, prepared and tested to achieve this aim.

2. Procedure of experimental program

2.1 Materials

Portland cement 42.5R, fine aggregate, water, and a water reduction from 10-15% at small dosage rates, and achieve water reduction up to 30% at high dosage rates were used to adjust the workability of the concrete mixtures.

Tables 1 and 2 present the cement compositions and mechanical properties of PP fibres, respectively. Distribution of fine aggregate and used PP fibre are depicted in Fig. 1 and Fig. 2a, respectively.

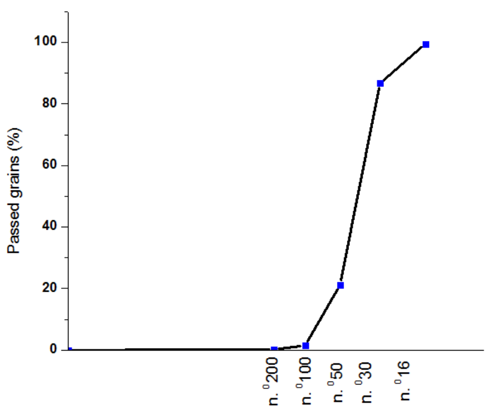
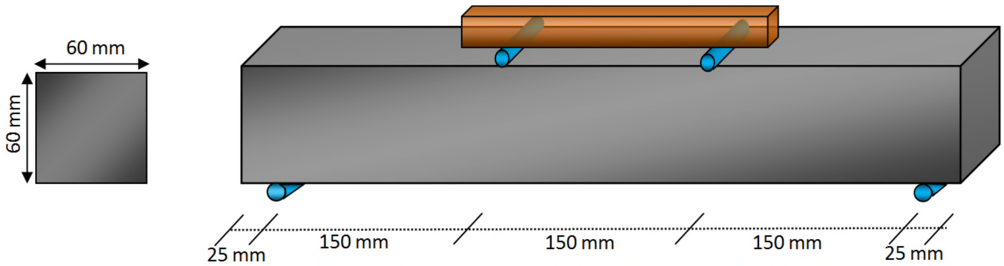


Fig. 1 Distribution of Fine aggregate

(a) (b)

Fig. 2 (a) The used PP fiber; (b) Flow slump test

(a)



(b)

Fig. 3 (a) Some de-molded specimens for execution of the impact and mechanical tests; (b) Schematic view of FPB test setup

During the batching process, cement was mixed with fine aggregate for 1 minute. The water and super plasticizer were then added, and mixed for another 6-8 minutes. Finally, the concrete-fibres mixtures were prepared by gradually adding the fibres to the fresh self-compacting concrete while mixing. The fibre was added enough to reach the desired percentage of fibre volume. In order to avoid balling, PP fibres were added slowly to concrete while the mechanical mixer was rotating. Homogeneity of the mixture was assessed visually.

The slump flow test and the V funnel test were used to assess the fresh-state behaviour of plain self-compacting concrete (Alberti *et al*. 2015, EN 12350-8 2010, EN 12350-9 2010). Therefore, to attain the properties of fresh state self-compacting concrete, these tests were conducted and for slump flow test T_{500} and d_f were recorded 5 (s) and 580 mm, respectively (see Fig. 2b). Moreover, Tv was registered 10 (s) for V funnel test. Following the casting of specimens for each designed test, the specimens were de-molded after 24 hours and cured in water for 28 days. All specimens were prepared to test at age of 28 days. Fig. 3a represents de-molded specimens for flexural and impact tests.

2.2 Procedure of experimental tests

2.2.1 Compressive and split tensile tests

Respect to the mix compositions, listed in Table 1, 54 cubic specimens with dimensions of 100 ×100×100 mm^3 were cast and tested for assessment of compressive strength of specimens with PP fibre. Moreover, three cylinders with 150 mm diameter and 300 mm height were cast and tested to register tensile strength of specimens of each listed mix composition in Table 1. Rate of applying the displacement was applied 0.016 N/mm^2 s based on (ASTM C496 1994). In this study, the representative results for mechanical and impact properties of specimens are average of three tested specimens. To compute the splitting tensile strength following equation was used (Mastali *et al*. 2015)

$$\sigma_{xx} = \frac{2P}{\pi l D} \tag{1}$$

where, D is diameter of the cylindrical specimens, l is length of cylindrical specimens, and P is value of the point loads.

2.2.2 Flexural four point bending (FPB) tests

To assess the flexural performance of PP reinforced specimens, 54 beams with dimensions of 60×60×500 mm^3 were cast and tested under 0.45 mm/min loading rate. The prismatic beams were loaded to obtain a shear span to the depth ratio equal to or greater than 2.5 ($2.5 \leq \frac{a}{d}$, where "a" is a shear span and equal to 150 mm in Fig. 3 and d is depth of beams, equal to 60 mm). Providing a shear span to depth ratio equal or greater than leads to attain flexural failure in the beams (Mastali *et al*. 2016, Brandt *et al*. 2012).Moreover, the test setup that was adopted for execution of these tests is depicted in Fig. 3b. A Linear Variable Differential Transformer (LVDT) of 20 mm stroke was used to record mid-span deflection.

2.2.3 Drop weight tests

The adopted drop weight impact apparatus is depicted in Fig. 4. According to the displayed test setup, a steel hammer with weight of 4.45 kg drops from a height of 457 mm on a steel ball with diameter of 63 mm. This steel ball is in contact with central surface of the specimens. Totally, 54 cylinders with diameter of 150 mm and height of 65 mm were cast, prepared, and tested at age of 28 days. The following equation was given for calculation of energy absorption

$$\text{Impact energy } (E_n) = N \times m \times g \times H \quad (2)$$

Where N is number of blows, m is mass of the ball, g is 9.81 m/s^2, and H is height of the fall.

