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Original Article

Investigation of torsional behavior and capacity of reactive powder concrete (RPC) of hollow T-beam

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ABSTRACT

A hollow reinforced concrete T-beams were investigated under the effect of pure tension experimentally, which are made of reactive powder concrete (RPC). This concrete was produced with adding steel fiber and silica fume in different dosages. The present work aims at studying the effect of the steel fiber volumetric ratio (V_f) and silica fume content (S_f) on the behavior of hollow T-beam under pure torsion and so, on its torsional capacity. For this purpose T-beams were simply supported with 1400 mm length, 100 mm web width, flange width 220 mm and 160 mm height were tested. It was found that the addition of 2% steel fibers to concrete mix increased the cracking and ultimate torque of the RPC hollow T-beam. An increase of 184% in cracking torque and 66% in ultimate torque for hollow section was achieved while the other properties kept constant.

1. Introduction

Ultra-high performance concrete (UHPC) in recent decades has been considered as a new developed type of concrete. It became widely used in bridge construction and retrofit in the construction market at the beginning of the new millennium. UHPC mainly produced by mixing cementitious based composite materials reinforced by discontinuous fibers [1].

UHPC tends to exhibit superior properties such as advanced strength, durability, and long-term stability [2]. The compressive strength of this type of concrete is greater than 150 MPa, internal fiber reinforcement used to ensure non-brittle behavior, and a high binder content with special aggregates.

Furthermore, UHPC possesses sufficient rheological properties due to very low water content which causes by enhancing the packing of granular content and adding admixtures of ability in reduction the water absorption [3].

One of the types of UHPC is reactive powder concrete (RPC). RPC is recognized as an outstanding material that can be characterized by both, ultra-high strength and excellent durability through the inclusion of short steel fiber reinforcement [4]. RPC is of high compressive strength may reach more than 200 MPa along with flexural strength may exceed 40 MPa [5]. Many developments were done to enhance RPC properties and method of construction for many structures by many researchers [6].

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Silvia et al. [7] studied the effect of fiber type on the performance of RPC. The RPC mixture of 1 m^3 was composed of 904 kg cement, 226 kg silica fume, 944 kg sand of 0.1 mm particle size, 12.3 kg of carboxylate acrylic superplasticizer, 181 kg of steel fibers, and water–cement ratio (w/c ratio) was 0.24. Four different types of fiber were used; brass plated steel (13/0.18), deformed steel (30/0.45), deformed steel (30/0.62) and deformed galvanized steel fibers (30/0.62). The results showed that the RPC mixes produced with brass plated fibers gave compressive and flexural strength higher than RPC containing the other types of fibers.

Ma and Orgass [8] carried out a comparative investigation on two UHPC, one containing coarse aggregates of basalt type with grades of 2–5 mm, while the other was without coarse aggregate, i.e. RPC mainly was in the concrete proportion. The cementitious paste volume fraction in the first type of UHPC was about 20% lower than that in RPC type possessing similar compressive strength and fluid ability. It was found that the cement content in UHPC could be lower than 550 kg/m^3, while in RPC it could range between 700 kg/m^3 and 1000 kg/m^3, and that during mixing the UHPC containing coarse aggregate was easier to fluidize and homogenize and therefore the mixing time should be less. Both types of UHPC showed a high and quickly developing autogenous shrinkage.

Ibraheem [9] studied the compressive stress–strain relationships for different RPC mixes. A general mathematical equation for expressing such relationships was derived. The mechanical properties of RPC including compressive strength, density, absorption, and flexural behavior were all established experimentally in this study. Three main variables have been used for the purpose of this investigation to produce different RPC mixes, which were: type of pozzolanic admixture, type of fibers, and volume fraction of fibers. It was found that the use of steel fibers with high volume fraction in an RPC mix increased the compressive strength and density of the concrete and reduced its absorption unlike RPC mix using polypropylene fibers. With regard to the compressive stress–compressive strain relationships of RPC. The shape of the stress–strain curve drafted from the results of this study did not affect significantly due to these three main variables in its elastic region, while the shape of this curve of the descending portion has mainly affected by the type and volume of the fibers used. Moreover, RPC with the steel fibers of the highest volume fraction exhibited best results in terms of ductility and toughness.

