Flexural Behavior Of Reactive Powder Concrete Tee Beams

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Abstract

Reactive powder concrete (RPC) is one of the latest and most important developments in concrete technology. This research presents experimental study to investigate the influence of three ratios of steel fibers (0, 1 and 2%) and three ratios of silica fume (15, 20 and 25%) on flexural behavior of RPC tee beams. The experimental results showed that steel fibers volumetric ratio is an important parameter in enhancing flexural behavior of tee beams, however as steel fibers volumetric ratio increase from 0 to 2% the first crack load, the ultimate flexural load and the ultimate deflection increased with percentages 55.56%, 57.32%, and 57.88% respectively as compared with nonfiberous RPC T-beams. The tests results also showed that the influence of silica fume ratio in the range of 15 to 25% is less significant.

Keywords: Flexural Behavior, Reactive Powder Concrete& Tee Beams

سلوك الانثناء لعتبات خرسانة المساحيق الفعالة بمقطع (T)

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الخلاصة

تعتبر خرسانة المساحيق الفعالة واحدة من أحدث وأهم التطورات في تكنولوجيا الخرسانة. يقدم هذا البحث دراسة تجريبية تتحرى تأثير ثلاث نسب من ألياف الحديد (٠،١ و٢٪) وثلاث نسب من بخار السليكا (١٥،٢٠و٢٥٪) على سلوك الانثناء لعتبات خرسانة المساحيق الفعالة ذات المقطع (T) . بينت نتائج الفحوص التجريبية أن النسبة الحجمية لألياف الحديد هي عامل مهم في تحسين سلوك الانثناء للعتبات ذات المقطع (T) حيث أنه عند زيادة النسبة الحجمية لألياف الحديد من ٠الى ٢٪ فأن حمل التشقق الأولي ، حمل الانثناء الأقصى والهطول الأقصى ازداد بالنسب ٥٥,٥٦٪، ٥٧,٣٢٪ و ٥٧,٨٨٪ على التوالي بالمقارنة مع العتبة غير المحتوية على الألياف. كذلك بينت نتائج الفحوصات أن تـأثير نسبة بخار السليكا تكون أقل أهمية ضمن الحدود من١٥ إلى ٢٥٪.

1. Introduction:

Reactive powder concrete (RPC) has received great attention in recent years in the world due to its superior mechanical properties such as; high strength, high ductility, high durability, limited shrinkage, high resistance to corrosion and abrasion [1,2]. The first production of RPC belongs to the Richard and Cheyrezy[1,2] when they published their first papers about RPC in 1994 and 1995 respectively during their work in the scientific division at Bouygues company, latter many studies that were presented dealt with this new construction martial. Roux et al[3] investigated the durability of RPC, Biolzi et al[4] studied the effect of micro steel fibers on direct tensile strength, compressive strength and modulus of elasticity of RPC, Collepardi et al[5] studied the influence of superplasticizer type on the compressive strength of RPC. Orgass and Klug [6] investigated the influence of short steel fibers and a fiber cocktail of short and long fibers on the mechanical properties, Chan and Chu [7] studied the effect of silica fume on steel fibers characteristics in RPC, including bond strength , pullout energy, Gao [8]studied the influence of dynamic loads on the properties of plain RPC and fibers reinforced RPC**,** Peng et al [9] presented an experimental research on fire resistance of RPC. blast-resistant characteristics of RPC was studied by Yi et al [10]**.** All these reseaches studied the mechanical properties and microstructural analysis of RPC. Only limited number of researches studied flexural behavior of RPC beams. Mingbo et al [11], studied flexural performance of RPC prisms (100×100×400mm) with several usual contents of steel fibers and without tensile reinforcement**.** Ueda et al. [12] performed rapid flexural loading test for RPC I-beams**,** Jithu Raj and Jeenu [13]**,** studied flexural behavior of ultra high performance concrete composite rectangular section beams**,** Hannawayya [14] presented research to study the mechanical properties of RPC as a material as well as studying the flexural behavior of RPC rectangular section beams. Therefore there is a need to more contributions in this field to establish a scientific basis for the analysis and design of RPC beams and to develop understanding the mechanical properties of this new construction material. This research presents an experimental study on flexural behavior of simply supported RPC T-beams under simple static load effect.

