



BEHAVIOR AND ANALYSIS OF ECONOMICALLY REACTIVE POWDER RC BEAMS

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Received: 5 February 2014; **Accepted:** 20 May 2014

ABSTRACT

A study for the load deflection behavior of reinforced beams cast using reactive powder concrete RPC – as an ultra high strength concrete type – was executed experimentally and analytically. The experimental program was carried out to study the effect of cement content, using steel fiber and using two types of reinforcement. Results showed positive effect on cracking and ultimate loads of reactive concrete beams due to increasing of the cement content. The ductility of the reactive concrete beams is increased by using steel fibers. An analytical study was performed using a nonlinear computer program based on finite element technique. A comparison between analytical and experimental results was carried out to evaluate the efficiency and the accuracy of the used nonlinear computer program. The computer program results were practically close enough to the experimental results. The numerical analysis with the chosen finite element method presented a good simulation to the RPC beams.

Keywords: Reactive powder concrete; ultra high strength concrete; cement content; steel fibers; reinforcement type; nonlinear finite element.

1. INTRODUCTION

The Reactive Powder Concrete (RPC) is considered as ultra high strength concretes UHSC, Xiaoa et al. [1]. RPCs exhibit very high mechanical and durability properties. RPC has compressive strengths of 170 to 230 MPa and flexural strength of 30 to 50 MPa, depending on the type of fibers used, Moallem [2]. Additionally, it has a tensile strength of between 6 and 13 MPa that is maintained after first cracking. The traditional concrete has tensile strengths on the order of 2 to 4 MPa that is lost when cracking occurs, Washer et al. [3]. It has also an increased resistance to abrasion, erosion, corrosion and greatly reduced permeability to moisture, chlorides and chemical attack, Moallem [2].

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Ultra high strength concretes are characterized by high silica fume content and a very low water to cement (w/c) ratio. Granulometry and heat treatment have been optimized to obtain excellent mechanical and durability properties. Their composition is ordinary Portland cement OPC, silica fume, aggregates with very fine granulometry sand with average grain diameter of 250 μ m, crushed quartz (average grain diameter of 10 μ m). Metallic fibers can be added in order to increase concrete ductility and flexural strength [4-6].

Silica fume (SF) in a concrete mix enhances compressive strength and abrasion resistance while reducing permeability and thus improving resistance against the corrosion of steel reinforcement. It fills the voids remaining between cement and quartz powder particles as micro filler, Shihada and Arafa [7]. Using SF more than 10% of the cement weight is used to 'refine' the particle structure and thereby reduce the total pore volume and the average pore size. The size and spherical geometry of SF particles allow them to fill effectively the voids between the larger and angular cement grains, Rashid and Mansur [8], and AL-Hassani et al. [9]. SF also reacts with calcium hydroxide, thus increasing the final strength. Another important effect of the SF is the improvement of the interfacial transition zones between binder and aggregates and between binder and steel fibers, Habel et al. [10]. Chemically, it reacts with Calcium Hydroxide (CH) to produce additional Calcium Silicate Hydrate (C-S-H). The reaction between hydrated Portland cement compounds and Silica fume produces a very dense microstructure and thus improves the bond between the cement and the aggregates, Shihada and Arafa [7].

In a typical RPC mixture design, the least costly components of conventional concrete have been basically eliminated or replaced by more expensive elements. The fine sand used in RPC becomes equivalent to the coarse aggregate of conventional concrete, the Portland cement fills the role of the fine aggregate and the silica fume that of the cement, Jooss [11]; Matte and Moranville [11, 12]. Steel fibers enhance the performance of RPC and it can achieve remarkably flexural strength, Orgass [13].

Studying the performance of reinforced RPC and UHSC beams is conducted by a few researchers [14-20]. They addressed the outlines of behavior of UHSC under the flexure and shear loads.

Simulating reinforced concrete by using finite element "FE" method is a complicated process due to the variations in material properties. A suitable material model in the finite element method should inevitably be capable of representing both the elastic and plastic behavior of concrete elements in compression and tension. There are quite a large number of numerical material models available in the literature with the potential to develop complete stress-strain curves of concrete for compression and tension separately based on the experimental results.

In this research, beside the experimental program, a FE program by (Meleka [22]) is used to model the behavior of RPC reinforced concrete beams. A comparison between the results of the finite element model and experimental results on RC beam elements was performed in the following study.

2. RESEARCH SIGNIFICANCE

This study is carried out to investigate the experimental and analytical behavior of reactive

powder concrete beams cast using locally and economically available materials in North Sinai, Egypt. In this research, the available sand with its suitable size to this type of concrete is used despite of using expensive materials such as quartz powder to produce comparable mixtures as most researchers do. This research is also evaluates and analyzes the effect of using different cement content. The main variables in this investigation are; cement content, plain or fibrous mixes, reinforcement type (with or without shear reinforcement). Initial cracking loads, failure loads, deflections at different loading stages as well as the propagation of cracks for the tested beams are recorded.

The importance of this research is based on the need to know the available data addressing the behavior of reactive powder concrete beams with its ultra mechanical properties using economical materials. This research provides data for researchers concerning the behavior of ultra high strength reinforced concrete beams.

3. EXPERIMENTAL PROGRAM

The conducted experimental program including the tests carried out on different materials used for casting the reinforced ultra high strength concrete samples and beams as well as the tests performed on samples are shown in this section.

3.1 Concrete Materials

All tests in this research were carried out in the Construction Materials Laboratory in Civil Engineering Department, Faculty of Engineering Science, Sinai University.

The cement used was ordinary Portland cement CEM I N52.5, provided by Sinai cement factory. It satisfies the Egyptian Standard Specification E.S.S. 4756-1 [23].

The fine aggregate used was the natural siliceous clean and nearly free from impurities sand with a specific weight of 2.66 t/m^3 . It was obtained from El-Arish City in North Sinai, Egypt. Its maximum nominal size (0.6 mm) is suitable to be used in casting reactive powder concrete as ultra high strength concrete UHSC. Physical properties of the used sand are given in Table 1 and its grading is shown in Table 2 and Fig. 1. Sand was sieved over sieve of size 0.6mm to discard any impurities.

