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Properties of Reactive Powder Concrete with Various Water to Cement Ratios, Silica Fume, and Steel Fibers Contents

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Abstract
Reactive Powder Concrete (RPC) is an ultra-high performance concrete which has superior mechanical and physical properties. The RPC iscomposed of cement and very fine powders such as crushed quartz (100–600 μm) and silica fume with very low water/binder ratio and Super Plasticizer (SP). The RPC has a very high compressive and tensile strength with better durability properties than current high performance concretes. A compressive strength up to 165 Mpa, a flexural strength up to 42Mpa, and a splitting tensile strength up to 16 Mpa were achieved at age the 28 days.

Keywords*: Compressive Strength, Reactive Powder Concrete, Workability.*

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I. Introduction

Reactive powder concrete mixes are characterized by high silica fume content and verylow water/cement ratio. Coarse aggregate is eliminated to avoid weaknesses of themicrostructure, the addition of super plasticizer is used to achieve a low water/binder(cement and silica fume) ratio and heat-treatment is applied to achieve high strength.RPC mix is composed of fine sand, high content of cement, silica fume, quartz, and super plasticizer. The absence of the coarse aggregate reduced the heterogeneity between the cement matrix and the aggregate and hence enhances the microstructure and the performance.

II. Materials And Methods

Experimental program was achieved to study mechanical properties of reactive powder concrete (RPC). These properties divided into fresh properties and hardened properties.Experimental work included three groups (36 trial mixes). Group (A) consists of 12 mixes (W/C=0.17), Group (B) consists of 12 mixes (W/C=0.19), Group (C) consists of 12 mixes (W/C=0.21.

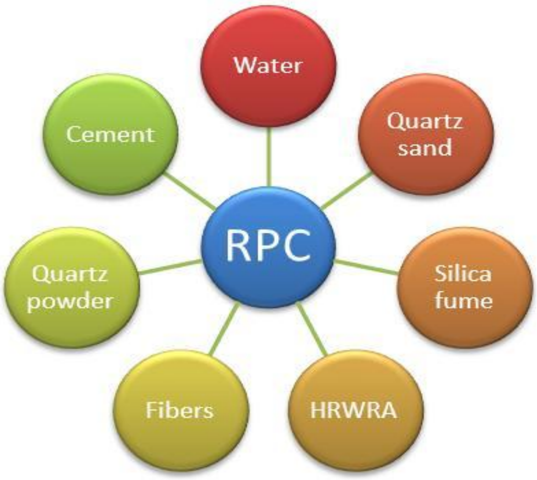


Figure 1: RPC Compositions

Table 1: RPC mix proportions (kg/m^3)

Mix no	Cement	Silica fume	Quartz powder	Quartz sand	SP	Water	Steel fibers	W/c	W/b
A1	900	225	225	886	36	153	0	0.17	0.14
A2		270		833					0.13
A3		315		779					0.13
A4		225	225	860			78		0.14
A5		270		807					0.13
A6		315		753					0.13
A7		225	225	834			156		0.14
A8		270		780					0.13
A9		315		727					0.13
A10		225	225	808			234		0.14
A11		270		754					0.13
A12		315		701					0.13
B1	900	225	225	861	27	171	0	0.19	0.15
B2		270		807					0.15
B3		315		754					0.14
B4		225	225	835			78		0.15
B5		270		781					0.15
B6		315		728					0.14
B7		225	225	809			156		0.15
B8		270		755					0.15
B9		315		702					0.14
B10		225	225	782			234		0.15
B11		270		729					0.15
B12		315		676					0.14
C1	900	225	225	831	19.8	189	0	0.21	0.17
C2		270		778					0.16
C3		315		724					0.16
C4		225	225	805			78		0.17
C5		270		752					0.16
C6		315		698					0.16
C7		225	225	779			156		0.17
C8		270		726					0.16
C9		315		672					0.16
C10		225	225	753			234		0.17
C11		270		700					0.16
C12		315		646					0.16

2.1.1 Cement

In this research ordinary Portland cement CEM I 52.5 N was made for the production of RPC for all mixes, it provided by EL- ARISH PORTLAND CEMENT Company- BENI-SUEF (El -Askary).

Table 2: Mechanical and physical properties of cement CEM I 52.5 N

Property	Measured values	(ES 4756-1/2017)
Specific gravity	3.15	--
Setting time:		
Initial, min	70	≥ 45 min
Final,min	210	<= 10 hours
Compressive strength, MPa		
2 days	24.7	≥ 20 MPa
28 days	55.80	≥ 52.5 MPa
Cement fineness (Specific surface area)	360 m²/gm	Min. 275 m²/kg

2.1.2 Silica Fume

SF was provided from Sika Company in Egypt (Sika fume) as shown in Figure 3.4. SF content is partial replacement by weight of cement). Three ratios were employed (25%, 30% and 35%). Silica fume in RPC concrete fills micro voids and produces secondary hydrates by pozzolanic reaction

Table 3: Properties of Silica fume (source: from supplier)

Trade name	Composition	Particle size	Color	Bulk Density, kg/m^3
Sika Fume® - HR	A latently hydraulic blend of active ingredients	8 um	Grey powder	300 kg/m^3

Figure 2: Silica Fume used in mixtures

2.1.3 Quartz sand

The primary concerns of aggregate in mix design for Reactive Powder Concrete are gradation, maximum size, and strength. Quartz has Specific Gravity: 2.6 to 2.7. Figure 3.9 shows quartz particles before crushing, and Figure 3 shows crushed machine of quartz.

Figure 3: Quartz sand

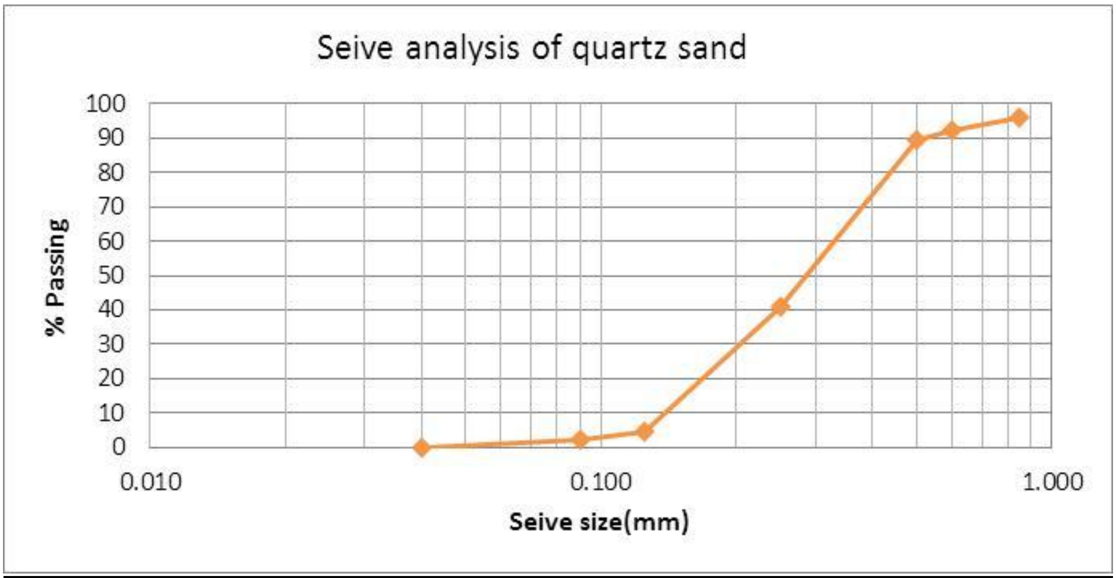


Figure Figure4: Grading of quartz sand.

2.1.4 Quartz powder

Quartz powder was used in RPC as high volumes of very fine particles.

Figure 5: Quartz powder.

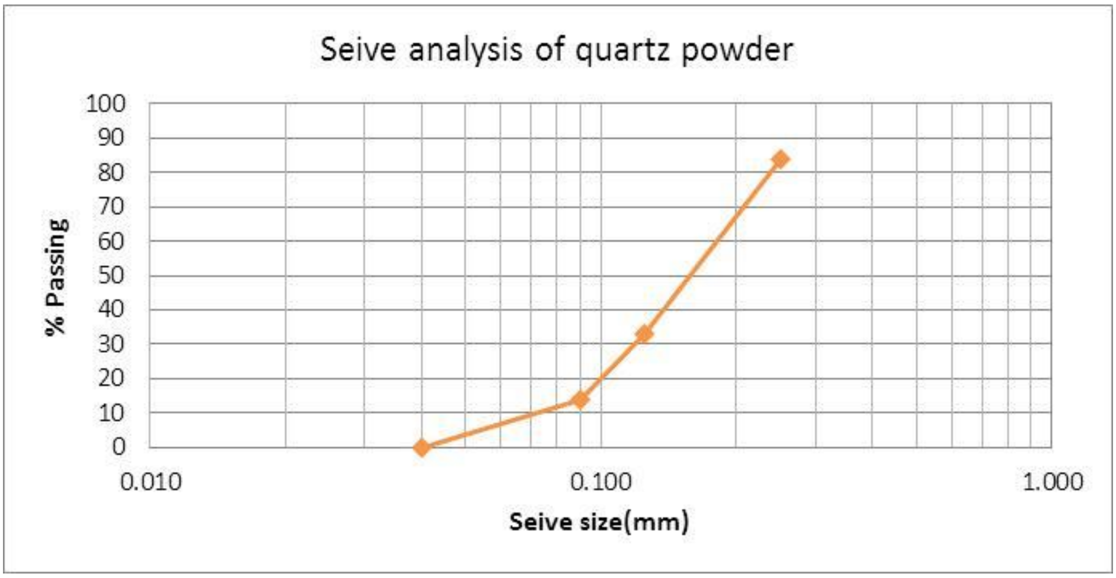


Figure 6: Grading of quartz powder.

