Journal of Engineering and Applied Sciences 13 (Special Issue 13): 10588-10593, 2018
ISSN: 1816-949X

Some Mechanical Properties of Reactive Powder Concrete

Jabor Al-Jeabory and Dhuha Abdul Amir Al-Saadi
AL-Mustaqubal University College, Hillah, Iraq

Abstract: The present research is devoted to study the mechanical properties of RPC as a material as well as studying the fracture behavior of RPC under bend load. The first part of the experimental program includes investigating the effect of steel fiber Volumetric ratio (V_f) and shape of fiber (crimped and straight) on some important mechanical properties of RPC such as compressive strength, splitting tensile strength, modulus of rupture, static modules of elasticity and impact strengths. The second part of the experimental test conducted to study the fracture mechanics of RPC in terms of (stress intensity factor K_{Ic}, J-integral J_{Ic}, fracture energy G_F, energy release rate G_{Ic} and Toughness Index T.I) of simply supported Fiber Reinforcements Reactive Powder Concrete (FR-RPC) beam having dimensions of 100×100×400 mm under symmetrical two point load.

Key words: Reactive powder concrete, crimped steel fibers, stress intensity factor, toughness index, shape, load

INTRODUCTION

Reactive powder concrete is a high strength ductile material formulated from a special combination of constituent materials. These materials include Portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer admixture, water and steel or organic fibers. Reactive Powder Concrete (RPC), offering compressive strength exceeding 200 MPa and flexure strength over 40 MPa, showing some ductility (Weeren, 2009).

The basic formulation of RPC is (1:1.1:0.25) volume percent (OPC, sand, silica fume) with w/b (water to cementious ratio) equal 0.18 in general. RPC mix design for cubic meter as 1000 kg/m^3 cement, 1000 kg/m^3 sand, 1-3 % by volume fiber, 5-30 % pozzolanic materials by weight of cement as addition or replacement and High-Range Water Reducing Admixtures (HRWRA) according to the percent which gives minimum W/B ratio (Richard and Cheyrezy, 1995). The silica fume is mostly used with RPC as a micro-silica, its content of SiO_2 is usually higher than 90% and its loss of ignition is lower than 1%.

Two RPC tested with different casting techniques (Roux *et al*., 1996), they concluded that compressive strength increased by 35% for pressurized concrete compared to table-vibrated concrete. The influence of the fiber type on the performance of RPC was investigated by several researchers (Collepardi *et al*., 1999). They concluded that the bond between cement matrix and fibers depends on the fiber type (size, shape and surface treatment). The inclusion of fibers improves tensile strength and also makes it possible to obtain the required level of ductility(Lee, 2006; Richard and Cheyrezy, 1994) by maintaining mixing and casting procedures as close as possible to existing concrete industry practice.

Research significant: The part one of the work is aimed to study the parameters which influence some mechanical properties of reactive powder concrete.

MATERIALS AND METHODS

Cement: The choice of cement is an important factor in the performance of RPC. Based on published works, the ideal cement has a high C_3S and C_2S and very little C_3A content. Therefore two types of Portland cement, Type V(Portland resisting cement) and Type I (ordinary Portland cement) were used in trail mixes to study the effect of cement compounds on the strength development of RPC and get the required compressive strength which specified the cement type that give the best result which can be adopted in this study. The chemical and physical properties of these cements are shown in Table 1 and 2.

Fine aggregate: Very fine sand with particles size between 600-150 μm was used. This sand was separated by sieving, its grading satisfied the fine grading in accordance with Anonymous (1984). Table 3 shows the chemical and physical properties of the sand used.