The water used is clean, drinkable, fresh and free from impurities tap water used for mixing and curing the tested samples according to the Egyptian Code of Practice E.C.P. 203 [24].

Table 1: Physical properties of the sand used

Property	Value
Specific gravity	(t/m^3) 2.71
Volumetric weight	(t/m^3) 1.62
Voids ratio	(%) 42.1%
Percent of clay, silt and dust	(by weight) 0.41%

Table 2: Grading of the sand used

Sieve size (mm)	0.6 mm	0.3 mm	0.15 mm	0.074 mm
Sieve No.	No. 30	No. 52	No. 100	No. 200
% Passing	100	86	52	0.7

Silica fume used is a waste by-product of silicon and silicon alloys industry consisting mainly of non-combustible amorphous silica (SiO_2) particles. It was produced by Egyptian Ferro Alloys Corporation (EFACO). It is used as 30% of cement content based on Arab [28]. The chemical components analysis is shown in Table 3 and the main properties are shown in Table 4. The silica fume used was met the main requirements of ASTM C 1240.

Table 3: The chemical components analysis result of silica fume used

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	L.O.I.
Average (%)	95.93	0.52	0.05	0.2	0.18	0.1	0.4	2.9

Table 4: Physical properties of the silica fume used

Property	Value
Specific gravity	(t/m^3) 2.20
Bulk density [uncompacted unit weight]	(t/m^3) 0.25
Fineness	(m^2/gm) 2.342

Super-plasticizer as high-range water-reducing (HRWR) admixture is used to increase the workability of concrete without additional amount of water. In this study a super-plasticizer (S.P.) of naphthalene sulphonate group based, supplied by Chemicals for Modern Buildings (CMB) Company, under the brand name of Addicrete BVF was used. The main properties are shown in Table 5. The used super-plasticizer complies with ASTM C494-Type F [25] and ESS 1899-1 [26].

Table 5: Technical information of Addicrete BVF (as provided by manufacturer)

Base	Appearance	Density	Chloride content	Air entrainment	Compatibility
Naphthalene sulphate	Brown liquid.	1.18 ± 0.01 kg/litre	Nil	Nil	All types of Portland cement

The steel fibers used in this investigation are clean of rust or oil of straight steel wire fibers. The length of fibers is 13 mm and its diameter 0.8 ± 0.02 mm with aspect ratio (l/d) of 16.25. The properties of the steel fibers used are shown in Table 6.

The steel rebars used in this experimental work are two types. The first was the normal strength mild steel rebars (St.37) which is used for the passive reinforcement and shear reinforcement (stirrups) with rounded plain bars of 8 mm diameter. The second type was high tensile steel rebars (St.52) which is used for the main reinforcement of 10mm diameter. Yield stress, ultimate strength and modulus of elasticity of both types are given in Table 6.

Table 6: Test results of steel fibers and reinforcement used (based on laboratory tests)

Steel Type	Yield Stress (MPa)	Tensile Strength (MPa)	Elongation (%)	Modulus of Elasticity (GPa)
Steel Fibers	355	525	14	200
Mild Steel	295	399	22.2	202
High Tensile Steel	368	531	13.2	200

3.2 Mixtures Proportions

The mixture ratios were based on guidelines and specifications given in several different approaches presented in literature. Mixture proportions used in this investigation are chosen based on (Meleka et al. [27]) and summarized in Table 7. The first group is coded by (B) and produced without using steel fiber content, while the second group is coded by (B..F), which casts using steel fibers.

Cement content that was chosen in this research as 700, 750 and 800 kg/m³ to be within the usual range (600-1000 kg/m³) that was adopted by many researchers as shown previously in the literature. Sand content was the same for all the mixtures in this research. It was chosen to be 1230 kg/m³ [28]. Many researchers (Reeves [17]; Lee et al. [29, 30]) choose the fine sand content to be 1020 kg/m³ but they used quartz powder of 210 kg/m³ content. In this research, El-Arish sand is used with its grading without adding any quartz powder to make the RPC beams are more economical so that, 1230 kg/m³ of sand was chosen. The water/cement ratio was taken between 0.17 and 0.19 for fibered reactive concrete and between 0.15 and 0.17 for plain reactive concrete according to Richard and Cheyrezy [4]; Cheyrezy et al. [5]. In this research the w/c ratio was chosen to be 0.18 for all mixtures.

Table 7: Concrete mixes used and their main mechanical properties

Mix	Cement (kg/m ³)	Water (kg/m ³)	Sand (kg/m ³)	Fibers (kg/m ³)	Silica Fume (kg/m ³)	Super- plasticiz er (kg/m ³)	Compressive Strength		Modulus of Elasticity E ₂₈ (GPa)	Flexural Strength F _t (MPa)
							F _{cu 7} (MPa)	F _{cu 28} (MPa)		
NSC	350	157.5	Sand=658 gravel=1237	without steel fibers	--	--	23	28.5	21	2.85
B700	700	126			210	70	111.5	114	31.58	9.49
B750	750	135	1230		225	75	123.5	127	35.44	13.31
B800	800	144			240	80	149.5	150.5	40.99	14.73
B700F	700	126		with steel fibers	210	70	116	120	35.45	24.51
B750F	750	135	1230		225	75	130.5	133	40.95	27.61
B800F	800	144		40 kg	240	80	153.5	154.5	45.10	30.26

Silica fume as 30% of the cement content and super-plasticizer as 10% of cement content were used [28].

Steel fibers are among the main parameters that divide the mixtures into two groups. The first group "B..F" was the reactive fiber reinforced concrete with 40 kg/m³ steel fiber content which was chosen in accordance to (Reeves [17]) (reported that the steel fiber content was ranging between 40 kg/m³ and 160 kg/m³). The lower limit of 40 kg/m³ was chosen for more cost saving. The second group "B" was the plain reactive concrete with no fiber content.