Al-Hassani et al. [10] carried out a parametric study of some mechanical properties of RPC, which are necessary for the design process. This study was devoted to investigate the effect of; silica fume content (S_f), steel fibers volume fraction (V_f) and superplasticizer type (Sikament®-163N, PC200) on the following properties: compressive strength, tensile strength (direct, splitting and flexural), flexural toughness, load-deflection capacity and static modulus of elasticity. This study resulted in increasing the compressive strength with an increase of S_f while it was noticed that the increase in the tensile strength was insignificant. Due to using the steel fibers, the tensile strength has been increased considerably. Both S_f and V_f variables enhanced the load-deflection behavior, and so, the ductility and fracture toughness of RPC increased.

Many types of the beam may experience torsion in addition to bending, and shear stresses when the line of loading is away from the vertical plane of bending. Spandrel beam and end beam and others beam may be considered as examples of the mentioned statues of loading.

For analysis the beam for torsion, it can be considered as a thin walled box for the hollow beam. As it is well-known that concrete is a brittle material, so torsion may cause sudden failure and crushing the concrete. Therefore, it is necessary to investigate the strength of RPC against torsion.

Abdul-Hussein [11] studied the behavior of reinforced RPC rectangular beams in torsion, the work included testing 15 beams segments of solid and hollow sections under torsional forces. In production these fifteen beams, it have been used different volumetric dosages of fibers along with variable ratios of transverse and longitudinal steel rebar. The study has been carried out to investigate the influence of volume of a fraction of fibers, beam shape (solid section and hollow section) and the effect of transverse and longitudinal reinforcement ratio on the ultimate torsional capacity of these beams. The results show that by adding 1% steel fibers to the concrete mix, significantly increasing the cracking and ultimate torques. An increase, as longitudinal and transverse reinforcement ratios (ρ_s) were both kept constant and equaled to 0.02, of 43% and 66% in cracking torque and 57.7% and 53.2% in ultimate torque for the solid and hollow section has been achieved respectively.

Al-Hassani and Ibraheem [12] proposed an equivalent bilinear compressive stress block for RPC sections under pure bending moment based on experimental stress–strain curves conducted by Ibraheem [9].

A research to investigated the effect of concrete cover on the behavior of ultra-high performance fiber reinforced concrete rectangular solid beams under pure torsion was performed by Ismail [13] as a PhD work at Kassel University in Germany. Four rectangular solid beams of under-reinforced ultra-high performance fiber reinforced concrete were prepared for testing under pure equilibrium torsion. The results of this study revealed that both peak torsional capacity and that at crack loads were increased up to 113% and 134% of the estimated value based on thin walled tube theory, respectively. In addition to that, it was found that the twisting angle at ultimate load and shear strain in concrete decreased up to 64.9%, 40.1%, respectively.

As per the summary done by Ismail [13] of the work performed by Oettel and Empelmann, which have been carried out for investigation of torsional carrying capacity of hollow beams produced using UHPC with reinforcing by one type of steel fibers of different volumetric dosages along with silica fume ratio (S_f) of 1.25% and 2.5%, it was found that the torsion carrying capacity increased by 20% of the cracking torsion for beams reinforced only by 2.5% of steel fibers.

Accordingly, this work devoted to studying experimentally the effect of adding silica fume in two different percentages with fibers of different volumetric content on the structural torsional capacity of RPC hollow T-beams and their torsional behavior under these circumstances.

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Table 1 – Chemical analysis and compound composition of the cement.[a]

Chemical component: Name	Symbol	By the weight, %	IQS 5/1984 limitations of ordinary cement
Loss on ignition	L.O.I	1.61	Not more than 4%
Silicon dioxide	SiO_2	22.9	N/A
Aluminum oxide	Al_2O_3	5.05	N/A
Iron oxide	Fe_2O_3	4.58	N/A
Calcium oxide	CaO	58.96	N/A
Magnesium oxide	MgO	2.05	Not more than 5%
Sulphur trioxide	SO_3	2.37	Not more than 2.8%when C_3A more than 5%
Insoluble residue	I.R	1.0	Not more than 1.5%
Tricalcium aluminates	C_3A	5.59	N/A
Lime saturation Factor	L.S.F	0.72	0.66–1.02
Main compounds (Bougue's equations)			
	C_3S	28.97	N/A
	C_2S	57.97	
	C_3A	5.72	
	C_4AF	13.97	

[a] Chemical analysis and compound composition of the cement.