2. Construction Materials:

2.1 Cement:

Ordinary Portland cement (type 1) supplied from Iraq, Sulymania, Tasloga factory is used in this study. Test results indicated that the chemical and physical properties of this cement conform to the Iraqi specification No.5/1984 [15].

2.2. Fine Aggregate:

Very fine sand with maximum size (600µm) is used for RPC. This type was separated by sieving. The results indicated that this type of fine aggregate grading was within the requirements of the Iraqi specification No.45/1984 [16].

2.3 Silica Fume:

A gray densified silica fume (which is a byproduct from the manufacture of silicon or ferro-silicon metal) was used, which was imported from Sika company. The used silica fume conforms to the chemical and physical requirements of ASTM C1240-04[17].

2.4 Superplasticizer (S.P.):

A high performance concrete superplasticizer (also named High Range Water Reduction Agent HRWRA) based on polycarboxylic technology, which is known commercially as Glenium 51, is used in this study. Glenium 51 is free from chlorides and complies with ASTM C494 type a [18].

2.5 Steel Fibers:

Hooked ends mild carbon steel fibers with aspect ratio of 80 were used in this study. According to ASTM-A820-04 [19], this type of steel fibers is classified as (Type I).

2.6 Steel Bars:

Deformed steel bars of nominal diameter (ϕ12mm) with 458MPa yield stress were used as tension reinforcement, while (ϕ8mm) deformed steel bars with 419 MPa yield stress were used as stirrups and (ϕ5mm) deformed steel bars with 376 MPa were used as transverse reinforcement of flange.

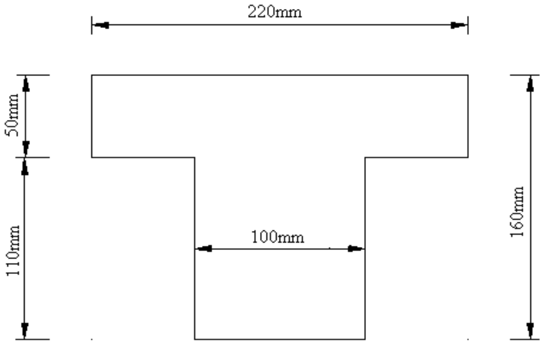
3. Experimental program:

The experimental program of this work includes studying the influence of two parameters on the flexural behavior and load carrying capacity of singly reinforced RPC T-beams. The parameters are:

1. Steel fibers volumetric ratio:
   Three RPC T- beams with three ratios of steel fibers (0%, 1% and 2%) were used to investigate the influence of steel fibers volumetric ratio on the behavior of RPC T-beams.
2. Silica fume ratio:
   Three RPC T- beams with three ratios of silica fume (15%, 20% and 25%) were used to investigate the influence of silica fume ratio on behavior of RPC T-beams.

4. Dimensions of Tested Beams:

The tested beams were designed to have appropriate dimensions that can be manufactured, handled and tested as easy as possible. The nominal dimensions of the tested beams were (1300mm) in overall length and (160mm) in depth. The flange was made with (220mm) width and (50mm) thickness. The web of the beam was made with (110mm) clear height and (100mm) width**. Figure (1)** shows the dimensions of test beams. All beams are simply supported with net span of 1200mm tested under the action of two point loads.



(a) **(b)**

Fig .(1) Details of tested beams (a) Beam cross-section (b) Isometric plate

5. Reinforcement Details:

The longitudinal and shear reinforcement of the beams was designed to ensure that the section failed in flexure with tensile mode of failure. For the flange, to prevent transverse bending failure of the flange transverse reinforcement (5mm diameter bars at 100mm c/c spacing) were used at the top of the flange overhangs. This reinforcement was calculated by treating the flange overhangs as cantilevers fixed at the face of the web and having a span equal to the length of the flange overhangs as shown in **Figure (2).** Also, to prevent shear failure of the section, 8mm diameter stirrups at 50mm c/c spacing in web was provided in the web. Also to fix these stirrups and the transverse reinforcement of the flange, 4ϕ5mm smooth bars were used at top of flange. The steel details of all the bars used as longitudinal reinforcement, stirrups and transverse reinforcement at the top of the flange overhangs are shown in **Figure (3).**