2.1.5 Water

Drinkable water was used in all concrete mixtures and in the curing of specimens. It was taken directly from the tap

2.1.6 Chemical Admixtures (Super plasticizer)

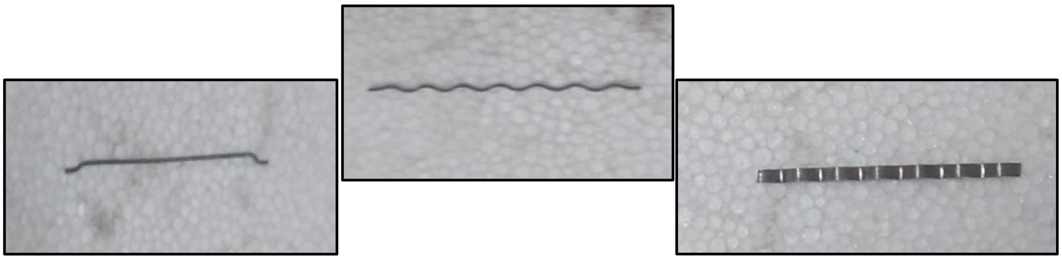
Very low water to cement ratios used in RPC would be promising by using high amount of high-quality super plasticizer.Polycarboxylate high-range water-reducing admixture that agrees with ASTM C494 specifications was used to maintain the table-flow of mixtures to 160 mm.

Table 4: Properties of Super plasticizer (source: from supplier)

Trade name	Base	Color	Density, kg/m^3	PH Value
SikaViscoCrete® -3425	Aqueous solution of modified polycarboxylates	Clear liquid	1.08 kg/lt (ASTM C494)	4.0

2.1.7 Steel fibers

The fibers 0.80/55 is high tensile undulated steel fibers made of cold drawn wire used to replace all other of reinforcement in concrete.The fibers are used to improve the tensile capacity and improve the ductility of the RPC. The steel wires are cut into the desired length that was 18.33 mm and density of 7.85 gm/cm^3. Figure 3.15 shows types of steel fibers available in Egypt markets.



(a) End hooked (b) Waved (c) Corrugated

Figure 7: Types of steel fibers available in Egypt markets

Aspect ratio is the length divided by the diameter. Aspect ratio ***(l /d)*** of the steel fibers used was 22.50. Table 3.20 shows properties of steel fibers used in this study.

Table 5: Properties of Steel fibers (source: from supplier)

Trade name	**Size** (D*L)	**Surface**	**Tensile strength**	**Quality**
wave fibers	0.80 × 55 mm	Clear, and loose round wavy fibers	Minimum 1000 (Mpa)	ASTM A820

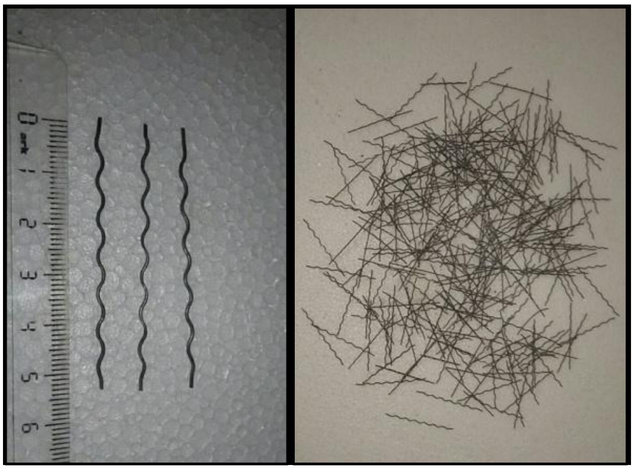


Figure 8: steel fibers before cutting

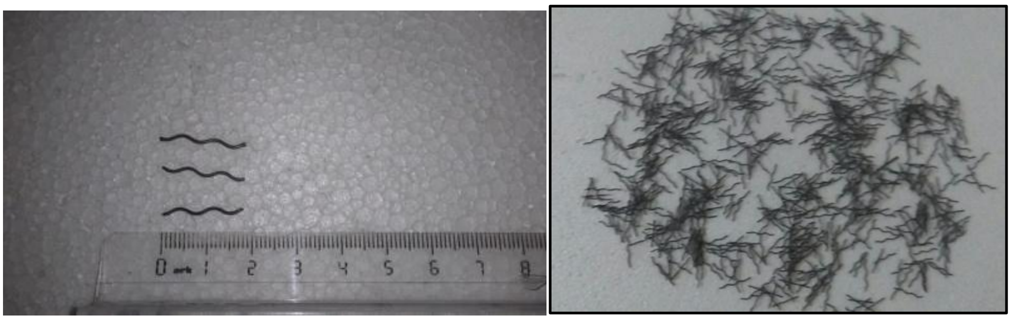


Figure 9: Steel fibers after cutting into three parts

3.2 The variables of this study include

1. Water to cement ratio; 0.17, 0.19, and 0.21by weight of cement.
2. Silica fume content; 25%, 30% and 35% by weight of cement.
3. Steel fibers content; 0%, 1%, 2% and 3% by total volume of concrete mix.

Table 6: Size of Specimen of tests

Name of test	Size of Specimen
Compression strength test	Cubes 50 × 50 × 50 mm
Split tensile strength test	Cylinders 50 mm diameter × 100 mm height
Flexural strength test	Prism40 × 40 × 160 mm

3.3 Mixing

Mixing was performed in a high speed-mixer to overcome the high viscosity and cohesiveness of the mixtures associated with the extremely low w/c, and to facilitate the dispersion of water and super plasticizer. Capacity of mixer is 60 liter. It was carried out in laboratory of concrete materials at Faculty of Engineering, Mansoura University.

Figure 10: RPC mix after dry mixing

Figure 11: RPC mixer

Figure 12: Size of Specimen

Figure 13: RPC mixer

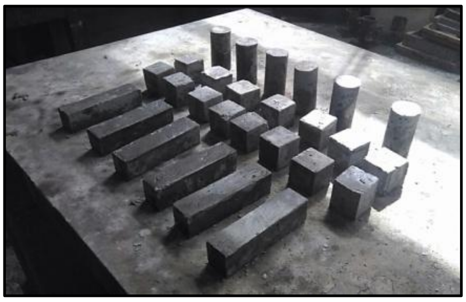


Figure 14: Concrete specimens after casting

4.1 Test results of fresh concrete

Workability of concrete mixtures was tested by the flow table test. It was kept constant for all mixtures (diameter of flow table was 160 mm), hence super plasticizers dosage were changed according to water to cement ratio. W/c ratios were 0.17, 0.19, and 0.21. Corresponding super plasticizers dosage were
4 %, 3 %, and 2.20 %, by weight of cement respectively

4.1.1 Flow table test

Figure 15 and Figure 16 represented flow table test before and after working samples respectively.

Figure 15: Flow table test before working samples

Figure 16: Flow table test after working samples

As presented in Figure 4.3 w/c =0.17 needs SP = 4%, w/c = 0.19 needs SP = 3%, and w/c = 0.21 needs SP = 2.2%,