Table 2 – Physical properties of the cement.[a]

Physical property: Name	Unit	Value	IQS 5/1984 limitations of sulphate resistance cement
Specific surface area	cm^2/g	3200	Not less than 2300
Initial setting time	minutes	175	Not less than 45
Final setting time	hour	3.8	Not more than 01
Compressive strength at 3 days	MPa	25	Not less than 15
Compressive strength at 7 days	MPa	32	Not less than 23
Soundness by autoclave method	%	0.35	Not more than 0.8

[a] Physical properties were found at construction laboratory of College of Engineering, University of Basra.

2. Experimental work

2.1. Materials and methods

The experimental program of this study is focusing on determination of torsional capacity and torsional behavior of a RPC hollow T-beam. The variables are silica fume (S_f) with different weight percentages and volume fractions of steel fibers (V_f), including 0%, 0.5%, 1.0%, and 2.0%. Hollow T-beams were cast using RPC considering the adding of silica fume and steel fibers. A reference beam was made of plain concrete.

Ordinary Portland cement (type I), which is brought from Taslouja cement factory in Iraq, was used in mixing all the concrete specimens. Chemical and physical properties of this cement were given in Tables 1 and 2, respectively [14]. The coarse and fine aggregate was brought from a local quarry. The grading of the fine aggregate is shown in Table 3 and in Fig. 1 in accordance with the B.S. specification No. 882/1992 [15,16]. The physical properties of the fine aggregate presented in Table 4. Three sizes of deformed steel reinforcing bars were used as longitudinal reinforcement of diameter (5, 6, and 8 mm), while deformed steel bars of diameter 8 mm, were used as closed stirrups, the properties of these steel rebars are shown in Table 5.

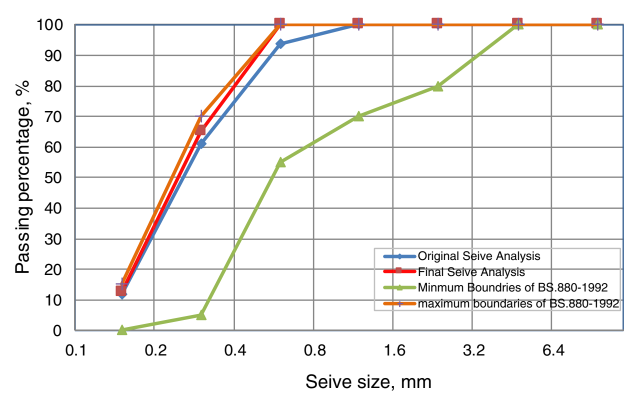

Figure 1 – Grading curve of the sand.

Table 6 shows the characteristics of the steel fibers used in this investigation. A photo presented in Fig. 2 shows this type of steel fiber. A superplasticizer, Flocrete PC 260, which conforms to ASTM C494-99 [17] type A and G, was used in the mixes, Appendix 1. Gray densified grade 920 D silica fume was used [18], it was brought from Elkem company in UAE, Appendix 2.

As shown in Fig. 3, a schematic diagram illustrating RPC T-beams of 1400 mm long were casted in six specimens. For

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Table 3 – Grading of aggregate.

Sieve size (mm)	Original cumulative passing, %	Final cumulative passing, %	Limits of B.S 882:1992 fine grading
9.52	100	100	100
4.75	100	100	100
2.36	100	100	80–100
1.18	100	100	70–100
0.600	93.80	100	55–100
0.300	60.90	66.67	5–70
0.150	11.75	14.14	0–15

Table 4 – Physical properties of fine aggregate.[a]

Properties	Test results	Limit of I.O.S.45/1984
Apparent specific gravity	2.88	
Bulk Density (kg/m^3)	1784	
Absorption (%)	0.79	
Density (kg/m^3)	2578	
Sulphate content, SO_3 (%)	0.4%	0.5%
Organic (%)	0.73%	
Clay content (%)	2.4%	5%

[a] The test was carried out by construction laboratory in the College of Engineering, University of Basra.

