AUT Journal of Civil Engineering

AUT J. Civil Eng., 2(1) (2018) 87-96
DOI: 10.22060/ceej.2017.12210.5145

Shear Behavior of Reactive Powder Concrete Beams with and without Coarse Aggregate

M. H. Mohammed*

Highway and Transportation Engineering Department, College of Engineering, Al-Mustansiriyah University, Baghdad, IRAQ

ABSTRACT: This paper presents an experimental investigation consists of casting and testing in shear seven rectangular simply supported reinforced concrete beams. Two of the tested beams are made with reactive powder concrete (RPC) without coarse aggregate and five with reactive powder concrete with coarse aggregate which is called modified reactive powder concrete (MRPC). Experimental results have generally shown that coarse aggregate had a positive effect on shear behavior of MRPC beams and higher ultimate loads (P_u) are obtained with the increase of steel fibers volumetric ratio (V_f) and longitudinal steel ratio (ρ). Results also showed that using relatively high steel fiber ratio of 2% changes the mode of failure from brittle shear to ductile flexural one. It is, therefore, concluded that RPC and MRPC beams can be made without transverse shear reinforcement bars (stirrups).

Review History:

Received: 3 December 2016
Revised: 29 January 2017
Accepted: 19 February 2017
Available Online: 28 February 2018

Keywords:

Reactive Powder Concrete
Shear Behavior
Coarse Aggregate

1- Introduction

Reactive powder concrete (RPC) is a type of ultra-high performance concrete (UHPC), which belongs to the family of ultra-high strength cementitious composites [1, 2]. It has high compressive and tensile strengths and excellent environmental resistance (durability) because it has compact matrix. The addition of steel fibers to UHPC further improves tensile cracking resistance, post cracking toughness and ductility, even when the amount of added fiber is low. Fibers also reduce crack width and spacing [1, 3, 4]. Since its first introduction at the 1990s, many RPC applications of prototype structures have been constructed in various countries such as France, USA, Germany, Canada, Japan, South Korea, Australia, New Zealand and Malaysia [5].

RPC was first developed by Richard and Cheyrezy (1995) [6] in the early 1990s. They reported achieving compressive strength in the range of 200-800 MPa and fracture energies up to 40 kj/m^2. Their work depends on the following basic principles:

- Enhancement of homogeneity by elimination of coarse aggregate.
- Enhancement of compacted density by optimization of the granular mixture, and application of pressure before and during setting.
- Enhancement of the microstructure by post-set heat treatment.
- Enhancement of ductility by incorporating steel fibers.

Most of researches on RPC were conducted based on the above principles (especially eliminating coarse aggregate), while little ones used coarse aggregate in producing RPC. Collepardi et al. (1997) [7] produced modified reactive powder concrete (MRPC) by replacing part of (or all) fine sand with or without replacing part of the cementitious binder by 8 mm crushed aggregate. Results showed that the replacement of the fine ground quartz sand (0.15-0.4 mm) by an equal volume of well graded natural aggregate (maximum size of 8 mm) did not change the compressive strength of the RPC at the same water-cement ratio but flexural strength was lower when graded coarse aggregate replaced all the very fine sand.

A comparative investigation on UHPC with and without coarse aggregate was carried out by Ma et al. (2004) [8]. Results showed that UHPC containing coarse aggregate was easier during fluidized and homogenized mixing. A noticeable decrease in autogenous shrinkage occurred which was only 60% of RPC autogenous shrinkage. Higher modulus of elasticity and lower strains at peak stress were also obtained.

Wille et al. (2011) [9] developed an UHPC with more than 150 MPa compressive strength without the need for either heat curing or pressure using a conventional concrete mixer. The developed UHPC mixtures had the additional benefit of exhibiting high workability. They recommended the following mixing procedure to obtain the mentioned advantages:

1. Mix silica fume and sand first for 5 minutes.
2. Add other dry components (cement and glass powder) and mix for another 5 minutes.
3. Add all the water within 1 minute.
4. Add all the superplasticizer and mix for an additional 5 minutes.

Corresponding author, E-mail: m_sahlani@yahoo.com

5. Add fibers, if applicable, and mix for an additional 2 minutes.

It should be mentioned that nearly all local researches on RPC used fine sand (without coarse aggregate) and heat curing (with or without presetting pressure) to develop the desired mechanical properties. RPC of compressive strength approaching 120 MPa is produced in the present research using coarse aggregate as partial replacement for fine sand and normal water curing at ambient temperature without presetting pressure. This makes the production of RPC more economic and more practical choice especially in field applications.