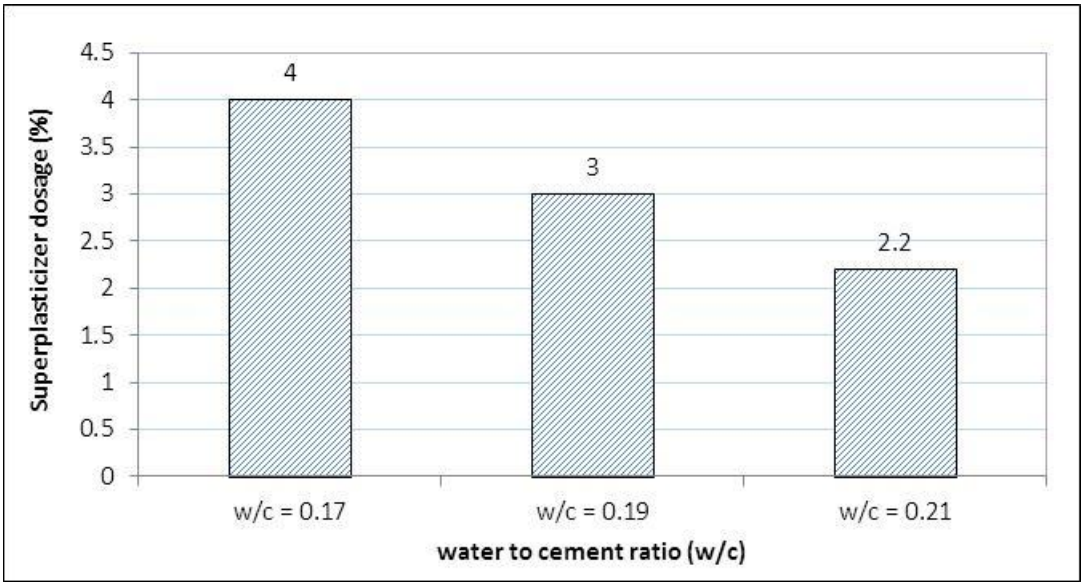


Figure 17: Correlation between w/c ratios and superplasticizers dosage

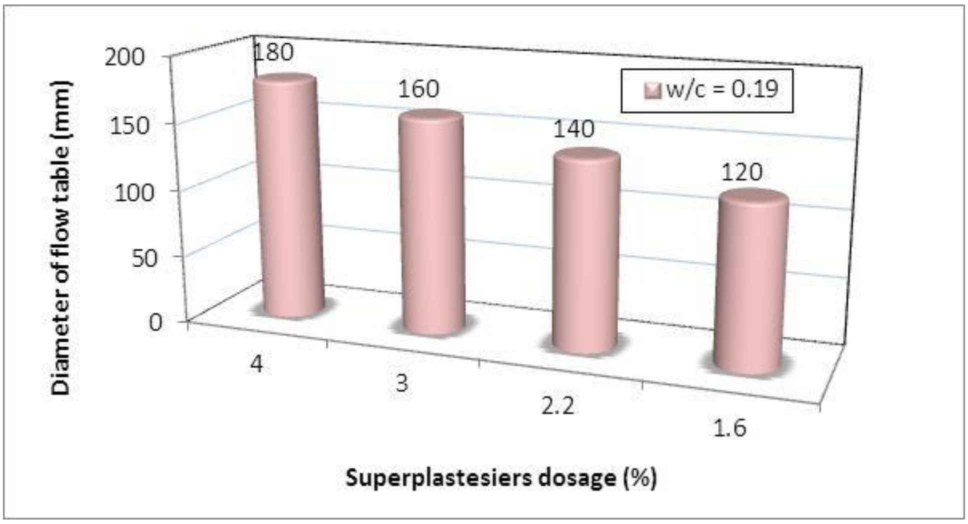


Figure 18: Relationship between of flow table and superplasticizers

4.2.2 Influence of SF and steel fibers on flow table.

Three dosages of SF are taken 25 %, 30 %, and 35 % by weight of cement. Ratios of steel fibers were 0%, 1%, 2%, and 3% by total volume of concrete mix to study their effects on fresh RPC properties. Figure 4.5 illustrate that increasing the silica fume percentage, decreasing the table flow values, this can be reasonable because SF is a very fine materials need much more content of water to break the flocculation forces. Moreover, as the steel fibers increases, the flow table results decreases.

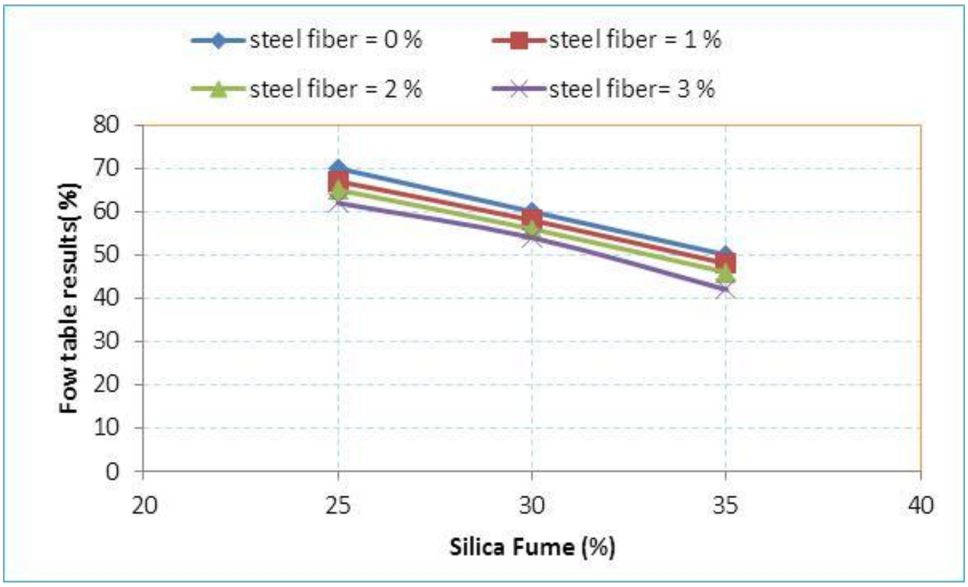


Figure 19: Influence of SF and steel fibers on flow table test results

4.3 Hardened properties results for normal water curing

4.3.1 Density of RPC

The unit weight of the concrete cube specimen (50× 50 ×50 mm) is the theoretical density.

4.3.1.1 Effects of silica fume on RPC density

Figures 4.10 and 4.11 illustrate the influence of SF on the RPC density. Test results illustrate that the density reduce when growing the SF percentage. This can be due he void existed by cement is partly replaced by SF.

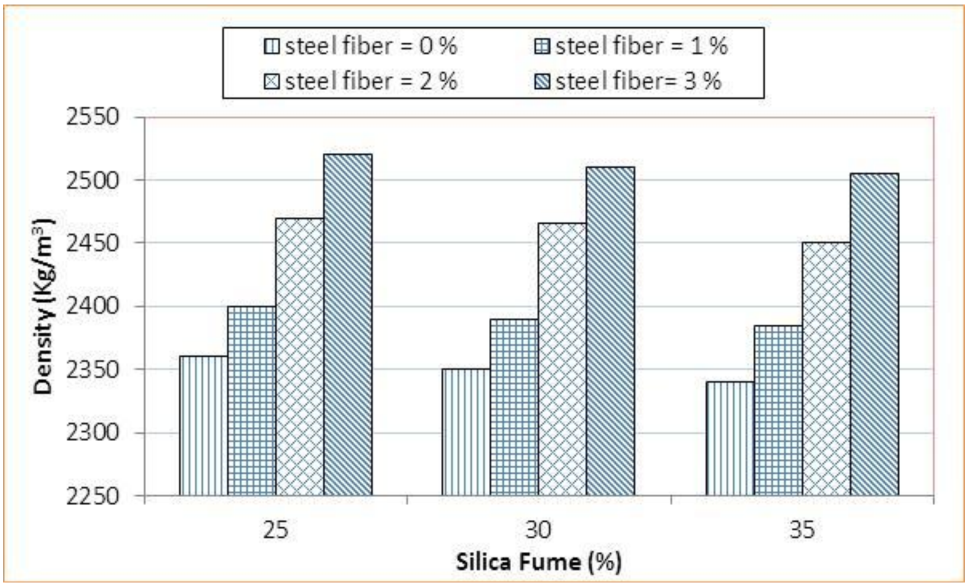


Figure 25: Impact of SF content on RPC density with different contents of steel fiber

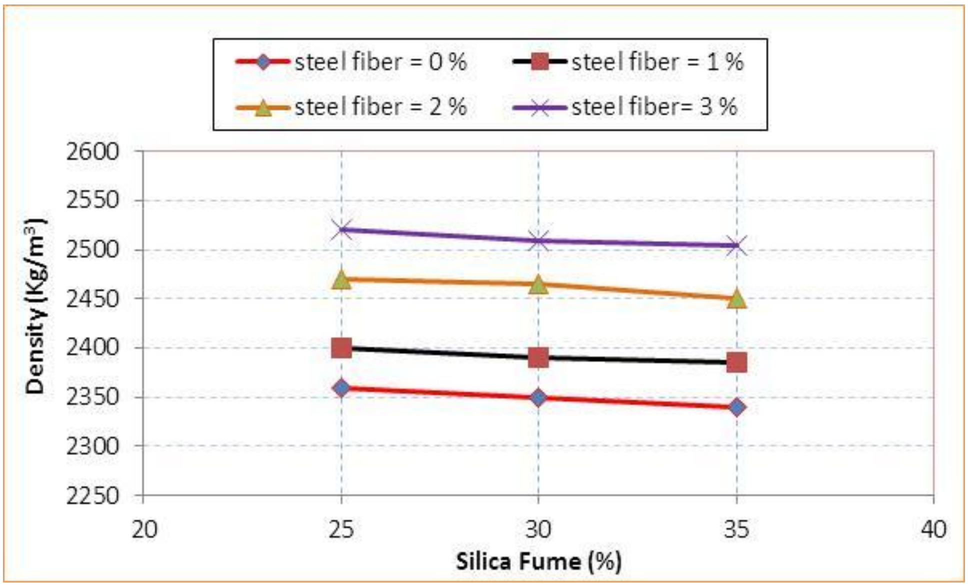


Figure 20: Impact of SF percentage on RPC density with various contents of steel fiber

4.3.1.2 Effects of steel fibers on RPC density

Figures 21, and 22 show that the influence of steel fibers on the RPC density. The analysis of results illustrate that the density of concrete improves when the amount of SF increases.