Figure 2 – A photo for steel fibers.

applying the torque on the ends of the beam, the cross section at the ends had a solid rectangular shape as shown in this

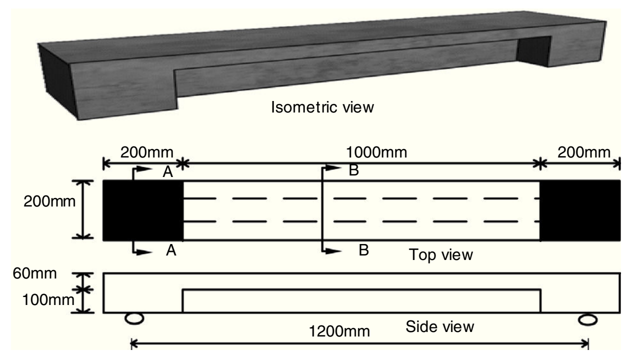

Figure 3 – Beam specimen: top; 3D view, middle; plan, lower; side view.

figure. The cross-section and reinforcement details are shown in Figs. 4 and 5.

The detail information of the loading arrangement was adopted by Zararis and Penelis [20]. To insure the failure will be in the mid zone of the beam, the solid rectangular block at each end of the beam was reinforced with (φ 8 mm) stirrups spaced at (50 mm) on center.

2.2. *Mixing and casting process*

Four plywood molds were used to cast the RPC beams of the present research. The dimensions and identification of these molds are shown in Table 7. The molds consist of a base and movable sides, with a thickness of plywood (18 mm). The sides were fixed by screws to form T shape with rectangular blocks at ends.

Table 5 – Specification and tension test results of steel bars [19].[a]

Nominal diameter, mm	Yield stress, MPa	Actual diameter, mm	Weight per unit length, kg/m	Ultimate strength, MPa	Elongation, %	Variation in diameter, %
5	679	4.88	0.146	985	–	2.7
6	666	6.06	0.225	912	–	2.5
8	580	7.82	0.407	733	13.6	–

[a] Specification and tension test results of steel bars [19].

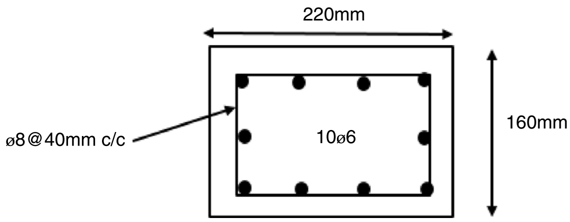

Figure 4 – Section A–A; end of beam with rebar's details.

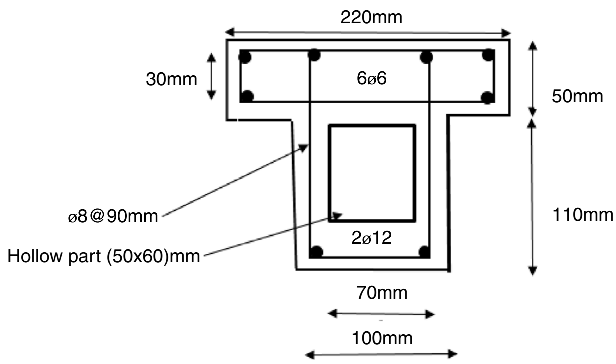

Figure 5 – Section B–B; showing rebar's details.

Before casting, the molds were oiled and the reinforcement mesh was placed in position, and then the molds were vibrated. Table 8 presents the mold dimensions and Fig. 6 shows the plywood mold.

The four types of RPC mixes, as presented in Table 9, were used to cast the main beam specimens as well as their control specimens.

3. Experimental results of concrete

3.1. *Results of mechanical properties*

It is necessary to determine the properties of the concrete mix used in production of the beam specimens. Control specimens include five cubes 100 mm, three 150 mm × 300 mm cylinders, three 100 mm × 200 mm cylinders, and two 100 mm × 100 mm × 500 mm prisms for each beam. These specimens were prepared and tested at the same age of beam specimens, all the results are shown in Table 10.