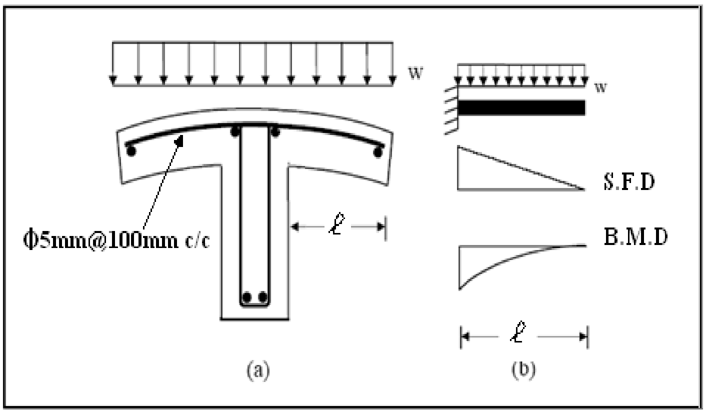


Fig .(2) (a) Transverse bending of T-beam flange (b) Shear and moment diagrams for flange overhang

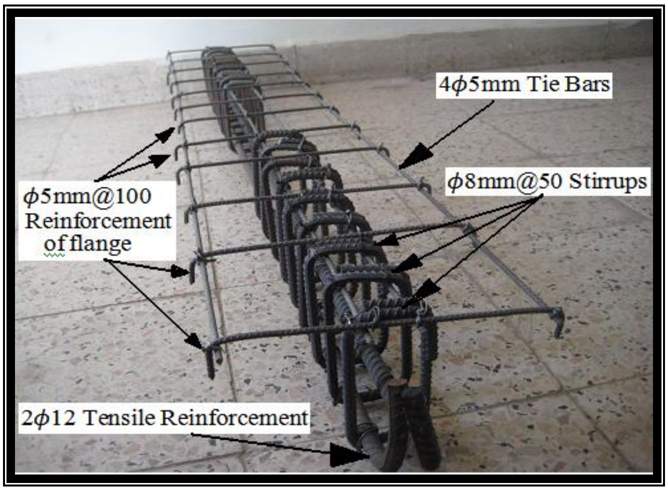


Fig .(3) Details of flexural beam reinforcement

6. Reactive Powder Concrete Mixes:

Reactive powder concrete mixes consist of cement , fine sand, silica fume, steel fibers , superplasticizers and water were used to cast RPC T-beams, as well as control specimens (cylinders and prisms) of RPC. Five RPC mixes were used in this study. Materials Proportions of each mix are listed in **Table (1).** Many mix proportions were tried to get maximum compressive strength .The variables used in these mixes were the volume ratio of steel fibers (three volume ratios were considered 0, 1 and 2%) and the ratio of silica fume (three ratios of silica fume as additive were studied 15, 20 and 25%).

Table (1) Properties of the different types of RPC mixes

Beam	Mix Type	Cement kg/m^3	Sand kg/m^3	Silica Fume* %	Silica Fume kg/m^3	w/c	S.P.** %	Steel Fibers*** %	Steel Fibers kg/m^3
B2	M2,25	1000	1000	25	250	0.2	1.7	2	156
B3	M2,20	1000	1000	20	200	0.2	1.7	2	156
B4	M2,15	1000	1000	15	150	0.2	1.7	2	156
B5	M1,25	1000	1000	25	250	0.2	1.7	1	78
B6	M0,25	1000	1000	25	250	0.2	1.7	0	0

* Percent of cement weight.

** S.P.: Superplasticizer, percent of binder (cement + silica fume) weight.

*** Percent of mix volume

7. Mixing Procedure:

RPC was mixed by using a horizontal rotary mixer with (0.1 m^3) capacity available in the structures laboratory, College of Engineering, Al-Mustansiriya University. Dry materials (cement, sand and silica fume) were first mixed for 3 minutes. Superplasticizer was added to the water and stirred, then the liquid was added to the dry mix during the mixing procedure and all were mixed for 3 minutes.

Then the mixing process was stopped to shovel the mix by hand and then restarted for 3 additional minutes. This step was repeated in three cycles to insure the homogeneity of the mix. After the third cycle, steel fibers were all added by hand while mixing was incorporated for 3 minutes. The total mixing time was about 25-30 minutes.