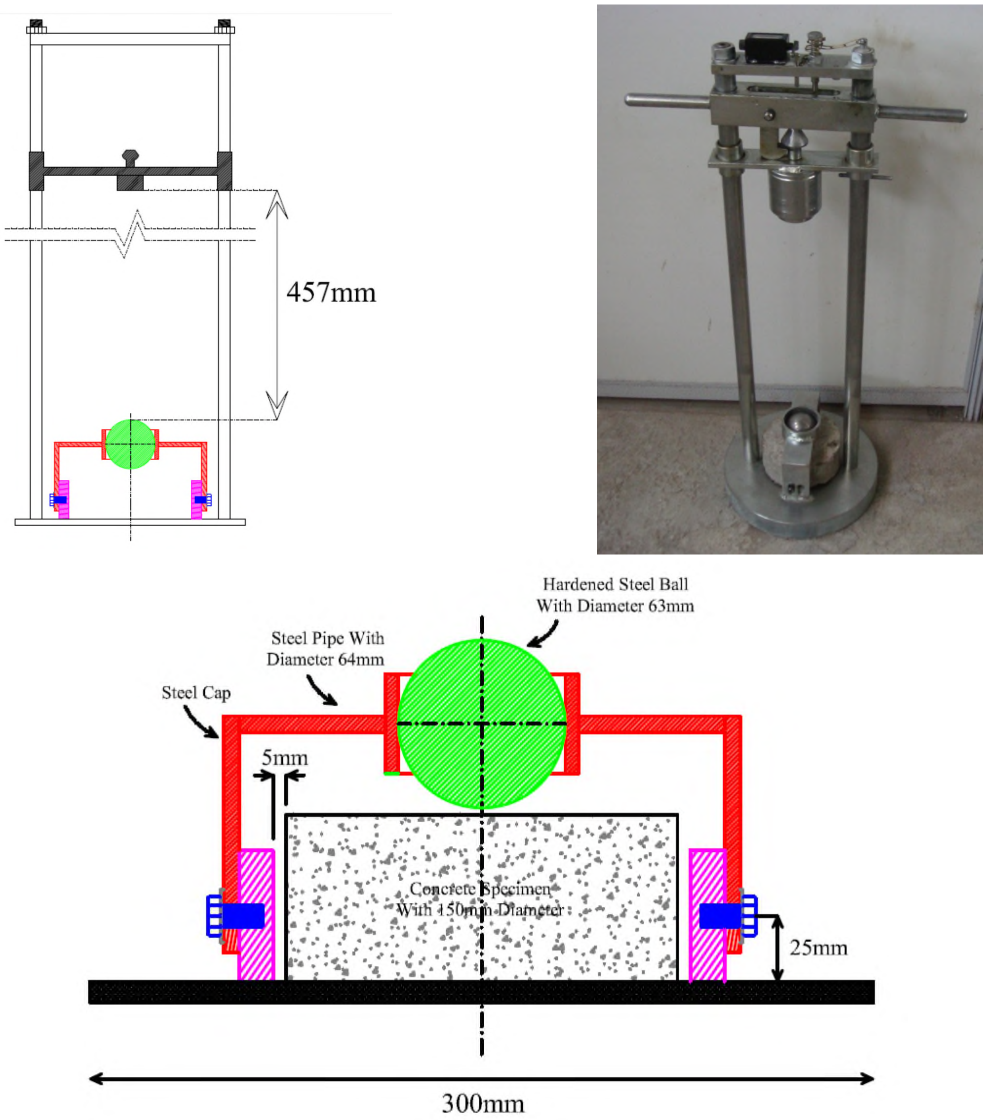


Fig. 4 Adopted test setup for drop weight impact test

3. Interpretation of experimental results

3.1 Compressive test

Concerning the gathered results in Fig. 5, increasing fibre content led to increase compressive strength due to action of PP fibres as crack arresters, so that regardless of water to cement ratio the

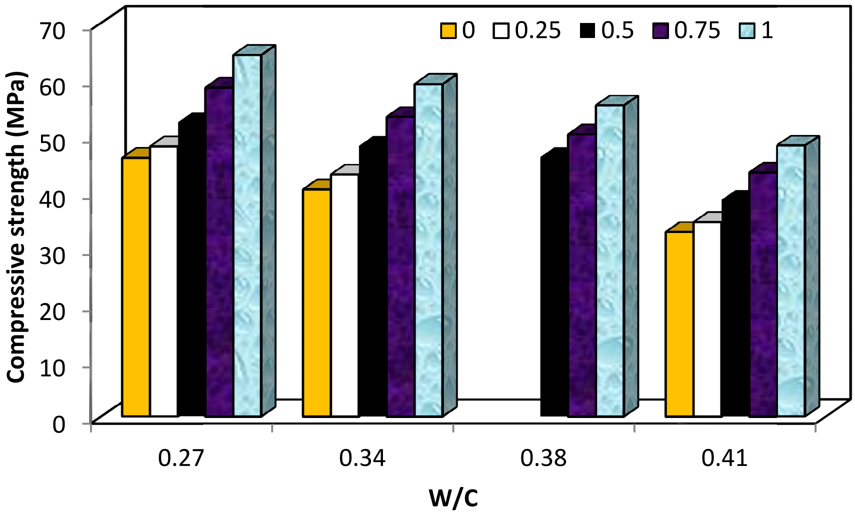


Fig. 5 Compressive strength of fiber reinforced and plain self-compacting concrete with different water to cement ratios

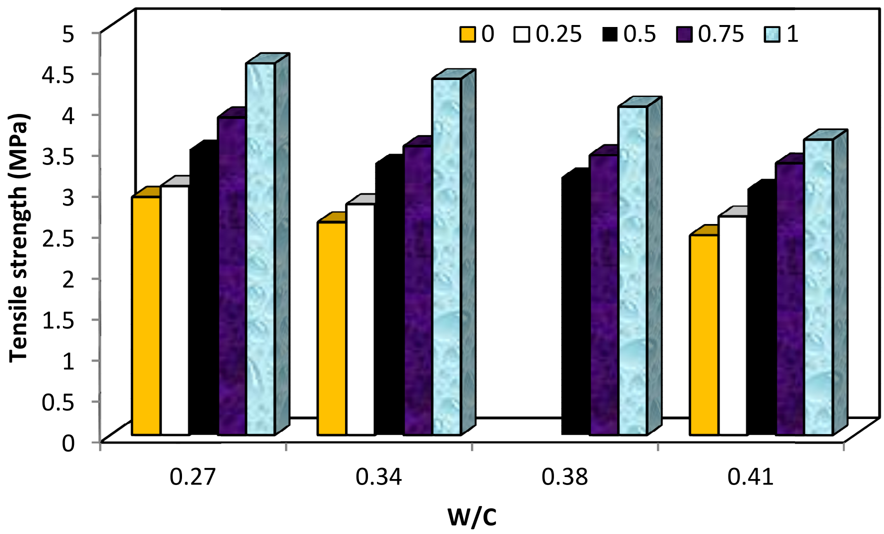


Fig. 6 Splitting tensile strength of fiber reinforced and plain self-compacting concrete with different water to cement ratios

maximum and minimum compressive strengths recorded for mixture with 1% and 0% PP fibre, respectively. Moreover, regardless of fibre content, increasing water to cement ratio results to decrease compressive strength. It can be derived from formation of coarse pore distribution, reduced void volume/solid volume, and weaker interfacial bond between PP fibre and matrix. Therefore, decreasing water to cement ratio from 0.41 to 0.27 in addition to reinforcement of plain concrete with 1% PP fibre led to attain 95.91% increase of compressive strength.

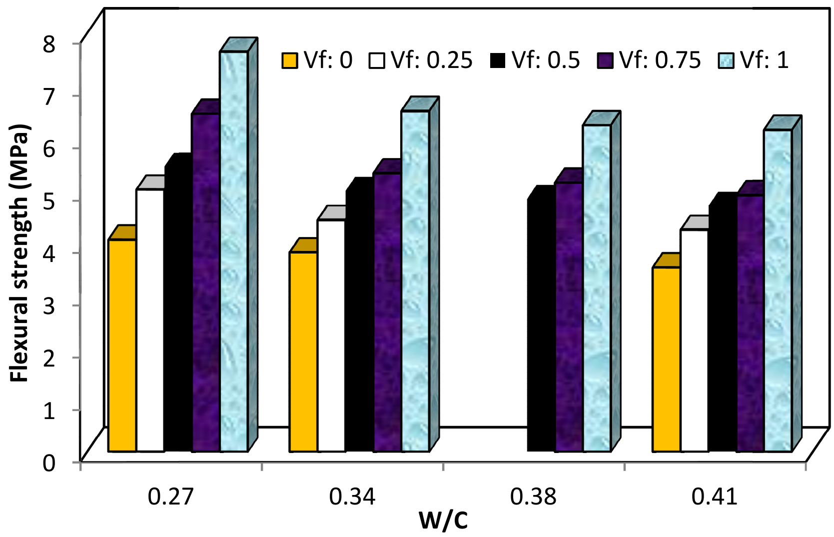


Fig. 7 Flexural strength of fiber reinforced and plain self-compacting concrete with different water to cement ratios

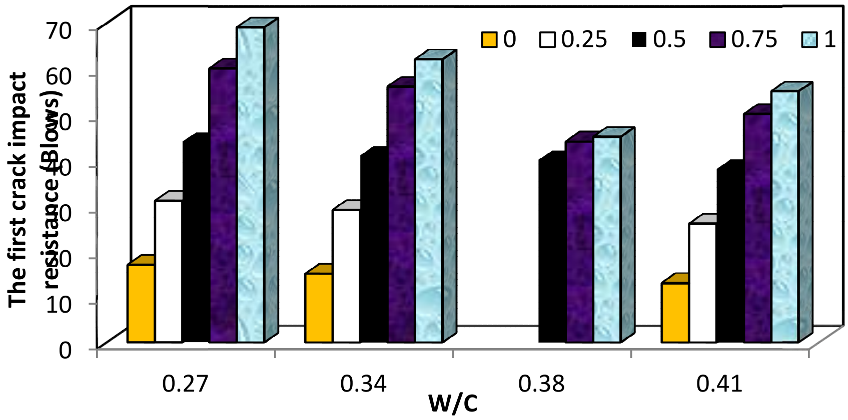
3.2 Tensile test

Fig. 6 presents the recorded tensile strength of specimens. Increasing fibre content led to increase tensile strength due to bridging action of PP fibres. Tensile strength was increased by transferring of tensile stress from fibre to matrix, as well as increasing PP fibre content from 0 to 1% is intensified by transferring tensile stress from fibre to matrix, so that the maximum efficiency of fibre bridging is attained in each mix composition with 1% fibre content, regardless of water to cement ratio. Moreover, regardless of fibre content, increasing water to cement ratio results to decrease tensile strength due to form weaker interfacial bond between PP fibre and matrix, so that the maximum efficiency of fibre bridging is achieved in the mix composition with water to cement ratio of 0.27.