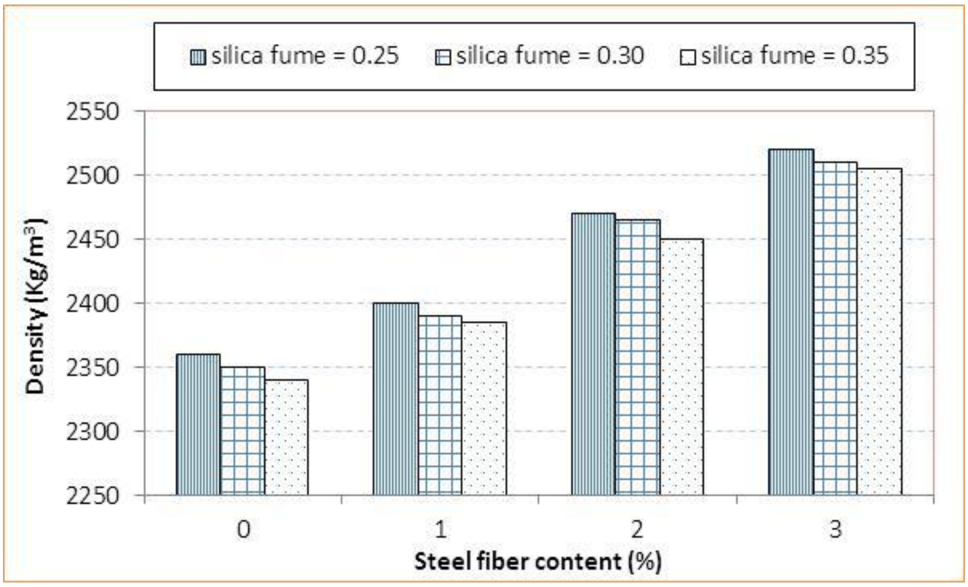


Figure 21: Impact of SF amount on RPC density with various contents of SF

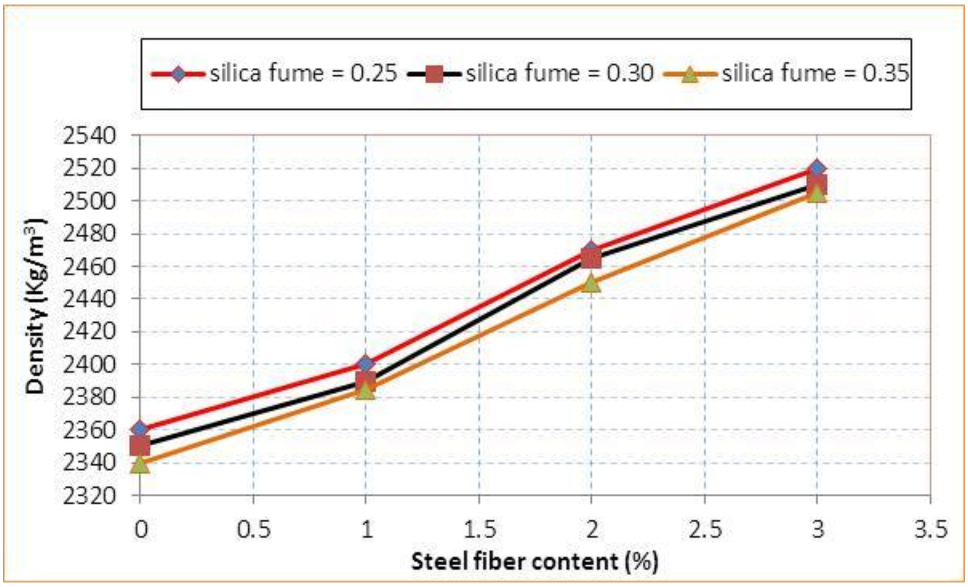


Figure 22: Impact of steel fibers content on RPC density with different contents of silica fume

4.3.2 Results of compressive strength

Results of compressive strength of RPC mixes at ages (7, 28, 56, 90, and 180 days) for Group (A - D), and Group (E) of the experimental program are listed in tables 4.1 - 4.5, and presented graphically in Figures 23 The values shown in tables are the average of the results of testing of three cubes 50 × 50 × 50 mm.

Table 7: Test results of different mixtures

Mix no	Density (t/m3)	Compressive strength (Mpa)			Splitting tensile strength(Mpa)	Flexural strength(Mpa)
		7 days	28 days	56 days	28 days	28 days
A1	2.41	71	79	84	5.22	13.09
A2	2.40	83	94	99	6.28	16.72
A3	2.38	74	83	88	4.69	13.99
A4	2.45	69	83	88	6.96	17.78
A5	2.44	84	101	107	8.70	21.18
A6	2.43	74	89	95	6.73	15.81
A7	2.52	77	92	98	7.87	20.50
A8	2.51	90	108	115	9.98	25.34
A9	2.50	82	98	104	8.47	21.63
A10	2.57	80	97	103	9.15	25.57
A11	2.56	94	113	119	11.42	28.67
A12	2.55	87	104	111	10.14	26.32
B1	2.53	93	105	111	6.90	17.3
B2	2.52	110	124	131	8.30	22.1
B3	2.51	98	110	117	6.20	18.5
B4	2.57	91	110	117	9.20	23.5
B5	2.56	111	134	142	11.50	28.0
B6	2.55	98	118	125	8.90	20.9
B7	2.65	101	122	129	10.40	27.1
B8	2.64	119	143	152	13.20	33.5
B9	2.62	108	130	138	11.20	28.6

B10	2.70	106	128	136	12.10	33.8
B11	2.69	124	149	158	15.10	37.9
B12	2.68	115	138	146	13.40	34.8
C1	2.45	85	96	101	6.3	15.7
C2	2.44	100	113	120	7.6	20.1
C3	2.43	89	100	106	5.6	16.8
C4	2.50	83	100	106	8.4	21.4
C5	2.49	101	122	129	10.5	25.5
C6	2.48	89	107	114	8.1	19.0
C7	2.57	92	111	118	9.5	24.7
C8	2.56	108	130	138	12.0	30.5
C9	2.55	98	118	125	10.2	26.0
C10	2.62	97	117	124	11.0	30.8
C11	2.61	113	136	144	13.7	34.5
C12	2.60	104	126	133	12.2	31.7

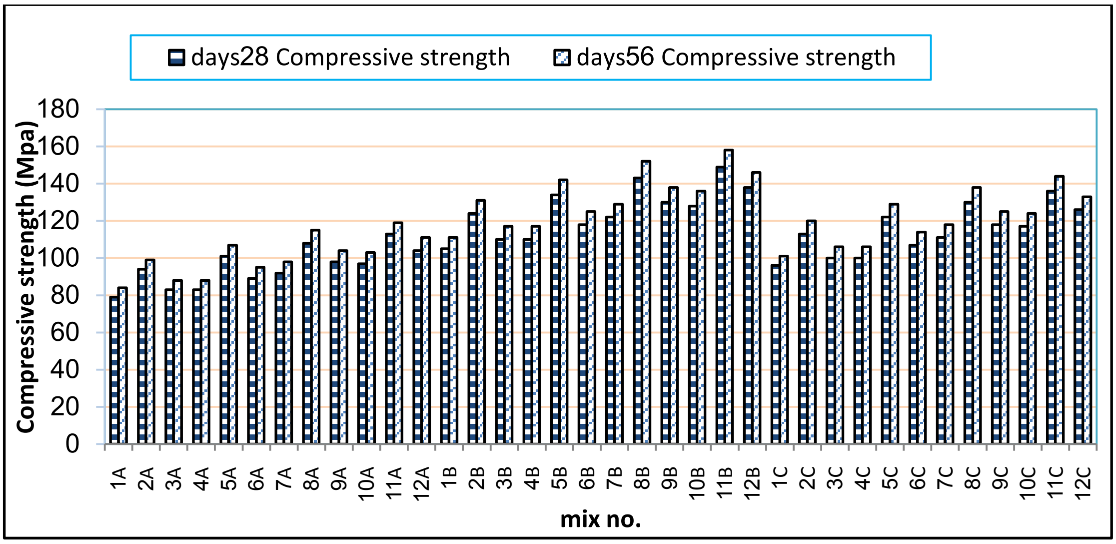


Figure 23: Results of compressive strength of different mixes

4.3.2.1 Effects of SF content on RPC compressive strength

The results show that by changing the SF amount, from 25% to 30%, the compressive strength improved. On the other hand when percentage is more than 30%, it was minimized. It is conclude that the optimum percentage of SF is 30% at 28 days. This can be explained that the SF mechanism of the pozzolanic reaction and the physical function.

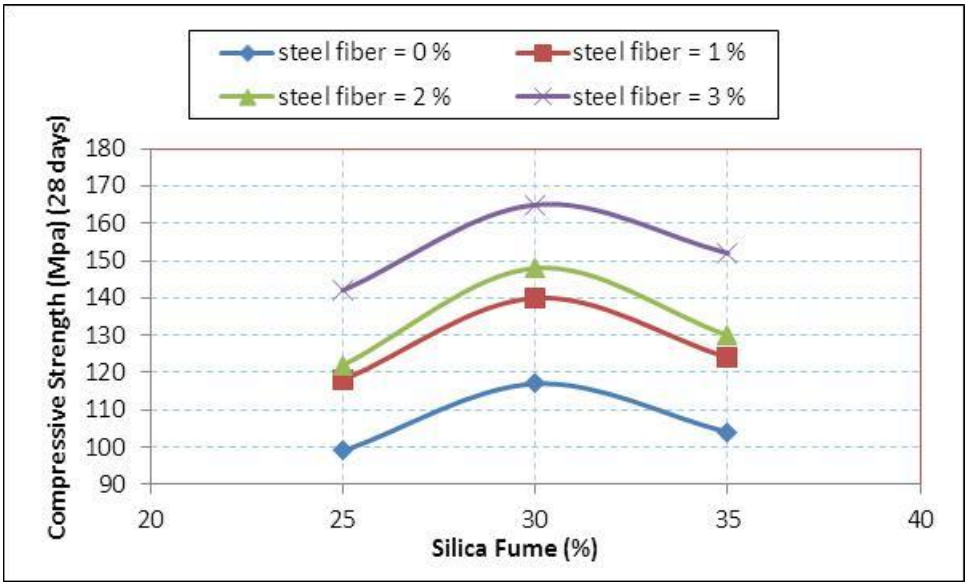


Figure 24: Impact of SF content on RPC compressive strength containing different ratio of SF at 28 days