3.3 Mixing, Casting and Curing Processes

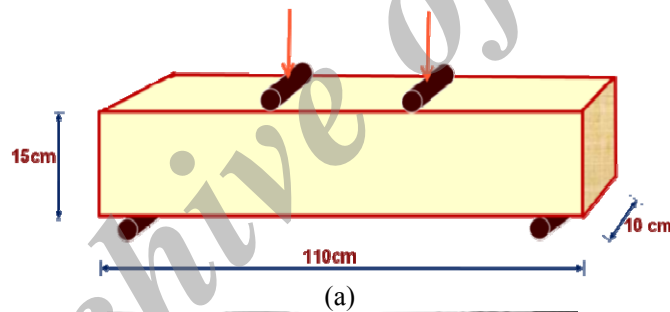
The mixing process was performed using a ring concrete mixer of 15 liters capacity as shown in Fig. 1. The compaction process were performed by concrete vibrator which was slowly insert and was not allow being rest on or touching the bottom or sides of the mould. After vibrating, rod strokes were distributed uniformly over the cross section of the mould to

ensure the best compaction especially for the final layer.

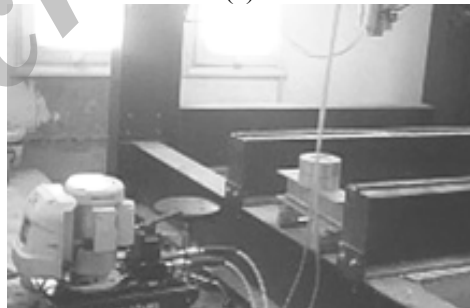
Specimens were demoulded 24 hours after casting and water cured at about 75°C for 3 days then in 25°C for another 3 days after those specimens were gotten out from the water to a dry place till the age of testing. For maintaining uniform curing all the specimens were cured in the same curing tanks.



Figure 1. The concrete mixer used



(a)



(b)

Figure 2. (a) Dimensions of the tested specimens, and (b) The loading frame

3.4 Concrete Samples

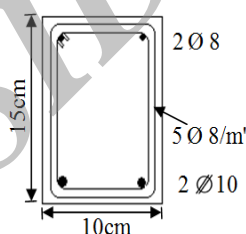
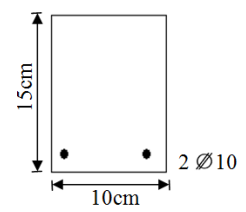
Concrete samples are cast to evaluate the main mechanical properties of RPC mixes used. Standard cubes of dimensions 10x10x10 cm for measuring the compressive strength, cylinders of 10 cm diameter and 20 cm height for measuring the indirect tensile strength and

the modulus of elasticity and their results are given in Table 7.

As shown in Fig. 8, two NSC beams as well as twenty four simply support reinforced RPC beams of dimensions 10x15x110cm were cast. The twenty four beams are divided in to two main groups and each group is divided to two types, plain and fibrous beam types.

The groups and the reinforcing details of beams are shown in Table 8. The first main group was carried out by placing shear and bending steel reinforcement abbreviated as (S-B) and the second system was carried out by placing bending steel reinforcement only abbreviated as (B) as shown in Table 8.

Table 8: Codes and reinforcing details of the tested beams.

Rft type	Beams' Code*	Fibers	Dimensions (cm)	Reinforcement	Beam cross section with Reinforcement
Shear and Flexure Reinforcement (S-B)	NSC	without	10x15x110 cm	Main Rft (2 \varnothing 10) Secondary Rft (2 \varnothing 8) Shear Rft (5 \varnothing 8/m')	
	S-B700F	with Steel Fibers			
	S-B750F				
	S-B800F				
	S-B700	without Steel Fibers			
	S-B750				
S-B800					
Flexure (Bending) Reinforcement (B)	B700F	with Steel Fibers	10x15x110 cm	Main Rft (2 \varnothing 10)	
	B750F				
	B800F				
	B700	without Steel Fibers			
	B750				
	B800				

*The beams' code is the same as mixes but the shear reinforced beams are referee by S

3.5 Testing Procedures and Equipments

All tests in this research were carried out to investigate the main properties of reinforced RPC beams as reported in this section.

Compression Test: was carried out to determine the compressive strength of specimens of concrete cubes. A 2000 kN capacity compression testing machine was used.

Modulus of Elasticity Test: The moduli of elasticity of cylindrical specimens were determined. Stresses and corresponding strains were evaluated and average values were calculated. A 2000 kN capacity compression testing machine was used to apply a compressive axial load and Compress meter (dial gauge with accuracy 0.01 mm and a maximum capacity of 10 mm) was used.

Tension Test: Indirect tension test (splitting method) was performed to determine the tensile strength of concrete mixes using cylindrical specimens of RPC. A 2000 kN capacity compression testing machine was used.

Prism Flexural Test: This test evaluates the flexural strength of the tested prism specimens using a flexure testing machine of 150 kN capacity.

Beam Flexural Test: It is performed using four-points load system. Fig. 2 shows the beam

dimensions. A steel frame with two movable I-beam girders to work as a support for beams was used. The load was applied by a hydraulic cylinder double acting with 150 ton capacity and 150 mm maximum Stroke which was connected to a hydraulic electric oil pump for feeding the hydraulic jack. The applied load was measured by a load cell of 150 ton capacity. An LVDT for measuring displacements up to at least 100mm was placed under each beam at the center of its span to measure deflections were used for deflection measurements within the region of pure bending between the two load points. The load cell and the LVDT were connected to a data logger that showed a continuous record of the applied load and the corresponding deflection at mid span.

The behavior of the materials used as well as beam behavior are estimated from the results recorded during testing of RPC samples. The results of beam samples in terms of initial cracking load, deflection at each load increment at the center of the lower surface of each beam, ultimate load, and crack propagation were recorded at each stage of loading.