Silica fume: Densified Macro silica fume under commercial name (LEYCO®-ACC Micro silica/Grade 85D) has been used which conforms to the chemical and physical requirements of Anonymous (2005). Silica fume is an extremely fine powder with particles about 100

Corresponding Author: Jabor Al-Jeabory, AL-Mustaqubal University College, Hillah, Iraq

Table 1: Chemical composition and main compound for the two cements type

Compound composition	Chemical simple	Type V-content (%)	Type I content (%)	IQS No. 5/1984
Lime	CaO	63.00	63.71	-
Silica	SiO_2	19.38	19.88	-
Alumina	Al_2O_3	4.5	4.34	-
Iron oxide	Fe_2O_3	5.00	3.36	-
Magnesia	MgO	2.00	2.1	<5.0, <5.0
Sulfate	SO_3	1.44	1.78	≤2.5, ≤2.80
Loss on ignition	L.O.I.	3.47	3.84	<4.00
Insoluble residue	I.R.	0.51	0.6	<1.5
Total	-	98.79	99.01	-
Free lime	F.L.	0.95	1.23	-
Lime saturation factor	L.S.F.	0.97	0.97	0.66-1.02
Main compounds (Bogie's equation) as % for type				V I
Tricalcium silicate	C_3S	63.83	64.23	-
Dicalcium silicate	C_2S	7.41	8.54	-
Tricalcium aluminates	C_3A	3.47	5.82	<3.5, >5.0
Tetra-calcium aluminoferrite	C_4AF	15.22	10.22	-

Table 2: Physical properties of the two cements types

Physical properties	Type V cement	Type I cement	IQS No. 5/1984
Fineness using Blaine air permeability apparatus (m^2/kg)	405	310	≥230
Soundness (Autoclave method) (%)	0.12	0.35	<0.8%
Setting time (Vicat apparatus) Initial setting min. Final setting h:min	1405:35	1353:05	≥45 min ≤10 h
Compressive strength (MPa)			
3 days	24.60	24.44	≥15.00
7 days	28.96	7.2	≥23.00

Table 3: Chemical and physical properties of sand

Properties	Test results	Limit of Iraqi specification No. 45/1984 and B.S. 882:1992
Specific gravity	2.69	-
Absorption (%)	0.73	-
Sulfate content as SO_3 (%)	0.25	≤0.5
Materials finer than 75 μm (%)	1.29	≤5.0

Table 4: RPC mixes used in the present research (kg/m^3)

Group/Mix symbol	Cement	Fine sand	Silica fume* (%)	Silica fume	Steel fiber** (%)	Steel fiber	w/b ratio	HRWRA (%)***	HRWRA type
1									
TSP-B	900	1050	17	160	2	156	0.18	7.2	BETONAC
TSP-G	900	1050	17	160	2	156	0.18	5	G54
TSP-S	900	1050	17	160	2	156	0.18	6.3	Sika V5930
TSP-C	900	1050	17	160	2	156	0.18	9	Cemtec504
2									
TMS+	900	1050	17	160	2	156	0.2	6.3	Sika V5930
TKS	900	1050	17	160	2	156	0.2	7	Sika V5930
3 (%)									
TSF 0	1050	1050	0	0	2	156	0.18	4	Sika V5930
TSF 10	945	1050	10	90	2	156	0.2	4.7	Sika V5930
TSF17$^+$	900	1050	17	160	2	156	0.19	6.2	Sika V5930
Ref.									
MK 0%	900	1050	17	160	0	0	0.18	3.7	Sika V5930
4 (%)									
MKC 0.5	900	1050	17	160	0.5	39	0.18	4	Sika V5930
MKC 1	900	1050	17	160	1	78	0.18	4.5	Sika V5930
MKC 1.5	900	1050	17	160	1.5	117	0.18	5	Sika V5930
MKC 2$^+$	900	1050	17	160	2	156	0.18	6.3	Sika V5930
5 (%)									
MKS 0.5	900	1050	17	160	0.5	39	0.18	4	Sika V5930
MKS 1	900	1050	17	160	1	78	0.18	4.4	Sika V5930
MKS 1.5	900	1050	17	160	1.5	117	0.18	5.3	Sika V5930
MKS 2	900	1050	17	160	2	156	0.18	6	Sika V5930