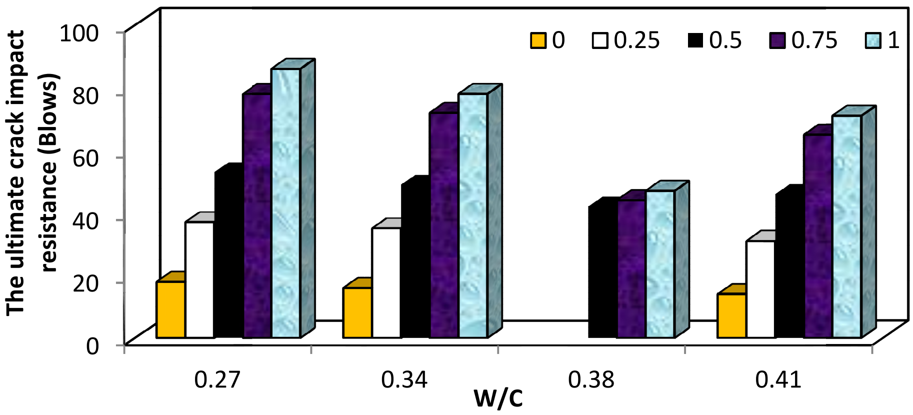
Thus, respect to gathered results in Fig. 6, it can be observed that decreasing water to cement ratio from 0.41 to 0.27 in addition to reinforcement of plain self-compacting concrete with 1% PP fibre led to attain 86.06% increase of tensile strength.

3.3 Flexural test

The flexural behaviour of prismatic beams is depicted in Fig. 7. Like tensile and compressive behaviour of specimens, regardless of water to cement ratio, increasing fibre content led to increase flexural strength due to bridging action of PP fibres. Furthermore, regardless of fibre content, increasing water to cement ratio results to decrease flexural strength due formation of coarse pore distribution and weaker interfacial bond between PP fibre and matrix. Therefore, the maximum flexural strength was detected about 7.5 MPa in the specimens of PFRSCC1 with highest fibre content (1%) and the lowest water to cement ratio (0.27). Since, the maximum efficiency for combination of decreasing water to cement ratio and increasing fibre content was



(a)



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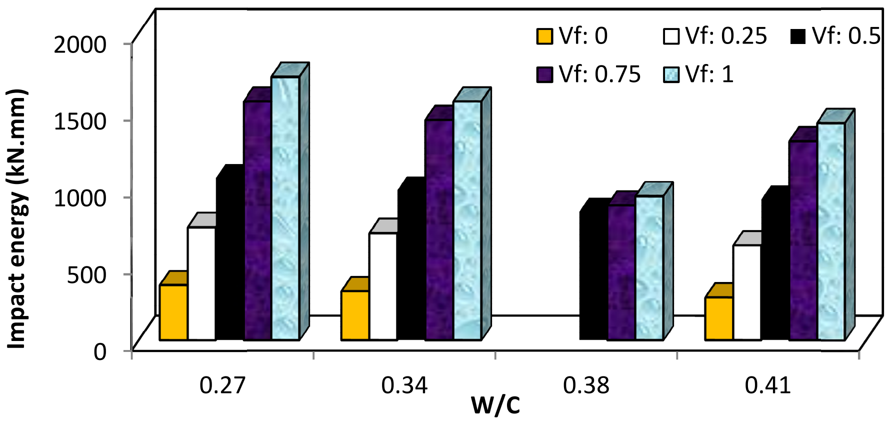


(c)

Fig. 8 Impact resistance of fiber reinforced and plain self-compacting concrete with different water to cement ratios for: (a) The first crack impact resistance; (b) The ultimate impact resistance; (c) Impact energy

Fig. 9 Formed crack patterns in the cementitious disk specimens with water to cement ratio of 0.27

recorded more than 2 times in the specimens PFRSCC1 with water to cement ratio of 0.27 when compare to PFRSCC0 with water to cement ratio of 0.41.

3.4 Impact test

The drop weight impact was implemented on 54 cementitious disk specimens and its average results for the first crack impact resistance, the ultimate failure crack resistance, and impact energy is depicted in Fig. 8. According to the indicated results, both increasing fibre content and decreasing water to cement ratio results to increase of the first crack impact resistance. Except specimens of PFRSCC0.75 and PFRSCC1 with water to cement ratio of 0.38 which leads to decrease of the first crack impact resistance, while the trend of increase of the first crack impact resistance due to both increasing fibre content and decreasing water to cement ratio followed for specimens of PFRSCC0.5. This debility in increasing the first crack impact resistance for PFRSCC0.75 and PFRSCC1 may be derived from unfavourable randomly distribution of PP fibre and geometry of specimens. Since, these unfavourable effects led to provide debility in increasing the ultimate crack impact resistance for all mix compositions with water to cement ratio of 0.38 regardless of fibre content. It is worth stating that small numbers of blows were recorded for the first and ultimate crack impact resistance of specimens PFRSCC0 and PFRSCC0.0.25 under impact test, therefore, this information did not mention in the paper. The combination effects of increasing fibre content and decreasing water to cement ratio results to increase more than 5 and 6 times more the first crack impact resistance and the ultimate failure impact resistance, respectively in specimens of PFRSCC1 with water to cement ratio 0.27 compare to PFRSCC0 with water to cement ratio 0.41.

Fig. 9 presents the formed crack patterns on some tested specimens with water to cement ratio of 0.27. Increasing fibre content resulted to form more cracks on the surface of specimens, as

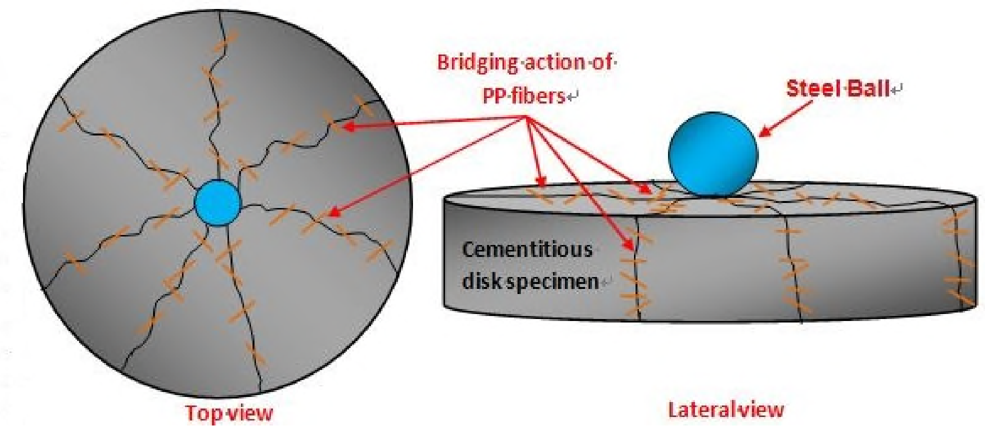
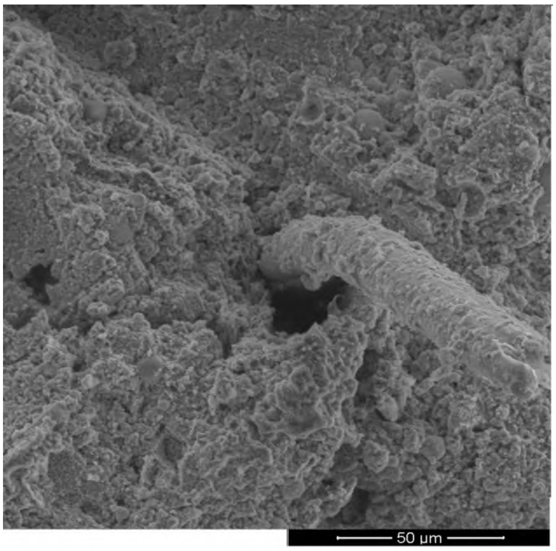


Fig. 10 Bridging across the micro-cracks developed in cracking region of cementitious disk specimens under drop weight impact test