3.2. *Effect of volume fraction of fibers*

Figure 7 show the torsional behavior of hollow RPC T-beams (HR1, HR2, HR3 and HR4) with volume fraction of fibers (V_f) of 0%, 0.5%, 1.0%, and 2.0%, respectively. For these beams, transverse steel ratio (ρ_s) and longitudinal (ρ_c) were 0.02 and 0.01 respectively, and (S_f) was constant and equaled 25%. This behavior was presented by the torque value in relation with twist angle for each beam. It can be seen clearly that the beams containing steel fibers

Experienced more torsional capacity rather than that beam of zero content of steel fiber. This may be interpreted to the ductility furnished by the steel fibers. It may also be noticed that the first portion of the curves for three beams producing by adding steel fibers has the same trend in spite of different dosage of steel fibers and it can be described as linear trend, while for the control specimen (zero steel fiber) the whole curve does not show this trend.

Table 11 shows both the cracking (T_{cr}) and ultimate (T_{ult}) torque in relation with volumetric ratio of steel fibers. As the dosage of steel fibers increase, these two torsional capacity increased as shown in Fig. 8. The ultimate torque was

Table 6 – Characteristics of used steel fibers.[a]

Type of steel fiber	Density (kg/m)	Length of fiber (mm)	Diameter of fiber (mm)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Straight	7800	13	0.175	2600	210

[a] As per the manufacturer data (Bekaert Corporation).

Table 7 – Test specimen dimensions and identification.

Beam identity	Silica fume % (S_f)	Steel fiber % (V_f)	ρ	ρ	Flange width (bf), mm	Flange thickness (t_f), mm	Type of section
HR1	25	0.0	0.01	0.02	220	50	Hollow T-beam
HR2		0.5					
HR3		1.0					
HR4		2.0					

Table 8 – Dimensions of molds.

Flange, mm	Web, mm	End block, mm	Shape
220 × 50 × 1000	100 × 110 × 1000	220 × 160 × 200	T

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Figure 6 – Plywood molds.

Table 9 – Properties of the different types of RPC mixes [21].

Mix type	Cement, kg/m^3	Sand, kg/m^3	Silica fume[a], %	Silica, fume, kg/m^3	w/c	Flocrete PC260[b], %	Steel fiber content[c], %	Steel fiber content, kg/m^3
M0-25	1000	1000	25	250	0.2	3.0	0	0
M0.5-25	1000	1000	25	250	0.2	3.0	0.5	39
M1-25	1000	1000	25	250	0.2	3.0	1	78
M2-25	1000	1000	25	250	0.2	3.0	2	156
M2-15	1000	1000	15	150	0.2	3.0	2	156
M2-20	1000	1000	20	200	0.2	3.0	2	156

[a] Percentage of cement weight.
[b] Percentage of binder (cement + silica fume) weight.
[c] Percentage of mix volume.

Table 10 – Properties of RPC, control specimen.

Specimen designation	V_f, %	S_f, %	Compressive strength, $f'c$, (MPa)	Splitting tensile strength, $f't$ (MPa)	Modulus of rupture, $f'r$ (MPa)	Modulus of elasticity, E_c, (GPa)
M0-25	0.0	25	96	4.67	4.97	43.96
M0.5-25	0.5	25	110	8.58	8.08	49.03
M1-25	1.0	25	122	13.95	14.68	51.04
M2-25	2.0	25	141	19.98	21.91	54.88
M2-15	2.0	20	136	16.92	18.38	52.97
M2-20	2.0	15	130	14.93	17.13	50.08

increased by about 22%, 44%, and 59% and the crack torque increased by 98%, 139% and 173% as the volume fraction of fibers was increased from zero to 0.5%, 1.0% and 2.0%, respectively. This is due to the presence of steel fiber which improved the ductile behavior of the beams by increasing the tensile strength of RPC concrete.

Several diagonal cracks were observed at faces of all fibrous beams with relatively high percentage of fibers, which indicates that the fibers (after beam cracking) continue to resist increasing tensile stresses until the complete pullout of all fibers at a critical crack. The experimental results indicate that the type of beam (hollow) has no major effect on the angle of inclination of the cracks. In general, the number of cracks was larger in hollow beams. All hollow T-beams failed by forming an extensive diagonal torsional crack in the flange due to high torsional shear stress. Fig. 9 shows that increasing the steel fibers content resulted in a decrease in the elongation of the T-beams.