4. FINITE ELEMENT ANALYSIS

Several researchers [22, 31] have studied the nonlinear analysis of beams. A nonlinear computer program based on the finite element techniques is applied to study the behavior of reinforced RPC beams using quadrilateral isoparametric degenerated layered thick shell elements. Each element has eight nodes and each node has three degrees of freedom. Geometric and material nonlinearities have been considered. The material nonlinearities are taken into consideration. The nonlinearities include the stress-strain relationship for concrete and steel reinforcement, concrete cracking and tension stiffening effects. The efficiency and accuracy of the computer program are verified by comparing its results with the experimental results.

A nonlinear finite element FE computer program performed by (Meleka [22]) is used. Longitudinal direction is consists of 8 elements as shown in Fig. 3.

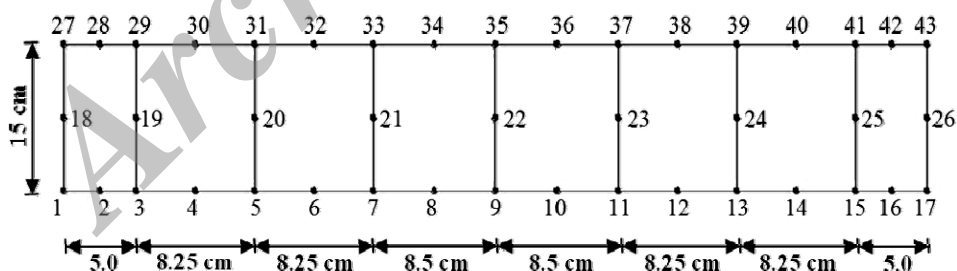


Figure 3. Finite element mesh in XZ plan for beam model

For support (A), node "3" is restrained only in X and Z directions while free in Y direction also the rotation about Y axis is permitted. At support (B), node "15" is restrained only in X and a Z directions while free in Y direction also the rotation about Y axis is permitted.

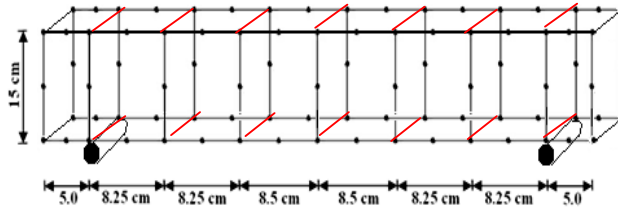


Figure 4. Finite element model for beam model

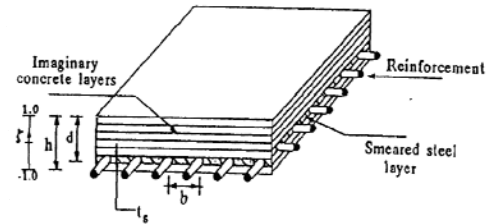


Figure 5. Modeling of reinforced concrete layered element.

The tested beams are analyzed by a nonlinear finite element computer program based on nonlinear finite element method. Four-point load test is used. The dimensions of tested simply supported beam samples are $10 \times 15 \times 110$ cm. The reinforcing details of the specimens are illustrated in Table 8. The load increment is applied by 200 kg up to failure to simulate the experimental program. The material properties and dimensions are:

1. Height of the beam = 15 cm
2. Width of the beam = 10 cm
3. Compressive strength values " $F_{cu\ 28}$ " were considered as given in Table 7.
4. Modulus of rupture " f_t " was considered as given in Table 7.
5. Yield strength of steel $f_y = 360$ MPa
6. Young's modulus of steel $E_s = 2.1 \times 10^5$ MPa
7. Young's modulus of concrete $E_c = 2 \times 10^4$ MPa
8. Poisson's ratio $\nu = 0.2$
9. Concrete cover $c = 1$ cm

A normal strength concrete NSC beam of the same dimensions and reinforcement as the case of shear and flexure reinforcement shown in Table 7 were cast to investigate the efficiency of the nonlinear finite element program when dealing with NSC and compare that to the results obtained when dealing with the tested reactive concrete beams. The boundary conditions are the same as given before. The used NSC properties were as follows:

- | | |
|-------------------------------------|-------------------------|
| 1. Compressive strength of concrete | $F_{cu\ 28} = 28.5$ MPa |
| 2. Modulus of rupture of concrete | $f_t = 2.85$ MPa |
| 3. Young's modulus of concrete | $E_s = 21000$ MPa |
| 4. Poisson's ratio | $\nu = 0.2$ |

The used material properties for the tested beams were indicated from the executed experimental program. The compressive strength used in the finite element analysis was:

$$f'_c = 0.8 f_{cu} \quad (1)$$

where f_{cu} was the 28 days compressive strength of the reactive concrete type that used in beam casting. The tensile strength used in the finite element analysis was:

$$f'_t = 0.8 f_t \quad (2)$$

where f_t was the 28 days tensile strength of the reactive concrete type that used in beam casting indicated from indirect tension test results.

The modulus of elasticity (E_c) used in the finite element analysis was obtained from the 28 days modulus of elasticity of the reactive concrete type that used in beam casting. Poisson's ratio (ν) was chosen to be 0.2 for all the tested beams according to JSCE [6].

Modeling beam in the nonlinear finite element computer program was by divided the beam into 8 element which translated into 43 nodes in the XY plan and 8 layers of reactive concrete in Z direction while the steel reinforcement was modeled according to the tested beam type to simulate the reinforcement in the real beam as shown in Figs. 3 and 4.

5. TEST RESULTS

Initial cracking loads and failure loads for each beam are shown in Fig. 6. Load-deflection curves at lower mid point of different beams are shown in Figs. 7 to 12.

5.1 Cracking Loads

The first crack load (P_{cr} in Fig. 6) was determined from the main curve in the load deflection curve at initial stages of loading. The cracking loads for beams cast using different cement contents, with and without steel fibers and having shear and bending steel reinforcement was shown in Fig. 6. The increasing of the cracking load with respect to the cracking load of beam SB700F was 8.8% and 18.0% for beams SB750F and SB800F respectively. The cracking load for beams cast using different cement content without fiber reinforcement and having shear and bending steel reinforcement indicated that the increases are about 17.6% and 28.1% for beams SB750 and SB800 respectively compared to SB700.