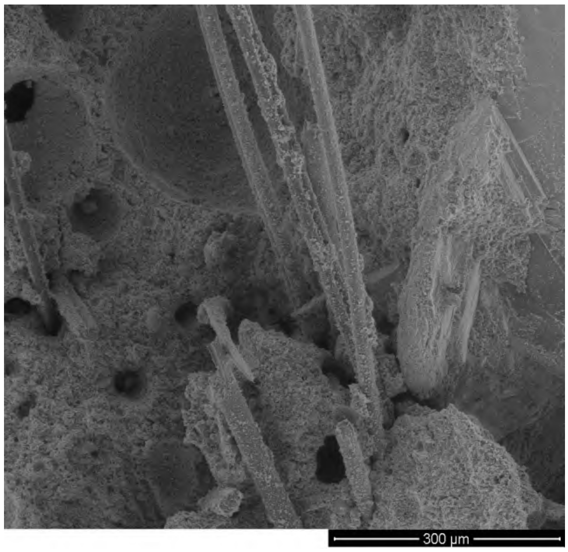


Fig. 11 SEM image from predominant failure mode for the PP fibers

shown in Fig. 9. Forming new cracks are consequences of fibre bridging action. This action involved interface slip-dependent friction as well as snubbing friction for fibres bridging at inclined angles.

Outer surface of PP fibre is nearly smooth, therefore, weak bond is formed between fibre/matrix. Moreover, variation of water to cement ratio influences the interface behaviour of slip-dependent friction, so that mix compositions with water to cement ratio of 0.27 provide higher slip strengths between PP fibres and matrix in compare to mix compositions with water to cement ratio of 0.41. Thus, it can be concluded that slip stress between fibre and matrix is increased up to its maximum slip stress in mix compositions with water to cement ratio of 0.27. Above the slip strength, PP fibres debonded from its surrounded matrix. This interface behaviour of slip-dependent friction is also occurred for mix compositions with water to cement ratio of 0.41, the only difference is derived from the slip strength value which this value for mix compositions with water to cement ratios of 0.27 is higher.

In addition to effect of water to cement ratio on the interface behaviour of slip-dependent friction, fibre content of PP is also an effective parameter on crack arresting and fibre bridging action between PP fibre and matrix, as shown in Fig. 10, so that increasing PP fibre content results to increase arresting and fibre bridging action between PP fibre and matrix. Therefore, increasing PP fibre content concludes to improve mechanical properties of specimens.

SEM images were used to better understand the fibre reinforcement mechanisms provided by the hydrophilic PP fibres. As shown in Fig. 11, due to the desirable bonding between PP fibres to cement based materials, surface of the fibres is almost covered by cement hydrated particles. The SEM images obtained in the fracture surface of the tested specimens show a tendency for PP fibres, which have preponderantly failed by debonding (Fig. 11).

4. Statistical and analytical analysis

4.1. Statistical analysis

This part has been assigned to discuss about probability distributions of compressive strength, tensile splitting strength, flexural strength, and impact resistance of fibre reinforced self-compacting concrete. To implement the statistical calculations, the statistical computer program OriginLab was used to find probability distributions of mechanical properties as well as impact resistance of fibre reinforced concrete. Additionally, the Kolmogorov–Smirnov (K-S test), Shapiro-Wilk, and Anderson–Darling methods were used to test normality of the data. The Kolmogorov-Smirnov test is concentrated on the maximum deviations between the observed cumulative histogram and the hypothesized cumulative distribution function (Benjamin *et al.* 1970). This goodness of fit test examines whether or not the observations could reasonably have come from the normal distribution. In all three methods, a p-value is obtained which quantifying the strength of the evidence against the null hypothesis. A p-value smaller than 0.05 means the null hypothesis (that the distribution is normal) is rejected. The hypotheses for the normal distribution are as follows:

H_{o1}. The compressive strength of fibre reinforced self-compacting concrete follows the normal distribution;

H_{o2}. The tensile strength of fibre reinforced self-compacting concrete follows the normal distribution;

H_{o3}. The flexural strength of fibre reinforced self-compacting concrete follows the normal distribution;

H_{o4}. The first crack impact resistance of fibre reinforced self-compacting concrete follows the normal distribution;

H_{o4}. The ultimate impact resistance of fibre reinforced self-compacting concrete follows the normal distribution;

H_a. Not $H_{o1,\ 2,\ 3,\ 4.}$

The obtained p-values for the above tests are listed in Table 3 which all values are greater than 0.05. This confirms the null hypothesis at the 0.05 significance level, which means the compressive strength, tensile strength, flexural strength, the first crack impact resistance, and ultimate impact resistance of fibre reinforced self-compacting concrete follow the normal

Table 3 p-values for the normality test of data

	Compressive strength	Tensile strength	Flexural strength	First crack resistance	Ultimate crack resistance
SW*	0.986	0.754	0.636	0.725	0.453
KS**	0.999	0.999	0.998	0.999	0.998
AD***	0.984	0.846	0.540	0.830	0.539

SW: Shapiro-Wilk*
*KS**: Kolmogorov–Smirnov*
*AD***: Anderson–Darling*

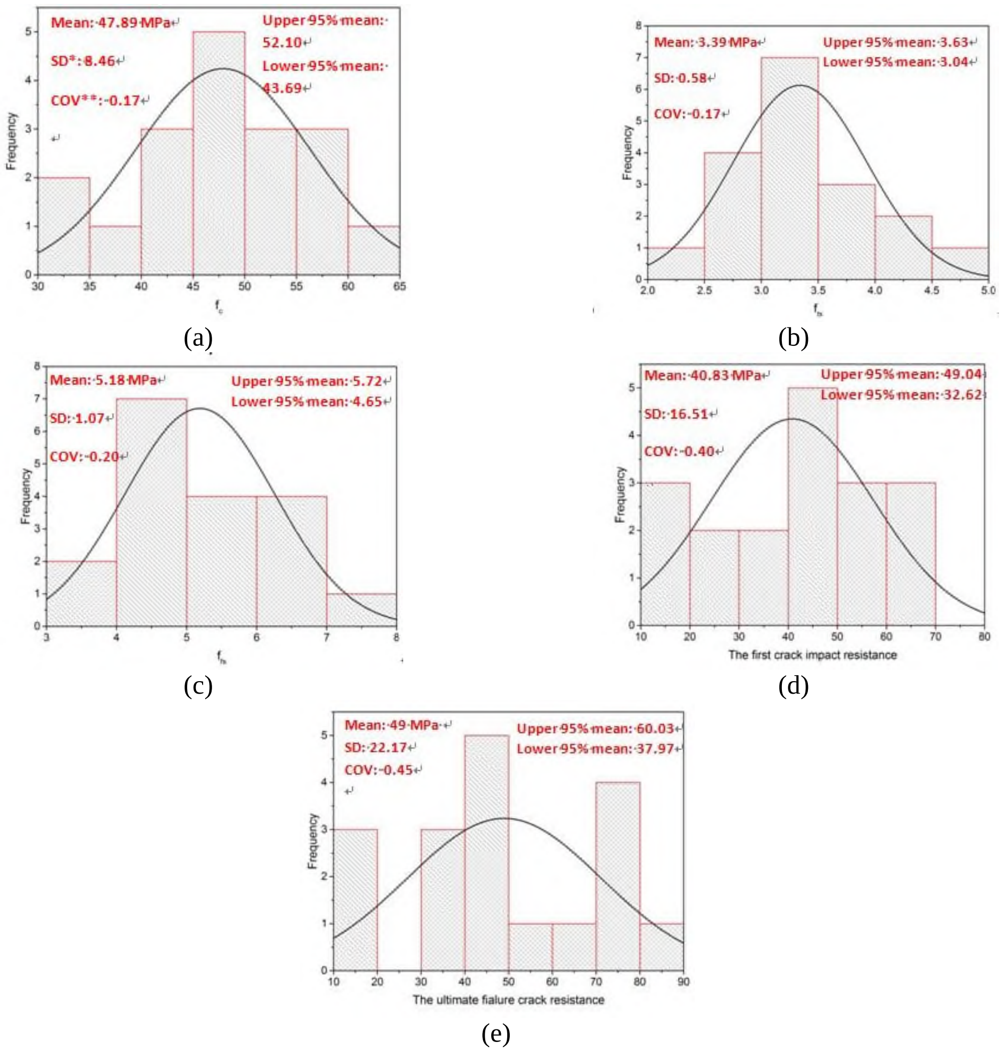


Fig. 12 Statistical parameters and probability distributions for: (a) Compressive strength; (b) Tensile strength; (c) Flexural strength; (d) The first crack impact resistance; (e) The ultimate crack impact resistance