$^+$ is the major mix in this work, *Percent by weight of cement, **Percent of mix volume, ***Percent of cementitious materials (cement+silica fume) Weight. T: Trial mix, M: Mix symbol, SP: Superplasticizer, B: BETONAC®-BVD, G: Glenium 54, S: Si1ka viscocrete®-5930 and C: Cemtec 504TP.M: cement type I, K: Cement type V, SF: Silica Fume content, C: Crimp steel fibers and S: Straight steel fibers

times smaller than an average cement grain. It is generally used as a partial replacement of cement for concrete structure that need high strength or significantly reduced permeability to water. After many trial mixes the replacement of 17% by weight of cement by silica fume was considered the best percent to get the target strength in this research (Table 4).

High-range water reducing admixture (Superplasticizer): The purpose of using high-range water reducing admixture HRWRA is to get mix with minimum water content and this admixture has significant effect on the present research. The percentage and type of this admixture use in trial mixes is tabulated in Table 4.

Mixing procedure: Sufficient mixing is necessary to achieve desirable concrete performance and homogeneity. In RPC mixes, extending mixing time is necessary to fully disperse the silica fume, breaking up any agglomerated particles and to allow HRWRA to develop its full potential, the mixing continue for five minutes. Then half HRWRA dosage is dissolved in water and added in three steps with combination with water as 1/3% in each step separated and continue mixing for 3 min. Before each step the mixer was stopped and mixing was continued manually, especially for the portions not reached by the blades of the mixer to get humongous mix. The total mixing time duration is 20 min from the adding of water to the mix (British Standards Institutions, 1992; Lee, 2006).

Casting and curing: Before casting, all molds were well cleaned and their internal surfaces were lightly oiled to avoid the adhesion of hardened concrete to them. All molds were filled with the concrete mix in layers. Each layer was compacted by tamping rod to minimize the air voids and to get well compacted concrete. The top surface of the molds was leveled and the specimens were covered with polythene sheets and kept in room temperature 20°C±2 with a relative humidity 90%±5 to minimize moisture lose and shrinkage effect. The specimens were demolded after 24 h and cured by steam for 72 h at (85±5°C) in a water bath by raising the temperature at 15°C/h. According to ACI specifications until the day of test.

RESULTS AND DISCUSSION

Compressive and tensile strength: The results in Table 5 indicated that the compressive strength of (100 mm cube) is slightly affected by the addition of the two types of steel fibers. The compressive strength increased by about 20.63% and 20.19 for RPC containing 2% by volume crimped and straight steel fibers, respectively. The improved compressive strength likely reflects the contribution of the steel fiber to the tensile capacity of the RPC which gives the accepted view that concrete under uniaxial compressive load fails because of lateral strain induced by poison's ratio effects. However, the increase in compressive strength is effected by the kind of supper superplasticizer used as shown in Table 6.

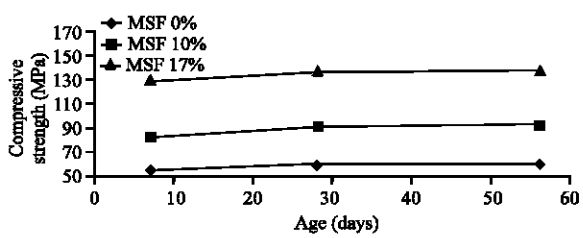

Fig. 1: Effect of silica fume content on compressive strength

Splitting tensile strength: Table 7 shows that the splitting tensile strength increased as the fiber volume fraction increased. The percentage increase in splitting tensile strength is about 150 and 177% for concrete mix containing 2% straight and crimped steel fibers, respectively. The splitting tensile strength is calculated by the following Eq. 1:

$$f_{SP} = \frac{2P_s}{\pi d_c I_c} \quad (1)$$

The extreme fineness of silica fume provides a greater densification and continuity to the cement paste in concrete. The pozzolanic reaction between the amorphous silica in silica fume and calcium hydroxide produced by the hydration of Portland cement improves the strength of concrete (Yang *et al.*, 2010). Figure 1 shows that increasing Silica Fume content (SF) from 0-10 and 17% caused a considerable increase in compressive strength by 55.18 and 139.14%, respectively with respect to 0% silica fume content at 28 day.

