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MECHANICAL PROPERTIES OF REACTIVE POWDER CONCRETE WITH VARIOUS STEEL FIBER AND SILICA FUME CONTENTS

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Abstract: *An experimental work was carried out to investigate some mechanical properties of Reactive Powder Concrete (RPC) which are particularly required as input data for structural design. These properties include compressive strength, tensile strength (direct, splitting and flexural), flexural toughness, load-deflection capacity and static modulus of elasticity. The effects of three variable parameters on these properties were carefully studied which are the silica fume content SF (0%, 10%, 15%, 20%, 25%, and 30%) as a partial replacement by weight of cement, steel fibers volume fraction V_f (0%, 1%, 2% and 3%) and superplasticizer type (Sikament®-163N, PC200). The experimental results showed that as the silica fume content (SF) increases from 0% to 30% the compressive strength significantly increases, while the increase in tensile strength is relatively lower. The inclusion of steel fibers leads to a considerable increase in tensile strength, while the addition of steel fibers causes a slight increase in compressive strength of RPC as fiber volume fraction increases from 0% to 3%. The increase in the steel fibers volume fraction and silica fume content improved the load-deflection behavior and consequently gave larger ductility and fracture toughness of RPC.*

Keywords: *reactive powder concrete, mechanical properties, load-deflection capacity, steel fiber, silica fume*

INTRODUCTION

Research over the past decades has yielded a new classification of highly resilient concrete called Reactive Powder Concrete (RPC), now labeled and classified as Ultra High Performance Concrete (UHPC). RPC is one of the latest advances in concrete technology and it addresses the shortcomings of many concretes today [16]. RPC possess ultra high static and dynamic strength, high fracture capacity, low shrinkage and excellent durability under severe condition. The microstructure of RPC is optimized by precise gradation of all particles in the mix to yield maximum compactness [21]. RPC has been shown to exhibit significantly improved tensile strength, both before and after cracking. This tensile strength of RPC is achieved as a result of the interaction of the randomly oriented steel fibers acting as reinforcement on a micro level which prevents cracks from forming. After cracking has occurred, the steel fibers are capable of sustaining additional tensile loads until the fibers are pulled from the matrix and the section severs [15]. The basic principles for the development of RPC were explained by many researchers [13, 18]. These principles can be listed as below:

- There is no coarse aggregate and maximum aggregate size may be between 0.3 to 0.6 mm.
- Powder is carefully optimized to achieve very high compactness.
- Using high cement content, low water to cement ratio (less than 0.2).
- Silica fume or another suitable pozzolanic material can be added to the mix.
- Superplasticizer is in need to get high flowable concrete.
- Steel fibers are to be added to increase the concrete ductility.
- Pressing during hardening may be helpful to get rid of excess water and to increase the paste density.
- Heat treatment during curing can improve the chemical process and strength gain.

Lee and Chisholm [9] studied the effect of steel fibers on the mechanical properties of RPC. They observed that the addition of 2% straight steel fibers with aspect ratio of 65 to the RPC mix primarily improve the normally poor tensile strength of composite cementitious materials. They also found that the addition of steel fibers provided a marked improvement in the measured compressive strength.

Wille et al. [20] carried out an experimental study on the tensile behavior of different Ultra High Performance Fiber Reinforced Concrete (UHPFRC) mixes using four types of high strength steel fibers; straight with aspect ratio 65, hooked with aspect ratio 79, high twisted with aspect ratio 100, and low twisted with aspect ratio 100 with different volume fractions (1%, 1.5%, 2% and 2.5%). The results showed that both the tensile strength and the maximum post-cracking strain are significantly improved by using deformed steel fibers instead of smooth fibers. Moreover the path of the stress strain curves of UHPFRC reinforced with hooked steel fibers and UHPFRC reinforced with twisted steel fibers are similar up to the peak load of UHPFRC reinforced with hooked steel fibers. While UHPFRC reinforced with hooked steel fibers begins softening at post cracking strain ε_{tp} = 0.46%, UHPFRC reinforced with twisted steel fibers keeps increasing the tensile stress up to post cracking strain $\varepsilon_{tp} \approx$ 0.6%.

EXPERIMENTAL PROGRAM

Materials:

– **Cement**

Aljisir sulfate resisting Portland cement, Type V, manufactured in Iraq was used throughout this research. Its chemical and physical properties conform to the provisions of Iraqi specification No.5.

– **Fine Aggregate**

AL-Ukhaider natural sand of maximum size 600 µm was used. Its gradation lies in zone (4). The gradation and sulfate content results of fine aggregate were within the requirements of the Iraqi specification No. 45.

– **Admixtures**

Two types of concrete admixtures were used in this work:

▪ **Superplasticizer**

Two different types of superplasticizer were used to produce the RPC mixes. They are, Naphthalene formaldehyde sulphonate polymer manufactured and supplied by SIKA® company under the commercial name Sikament®-163N, and polycarboxylate ether polymer manufactured by PAC Technologies company under the commercial name PC 200. These admixtures comply with the requirement of ASTM C494.

Table 1. Fine aggregate properties

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No.45/1984, zone 4
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.60	100	80-100
0.30	44	15-50
0.15	7	0-15
Fineness modulus = 1.5		
Specific gravity =2.69		
Sulfate content =0.13% (Iraqi specification requirement ≤ 0.5%)		
Absorption = 0.73%		

▪ **Silica Fume**

Silica fume has been used as a mineral admixture added to the RPC mixes of this study. The percentages used were 10%, 15%, 20%, 25%, and 30% as partial replacement of cement weight. The chemical composition and physical requirements show that the silica fume conforms to the chemical and physical requirements of ASTM C1240 specifications.