8. Mechanical Properties of RPC mixes:

The mechanical properties of RPC mixes are listed in **Table (2)** the compressive strength tests were carried out on cylinders (100x200mm) in accordance with ASTM-C39 [20]. Flexural strength (modulus of rupture) tests were carried out on prisms (50x50x500mm) in accordance with ASTM C78 [21]. While the indirect tensile strength (splitting tensile strength) tests were carried out on cylinders (150x300mm) in accordance with ASTM C496 [22].

Table (2) Mechanical properties of RPC mixes

Mix type	Steel fibers V_f %	Silica fume SF %	f_c' (MPa)	f_{sp} (MPa)	f_r (MPa)
M2,25	2	25	124.95	16.29	19.0
M2,20	2	20	120.45	15.24	18.1
M2,15	2	15	114.33	14.86	17.4
M1,25	1	25	113.53	11.95	14.7
M0,25	0	25	92.52	6.71	6.3

9. Testing of Beams:

At the age of 28 days, all beams were lifted from the curing water tank, left to dry, and then painted with white color so that cracks can be easily detected. All beam specimens were tested by using the universal testing machine (MFL system) of capacity 2500 kN under monotonic loads until failure occurs. A dial gage of 0.002 mm accuracy was attached firmly to the bottom face of midspan to record midspan deflection. The schematic diagram for the beam is shown in **Figure (4).** One of the beams under testing is shown in **Figure (5).** The test beams were simply supported over an effective span of (1200mm) and loaded with two-point loads.