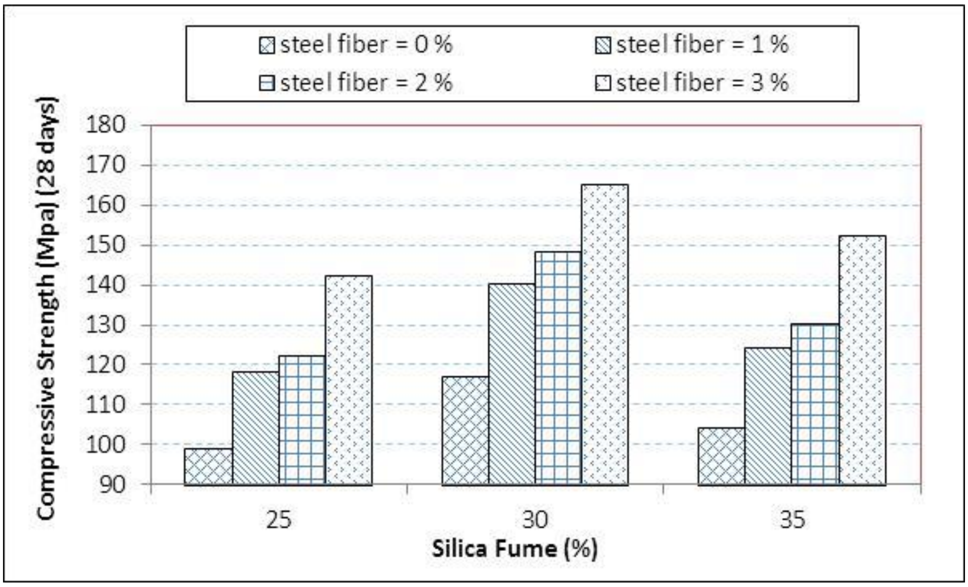


Figure 25: Impact of SF percentage on RPC compressive strength containing different ratio of steel fibers at 28 days

4.3.2.2 Optimization of SF percentage

The ultimate compressive strength was created by adding silica fume by 30 % of the weight of cement.

4.3.2.3 Effects of steel fibers content on RPC compressive strength

Steel fibers in RPC mixtures are primarily responsible for improving the ductility of the concrete. The results show that by changing the S_tF amount, from 1% to 3%, the compressive strength also improves. Richard and Cheyrezy (1995) recommended using 3% by mixture volume of steel fibers for an economical and workable RPC mixture design, over 3% steel fiber not economic and not workable.

The test results in Figures 4.23 and 4.24 illustrate that changing fibers content from 0% to 1.0%, 2.0%, and 3.0% leads to improve in the compressive strength by 20%, 26%, and 41% respectively. Figure 26shows influence of steel fibers content on shape of specimen's failure in compressive strength test.

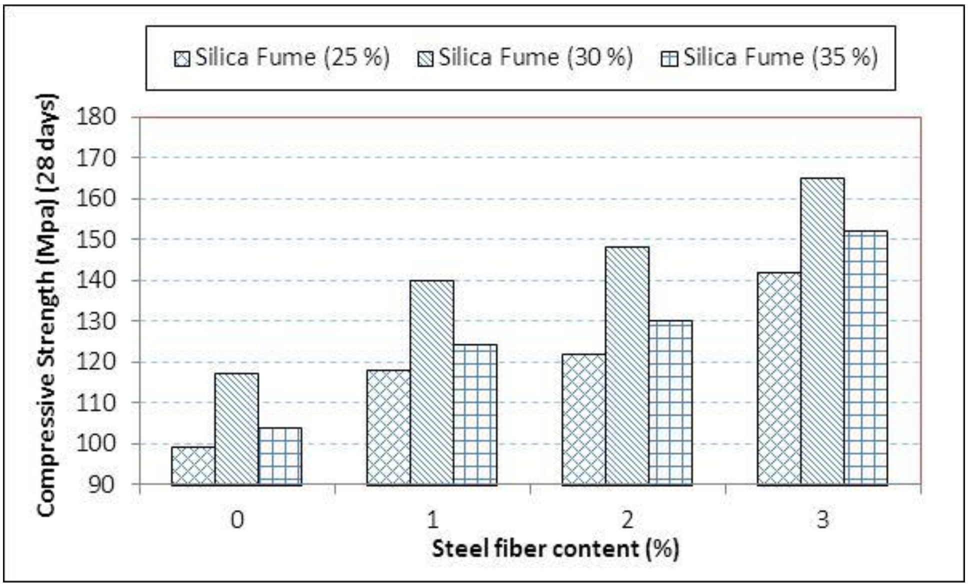


Figure 26: Impact of steel fibers on RPC compressive strength containing various ratio of silica fume at 7 days

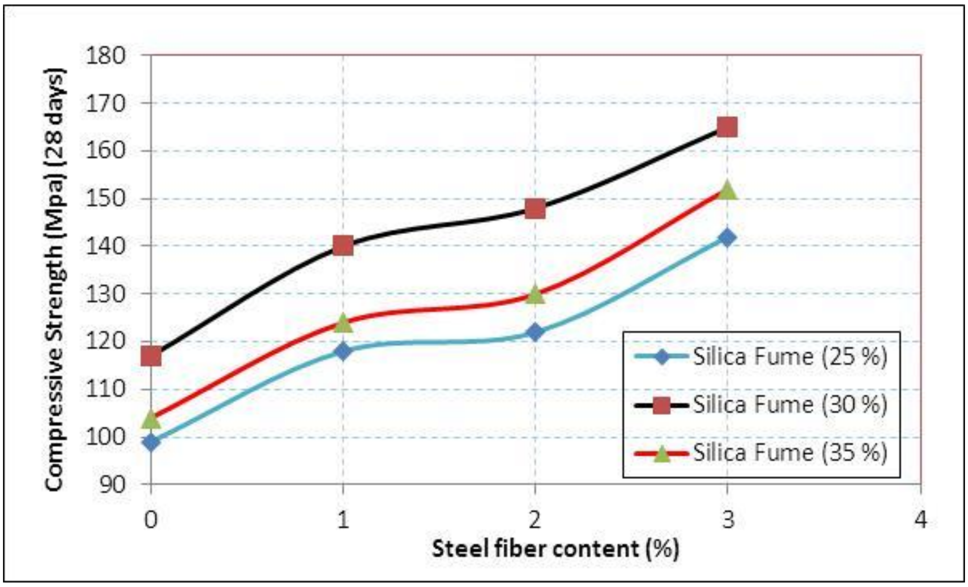


Figure 27: Impact of steel fibers on RPC compressive strength containing different ratio of silica fume at 28 days

Mixes without steel fibers (0%)

Mixes with steel fibers (78 kg/m^3)

Mixes with steel fibers
(156 kg/m^3)

Mixes with steel fibers
(234 kg/m^3)

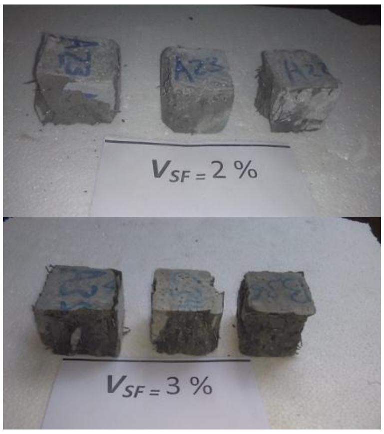


Figure 28: Effect of steel fibers content on shape of specimen's failure in compressive strength test

4.3.2.4 Optimization of steel fibers content

By addition 3% of S_tF in concrete mix, the maximum compressive strength was 165 MPa at 28 day. Figures4.26 and 4.27 show effect of steel fibers on compressive strength of RPC.

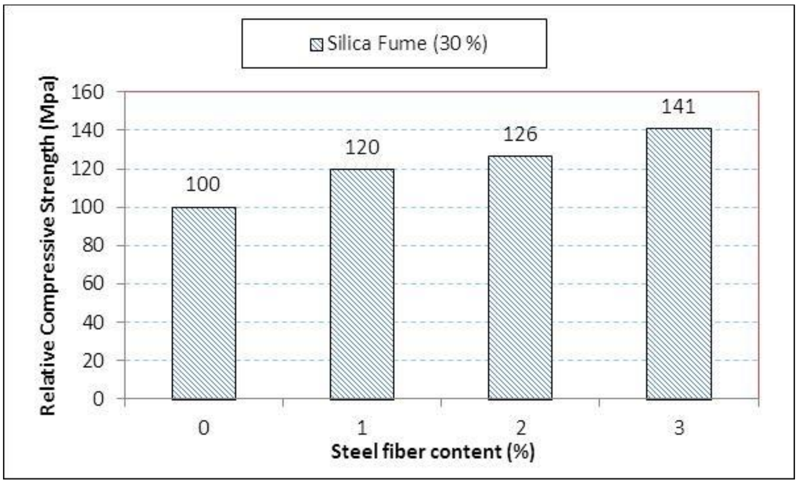


Figure 29: Influence steel fibers on Relative compressive strength of RPC having SF (30%)

4.3.2.5 Effect of w/c ratio on compressive strength

Figures 30, , and 31 with SF 25, 30, 35 % respectively summarize the behavior of w/c ratio.