– **Steel Fibers**

Hooked steel fibers used throughout the experimental program. The steel fiber used has diameter 0.5mm, length 30mm (aspect ratio lf /df = 60), density 7800 kg/m³ and ultimate tensile strength of 1180 MPa.

Concrete Mixes

The key features of RPC mix design include high Portland cement content, fine sand with a particle size of between 150 and 600 µm, extremely low w/c ratio made possible by high dosages of the latest generation of superplasticizer, the presence of a high reactivity silica fume, and the incorporation of steel fibers. Sand to cement ratio (S/C) in mortar has a significant effect on compressive strength, S/C ratio equal to 1.0 was found to be very effective for the optimization of mortar mixture with superplasticizer and mineral admixture [14].

Within the above limits and according to pervious researches [2,4,6,12,17] many mix proportions were tried in this investigation to have maximum compressive strength and flow of (110+5%) according to ASTM C109 and ASTM C1437 respectively. Ten RPC mixes were used in the present research as listed in Table (2) to investigate the performance of RPC in the fresh and hardened state.

Table 2. RPC mixes used in the present research

Group	Mix symbol	cement kg/m³	fine sand kg/m³	silica fume* (%)	silica fume content kg/m³	steel fibers** (%)	steel fibers content kg/m³	w/cm ratio	HRWRA *** (%)	HRWRA type
1	MSP-N	935	1100	15%	165	2%	156	0.181	9.5%	Sikament ®-163N
	MSP-P	935	1100	15%	165	2%	156	0.169	8.7%	PC200
2	MSF0	1100	1100	0%	0	2%	156	0.161	8.7%	PC200
	MSF10	990	1100	10%	110	2%	156	0.166	8.7%	PC200
	MSF15†	935	1100	15%	165	2%	156	0.169	8.7%	PC200
	MSF20	880	1100	20%	220	2%	156	0.174	8.7%	PC200
	MSF25††	825	1100	25%	275	2%	156	0.180	8.7%	PC200
	MSF30	770	1100	30%	330	2%	156	0.188	8.7%	PC200
3	MFR0	825	1100	25%	275	0%	0	0.171	8.7%	PC200
	MFR1	825	1100	25%	275	1%	78	0.175	8.7%	PC200
	MFR2	825	1100	25%	275	2%	156	0.180	8.7%	PC200
	MFR3	825	1100	25%	275	3%	234	0.187	8.7%	PC200

†MSF15 in group 2 is the same mix designated MSP-P in group 1

†† MSF25 in group 2 is the same mix designated MFR2 in group 3

* Percent by weight of cement.

** Percent of mix volume.

*** Percent of cementitious materials (cement + silica fume) by weight.

Three variable parameters were considered in the preparation of these ten RPC mixes. They were;

1. The silica fume content (as partial replacement by weight of cement). Six ratios were employed (0%, 10%, 15%, 20%, 25% and 30%).
2. The steel fibers volume fraction (as ratio of the mix volume). Four ratios were used (0%, 1%, 2% and 3%).
3. The type of the superplasticizer used in the mix, which was either type N (Sikament®-163N) or type P (PC200).

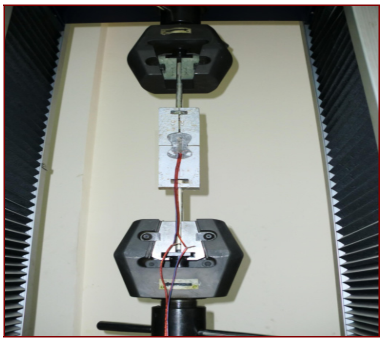
All mixes shown in Table (2) had a flow ranging between 105% and 115%.

Mixing of Concrete

All RPC mixes were performed in a rotary mixer of 0.1m³. For RPC concrete, the silica fume and cement were mixed in dry state for about 3 minutes to disperse the silica fume particles throughout the cement particles, then the sand was added and the mixture was mixed for 5 minutes. The superplasticizer is dissolved in water and the solution of water and superplasticizer is gradually added during the mixing process then the whole mixture was mixed for 3 minutes. The mixer was stopped and mixing was continued manually especially for the portions not reached by the blades of the mixer. The mixer then operated for 5 minutes to attain reasonable fluidity. Fibers were uniformly distributed into the mix in 3 minutes, and then the mixing process continued for additional 2 minutes. In total, the mixing of one batch requires approximately 15 minutes from adding water to the mix.

Preparation and Testing of Specimens

All specimens were prepared, cured for 28 days then tested to study some properties of RPC. These properties are compressive strength (using cubes of 100 mm and cylinders of 100 x 200 mm), direct tensile strength (using dog bone-shaped briquettes of 76 mm long, 25 mm thick, and 645-mm² cross section at mid-length) as shown in Figure (1a), splitting tensile strength (using cylinders of 100 x 200 mm) as shown in Figure (1b), flexural tensile strength and toughness (using prisms of 100 x100 x400 mm) as shown in Figure (1c), and static modulus of elasticity (using cylinders of 100 x 200 mm) as shown in Figure (1d).



(a) Direct tensile

(b) Splitting tensile

(c) Flexural toughness

(d) Static modulus of elasticity

Figure 1. Tests set-up

Curing

All specimens were demolded after 24 hours, and then they were steam cured at about 90°C for 48 hours in a water bath. After that they were left to be cooled at room temperature, and then they placed in water and left until the end of water curing at 28 days.

RESULTS AND DISCUSSIONS

Compressive Strength

The results of the compression test on RPC cubes and cylinders are shown in Table (3) and Figures (2) and (3). The ratios of cube compressive strength to cylinder compressive strength (f_{cu} / f'_c) at 28 days ranged between (1.008 - 1.067). These ratios are lower than 1.25 that was stated by Neville [11] for conventional concrete and so close to the range of (1.0 - 1.075) for UHPFRC found by Graybeal [7]. This phenomenon can be explained by the high powder content and smaller maximum aggregate size of RPC [8].