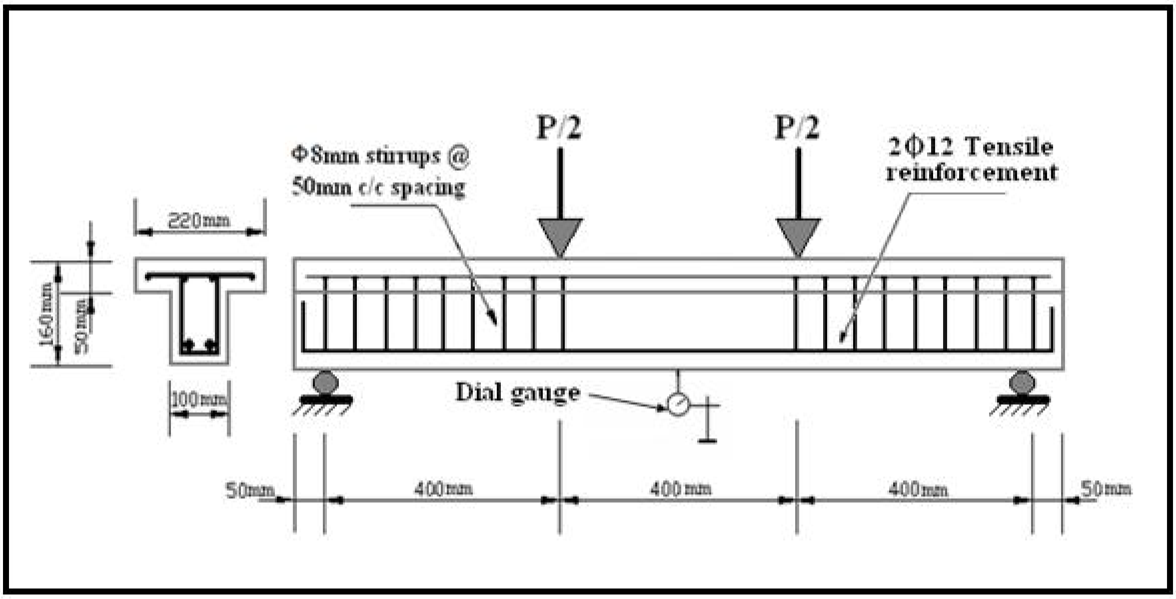


Fig .(4) Details of the tested beams

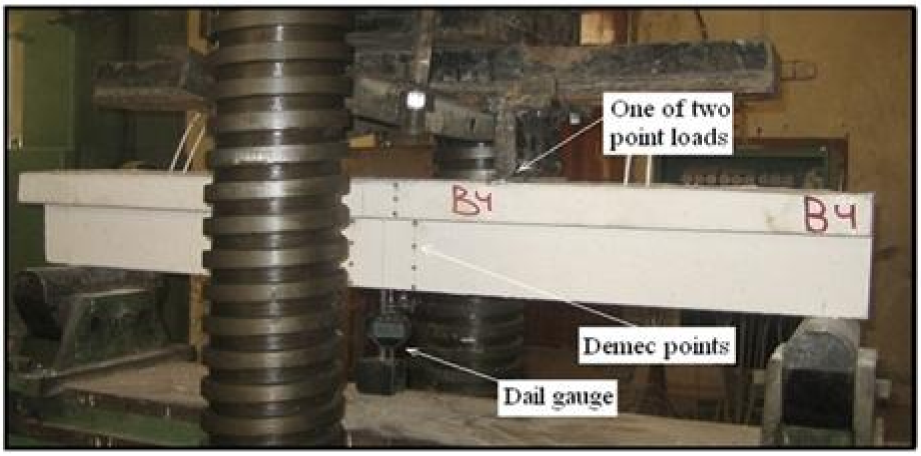


Fig .(5) One of the beams under testing

10. Beams Results:

10.1 General Behavior:

RPC beams tests showed that the general behavior of all beams under flexural loading can be described as follows: at early stage of loading, the first cracks appeared at bottom of midspan in the tension zone, the load in this stage is known as first crack load. With increasing loads, these cracks became wider and propagate upwards, also other cracks developed in the same zone. Further loading made the cracks to propagated and extend faster; some of them reached the compression zone until the failure occurred at ultimate load capacity.

Effects of steel fibers volumetric ratio and silica fume ratio on flexural behavior of RPC T-beams in terms of first cracking load, ultimate flexural load, maximum deflection, load-deflection curves, and cracks pattern in the failure are discussed in the following articles:

10.1.1 Effect of Volumetric ratio of Steel Fibers (Vf):

For nonfibrous beam (B6), the first cracks appeared when the load reached 22.5 kN and the failure occurred when the load reached 82kN. Hence the cracking load actually represented at about 27.44 % of ultimate flexural failure load.

With addition of steel fibers both the first cracking load and ultimate load increase. Table (3) shows that when the fibers volumetric ratio increased from 0% in B6 to 1.0% in B5 and 2.0% in B2 , the first cracking load increases to 30 kN and 35 kN which represent an increase of 33.34 and 55.56 % respectively as compared with the control nonfibrous RPC beam (B6) (P_{cr} =22.5kN). Also for the same increase in the volumetric ratio of fibers, the ultimate flexural strength increases to 110 kN and 129 kN which represent an increase of

%34.14 and %57.32 respectively as compared with the control nonfibrous RPC. These increases in first and ultimate load with increased steel fibers volumetric ratio belong to the reason that fibers across the initiating flexural cracks restricted growth and extension of the cracks and transmitted the tensile stresses uniformly to the concrete surrounding the cracks resulting in more bearing capacity.

Curves in **Figure (6)** were plotted to illustrate the role of steel fibers volumetric ratio with volumetric ratio 0, 1 and 2% on load-midspan deflection relationship of RPC T-beams. It is clear from the figure that the curves had three portions; the first portion is linearly elastic zone until the first crack load, the second portion began beyond the elastic zone until yielding tensile reinforcement steel, and the final portion is the stage of loading in which steel fibers effectively contribute in carrying tension stresses until failure occurs. It can be also noted from this figure that the slope of elastic portion is approximately identical for three curves, but each curve has a different path beyond the first crack loads, at all stages of loading the deflection decreases as the fibers volumetric ratios increased. This behavior can be attributed to enhanced stiffness of RPC beams and improving the mechanical properties of RPC concrete such as (modulus of elasticity, tensile strength and compressive strength) when the amount of steel fibers is increased.

On the other hand the deflection at ultimate load increased by the presence of steel fiber. However, increased percentage of maximum deflection in midspan with respect to deflection of nonfibrous RPC beam was 23.92% for beam B5 of 1% steel fibers and was 57.88% for beam B2 of 2% steel fibers. This behavior is normally explained by the efficiency of steel fibers in arresting crack propagation and controlling the growth of the flexural cracks within the beam when they are crossed by them; hence, steel fibers maintain the beam integrity throughout the postcracking stages. The beam, hence could withstand greater loads and deflection before failure.