SD: Standard Deviation*
*COV**: Coefficient of variation*

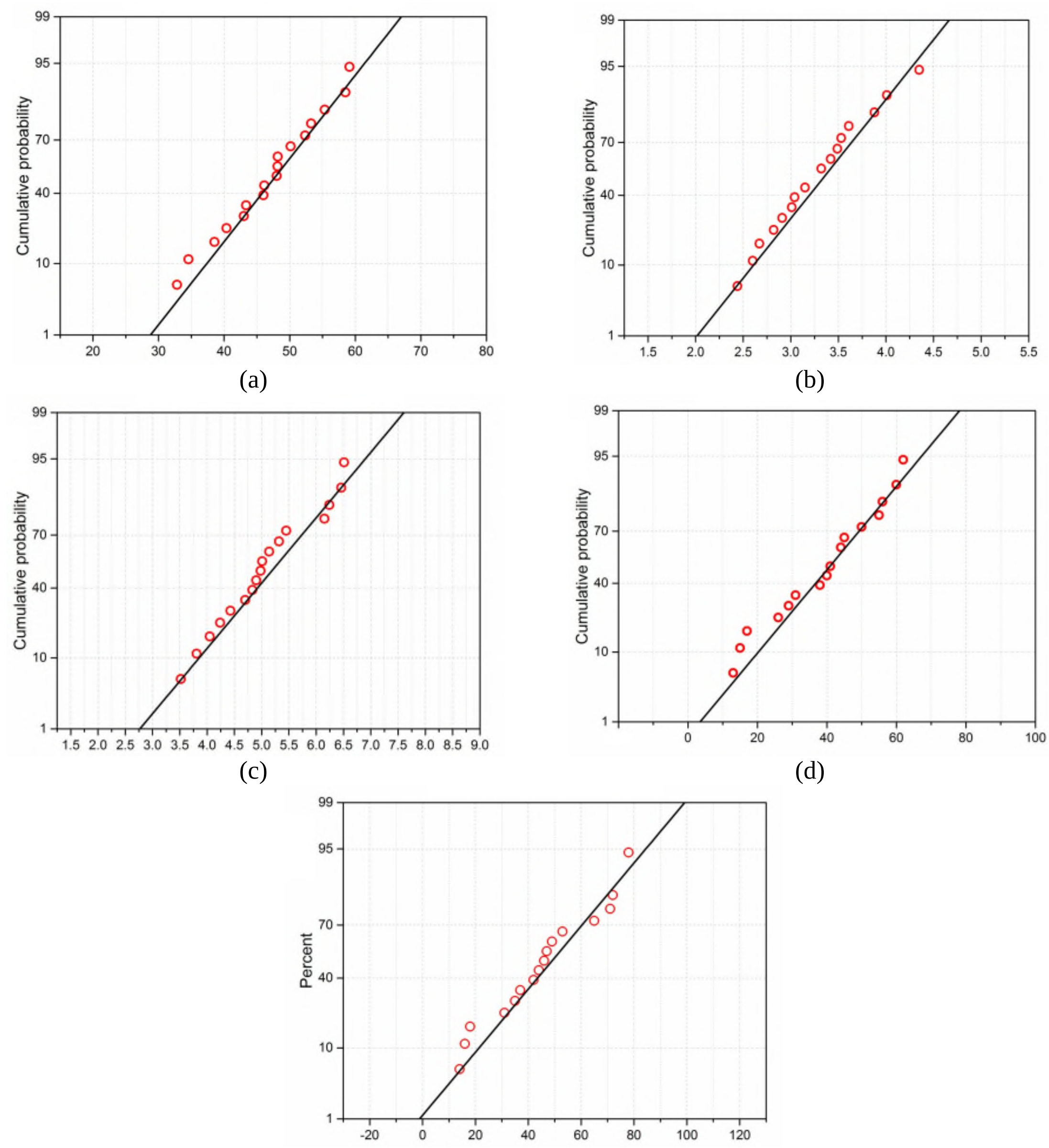


Fig. 13 Normal probability plots for: (a) Compressive strength; (b) Tensile strength; (c) Flexural strength; (d) The first crack impact resistance; (e) The ultimate crack impact resistance

distribution. It is worth stating that the compressive strength, tensile strength, flexural strength, and the first crack impact resistance of the specimens fit better to the normal distribution compared with the ultimate crack impact resistance and flexural strength of the specimens.

Mechanical properties of PFRSCC could be affected by many factors, which mainly include specimen geometry, curing time, water/cement ratio (w/b), types of cement and supplementary cementitious material, PP fibre geometry, aspect ratio, volume fraction, etc. In this regard, all obtained experimental data in this study used to approach a global probability distribution for impact resistance and mechanical properties of PFRSCC specimens.

Fig. 12 presents the histogram of compressive strength, tensile strength, flexural strength, the first crack impact resistance, and ultimate impact resistance for specimens. This figure depicts that the impact resistance and mechanical properties of PP fiber reinforced self-compacting concrete are normally distributed. Additionally, respect to gathered results in Fig. 12, it indicates that the first crack impact resistance had a mean about 41 blows, a standard deviation about 17 blows, and a coefficient of variation of 40%, while for the failure crack impact resistance, these statistical parameters were 49 blows, 22 blows, and 45%, respectively. The 95% confidence interval on the mean for the first crack impact resistance was about 33–50 blows, and that of the failure crack impact resistance, 38-60 blows.

The normal probability curves for mechanical properties of PFRSCC specimens are presented in Fig. 13. As seen, the nearly linear pattern of the data points in Fig. 13 implying that the mechanical properties of PFRSCC specimens were normally distributed.

The coefficient of variation (COV) of the test results, presented in Fig. 13 can be employed to determine the minimum replication number of tests ‘‘n’’, required for ensuring that the percentage error “e” in the measured average value is below a specified limit. This number of tests can be calculated using equation (3) (Swamy *et al*. 1976)

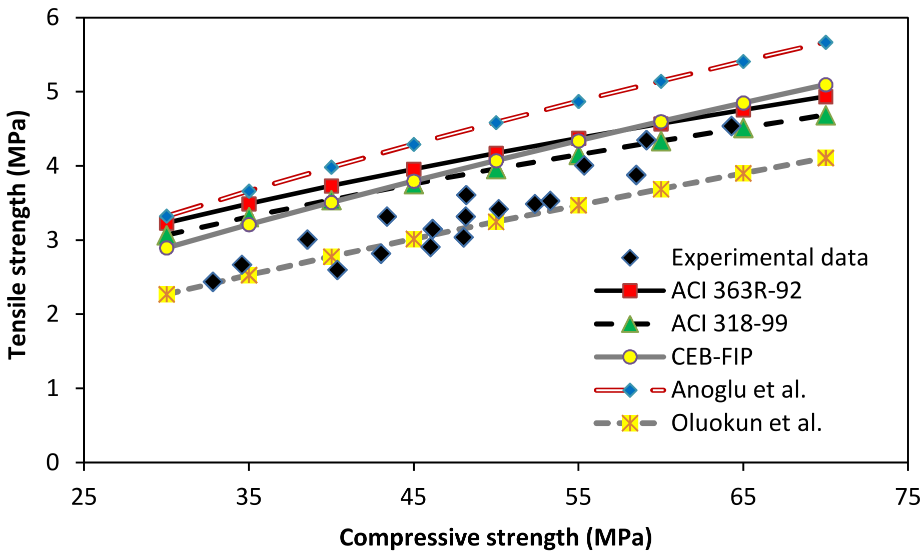
$$n = \frac{[COV]^2 t^2}{e^2} \tag{3}$$

Where, t is the value of Student t-distribution for the specified level of confidence (Fakharifar *et al*. 2014). The value of Student t-distribution ‘‘t’’ depends on the level of confidence and the degree of freedom, which is related to the number of samples. For degrees of freedom more than 120, the value of “t” approaches to 1.645 and 1.282 at 95% and 90% level of confidence, respectively (Box *et al*. 1978, Moore *et al*. 1989). The minimum number of replications required to keep the error under specified limits at the 90% level of confidence for tested reinforced SCC specimens listed in Table 4. This table indicates that, if the error is retained lower than 10% for first crack impact resistance and the ultimate crack impact resistance, the minimum number of required replications would be 27 and 34, respectively at 90% level of confidence. Furthermore, if the error is retained lower than 10% for first crack impact resistance and the ultimate crack impact resistance, the minimum number of required replications would be 44 and 55, respectively at 95% level of confidence.