Table 3. Cube and cylinder compressive strengths of RPC

Group	Mix Symbol	Silica Fume content SF (%)	Steel fibers V_f (%)	f_{cu} (MPa)	%Increase in f_{cu} with respect to the first mix in each group	f'_c (MPa)	%Increase in f'_c with respect to the first mix in each group	f_{cu}/f'_c
1	MSP-N	15%	2%	126.84	0	118.91	0	1.067
	MSP-P	15%	2%	139.56	10.03	134.33	12.97	1.039
2	MSF0	0%	2%	118.26	0	111.66	0	1.059
	MSF10	10%	2%	134.28	13.54	131.27	17.56	1.023
	MSF15	15%	2%	139.56	18.02	134.33	20.30	1.039
	MSF20	20%	2%	147.49	24.72	146.19	30.92	1.009
	MSF25	25%	2%	153.57	29.86	149.39	33.79	1.028
	MSF30	30%	2%	158.67	34.17	157.48	41.04	1.008
3	MFR0	25%	0%	141.72	0	135.93	0	1.043
	MFR1	25%	1%	146.99	3.72	144.57	6.36	1.017
	MFR2	25%	2%	153.57	8.36	149.39	9.90	1.028
	MFR3	25%	3%	154.33	8.89	151.62	11.54	1.018

The results in Table (3) and Figure (2) demonstrate that increasing fibers volume fraction from 0% to 1.0%, 2.0%, and 3.0% causes slight increase in the cube compressive strength (f_{cu}) of 3.72%, 8.36%, and 8.89% respectively and the cylinder compressive strength (f'_c) slightly increased by 6.36%, 9.9%, and 11.54% respectively. Such increase may be associated with crack arrest theory of the fibers which accounts for the increase in compressive strength. The effect of steel fibers on compressive strength was also *observed by others like Orgass and Klug [12] and Lee and Chisholm [9]. According to the latter the improved compressive strength does likely reflect the contribution of steel fibers to the tensile capacity of RPC. An accepted view was given that concrete under uniaxial compressive load fails because of lateral strain induced by Poisson's ratio effects leading to lateral swelling of unconfined central section accompanied by cracking parallel to the loading axis and shear failure near the specimen ends.*

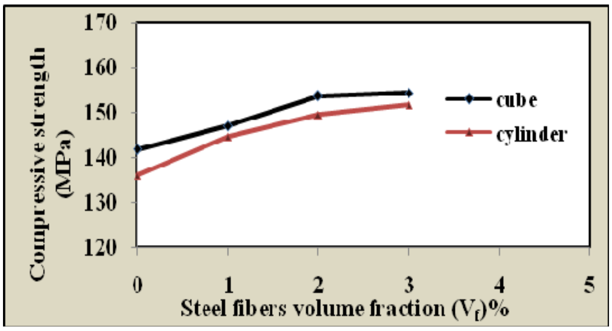


Figure 2. Effect of steel fibers content on cube and cylinder compressive strength of RPC

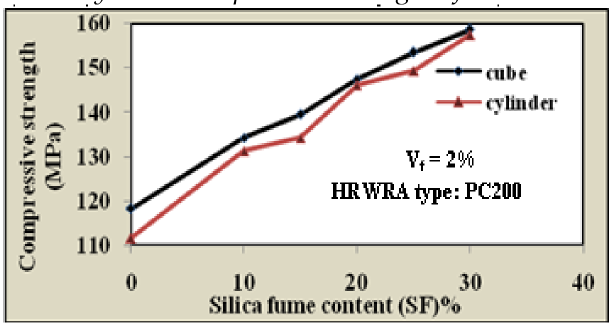


Figure 3. Effect of silica fume content on cube and cylinder compressive strength of RPC

Table (3) and Figure (3) show that increasing silica fume content (SF) from 0% to 10%, 15%, 20%, 25%, and 30% causes a considerable increase in both the cube compressive strength (f_{cu}) by 13.54%, 18.02%, 24.72%, 29.86%, and 34.17% and the cylinder compressive strength (f'_c) by 17.56%, 20.30%, 30.92%, 33.79%, and 41.04% respectively. This can be explained by the high pozzolanic reaction of silica fume particles with calcium hydroxide released from cement hydration leading to pore size and grain size refinement processes which can strengthen the microstructure and reducing the microcracking. The extreme fineness of the silica fume particles provides nucleation sites for calcium hydroxide and the additional contribution to the progress of hydration of the cement occurs. The beneficial effects of silica fume are not limited to its pozzolanic reaction; there is also a physical effect which comes from the enhanced particle packing, this leads to improving the microstructure of RPC matrix and increases its density and the bond strength between cement matrix and fibers [11].

The influence of superplasticizer type on RPC performance in terms of w/cm and compressive strength was also studied in the present research. The results show that in the presence of PC200 the w/cm was much lower than that with the Sikament®-163N, accordingly the compressive strength with PC200 (MSP-P) was much higher than that with Sikament®-163N (MSP-N).

Tensile Strength of RPC

Table (4) and Figures (4) to (9) illustrate the tensile strength results for different RPC mixes used throughout this investigation [direct (f_{td}), splitting (f_{sp}) and flexural (f_r)].