Influence of steel fibers volumetric ratio on maximum deflection reveals that increasing steel fibers volumetric ratio to 2% makes RPC T-beams more ductile and capable of undergoing large deflections before reaching ultimate load carrying capacity. This property is very important for structural members as it makes concrete give warning before failure and prevents sudden collapse.

10.1.2 Effect of Silica Fume (SF):

To study the effect of silica fume on the flexural strength of RPC T-beams, with three percentages of (SF) were adopted, the experimental results from this investigation are shown in **Table (3).** In this table, it is obvious that for the same value of fibers content there is a slight increase in the percentage of first crack load and ultimate flexural strength of the RPC beam as the percentage of silica fume (SF) of the RPC T-beams is increased. However, as silica fume increased from 15% to 20% and 25%, the first cracking load increased with percentage 6.67% for beam (B3) of 20% silica fume and with percentage 16.67% for beam B2 of 25% silica fume with respect to the first crack load of beam B4 of 15% silica fume. On the other hand, the influence of silica fume is less significant on the ultimate flexural load than that on first crack load. However, when silica fume increased from 15% to 20% and 25%, the increase in flexural strength increased with percentage 3.39% for beam B3 of 20% (SF) and 9.32% for beam B2 of 25% (SF) with respect to the flexural strength of beam B4 of 15% (SF). The slight increase in flexural strength may belong to the changing range of silica fume ratio which gives less significant enhancements on mechanical properties as compared with enhancements on mechanical properties of range from 5% to 15% ratio.

Figure (7) shows the influence of three percentages of silica fume on the load-deflection behavior. It can be noted that the slope of linear stage is identical for the three curves with approximate first crack load and the curves are approximately parallel in three stages beyond first crack. Also these curves reveal that the deflection decreases as silica fume increase at all stages of loading. On the other hand the area under load-deflection curve which denotes energy absorption capacity increased with increasing silica fume.

Table (3) Experimental results of tested beams

Group One : Changing Steel Fibers Volumetric ratio (V_f)			
Beam No.	B6	B5	B2
Mix	M0,25	M1,25	M2,25
Silica fume (SF) %	25	25	25
Steel fibers (V_f) %	**0**	**1**	**2**
P_{cr} * kN	22.5	30	35
$(P_{cr} - P_{cr\ B6}) / P_{crB2} \times 100$	0	33.34	55.56
P_{ult} ** kN	82	110	129
$(P_{ult} - P_{ult\ B6}) / P_{ult\ B6} \times 100$	0	34.14	57.32
Δ_{ult} mm ***	9.07	11.24	14.32
$(\Delta_{ult} - \Delta_{ult\ B6}) / \Delta_{ult\ B6} \times 100$	0	23.92	57.88
Type of failure	Tension steel yielding	Tension steel yielding	Tension steel yielding
Group Two : Changing Silica Fume Ratio (SF)			
Beam No.	B4	B3	B2
Mix	M2,15	M2,20	M2,25
Silica fume (SF) %	**15**	**20**	**25**
Steel fibers (V_f) %	2	2	2
P_{cr} * kN	30	32	35
$(P_{cr} - P_{cr\ B4}) / P_{cr\ B4} \times 100$	0	6.67	16.67
P_{ult} ** kN	118	122	129
$(P_{ult} - P_{ult\ B4}) / P_{ult\ B6} \times 100$	0	3.39	9.32
P_{cr} / P_{ult} %	25.42	26.23	27.13
Δ_{ult} mm ***	13.71	13.84	14.32
$(\Delta_{ult} - \Delta_{ult\ B4}) / \Delta_{ult\ B4} \times 100$	0	0.95	4.45
Type of failure	Tension steel yielding	Tension steel yielding	Tension steel yielding