3.3. *Crack patterns of tested RPC hollow T-beams*

All the tested beams failed by full cracking and the rotation took place around the longitudinal axis. The inclination of the failure cracks at the web and flange was the same. Fiber reinforced beams were seen to continue their twisting resistance even after the peak load was reached. Several diagonal cracks

Table 11 – Effect of variation in steel fiber ratio on cracking and ultimate torque of hollow beams.

Beam no.	V_f, %	T_{cr} (kN m)	% Increase in T_{cr}	T_{ult} (kN m)	% Increase in T_{ult}	T_{cr}/T_{ult}, %
HR1	0	4.3	–	18.7		23
HR2	0.5	8.1	88	21.4	15	37
HR3	1	10.2	137	24.7	32	38
HR4	2	12.2	184	31.1	66	40

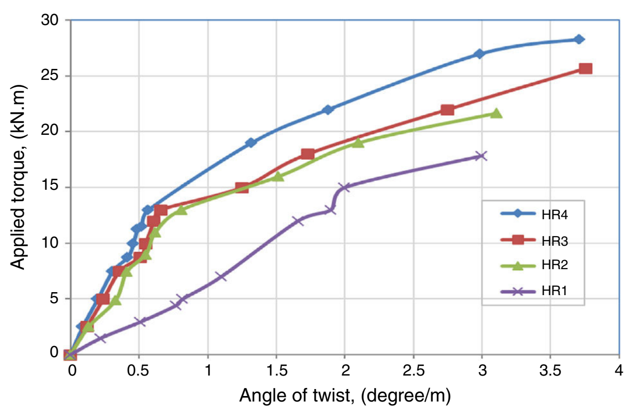

Figure 7 – Torque–twist behavior of RPC hollow T-section beams.

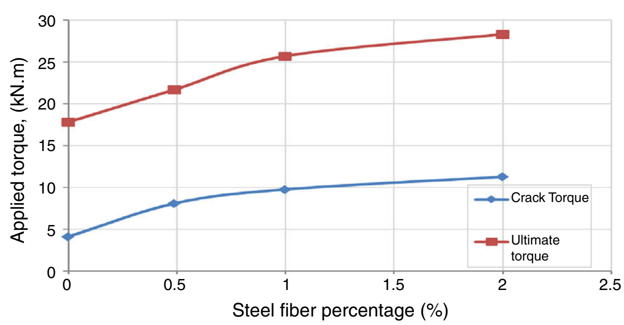

Figure 8 – Crack (T_{cr}) and ultimate (T_{ult}) torques of RPC hollow T-beams.

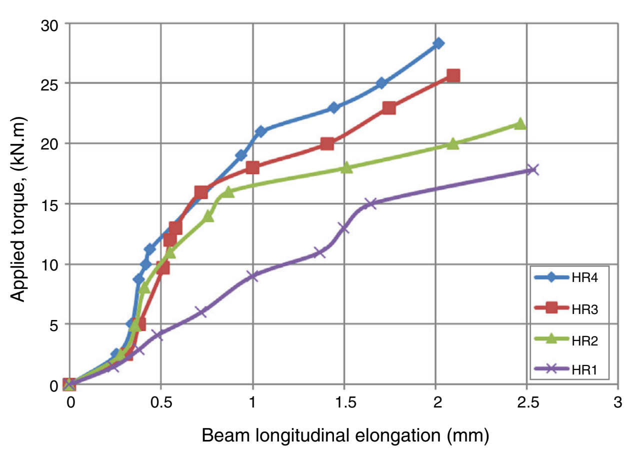

Figure 9 – Effect of steel fiber content on longitudinal elongation of hollow T-beam.

were observed to form at all faces of the beam, this assume the redistribution of stresses beyond cracking and the beam continued to resist increasing tensile stresses until a complete pullout of all fibers occurred at critical crack. The beam failed after extensive diagonal torsional cracks were formed in the web and flange, for each tested beam (HR2, HR3, and HR4), the total number of cracks and the maximum crack width at the onset of beam failure were found to be proportional to the percentage of steel content fibers in the beam. Initially, a crack formed at one side of the web and with increasing the applied torque, other cracks developed at the other side of the web and both extended toward the flange to form a complete helical crack pattern around the beam. Failure of beam HR1 was associated with concrete cover spalling at the edge of the flange.