Table 4. Tensile strength results of RPC mixes

Group	Mix Symbol	Silica Fume content (SF) (%)	Steel fibers V_f (%)	f_{td} (MPa)	f_{sp} (MPa)	f_r (MPa)	f_{td}/f'_c (%)
1	MSP-N	15%	2%	7.65	14.78	20.86	6.43
	MSP-P	15%	2%	8.13	15.90	22.77	6.05
2	MSF0	0%	2%	7.82	15.19	20.97	7.00
	MSF10	10%	2%	8.03	15.40	22.12	6.12
	MSF15	15%	2%	8.13	15.90	22.77	6.05
	MSF20	20%	2%	8.56	16.23	24.19	5.86
	MSF25	25%	2%	8.92	17.25	24.57	5.97
	MSF30	30%	2%	9.14	17.55	24.96	5.80
3	MFR0	25%	0%	3.64	6.32	9.22	2.68
	MFR1	25%	1%	5.80	10.50	15.07	4.01
	MFR2	25%	2%	8.92	17.25	24.57	5.97
	MFR3	25%	3%	12.32	21.59	29.24	8.13

Generally, the addition of steel fibers to all RPC mixes improves the direct tensile strength *significantly relative to the nonfibrous RPC specimens. Increasing the volume fraction of fibers from 0% to 1.0%, 2.0%, and 3.0% increase the direct tensile strength by 59.4%, 145.05%, and 238.35%, the splitting tensile strength by 90.88%, 186.51%, and 258.45% and the flexural tensile strength by 52.62%, 166.61%, and 217.27% respectively. This is due to the fact that fibers are able to: (1) bridge tensile cracks and retard their propagation, (2) transmit stress across a crack and counteract crack growth [10]. In general, hooked end fibers lead to a great increase in tensile strength because of the fact that geometry of hooked end fibers influence the bond development between fiber and the matrix causing an increase in energy required to pull the fiber out of the matrix.*

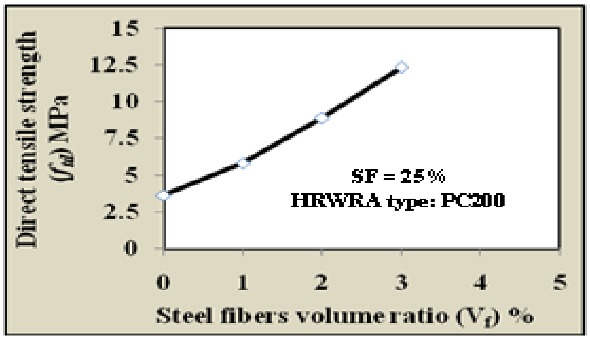


Figure 4. Effect of steel fibers volume fraction on direct tensile strength of RPC

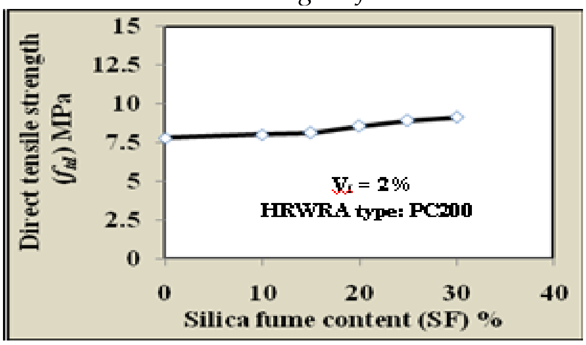


Figure 5. Effect of silica fume content on direct tensile strength of RPC

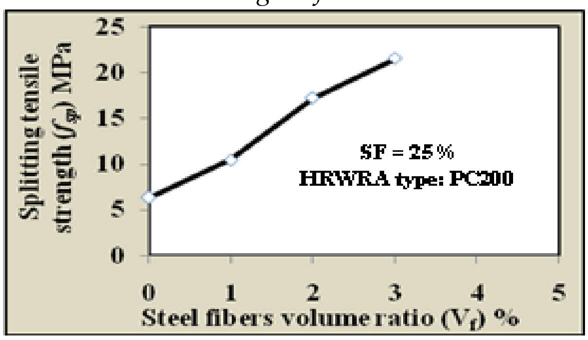


Figure 6. Effect of steel fibers volume fraction on splitting tensile strength of RPC

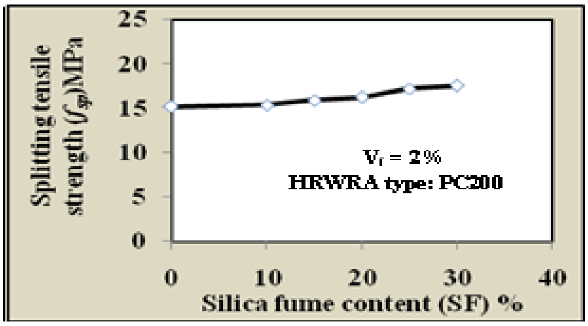


Figure 7. Effect of silica fume content on splitting tensile strength of RPC

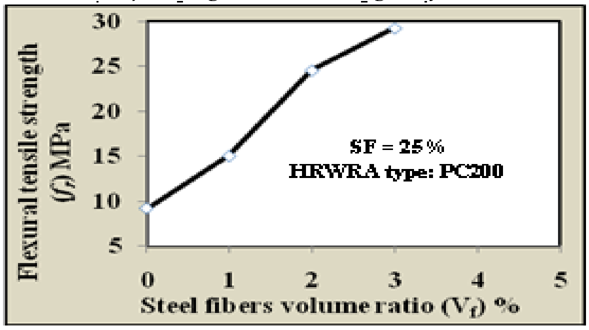


Figure 8. Effect of steel fibers volume fraction on flexural tensile strength of RPC