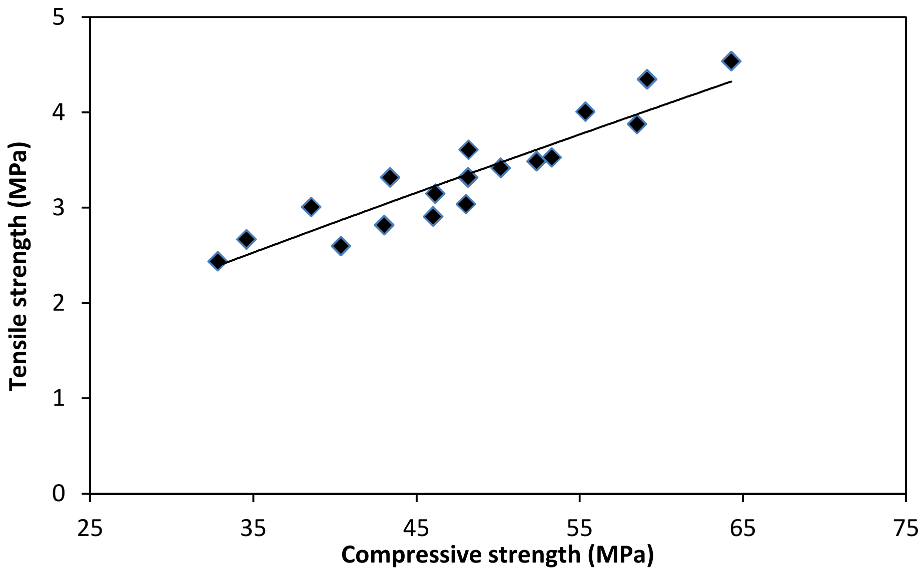
4.2 Analytical analysis

Table 4 Number of replications required to keep the error under a specified limit at 90% and 95% level of confidence

	<10	**<15**	**<20**	**<25**	**<30**	**<35**	**<40**	**<45**	**<50**	**Error (%)**
FC	44	20	11	7	5	4	3	3	2	**95% Level of confidence**
UC	55	25	14	9	7	5	4	3	3	
FC	27	12	7	5	3	3	2	2	2	**90% Level of confidence**
UC	34	15	9	6	4	3	3	2	2	



(a)



(b)

Fig. 14 (a) Comparison between experimental and predicted data for the published empirical relations between splitting tensile strength and compressive strength PFRSCC; (b) The proposed equation based on experimental data

Splitting tensile and flexural strengths can be computed based on compressive strength of concrete through various equations that proposed by different sources, while respect to the authors´ best knowledge, there are only two studies reported in (Rahmani *et al*. 2012, Fakharifar *et al*. 2014) about correlation of the mechanical properties of PP fibre reinforced concrete which did not cover all mechanical properties of PP fibre reinforced concrete. Thus, herein this study, it is

Table 5 Published empirical relations between compressive strength and splitting tensile strength of PFRSCC, and the corresponding IAE (%)

Sources	**ACI 363R-92 (1992)**	**ACI 318-99 (1999)**	**CEB-FIB (1991)**	**Anoglu *et al.* (2006)**	**Oluokun *et al.* (1991)**
Empirical relation	$f_{ts} = 0.59 f_c^{\,0.5}$	$f_{ts} = 0.56 f_c^{\,0.5}$	$f_{ts} = 0.3 f_c^{\,(\frac{2}{3})}$	$f_{ts} = 0.39 f_c^{\,0.63}$	$f_{ts} = 0.21 f_c^{\,0.7}$
IAE (%)	5.50	4.21	4.55	7.97	2.30

required to derive equations to correlate the mechanical properties of PP fibre reinforced self-compacting concrete based on the experimental database recorded in this study. Moreover, a comparative study was executed on the recorded experimental data based on the various empirical relations, which were proposed by different sources.

4.2.1 Compressive strength and splitting tensile strength

In general, the empirical relations can be summarized by the given equation

$$f_{ts} = \alpha (f_c)^{\beta} \tag{4}$$

where, f_{ts} is splitting tensile strength/flexural strength (MPa); f_{cs} is compressive strength (MPa); α and β are regression coefficients.

To provide a correlation between compressive strength and splitting tensile strength previously published empirical relations for PFRSCC, which presented in Table 5.

Additionally, to assess the deviation between experimental data and prediction curves shown in Fig. 14, integral absolute error (IAE) is employed, which is written

$$IAE = \Sigma \frac{[(Q_i - P_i)^2]^{0.5}}{\Sigma Q_i} \times 100 \tag{5}$$

Where, Q_i is experimental result; P_i is prediction result. Lower values of IAE indicate the reliability of the proposed equations to use for PFRSCC.

Fig. 14 indicates the comparison between the predicted and experimental data respect to the proposed equations that mentioned in Table 5. As indicated, the proposed equation by Oluokun *et al*. is better fitted to experimental data compare to other proposed equations. Moreover, the lowest value of its IAE (2.3%) confirms that the proposed equation is reliable to be used for PFRSCC as well as it has good agreement with experimental data.

In addition, regarding the general presented equation for correlating compressive strength and splitting tensile strength, an exponential equation based on nonlinear regression analysis was developed in Fig. 14b for recorded experimental data here in this study with high coefficient of determination (R^2=0.85) and low IAE value (1.48%). This result indicates the proposed equation has good agreement with experimental results and reliable to predict splitting tensile strength based on compressive strength of PFRSCC.

4.2.2 Compressive strength and flexural strength

The developed equations between compressive and flexural strengths of plain concrete are indicated in Table 6. Comparison between experimental data and prediction curves obtained

Table 6 Published empirical relations between compressive strength and flexural strength, and the corresponding IAE (%)

Sources	ACI 318R-95 (1999)	ACI 363R-92 (1992)	Ahmad & Shah (1985)
Empirical relation	$f_{fs}=0.62f_c^{\ 0.5}$	$f_{fs}=0.94f_c^{\ 0.5}$	$f_{ft}=0.44f_c^{\ 0.5}$
IAE (%)	5.30	6.47	8.44