Compressive strength

Impact strength: The impact resistance depending on number of blows necessary to cause prescribed levels of distress in the test specimen, according ACI specifications (Anonymous, 1989) using drop-weight test. The number of blows serves as a qualitative estimate of the energy absorbed by the specimen at the level of distress specified. Figure 2 demonstrates the influence of fiber volume fraction and type used in RPC. It is clear that the impact strength or the number of blows causing first crack and ultimate failures significantly influenced by the shape and the percentage of fiber inclusion. The percentage of increase in number of blows causing first crack in range of about 37-86% while for ultimate failure in range 46-119%.

Crimped fibers show higher impact strength (No. of blows) at both first crack and ultimate load, this may be

Table 5: Effect of fiber volume frication and shape on compressive strength

	Straight fiber (MKS)			Crimped fiber (MKC)		
V_f (%)	Compressive strength (MPa)	CV (%)	Increase in compressive strength (%)	Compressive strength (MPa)	CV (%)	Increase in compressive strength (%)
0	119.48	0.69	-	-	-	-
0.5	125.53	0.79	5.06	126.87	0.60	6.19
1	129.67	0.72	8.53	130.87	0.51	9.53
1.5	134.57	0.27	12.40	133.38	0.48	11.63
2	143.20	0.6	20.19	144.13	0.73	20.63

Table 6: Compressive strength at 7, 28 and 56 days

				Compressive strength (MPa)		
Group/Mix simple	Flow (%)	Percentage of add.*	Target	7 days	28 days	56 days
1						
TSP-B	90	7.2	Type of the HRWR	77.3	83.4	80.63
TSP-G	98	5		88.47	98. 6	110.3
TSP-S+	100	6.3		135.6	143.8	145.5
TSP-C	93	9		70.3	73.64	72.65
2						
TMS+	94	6	Cement type	137.24	145.3	145.0
TKS	93	7.2		106.36	120.2	122.3
3 (%)						
TSF 0	95	4	Dosage of micro silica fume	55.4	60.35	60.7
TSF 10	94.12	4.5		85.74	93.65	95.3
TSF 17+	94	4.3		136.41	144.32	145.4

+Major mix

Table 7: Splitting tensile strength results of FR-RPC

	Straight fiber (MKS)			Crimped fiber (MKC)		
V_f (%)	Splitting tensile strength (MPa)	CV (%)	Increase in splitting strength (%)	Splitting tensile strength (MPa)	CV (%)	Increase in splitting strength (%)
0	6.3	1.96	-	6.3	1.96	-
0.5	9.16	8.1	45.4	10.3	3.63	63.49
1	11.3	3.34	79.37	13.46	2.5	113.65
1.5	14.63	4.33	131.75	15.3	2.45	142.85
2	15.83	4.39	150.8	17.47	3.32	176.98

Table 8: Modulus of elasticity for different vol. fraction and shape of RPC

	Crimp fiber			Straight fiber		
V_f (%)	ES (GPa)	CV (%)	Percentage of increase with respect to zero fiber	ES (GPa)	CV (%)	Percentage of increase with respect to zero fiber
0	40.07	6.3	-	40.07	6.3	-
0.5	42.89	4.66	7.04	43.16	4.62	7.71
1	45.01	3.26	12.33	48.8	4.05	16.80
1.5	46.7	3.32	16.55	46.74	5.32	16.65
2	48.15	4.73	20.16	47.25	9.02	17.92

due to the excellent mechanical anchorage of crimped steel fibers at their surface which causes high bond strength. w = n*m impact toughness of RPC was measured by No. of blows for first crack and failure, using the Eq. 2:

$$w = n*m*g*h \quad (2)$$

Static modulus of elasticity: The specimens were tested at age 28 days and the average of three specimens was adopted (Anonymous, 2002). Static modulus of elasticity is calculated by the following Eq. 3:

$$E_s = \frac{S_2\text{-}S_1}{\varepsilon_2 - 0.0005} \quad (3)$$

The modulus of elasticity is strongly influenced by the concrete materials and their proportions. It is a function of modulus of elasticity of each component and its content ratio in the composite. Table 8 illustrates the influence of steel fiber content and its type and the percentage increase in modulus of elasticity.

The increase due might be to the transfer of stresses from the matrix to the fibers by interfacial bond between the steel fibers and matrix where the fibers play the role of obstacles in front of crack tip and the crack path will became tortuous. This will need more energy to crack propagation from the inside of the matrix due accumulation of many micro cracks to make macro cracks before they appear on the surface. This means more applied load.

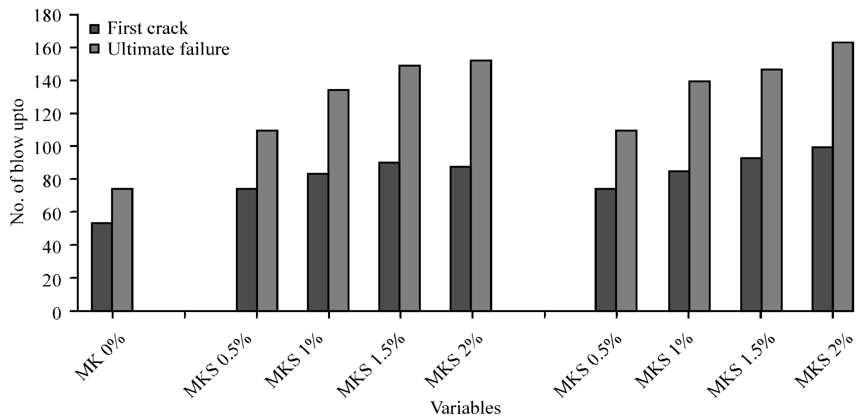

Fig. 2: Effect of volume fraction and type of steel fibers on the impact strength

CONCLUSION

The addition of steel fibers enhanced the properties of reactive powder concrete. The increase in compressive strength was 20.6 and 20.19% with 2% fiber addition for straight and crimped steel fibers, respectively. The enhancement in splitting tensile strength was 150 and 177 with 2% fiber content for straight and crimped steel fibers, respectively. The increase in impact strength was increase in number of blows causing first crack in first crack in range of about 37-86% while for ultimate failure in range 46-119%. For straight and crimped steel fibers, respectively. The modulus of elasticity increased for both straight and crimped steel fibers and this increment was less for crimped 17.92 and for straight 20.16 with 2% fiber content. This due to difficulty in crimped fiber distribution in the matrix at 2% fiber inclusion by volume. The modified polycarboxylic either admixture (Sika Viscocrete®-5930) gives the best result in terms of reducing the w/b ratio in a specified RPC mixes. Accordingly the compressive strength of trial mixes. The dosage of the Sika Viscocrete®-5930 depends on the volume fraction and type of fiber. It increased by about 10, 21-22, 40-43 and 60-65%, over reference mixes without fibers by adding crimp and straight fiber at 0.5, 1, 1.5 and 2% by volume, respectively.

NOTATIONS

C_3S = Tricalcium Silicate
C_2S = Dicalcium Silicate
C_3A = Tricalcium Silicate
HRWRA = High Range Water Reducing Admixture
SF = Silica Fume
S = Silica viscocrete
f_{sp} = Splitting tensile strength
w = Impact energy (Joule (J) or kN.m)
n = Impact number
h = The height hammer drops (457 mm)
g = Accelerating velocity (9.81 m/sec^2)
m = Weight of hammer (4.536 kg)

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