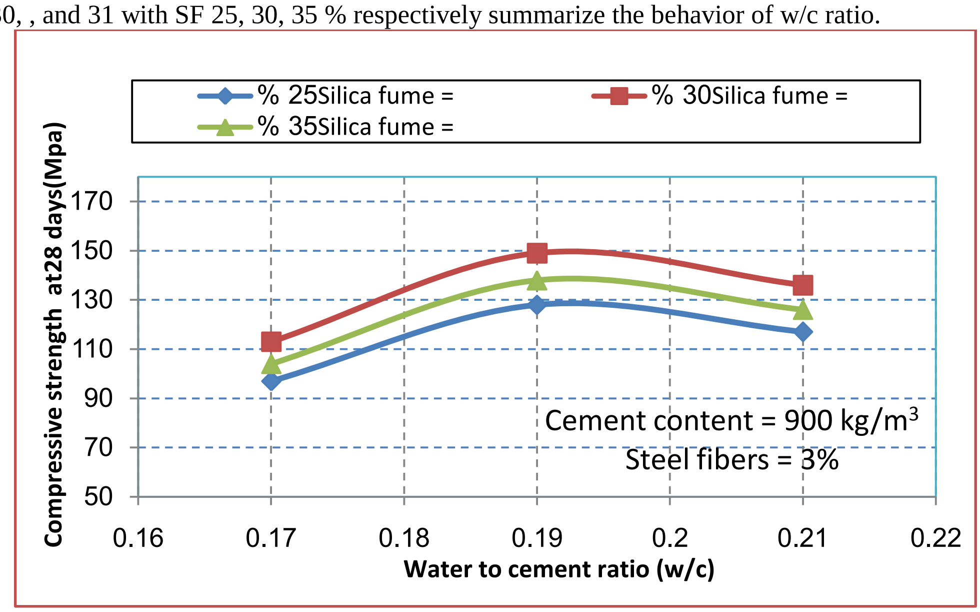


Figure 30 Effect of water to cement ratios (w/c) on Compressive Strength.

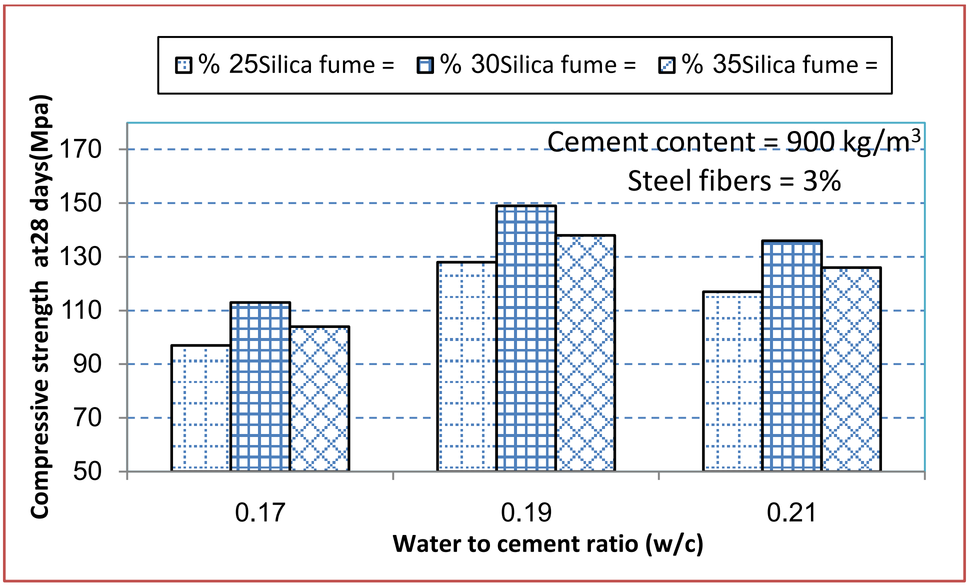


Figure 31 Effect of water to cement ratios (w/c) on Compressive Strength.

Figures 31 show that w/c ratio of 0.19 is the best ratio for mixtures which give higher compressive strength than RPC mixes having w/c ratio 0.17, 0.21, and 0.23.

4.3.2.6 Optimization w/c ratio

In order to determine the optimum water cement (w/c) ratio for the RPC mixes the relationship between w/c ratio and compressive strengths of the mixes at 7, 28, and 56 days is illustrated in Figure 1. The figure shows that the RPC mix with w/c ratio of 0.19 had higher compressive strengths than those mixes with 0.17, and 0.21 w/c ratios.After reviewing results of compressive strength we can conclude the following relationships between compressive strength at 7. 28, and 56 days as follow:

$$f_c \text{ at 56 days} = f_c \text{ at 7 days} *1.277 \quad (1.1)$$

$$f_c \text{ at 56 days} = f_c \text{ at 28days} *1.066 \quad (1.2)$$

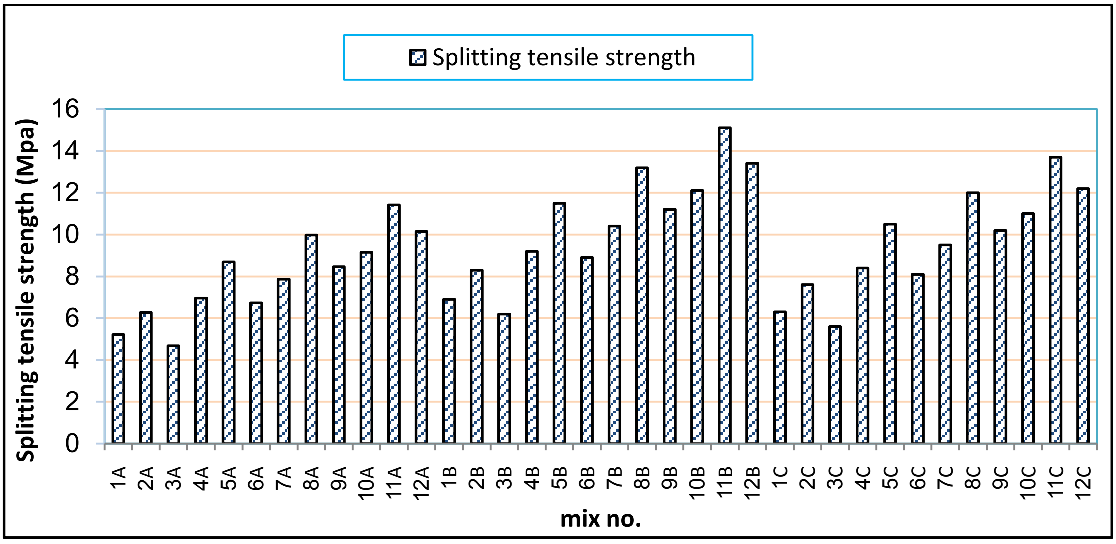


Figure 32: Results of splitting tensile strength of different mixes

4.3.3.1 Impact of SF on RPC splitting strength

Figures 33 indicate that when SF changed from 25% to 30% the tensile strength improved. On the other hand when percentage was more than 30%, it was reduced.

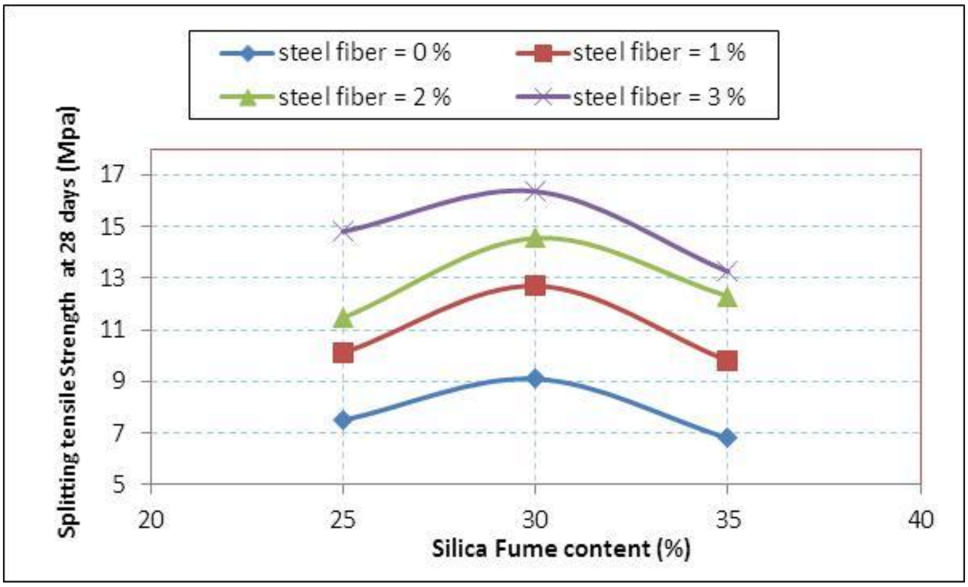


Figure 33: Influence of SF and steel fibers on tensile with various percentage of steel fiber at 28 days

It can conclude that the optimal value of silica fume is 30% and this result agrees with that of Meleka et al. (2013) who found a similar result. The mix created a maximum splitting tensile of RPC samples was 16.51 MPa at 28 days.

4.3.3.2 Impact of steel fibers percentage on tensile strength

The short fibers are added into the cement matrix as micro-reinforcement and create high bond strength between them. Figure 4.51shows effect of steel fibers on RPC tensile strength. By changing the amount of fibers from 0% to 1.0%, 2.0%, and 3.0% the splitting tensile strength increases by 40%, 60%, and 81% respectively as shown in Figure 34. The optimal value of steel fiber is 3 %, and this result agrees with that of Abdul Hussain (2013).