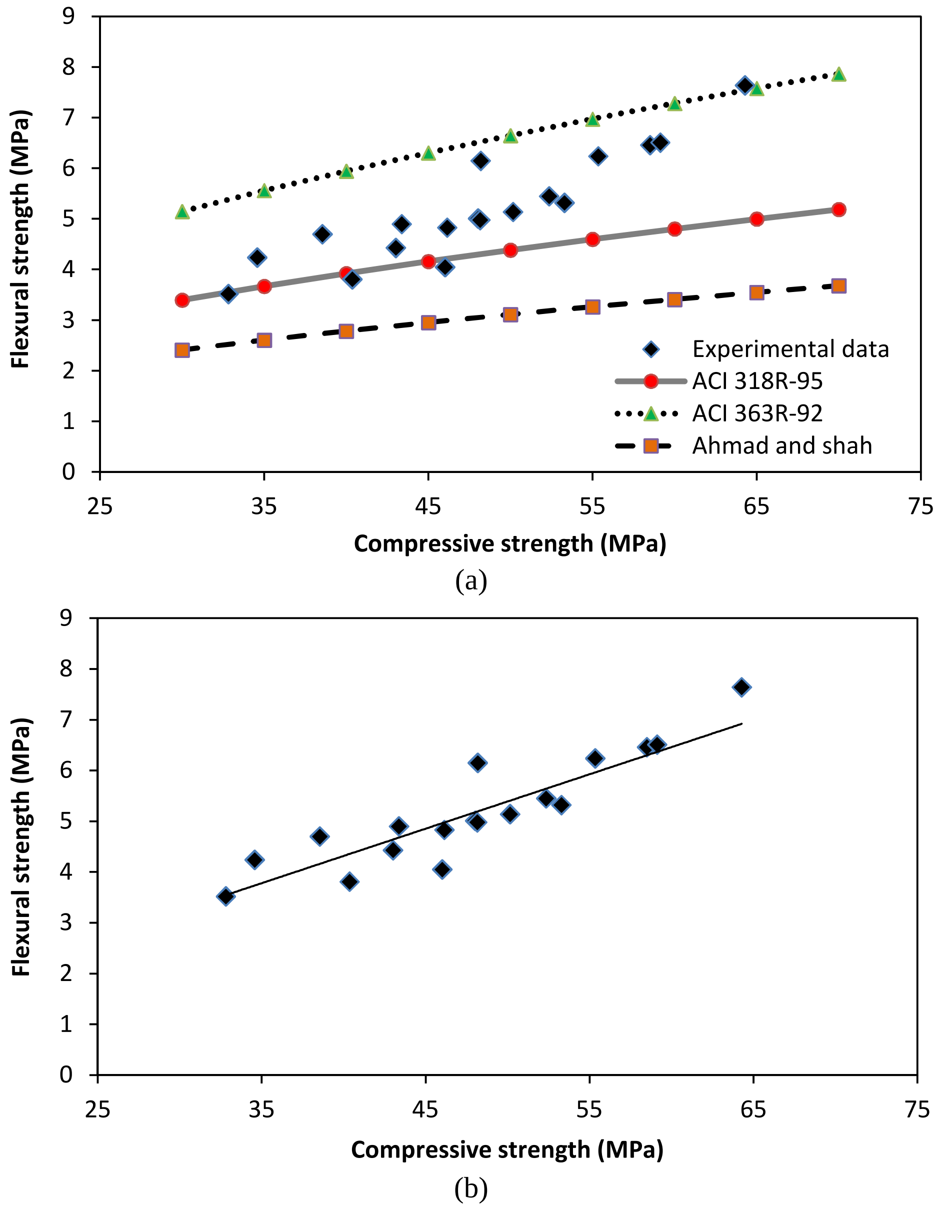


Fig. 15 (a) Comparison between experimental and predicted data for the published empirical relations between flexural strength and compressive strength; (b) The proposed equation based on experimental data

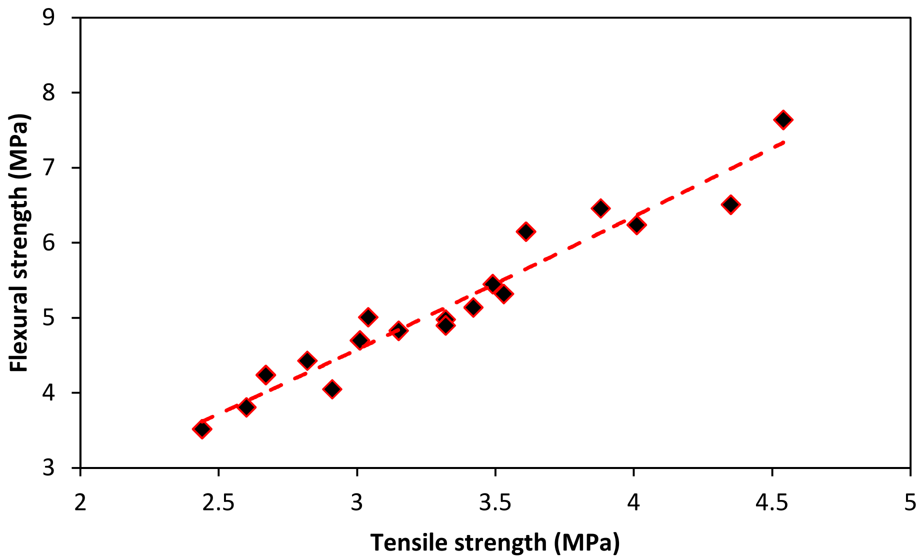
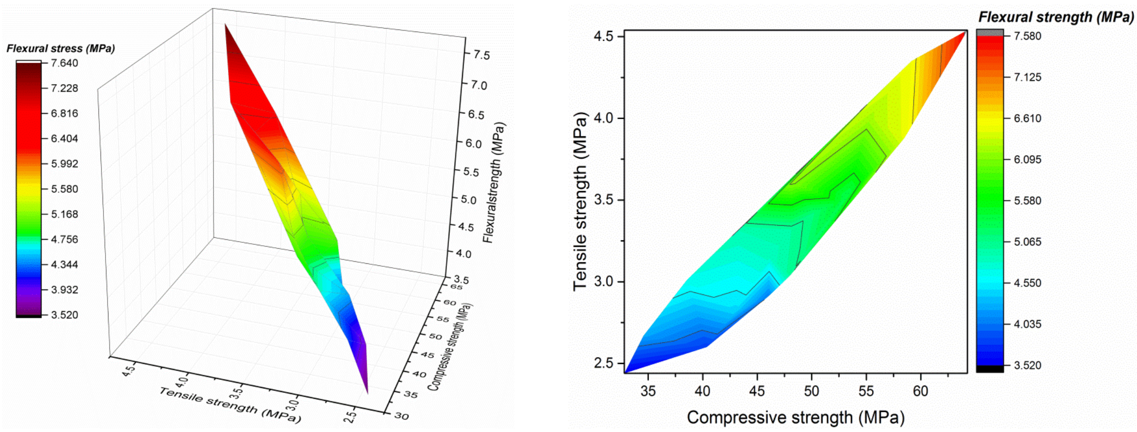


Fig. 16 The proposed equation between flexural strength and tensile strength based on experimental data

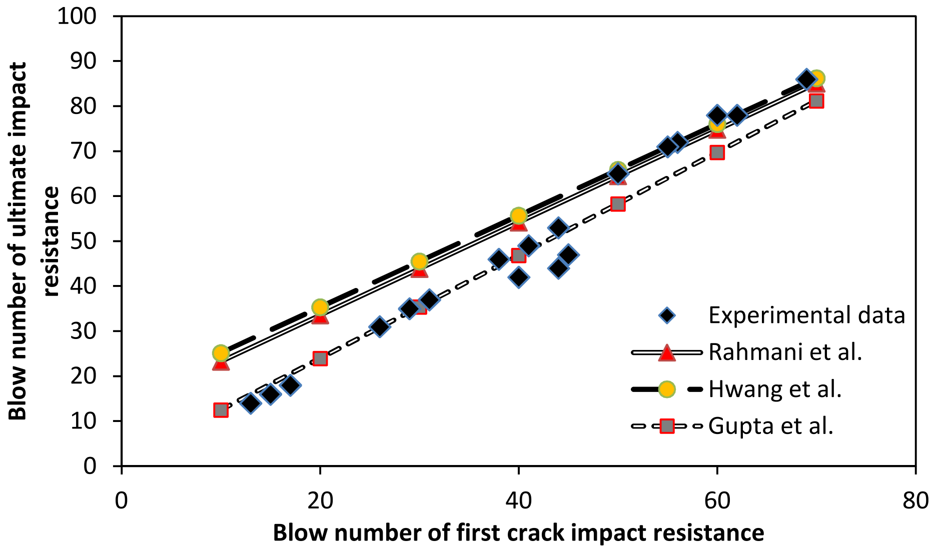


(a) (b)