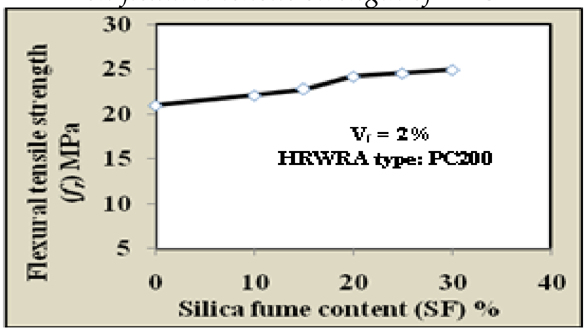


Figure 9. Effect of silica fume content on flexural tensile strength of RPC

The results also indicated that when SF content increased from 0% to 10%, 15%, 20%, 25%, and 30% the direct tensile strength increased by 2.63%, 3.96%, 9.5%, 14.04%, and 16.89%,the splitting tensile strength increased by 1.4%, 4.68%, 6.85%, 13.61%, and 15.57%, and the flexural tensile strength increased by 5.49%, 8.58%, 15.35%, 17.17%, and 19.01% respectively. This can be attributed to the fact that the increase of SF content in RPC matrix enhanced the steel fiber-matrix bond characteristics due to the interfacial-toughening effect. This effect of SF results in densification of the RPC matrix which comes from the enhanced particle packing, which leads to improving the microstructure of RPC matrix and increase its density as well as from the intensive chemical reaction due to pozzolanic reaction [3]. It can be noticed that, the influence of *silica fume content and superplasticizer type on direct tensile strength is less pronounced than that on compressive strength. This is due to the fact that tensile strength of RPC is related to the strength, volume fraction, and geometry of the fiber used as well as the bond between fiber and the matrix [19].*

The ratio of direct tensile strength to cylinder compressive strength (f_{td}/f'_c) for RPC mixes investigated in the present study is illustrated in Table (4). It was found that this ratio at 28 days is 2.68% for the nonfibrous RPC mix and ranged between 4.01-8.13% for RPC mixes with 1-3% steel fibers volume fraction.

Static Modulus of Elasticity

The modulus of elasticity is strongly influenced by the concrete materials and their proportions [10]. The static modulus of elasticity results for all RPC mixes are presented in Table (5) and Figures (10) and (11).

Table 5. Static modulus of elasticity results of RPC mixes

Group	Mix Symbol	Silica Fume content SF (%)	Steel fibers V_f (%)	Ec (MPa)	% Increase in E with respect to the first mix in each group
1	MSP-N	15%	2%	44841	0.00
	MSP-P	15%	2%	46398	3.47
2	MSF0	0%	2%	43836	0.00
	MSF10	10%	2%	45900	4.71
	MSF15*	15%	2%	46398	5.84
	MSF20	20%	2%	47422	8.18
	MSF25**	25%	2%	48295	10.17
	MSF30	30%	2%	49103	12.02
3	MFR0	25%	0%	46262	0.00
	MFR1	25%	1%	47363	2.38
	MFR2	25%	2%	48295	4.39
	MFR3	25%	3%	48538	4.92

It can be noticed that the increase in steel fibers ratio show only slight increases in the static modulus of elasticity. This may be because the modulus of elasticity was calculated to the stress corresponding to 40% of the ultimate load, so it is determined prior to concrete cracking; therefore, the fibers were not activated. In general increasing silica fume content show increases in the static modulus of elasticity and this may be attributed to the interfacial-toughening effect and densification of the RPC matrix which comes from the enhanced particle packing as well as from the intensive chemical reaction due to pozzolanic reaction. This leads to improving the microstructure of RPC matrix and increase its density [3].

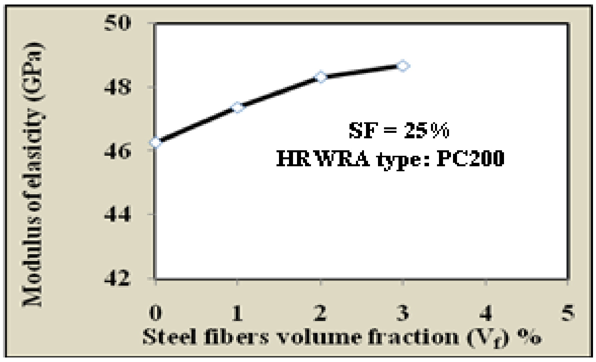


Figure 10. Effect of steel fibers volume fraction on the modulus of elasticity of RPC

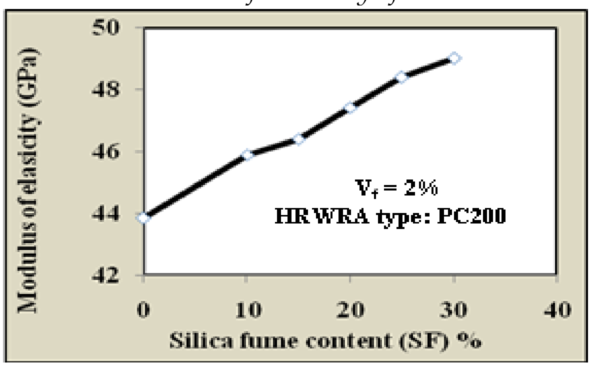


Figure 11. Effect of silica fume content on the modulus of elasticity of RPC

Flexural Toughness and Load-Deflection Capacity

Flexural toughness can be defined as the area under the load-deflection curve in flexure, which is the total energy absorbed prior to complete separation of the specimen [1]. The values of the toughness indices I_5 and I_{10} of the entire tested RPC prisms are presented in Table (6).

The load-deflection curves of RPC for typical nonfibrous control specimens and specimens with 1%, 2%, and 3% steel fibers are plotted in Figure

(12). It can be concluded that plain RPC fails suddenly at a small deflection by separation into two pieces, while fibrous RPC suffers damage by gradual development of single or multiple cracks with increasing deflection, but retains some degree of structural integrity and post-crack resistance even with considerable deflection.