For beams cast using only bending steel reinforcement, the cracking load increased with respect to the cracking load of beam B700F by about 9.7% and 16.4% for beams B750F and B800F respectively. For beams cast using different cement content without fiber reinforcement and having only bending steel reinforcement, the increasing of the cracking load with respect to the cracking load of beam B700 was 12.6% and 25.7% for beams B750 and B800.

There was a positive effect on the cracking load of reactive concrete beams due to increasing of the cement content regardless the steel fibers reinforcement and the type of steel reinforcement as shown in Fig. 6. Using steel fibers enhances the performance of RPC beams in agree with JSCE; Al-Hassani *et al.*; Habel *et al.*; Orgass *et al.*; Voo *et al.*; Kamal *et al.* [6, 9, 10, 13, 20, 21].

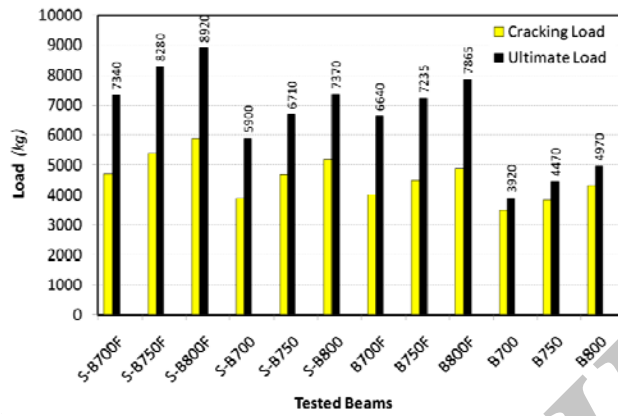


Figure 6. Initial cracking loads and ultimate loads for all tested specimens.

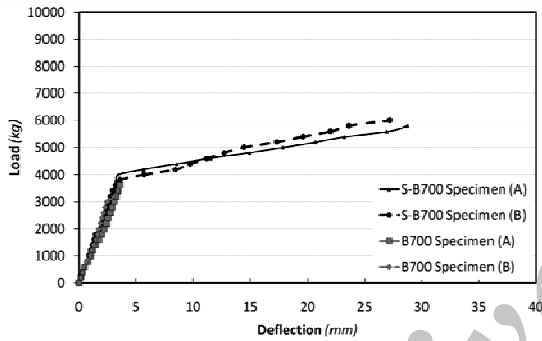


Figure 7. Deflection values of S-B700 & B700 (700kg/m^3 cement content without steel fibers)

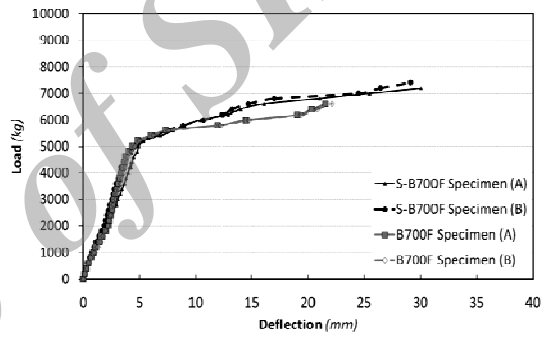


Figure 8. Deflection values of S-B700F & B700F (700kg/m^3 cement content with steel fibers)

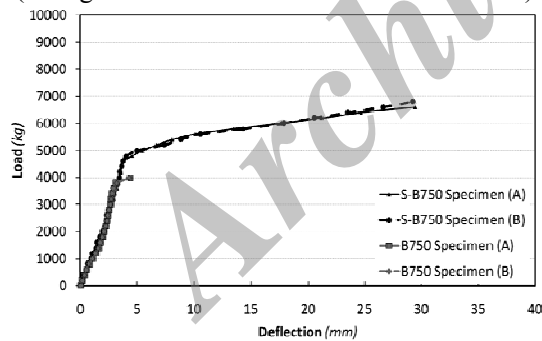


Figure 9. Deflection values of S-B750 & B750 (750kg/m^3 cement content without steel fibers)

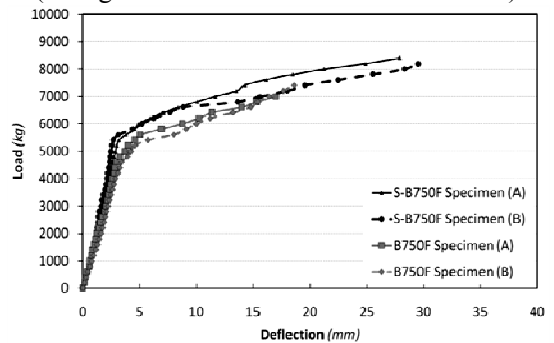


Figure 10. Deflection values of S-B750F & B750F (750kg/m^3 cement content with steel fibers)

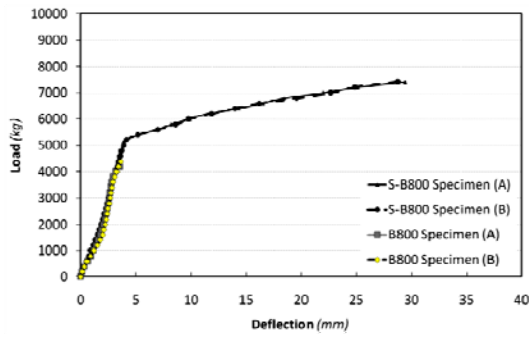


Figure 11. Deflection values of S-B800 & B800 (800kg/m³ cement content without steel fibers)

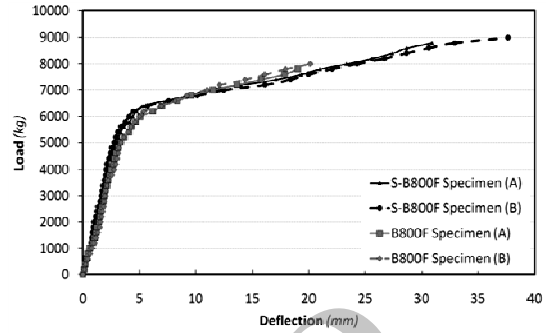


Figure 12. Deflection values of S-B800F & B800F (800kg/m³ cement content with steel fibers)