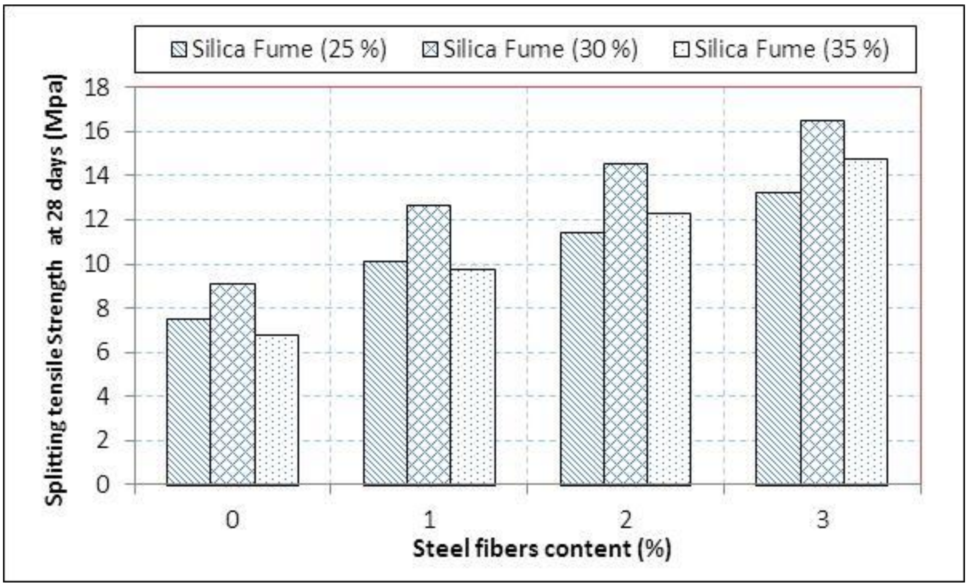


Figure 34: Impact of steel fibers on RPC tensile with various percentage of SF

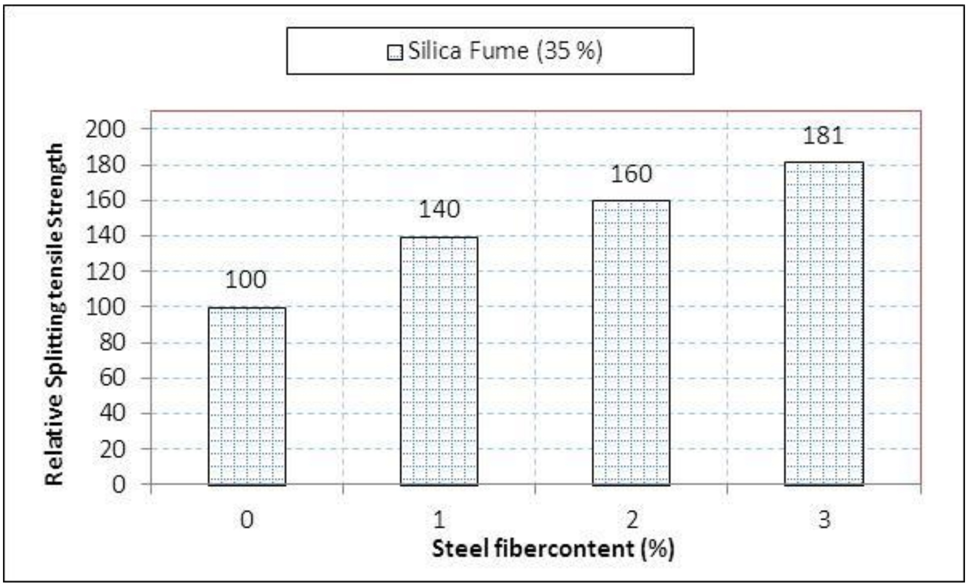


Figure 35: Relative tensile to S_tF with silica fume (35%)

Figure 36 shows relation between compressive and splitting tensile strength.

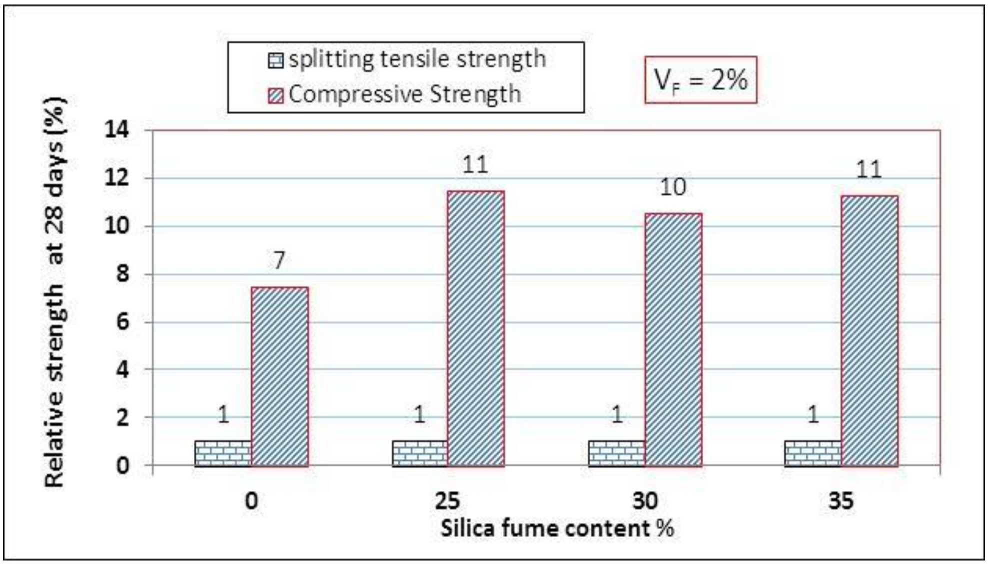
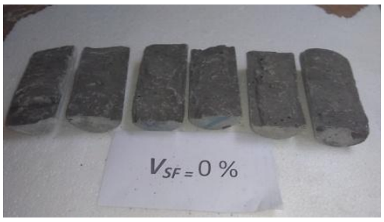
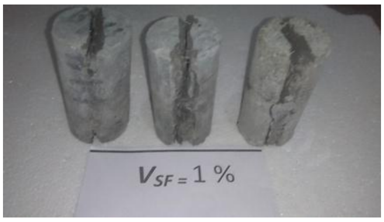


Figure 36: Relative compressive and splitting tensile strength with steel fiber (2%)

Mixes without steel fibers
(0%)



Mixes with steel fibers
(78 kg/m^3)



Mixes with steel fibers
(156 kg/m^3)

Figure 37: Effect of steel fibers content on shape of specimen's failure in Splitting tensile strength test

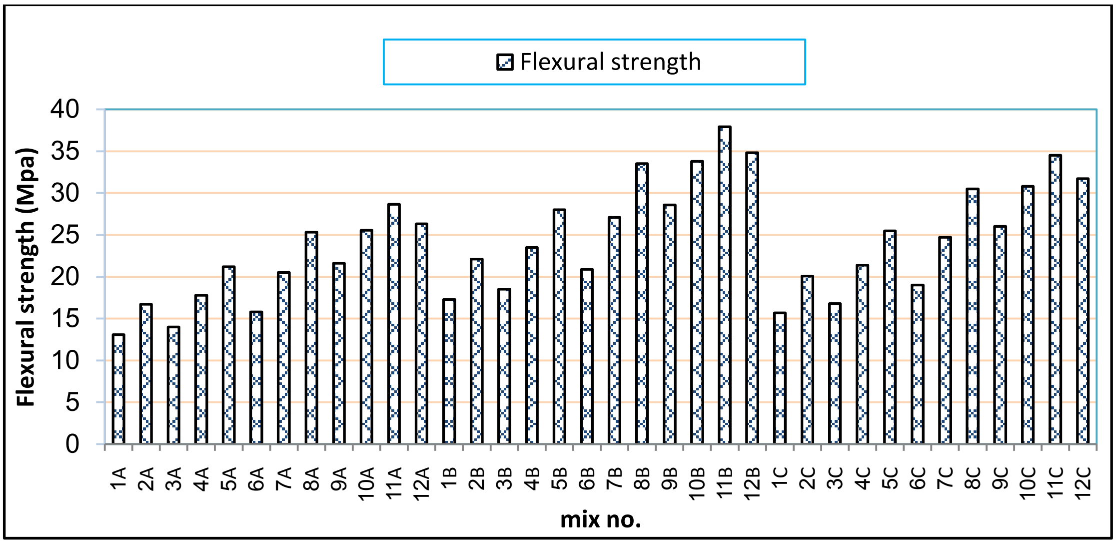


Figure 38: Results of Flexural strength of different mixes

4.3.4.1 Effect of steel fibers on RPC flexural

By increasing of the steel fiber amount, improve the flexural strength as shown in Figure 39.