Table 6. Toughness indices for RPC mixes

Group	Mix Symbol	Silica Fume SF (%)	Steel fibers V_f (%)	δ_{cr} (mm)
1	MSP-N	15%	2%	0.55
	MSP-P	15%	2%	0.52
2	MSF0	0%	2%	0.56
	MSF10	10%	2%	0.58
	MSF15	15%	2%	0.52
	MSF20	20%	2%	0.54
	MSF25	25%	2%	0.47
	MSF30	30%	2%	0.53
3	MFR0	25%	0%	0.45
	MFR1	25%	1%	0.43
	MFR2	25%	2%	0.47
	MFR3	25%	3%	0.46

Group	P_{cr} (kN)	def. at peak load (mm)	peak load (kN)	Toughness indices	
				I_5	I_{10}
1	49.9	1.33	69.5	5.31	9.71
	51.5	1.41	75.9	5.36	9.98
2	51.1	1.35	70.0	5.28	9.65
	53.6	1.45	73.7	5.34	9.95
	51.5	1.41	75.9	5.36	9.98
	52.9	1.50	80.6	5.51	10.88
	50.3	1.39	81.9	5.55	11.07
	54.7	1.49	83.2	5.61	11.30
3	30.7	0.45	30.7	1	1
	43.1	0.90	50.2	5.15	9.06
	50.3	1.39	81.9	5.55	11.07
	54.8	1.51	97.4	5.84	12.99

Figure (12) shows that the addition of steel fibers to plain RPC changes the brittle nature of the nonfibrous matrix to a composite mass with a plastic behavior after first crack. On the other hand, the presence of steel fibers led to a continuation of the load-carrying capacity beyond the peak load implying an improved post-peak toughness. It can be seen from Table (6) and Figure (12) that with the increase of the fibers volume fraction from 0% to 3% the load-deflection behavior and consequently the ductility and fracture toughness can be improved.

This can be traced back to the fact that, the fibers are able to transfer emerging loads by bridging the cracks. After reaching the maximum load the descending part of the load-deflection curve doesn't drop down at once.

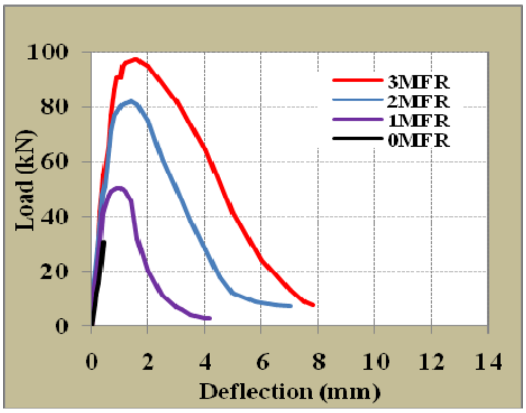


Figure 12. Load-deflection relationship of RPC prisms with various steel fibers contents

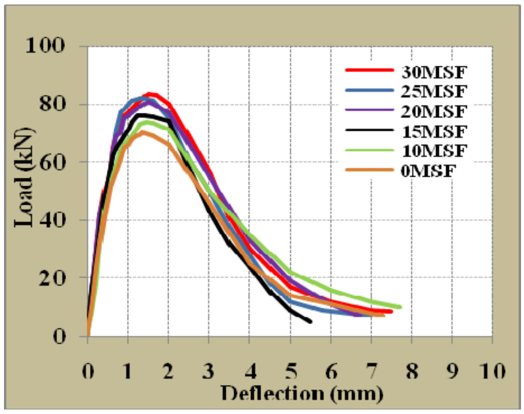


Figure 13. Load-deflection relationship of RPC prisms with various silica fume contents

The load-deflection curves of RPC for specimens with silica fume content of 0%, 10%, 15%, 20%, 25%, and 30% are plotted in Figure (13). The results illustrate that increasing silica fume content causes an increase in the flexural toughness of RPC. This behavior can be attributed to the fact that the incorporation of silica fume will effectively enhance the fiber–matrix interfacial properties due to densification of the mix by the effect of micro filling and pozzolanic reaction of silica fume. This increases the bond between the matrix and the fibers and therefore the pullout energy is remarkably enhanced causing an improvement in toughness [3, 5].

Regression Analysis for RPC Properties

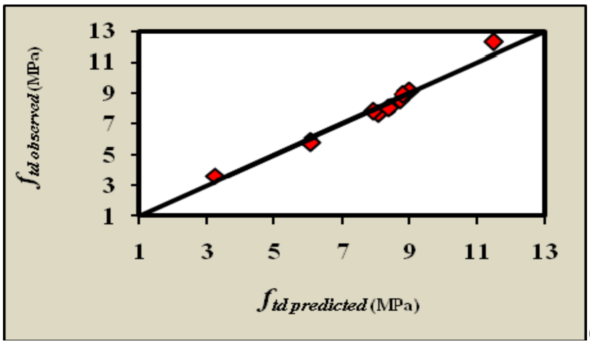
Regression analysis is an important statistical method that uses the relationships between two or more quantitative variables to generate a model that may predict one variable from the other(s).

- ***Relationship between Direct Tensile Strength and Cylinder Compressive Strength***

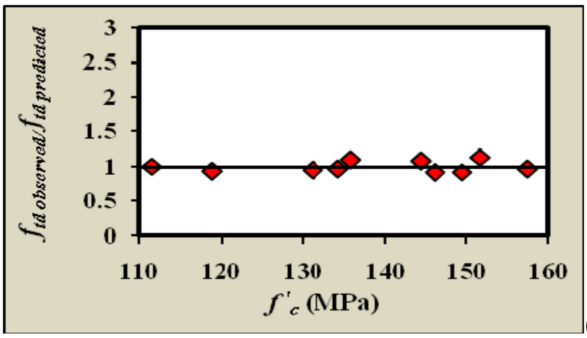
Compression test is frequently used as a quality control method for structural concrete; therefore, engineers often attempt to relate other characteristics of concrete behavior to this parameter. Results of tests carried out on the ten RPC mixes investigated in the present study show that fibrous RPC has direct tensile strength to compressive strength ratio higher than that for nonfibrous RPC. This is expected since the inclusion of steel fibers leads to a considerable increase in direct tensile strength while the increase in compressive strength is relatively lower. Therefore to include this important effect of steel fibers volume fraction, a data fit computer program has been adopted to carry out a regression analysis for the sake of establishing an empirical equation to predict the relationship between direct tensile strength and cylinder compressive strength for the ten RPC mixes investigated in the present study with $R^2 = 0.969$ *as given below.*

$$f_{td} = 0.024\,(f'_c) + 2.614\,(V_f) \qquad (1)$$

where: f_{td}*: direct tensile strength (MPa).*
f_c*: cylinder compressive strength (MPa).*
V_f*: steel fibers volumetric ratio.*