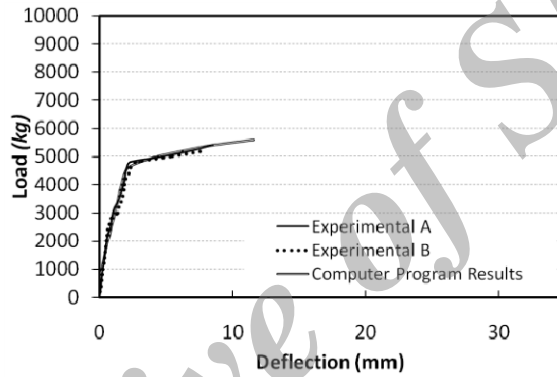


Figure 13. Comparison between experimental and FE method for NSC beams

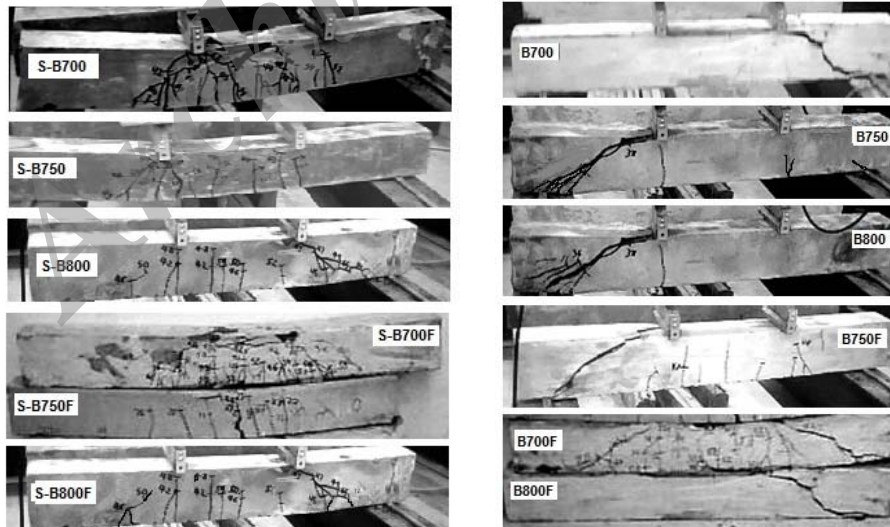


Figure 14. Crack patterns of tested beams

5.2 Load Capacity of Beams

The four major stages are observed on load deflection curves for all the beams as shown in Figs. 7 to 13. The load corresponding to stage 1, 2, 3, 4, on load deflection curves are noticed as first cracking load (P_{cr}), Yield point load (P_y), maximum load (P_m), and ultimate load (P_u) respectively. Using shear reinforcement enhances the load capacity of RPC beams. Also, steel fibers are efficient in increasing both initial and ultimate loads.

5.3 Deflection of Tested Beams

Typical load-deflection curves for reinforced concrete beams of two types, PRC and NSC reinforced beams are recorded. Figs. 7 to 12 illustrate the typical load-deflection characteristics of all types of beams. Comparison shows clearly that the deflection of RPC beams at all load stages is less than that of NSC RC beams at the same load. The tested beams with shear/web reinforcement (stirrups) are stiffer than those without shear reinforcement satisfying Kamal et al. [21]. Using fibers enhances the behavior of the tested beams.

Based on these observations, it is evident that RPC beams showed better stiffness characteristics than NSC reinforced concrete beams. Those results are in agree with Gao et al.; Warnock; Reeves; Yang et al. [14, 15, 17, 18].

5.4 Failure Loads for Beams

The ultimate load for tested beams using different cement content reinforced with steel fibers and having shear and bending steel reinforcement was shown in Fig. 6. The average cube strength Table 7 of control specimens were used to determine the ultimate load from FE analysis was compared with average ultimate load of RC beams tested under static loading. It was shown that the increase of the ultimate load with respect to the ultimate load of beam SB700F was 12.9% and 21.6% for beams SB750F and SB800F.

For tested beams using different cement content without fiber reinforcement and having shear and bending steel reinforcement, the increases of the ultimate loads for beams SB750 and SB800 were 13.8% and 25.0% compared to beam SB700. Increasing cement content and using steel fibers improve the behavior of RPC beams satisfying the previous researchers [14, 15, 17, 18].

5.5 Crack Patterns

The crack patterns were recorded, illustrated and photographed at each load increment as shown in Fig. 14. The number of cracks decreased in all RPC beams compared to NSC beams at the same load in agreement with previous researches [14, 15, 17, 18]. Using shear/web reinforcement changed the modes of failure for the tested beams compared to the beams without shear reinforcement in agree with Voo et al.; Kamal et al. [20, 21]. Fine flexure cracks propagated upwards with loading and were followed by shear cracks near the supports in the shear zone are noticed in beams with shear reinforcement. Failure took place due to shear in tested beams without web reinforcement. The results show that, there is a brittle failure behavior and therefore a limited post-crack behavior, so the elements fail explosively with a lower post-cracking ductile behavior and were able to reduce cracking which satisfies Orgass; Yang et al. [13, 18]. The improvement in the cracking behavior depends on the cement content and fiber content as shown in Fig. 14.

5.6 Comparison between Finite Element Analysis and Experimental Results

Reinforced RPC beams that have the designation and properties that illustrated in Table 7 were modeled using a finite element program that was developed by Meleka [22] and its modifications by Meleka et al. [31, 32]. The load deflection behavior of the 13 different tested beams types was analyzed by the computer program based on the nonlinear finite element analyses. Deflection was determined at mid span at the centre of the bottom face of the beam. Figs. 15 to 26 show the load deflection curves of the beams for both the experimental and numerical data. There was easy to model the two types of steel reinforcement used in this research even bending and shear reinforcement or bending reinforcement using the nonlinear FE program of Meleka [31]. A linear computer program SAP2000 (version 14) which based on the linear finite element method was used. The steel reinforcement in bending only could be modeled but when dealing with shear reinforcement SAP2000 program could not be modeled. The results of linear computer program SAP2000 was shown in Figs. 15, 16, 19, 20, 23, 24.