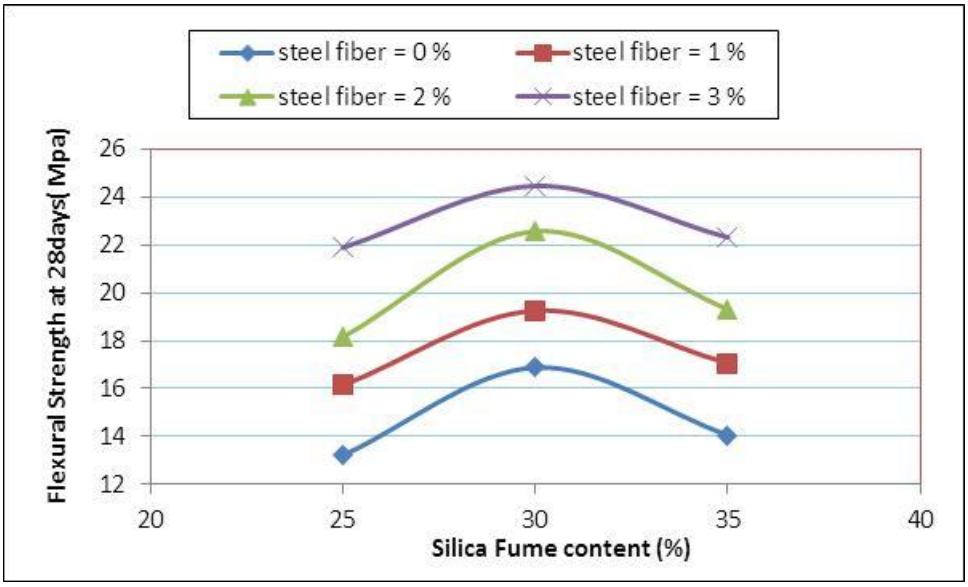
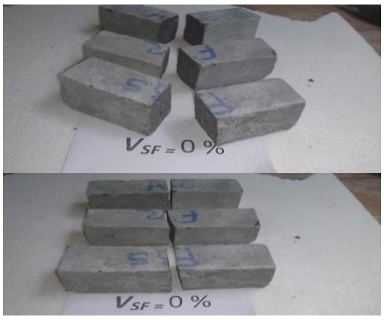


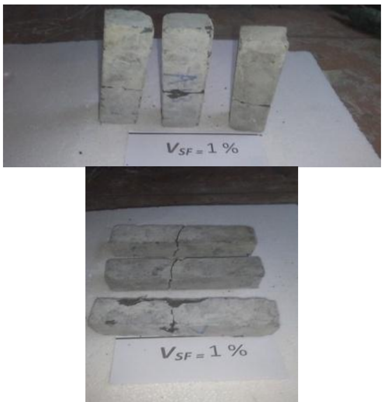
Figure 39: Influence of SF and steel fibers on RPC flexural strength with various percentage of steel fiber at 28days

Figure 40 shows effect of steel fibers content on shape of specimen failure in flexural strength test.

Mixes without steel fibers (0%)



Mixes with S_tF (78 kg/m^3)



Mixes with S_tF (156 kg/m^3)

Mixes with S_tF (234 kg/m^3)

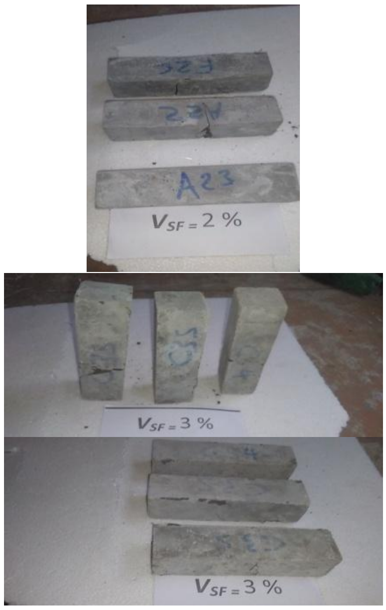


Figure 40: Impact of steel fibers percentage on shape of specimen failure in flexural strength test

Figures 41 and 42 show relationship between tensile and flexural strength.

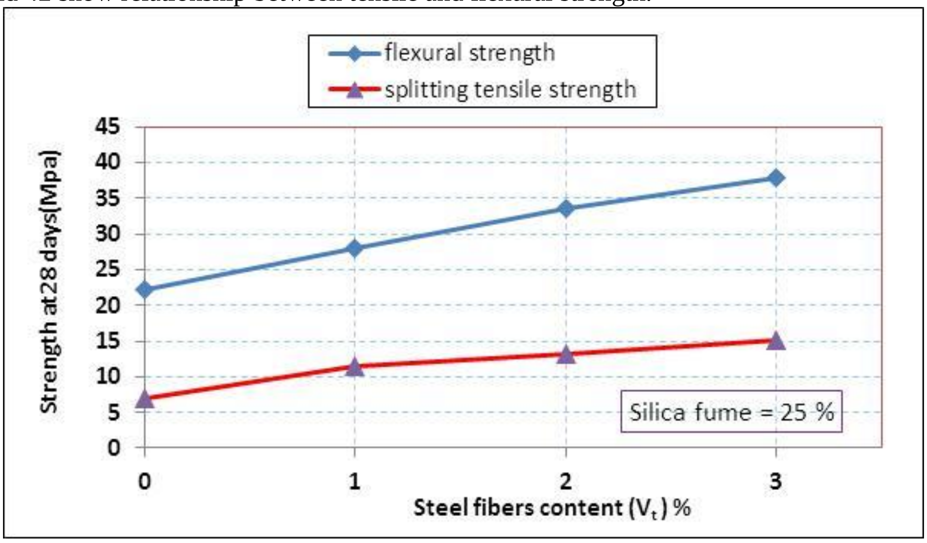


Figure 41: Relationship between tensile and flexuralstrength

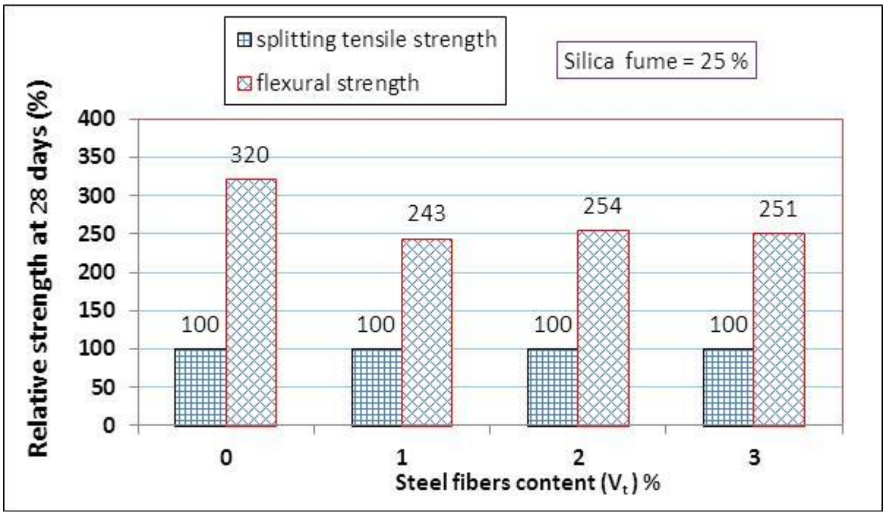


Figure 42: Relative relationship between tensile and flexural

V. Conclusions

Several conclusions were made after reviewing all data and test results from both phase (1) and phase (2) of the research. According to the experimental investigation, analysis of tests of results, and the discussions, we can summarize the following conclusions:

1) Reactive powder concrete can be made using materials available in Egypt.
2) Reactive powder concrete can be used at that place where application of normal concrete is not possible.
3) Changing silica fumes content from 25% to 30% and 30% to 35% reduce the flow table.
4) Increasing steel fibers percent will slightly minimize the flow table, when silica fume percentage 30 % the flow table decrease about 2.44%, 4.15%, and 5.58% at 1.0%, 2.0%, and 3.0% steel fiber respectively.
5) Changing the silica fume percentage from 30% to 35% caused reduction in the compressive strength.
6) The maximum compressive strength of the concrete specimens was achieved when adding 30 % silica fume.
7) Changing fibers content from 0% to 1.0%, 2.0%, and 3.0% with silica fume 30 % causes increase in the compressive strength by 20%, 26%, and 41% respectively.
8) Addition 3% of steel fibers of the total volume of concrete mix, where a compressive strength up to 165 MPa at 28 day.
9) RPC mix with water to cement ratio of 0.19 had higher compressive strengths than those mixes with 0.17, and 0.21.
10) The compressive strength of RPC improved as changed water to cement ratio from 0.17 to 0.19 by 24 %. On the hand the compressive strength of RPC decreases as increases water to cement ratio from 0.19 to 0.21, and 0.23 by 9 %and 21 % respectively.
11) The best mix B35 has optimum contents of silica fume is 30% of the cement weight, water to cement ratio is 0.19, and steel fibers 3% of total volume of concrete mix with cement content 1000 kg / m^3.
12) By changing the content of fibers from 0% to 1.0%, 2.0%, and 3.0% the splitting tensile strength by 40%, 60%, and 81% respectively.
13) When changed silica fume percentage from 25% to 30% the flexural strength increased, but when the amount was above 30%, it decreased.
14) By changing the ratio of fibers from 0% to 1.0%, 2.0%, and 3.0%, the flexural strength improved by 31%, 56%, and 76% respectively.
15) A compressive strength up to 165 Mpa, a flexural strength up to 42 Mpa, and a splitting tensile strength up to 16 Mpa were achieved at age of the 28 days for normal water curing.
16) A compressive strength up to 191Mpa, a splitting tensile strength up to 21Mpa ,and a flexural strength up to 55 Mpa were achieved at age of the 28 days for hot water curing.
17) Designer must be evaluating the compressive strength of RPC depended on its 56 days age rather than the 28 days used for conventional concrete due to continuous chemical reaction up to 56 days.
18) Compressive and splitting tensile strength of 30% silica fume was better than other percentages of RPC.

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