(a)



(b)

Figure 14. (a) Observed versus predicted values of direct tensile strength, (b) The ratio $f_{td\ observed}/f_{td\ predicted}$ *versus the cylinder compressive strength* f'_c

Eq. (1) gives a mean value statistic mean (μ) of ($f_{td\ observed}/f_{td\ predicted}$) *for the test results of this investigation of 1.0 with standard deviation (SD) of 0.0528 and coefficient of variation (COV) of 5.28%. Figure (14a) shows the direct tensile strength obtained from the experimental work (observed) versus the corresponding calculated strength using Eq. (1) (predicted), while Figure (14b) shows the ratio* $f_{td\ observed}/f_{td\ predicted}$ *versus the cylinder compressive strength* f'_c*.*

- ***Relationship between Static Modulus of Elasticity and Cylinder Compressive Strength***

Figure (15) shows the relationship between the static modulus of elasticity (E) and the cylinder compressive strength (f'_c) *for the different RPC mixes investigated in the present study. Results indicated that the static modulus of elasticity and compressive strength of RPC are related to each other such that when the compressive strength increases, the static modulus of elasticity also increases at a certain rate. A data fit computer program has been adopted to carry out a regression analysis for the sake of establishing an empirical equation to predict the relationship between E and* f'_c *for RPC. The equation obtained (Eq. 2) has* $R^2 = 0.985$*, as given below.*

$$E_c = 113.43\,(f'_c) + 31126.74 \qquad (2)$$

where: f'_c*: cylinder compressive strength (MPa).*
E_c*: static modulus of elasticity of RPC (MPa).*

Eq. (2) gives a mean value (μ) of ($E_{c\ observed}/E_{c\ predicted}$) *for the test results of this investigation of 0.99 with SD of 0.004 and COV of 0.406%. Figure (16a) shows the static modulus of elasticity obtained from the experimental work (observed) versus the corresponding calculated static modulus of elasticity using Eq. (2) (predicted), while Figure (16b) shows the ratio* $E_{c\ observed}/E_{c\ predicted}$ *versus the cylinder compressive strength* f'_c*.*

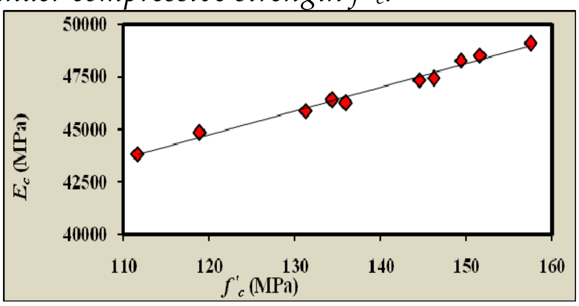


Figure 15. Relationship between compressive strength and static modulus of elasticity for RPC

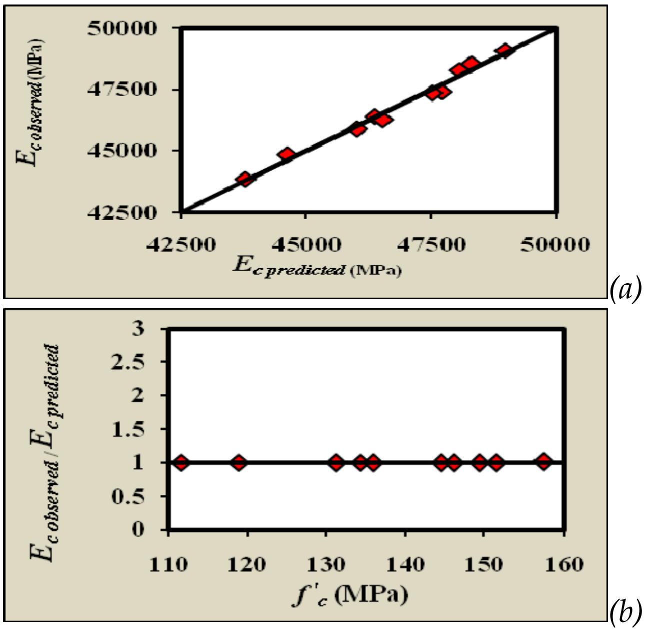


Figure (16) (a) Observed versus predicted values of static modulus of elasticity, (b) The ratio $E_{c\ observed}/E_{c\ predicted}$ versus the cylinder compressive strength f'_c

- ***Relationships between Direct Tensile Strength, Splitting Tensile Strength, and Flexural Tensile Strength***

A data fit computer program has been adopted to carry out a regression analysis for the sake of establishing two empirical equations, the first equation (Eq. 3) estimates the RPC direct tensile strength from the splitting tensile strength with $R^2 = 0.974$, while the second equation (Eq. 4) estimates the RPC direct tensile strength from the flexural tensile strength with $R^2 = 0.943$.

$$f_{td} = 0.53 * f_{sp} \tag{3}$$

$$f_{td} = 0.37 * f_r \tag{4}$$

where: f_{td}: direct tensile strength (MPa), which is f_{te} for RPC with strain softening behavior and f_{tp} for RPC with strain hardening behavior.

f_{sp}: splitting tensile strength (MPa).

f_r: flexural tensile strength (MPa).