4. Conclusions

Using silica fume in content of 25% as a filling material in production of RPC beam of hollow T-section leads to increase the compressive strength ($f'c$) by 12%, while splitting tensile strength, modulus of rupture and modulus of elasticity increased by 32%, 26% and 9%, respectively, in comparison with the concrete of zero content of silica fume.

A maximum of 2.0% fiber content was found optimum to achieve a practical and uniform distribution within the fresh and hardening concrete. If more than this percentage were used, mixing problems would arise as a result of the substantial immediate loss of mix workability and non-uniform fiber distribution with the formation of fiber balling so that great efforts and relatively long vibration time would be required to manufacture the beams.

Nonfibrous RPC is a brittle material and fails suddenly and violently. The addition of steel fibers in discrete forms into RPC changes its brittle mode of failure into a more ductile one and improves the concrete ductility, post-cracking load-carrying capacity, and energy absorption. Fiber addition results in more closely spaced cracks, reduces the crack width, bridges cracks and thus improves resistance to deformation. It was observed that the total number of cracks counted in a fibrous RPC T-beam under pure torsion failure was greater and the crack width was lesser than those in the identical non-fibrous beam for the hollow section.

Results show that there is a significant improvement in the compressive strength ($f'c$) of RPC due to the addition of steel fibers. The presence of fibers at volume fractions of 0.5%, 1.0% and 2.0% results in increasing the compressive strength by 15%, 27%, and 46%, respectively, and the modulus of elasticity increased by 11.5%, 16.10%, and 24.84%, respectively, over that of nonfibrous RPC. The influence of steel fibers on the splitting tensile strength and modulus of rupture is even more significant. For the same percentage increase in the volume of fibers, the splitting tensile strength increased by 83.72%, 198%, and 278%, respectively, and the modulus of rupture increased by 62.57%, 195%, and 226%, respectively, over the nonfibrous RPC.

The steel fibers became effective after the cracks formation and continued to resist the principal tensile stresses until the complete pullout of all fibers occurred at one critical crack.

An increase of 66% in the ultimate torque (T_{ult}) RPC T-beams was obtained by adding 2% fibers to the concrete mix. The corresponding increase in the cracking torque (T_{cr}) was 184% for hollow RPC beams, respectively.

It was found that at stages after cracking the length of hollow RPC beams increased almost linearly as the applied torque was increased.

The length of the elastic portion of the torque vs. angle of twist relation was affected by the width of the flange and the reserve strength after first diagonal cracking was less for a beam with small flanges than with wider flanges. The increase in the flange thickness delayed the appearance of the first diagonal crack, but the specimens eventually failed with excessive diagonal cracks in the concrete.

Conflicts of interest

The authors declare no conflicts of interest.

Appendix A. Technical Description of Flocrete PC 260*.

Chemical base	Modified polycarboxylates based polymer
Appearance/colors	Light yellow liquid
Freezing point	−7 °C approximately
Specific gravity@25 °C	1.1 ± 0.02
Air entrainment	Typically less than 2% additional air is entrained above control mix at normal dosages
Dosage	0.5–4.0 l/100 kg of binder
Storage condition/shelf life	12 months if stored at temperatures between 2 °C and 50 °C

Appendix B. Chemical and Physical Requirements of Silica Fume ASTM C 1240-04 [20].

Requirement	Analysis %	Limit of specification requirement ASTM C 1240
SiO_2	86.46[a]	>85.0
Moisture content	0.68[b]	<3.0
L.O.I	4.02[a]	<6.0
Percent retained on 45-μm (No. 325) Sieve, Max.	7	<10
Accelerated Pozzolanic Strength Activity Index with Portland Cement at 7 days, Min. Percent of Control	128.6	>105
Specific surface, Min, cm^2/g	210,000	>15

[a] Tests were carried out at the General Company of Geological Surveying and Mining/Iraq Ministry of Manufacturing/Baghdad.
[b] According to its certificate of conformity.

Appendix C. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jmrt.2017.10.008.

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