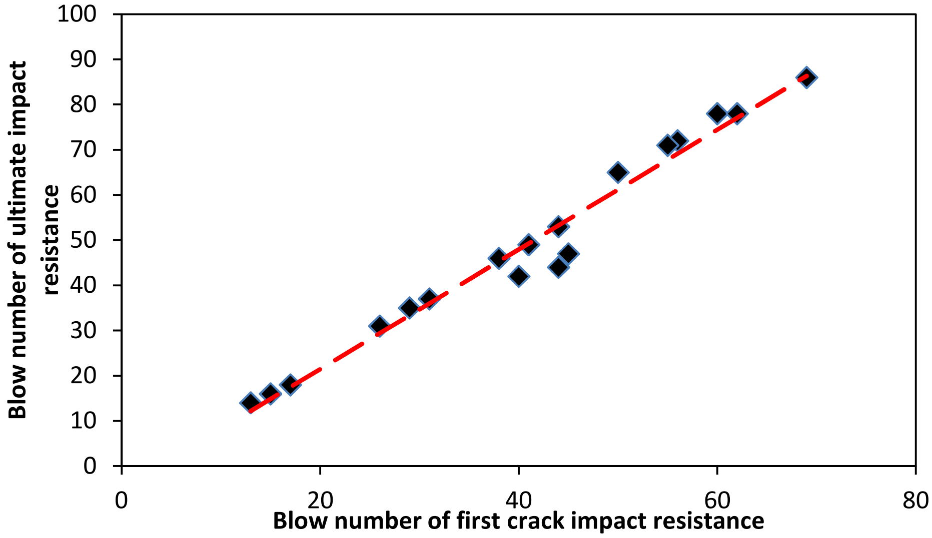
Fig. 17 (a) 3D view of correlation among experimental results of flexural, compressive, and tensile strength; (b) 2D view of correlation between experimental results of compressive and tensile strength

through the empirical relations is depicted in Fig. 15a. Respect to the indicated results in Fig. 15a and listed in Table 6 for IAE values, using proposed equations of ACI 363R-92 (with IAE 6.47%) and Ahmad and shah (with IAE 8.44%) results to provide differences significantly between experimental data and predicted results. As it can be observed, the obtained results based on empirical relations between compressive strength and flexural strength of normal concrete verify that these empirical relations are inapplicable for PFRSCC.

Therefore, based on nonlinear regression analysis an exponential equation was proposed in Fig.



(a)



(b)

Fig. 18 (a) Comparison between experimental and predicted data for the published empirical relations between the first crack impact resistance and the ultimate failure impact resistance; (b) The proposed equation based on experimental data

15b for correlating compressive strength and flexural strength with coefficient of determination of 0.79. The computed IAE value was 2.06% based on the proposed equation, which indicates that the variability of the proposed relation is small and has good reliability.

4.2.3 Tensile strength and flexural strength

To the authors´ best knowledge, there is no study reported about correlation of tensile strength and flexural strength of PFRSCC. The authors are completely aware that both tensile strength and

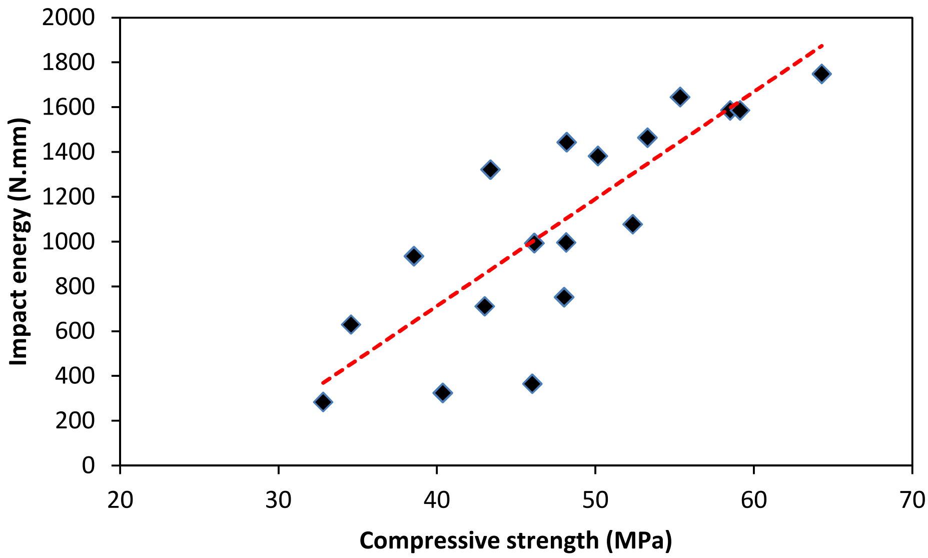


Fig. 19 The proposed equation between impact energy and compressive strength based on experimental data

Table 7 Published empirical relations between the ultimate failure impact resistance and the first crack impact resistance, and the corresponding IAE (%)

Sources	**Rahmani *et al.* (2012)**	**Gupta *et al.* (2015)**	**Hwang *et al.* (2003)**
Empirical relation	N_u=1.03N_f+12.96	N_u=1.145N_f+1.037	N_u=1.018N_f+14.968
IAE (%)	4.07	2.29	4.66

flexural strength can be correlated together through using compressive strength, but the main aim of this section is extracting direct equation between tensile strength and flexural strength based on the recorded experimental results.

Respect to experimental data, an exponential equation was developed between flexural strength and tensile strength, as shown in Fig. 16. The proposed equation had high coefficient of determination (R^2=0.94). This result indicates the proposed equation has very good agreement with experimental results and reliable to predict flexural strength based on tensile strength of PFRSCC.

Fig. 17 illustrates the correlation among obtained experimental results of flexural, compressive, and tensile strengths. Respect to the indicated results in Fig. 17 and using nonlinear regression analysis, Eq. (6) developed to approach flexural strength based on compressive strength and tensile strength with high coefficient of determination (R^2=0.95).

$$f_{fs} = (e^{0.433})(f_c^{-0.06})(f_{ts}^{1.196}) \tag{6}$$

4.2.4 Impact resistance

To the authors´ best knowledge, the most reported correlation about the parameters of impact test is related to the first crack impact resistance and ultimate failure impact resistance for PFRSCC. In this regard, the published empirical linear relations between the ultimate failure impact resistance and the first crack impact resistance of PFRSCC are listed in Table 7. Fig. 18a indicates the obtained experimental data from impact test and the predicted values through published empirical relations. Concerning the results presented in Fig. 18a and Table 7, the equation was presented by Gupta *et al*. had very good agreement with the measured experimental data in this study. This equation has low value of IAE (2.29%) which indicate high reliability and applicable for PFRSCC.

Additionally, a linear equation was developed between the first crack impact resistance and the ultimate failure impact resistance with high coefficient of determination (R^2=0.97), as shown in Fig. 18b. This result confirm previous finding in (Fakharifar *et al*. 2014) about existence of linear correlation between the first and ultimate impact resistance of fiber reinforced concrete. The computed IAE value for the presented equation indicates very low value (1.74%) which shows high reliability of this equation for PFRSCC. As mentioned, no specific empirical relation was derived for PFRSCC based on impact energy and compressive strength. Most empirical relations developed based on the first crack impact resistance and the ultimate failure impact resistance.

Using nonlinear regression analysis, a linear equation developed between impact energy and compressive strength, as shown in Fig. 19. The proposed equation had coefficient of determination of 0.68. The scatter of data points may be due to the consideration of affecting factors, including different water to cement ratios and different fibre contents.

5. Conclusion

In the present paper, initially the effects of polypropylene fibre on the impact resistance and mechanical properties of self-compacting concrete specimens with different water to cement ratios and different PP fibre volume fractions were investigated experimentally on two hundred and sixteen specimens. The specimens of reinforced self-compacting concrete with PP fibers divided in four groups, including 54 cubic specimens for compressive strength, 54 cylinder specimens for splitting tensile strength, 54 prismatic beams for flexural strength, and 54 disk specimens for impact resistance. Then, respect to the gathered relatively large experimental results an extensive statistical and analytical study was implemented and the following results can be concluded:

1. Increasing fibre content from 0 to 1% and decreasing water to cement ratio from 0.41 to 0.27 improve mechanical properties of PP fibre reinforced self-compacting concrete.

2. The best performance of specimens in terms of compressive strength, splitting tensile strength, flexural strength, impact resistance was detected in PFRSCC1 with water to cement ratio of 0.27.

3. The compressive, tensile, and flexural strength, first crack and ultimate impact resistance follow the normal distributions.

4. Respect to measured p-values for the normality test of data, compressive strength is better fitted to normal distribution in compare to other mechanical properties.

5. The maximum COV was registered for the impact resistance of specimens. This can be justified by contribution of some uncertainties involved in the impact test like roughness of specimen’s surface and loading position.

6. Exponential equations with high values of coefficient of determination were developed to correlate among compressive, tensile, and flexural strengths of PP fibre reinforced self-compacting

specimens.

7. The first crack and ultimate impact resistance are related together linearly with high coefficient of determination.

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