Eq. (3) gives a mean value (μ) of ($f_{td\ observed}/f_{td\ predicted}$) for the test results of this investigation of 1.0 with SD of 0.043 and COV of 4.299%. Figure (4-59 a) shows the direct tensile strength obtained from the experimental work (observed) versus the corresponding calculated strength using Eq. (3) (predicted), while Figure (4-59 b) shows the ratio $f_{td\ observed}/f_{td\ predicted}$ versus the splitting tensile strength f_{sp}.

Eq. (4) gives a mean value (μ) of ($f_{td\ observed}/f_{td\ predicted}$) for the test results of this investigation of 0.999 with SD of 0.052 and COV of 5.237%. Figure (4-60 a) shows the direct tensile strength obtained from the experimental work (observed) versus the corresponding calculated strength using Eq. (4) (predicted), while Figure (4-60 b) shows the ratio $f_{td\ observed}/f_{td\ predicted}$ versus the flexural tensile strength f_r.

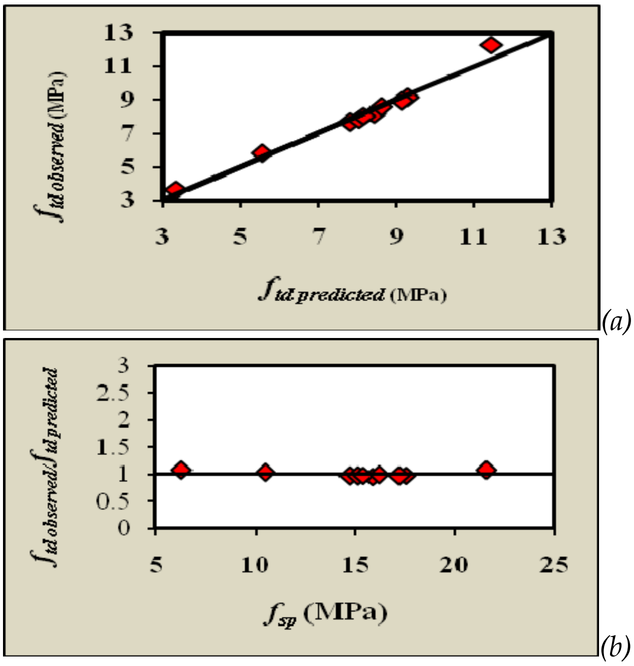


Figure 17. (a) Observed versus predicted values of direct tensile strength, (b) The ratio $f_{td\ observed}/f_{td\ predicted}$ versus the splitting tensile strength f_{sp}

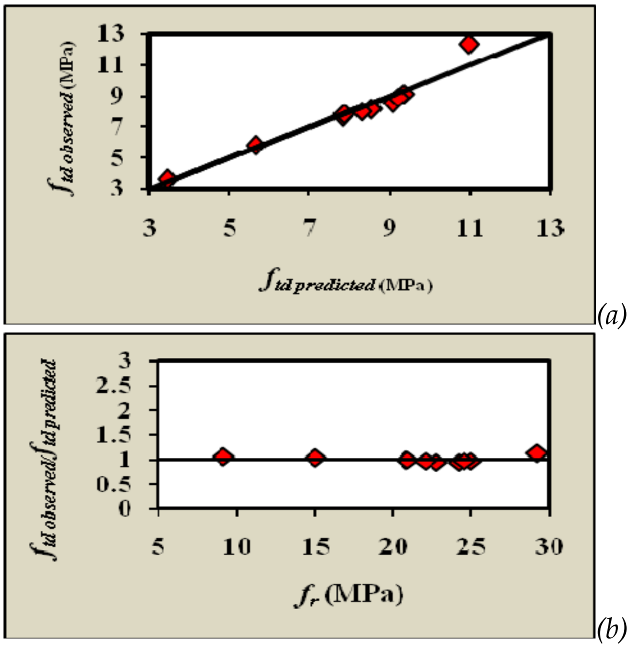


Figure 18.(a) Observed versus predicted values of direct tensile strength, (b) the ratio $f_{td\ observed}/f_{td\ predicted}$ versus the flexural tensile strength f_r

CONCLUSIONS

From the experimental results presented in this study, the following conclusions can be drawn:

1- *Results indicated that by increasing the volume fraction of fibers from 0% to 1.0%, 2.0%, and 3.0% the cube compressive strength was increased by 3.72%, 8.36%, and 8.89% respectively, while the cylinder compressive strength was increased by 6.36%, 9.9%, and 11.54% respectively.*

2- *Increasing SF content from 0% to 10%, 15%, 20%, 25%, and 30% caused a considerable increase in the cube compressive strength by 13.54%, 18.02%, 24.72%, 29.86%, and 34.17% respectively, as well as a comparative increase in the cylinder compressive strength by 17.56%, 20.30%, 30.92%, 33.79%, and 41.04% respectively.*

3- *The inclusion of steel fibers leads to a considerable increase in tensile strength (direct, splitting and flexural). Increasing the volume fraction of fibers from 0% to 1.0%, 2.0%, and 3.0% resulted in an increase in the direct tensile strength by 59.4%, 145.05%, and 238.35%, the splitting tensile strength by 90.88%, 186.51%, and 258.45% and the flexural tensile strength by 52.62%, 166.61%, and 217.27% respectively.*

4- *The increase in the steel fibers volume fraction and silica fume content improved the load-deflection behavior and consequently gave larger ductility and fracture toughness of RPC. Addition of steel fibers to nonfibrous RPC was found to change the brittle nature of the nonfibrous matrix to a composite mass with a plastic behavior after first crack. The presence of steel fibers gave a longer plastic range of the load-deflection behavior with higher peak load and larger post-peak toughness.*

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