* Pcr :First crack load

** Pult :Ultimate load

***Δult :Ultimate deflection

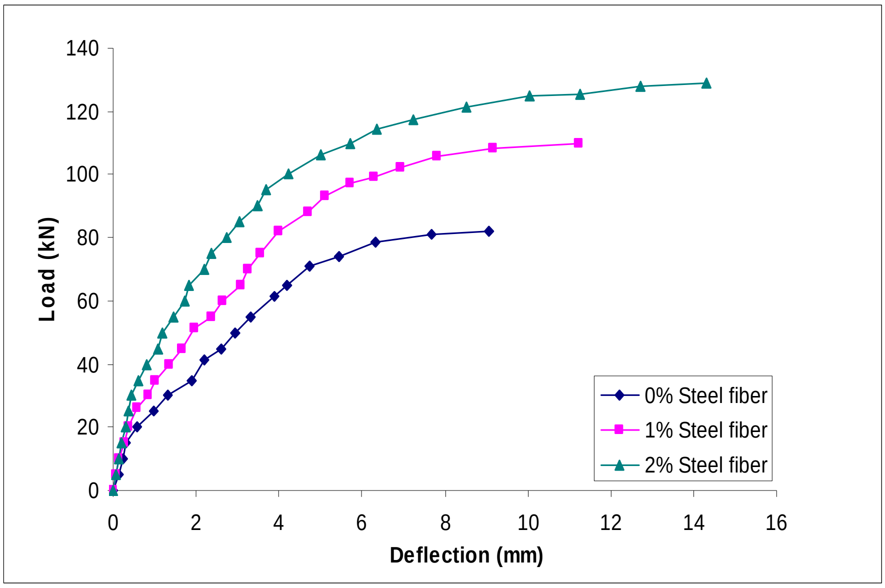


Fig .(6) Effect of steel fibers volumetric ratio on load-deflection curves of RPC T-beams

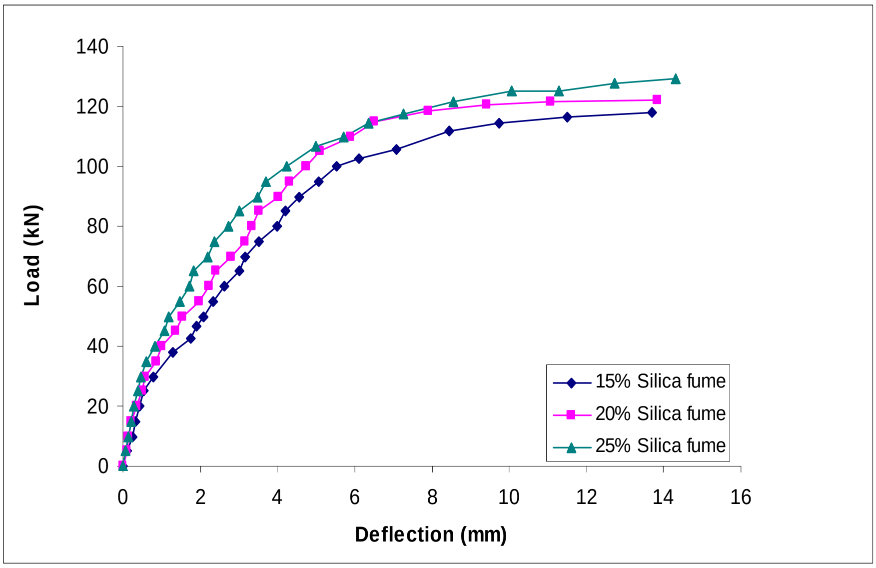


Fig .(7) Effect silica fume ratio on load-deflection curves of RPC T-beams

11. Crack Patterns:

Generally cracks in concrete are formed at regions where the tensile stresses exist and exceed the specified tensile strength of concrete. For concrete beams failing in flexure, cracks initiate at the tension face in the middle of the beam, thereby all tested beams of this study failing in flexure due to formation of cracking at the tension zone in middle third of the beam as shown in **Figures (8) And (9)** which show photographs of the crack patterns after the failure of the tested beams.

Effect of steel fiber volumetric ratio on crack can be recognized from group one as shown in **Figure (8)** it can be noted that failure of beams with higher steel fiber volumetric ratios (B2) is associated with multiple cracking, while beams with lower steel fiber volumetric ratios are associated with localized cracking (B5 and B6), this is attributed to the crack arrest mechanism of the fibers as it holds the part of the crushed concrete and prevents its disintegration. The multiple cracking leads to higher failure strain and the redistribution of stresses leads to higher residual strength.