Fig. 13 shows the load deflection curves for the two experimentally cast beams and the results obtained from the nonlinear finite element program. From the Figure it could be indicated that the used nonlinear finite element program results was identical to the experimental results and that was a prove to the great efficiency of the used program in analyzing NSC beams.

Figs. 12 and 14 to 26 show the load deflection curves for the 13 different tested beams types. The results of the 2 beams tested experimentally and the results indicated from the nonlinear finite element program were shown in the previous. The SAP2000 program results were shown in Figures for beams that have steel bending reinforcement only. It is noticed that the results of the nonlinear analysis approach the experimental results and that was a good prove to the effectiveness of using this nonlinear finite element program in analyzing and predicting the behavior of the reactive concrete beams. In general, the load deflection curve for the beam from the numerical results has excellent agreement with the experimental data.

It is clear that SAP2000 results were very close to the experimental and the nonlinear finite element program results in the linear phase of the load deflection curve but it were deviated after cracking load in the nonlinear phase of the load deflection curve.

Two normal strength concrete beams of the same dimension and reinforcement as the case of shear and flexure (Bending) reinforcement as shown in Table 8 were cast to investigate the efficiency of the nonlinear finite element program when dealing with normal strength concrete and compare that to the results obtained when dealing with the tested reactive concrete beams.

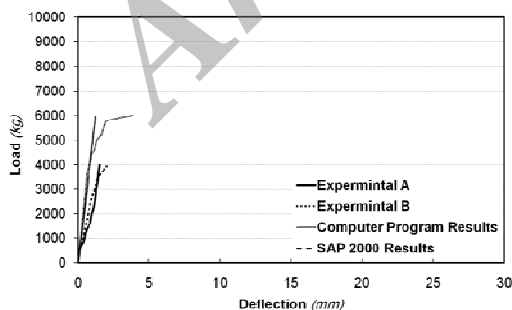


Figure 14. Comparison between deflection values of beam B700 experimentally and by using FE model

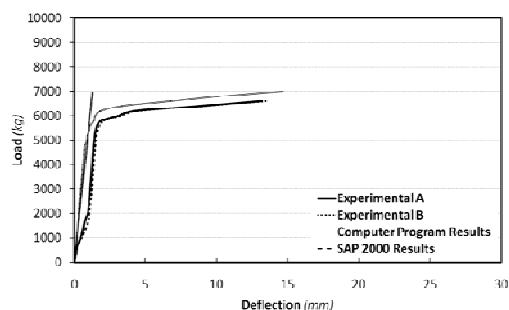


Figure 15. Comparison between deflection values of beam B700F experimentally and by using FE model

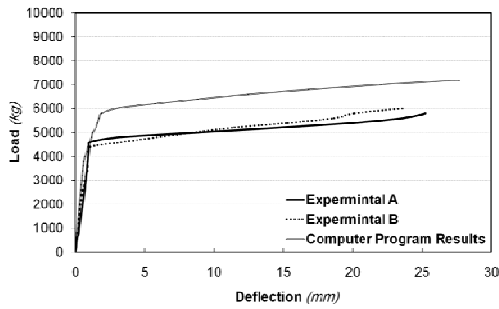


Figure 16. Comparison between deflection values of beam S-B700 experimentally and by using FE model

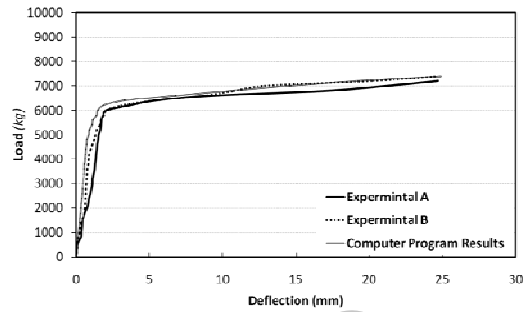


Figure 17. Comparison between deflection values of beam S-B700F experimentally and by using FE model

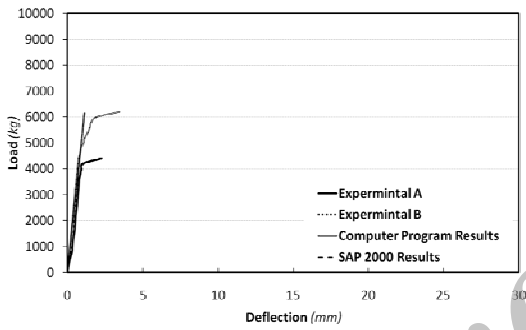


Figure 18. Comparison between deflection values of beam B750 experimentally and by using FE model

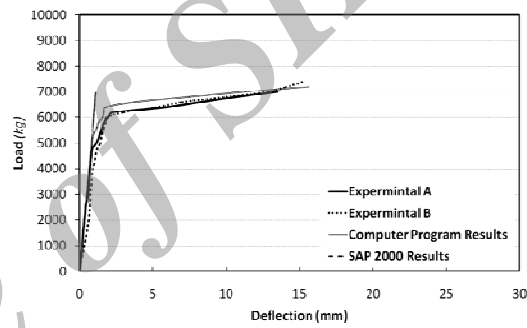


Figure 19. Comparison between deflection values of beam B750F experimentally and by using FE model

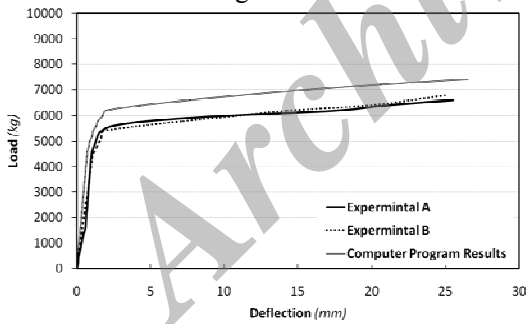


Figure 20. Comparison between deflection values of beam S-B750 experimentally and by using FE model

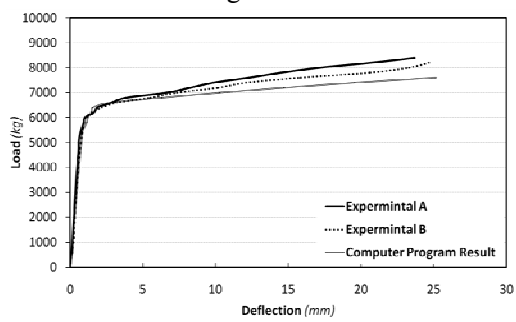


Figure 21. Comparison between deflection values of beam S-B750F experimentally and by using FE model

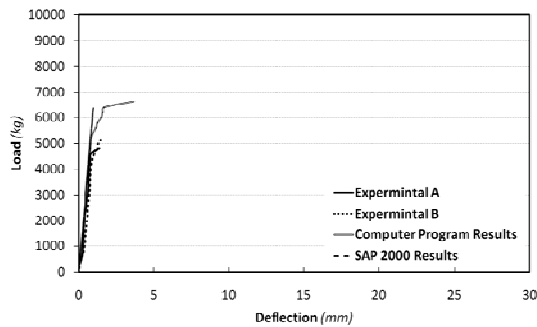


Figure 22. Comparison between deflection values of beam B800 experimentally and by using FE model

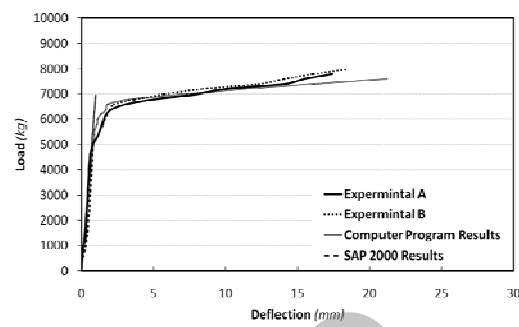


Figure 23. Comparison between deflection values of beam B800F experimentally and by using FE model

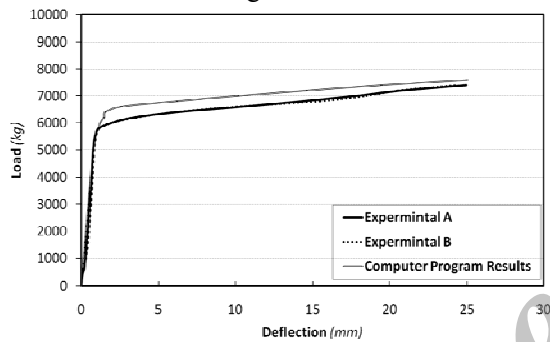


Figure 24. Comparison between deflection values of beam S-B800 experimentally and by using FE model

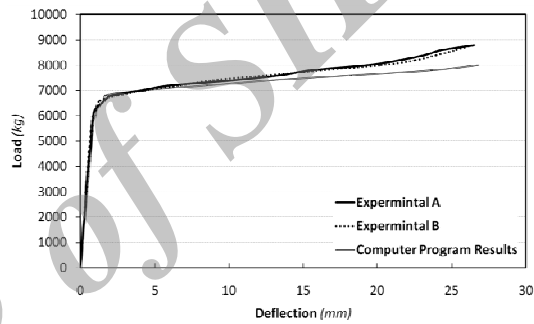


Figure 25. Comparison between deflection values of beam S-B800F experimentally and by using FE model

6. ECONOMIC STUDY

From the economic point of view (without taking into consideration labor costs), using Sinai sand is considered less cost compared to quartz powder used by other researchers. Sinai sand costs about $1.5 \text{ \$/m}^3$ while quartz sand powder costs about $50 \text{ \$/m}^3$. Other components of RPC are the same as other researches. Plain RPC costs about $250 \text{ \$/m}^3$. That led to less cost by about 10%. In case of using steel fibers, the steel fiber reinforced RPC costs about $340 \text{ \$/m}^3$ with increasing in cost by about 36% comparing to plain RPC. When comparing the plain RPC to the plain ordinary concrete (compressive strength = 30 MPa), RPC costs about $250 \text{ \$/m}^3$ while ordinary concrete costs about $70 \text{ \$/m}^3$. That means the RPC costs about 3.5 times larger than ordinary concrete but having 5 times compressive strength values comparing to plain ordinary concrete.

7. CONCLUSIONS

Based on the available research results, the following main conclusions for the behavior of

reinforced RPC beams are as follows:

1. The load deflection relationship of the tested beams indicated the great effect of the steel fiber content on the ductility of the reactive concrete beams especially for beams that has only flexure reinforcement.

2. Using steel fiber enhances the initial cracking loads and ultimate loads especially when there is no shear reinforcement.

3. There was a positive effect due to using shear reinforcement (the shear reinforcing in this research was by stirrups) and it is effective especially when using plain reactive concrete without any fiber reinforcement.

4. There is an increasing in the ultimate load of reactive concrete beams with respect to its cracking load which was ranging between 26.0% to 38.0% but in case of having only bending steel reinforcement and without steel fibers reinforcement there were nearly no increase in the ultimate load with respect to the cracking load.

5. The used nonlinear finite element computer program results are practically close enough to the experimental results and this program was found to be effective when dealing with reactive concrete beams.

6. The suggested (nonlinear) FE model of quadrilateral iso-parametric degenerated elements applied in this research can perform the analysis of RPC beams as well as ultra high strength concrete UHSC efficiently and it is quite accurate in representing the problem.

Generally, RPC can effectively use as prefabricated concrete beam elements due to its ultra high mechanical properties but it is not recommended to use with elevated temperatures [34].

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