Effect of silica fume on the crack pattern may be no evident, but as silica fume ratio increases compressive strength increases, then bonding of steel fibers with concrete increases resulting in less crack width as shown in **Figure (9).** In this figure beam (B2) of 25% silica fume has multiple small cracks as compared with cracks of beams (B3) and (B4) of 20% and 15% silica fume ratio respectively which have less and wide cracks. However, the effect of silica fume on crack pattern is less significant than the effect of steel fiber.

Fig .(8) Effect steel fibers volumetric ratio on crack pattern of RPC T-beams

Fig .(9) Effect silica fume ratio on crack pattern of RPC T-beams

12. Conclusion:

Based on experimental work results of this study it can be concluded that:

1. The performance of RPC T-beams (in terms of first crack load and ultimate load) under flexural loads can be significantly improved with increasing steel fiber volumetric ratio. However, as steel fiber increase to 2% the first crack load and the ultimate flexural strength increased with percentages (55.56% and 57.32%) respectively as compared with nonfiberous RPC T-beams.
2. Ultimate midspan deflection increased with increasing steel fiber volumetric ratio. However, as steel fiber increase to 2% the ultimate midspan deflection increased with percentage 57.88% as compared with nonfiberous RPC T-beams. This reveals that increasing steel fiber volumetric ratio to 2% makes RPC T-beams more ductile and capable of undergoing large deflections before reaching ultimate load carrying capacity. This property is very important to structural members as it makes concrete gives warning before failure and prevents sudden collapse.
3. Although the ultimate midspan deflection increases with increasing steel fiber volumetric ratio, the load-deflection curves of beams with (0, 1 and 2%) steel fiber volumetric ratio reveal that at particular load level, the deflection decreases with increasing steel fiber volumetric ratio at all stages of loading.
4. The increases in first crack load and ultimate load for RPC T-beams with increasing steel fiber volumetric ratio belong to the reason that fibers across the initial flexural cracks restrict growth and extension of the cracks and transmit tensile stresses uniformly to the concrete surrounding the cracks resulting in more bearing capacity and improve the bond between the matrix and the reinforcing bars. This maintains the beam integrity throughout the post cracking stages. Therefore the beam to withstand greater load and exhibit more deflection before failure. A larger ductility is achieved with a higher ratio of steel bars.
5. Silica fume ratio has little effect on the first crack load and ultimate flexural load of RPC T-beams. However as silica fume ratio increases from 15 to25%, the first crack load and the ultimate flexural strength increase with percentages of 16.67 and 9.32 % respectively as compared with RPC T-beam with silica fume ratio of 15%. The slight increase in flexural strength may belong to the changing range of silica fume ratio which gives less significant enhancements on mechanical properties as compared with enhancements on mechanical properties of range from 5% to 15% ratio.
6. Silica fume ratio has slight effect on the ultimate midspan deflection of RPC T-beams. However as silica fume ratio increases from 15 to25%, the ultimate midspan deflection increase with percentage 14.32% as compared with RPC T-beam with silica fume ratio of 15%.
7. Increasing silica fume ratio from 15 to 25% has no significant effect on increasing the ductility of RPC T-beams.

8. Load deflection curves of RPC T-beams had three portions; the first portion is linearly elastic zone until the first crack load, the second portion began beyond the elastic zone until yielding tensile reinforcement steel, and the final portion is the stage of loading in which steel fibers effectively contribute in carrying tension stresses until failure occurs. The transition zone between the second and third portion become less steeper with increasing steel fiber ratio.
9. The area under load midspan-deflection curve of RPC T-beam increases with increasing steel fiber volumetric ratio , while effect of increasing silica fume ratio with range from 15 to 25% has very slight effect on this area.
10. Cracking of RPC beams with higher steel fiber volumetric ratios is associated with multiple cracking, while beams with lower steel fiber volumetric ratios are associated with localized cracking.
11. As silica fume ratio increases compressive strength increases, then bonding of steel fibers with concrete increases resulting in less crack width.
12. The failure mode of all tested beams is of the type of yielding tensile reinforcement. This indicates that all tested beams are under-reinforced.

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