2- Shear Strength of RPC Elements

The enhanced post-cracking tensile behavior and improved crack control of RPC translate to potentially significant increase in the shear strength and ductility of RPC. The use of steel fibers therefore holds potential for reducing or eliminating conventional stirrups particularly in high strength, high performance concrete elements, which in turn can lessen the congestion of reinforcement and produce more efficient designs [3].

Ashour et al. (1992) [10] found that the addition of steel fibers to the high strength concrete beams containing no stirrups, transforms the typical brittle shear failure mode into one of a more ductile nature, increases the stiffness of the beam, thus reducing deflection and increases shear strength. Similar results were obtained by Kwak et al. (2002) [11].

Minelli and Vecchio (2006) [12] stated that due to the bridging effect provided by the fibers, less brittle shear failures were achieved. Moreover, the use of fibers with a high aspect ratio (fiber length = 30 mm, aspect ratio = 80) transformed the mode of failure from shear to ductile flexural mode.

Voo et al. (2006) [13] reported the experimental results of shear strength of RPC prestressed I-section girders (650 mm deep) without stirrups. The steel fibers used in the tests consisted of either 13 mm straight fibers and/or 30 mm end-hooked fibers. It was concluded that the quantity and type of fibers do not significantly affect the cracking load but have a significant influence on the rate of crack propagation and on the failure loads and stiffness which have lower values with increasing quantities of the 30 mm end-hooked fibers and reducing quantities of 13 mm straight fibers.

Ridha (2010) [14] investigated the shear behavior of RPC beams. She concluded that increasing steel fibers ratio from 0% to 2% increases both the ultimate shear strength by 132.4% and ductility by 159%. The inclusion of steel fibers also enhanced stiffness and reduced crack width. Increasing silica fume content from 5% to 15% increases ultimate shear strength by only 9.09%.

Susetyo et al. (2011) [3] performed a series of tests to assess the effectiveness of steel fibers as a possible replacement for conventional transverse reinforcing steel in concrete elements. It was found that, relative to conventionally reinforced concrete elements containing shear reinforcement, fiber-reinforced concrete elements can achieve comparable shear strength and deformation response with improved crack control characteristics.

This research presents an investigation on the shear behavior of RPC beams with and without coarse aggregate to examine the possibility of using coarse aggregate in RPC without affecting its exceptional properties particularly shear strength. The effectiveness of steel fibers as shear reinforcement was also studied using different steel fibers ratios in RPC beams without stirrups. Longitudinal steel ratio was the other variable studied in this research.

3- Experimental Program

The experimental work of this research consists of casting and testing in shear seven rectangular simply supported reinforced RPC beams without stirrups. Two of these beams are made with reactive powder concrete without coarse aggregate (RPC) and five with reactive powder concrete with coarse aggregate as partial replacement (50% of fine sand) which is, hereafter, referred to as modified reactive powder concrete (MRPC). Three longitudinal steel ratios (ρ= 1.1%, 1.58% and 2.37%) and three steel fibers ratios (V_f= 0%, 1% and 2%) are used. Details of all experimental work stages are presented in the following sections.

3- 1- Materials

Ordinary Portland cement (type I) and fine sand with maximum particle size of 600 μm were used for RPC and MRPC mixes. Crushed river gravel with maximum particle size of 8 mm was used as coarse aggregate for MRPC mixes only. RPC was made without coarse aggregate for comparing.

A grey colored densified silica fume and a superplasticizer commercially named Sika Visco Crete PC-20 were used as admixtures to produce RPC and MRPC mixes and to enhance their properties. The fineness of the used silica fume is 200000 m^2/kg.

Hooked end steel fibers with aspect ratio (L/d) of 80 (L=30 mm, d= 0.375 mm) were used in RPC and MRPC mixes. Deformed steel bars with two nominal diameters of 10 mm and 12 mm were used as the main reinforcing bars in tension, while, no shear reinforcement (stirrups) were used.Yield stress and ultimate strength of the used bars were 540 MPa and 720 MPa, respectively.

3- 2- Mix Proportions

Table 1 gives mix proportions of RPC and MRPC mixes used in different beams. Based on several trial mixes, two RPC mix and three MRPC mixes that differ from each other only in volumetric steel fibers ratio (Vf) were adopted in this research.

3- 3- Mixing and Casting

Wooden molds were used for beams with inner dimensions of 110 mm in width, 150 mm in depth and 1200 mm in length. After cleaning, oiling inner surfaces and fastening the parts of the mold, the steel reinforcement was placed in its required position in the mold.

Mixing was done using a horizontal rotary mixer with 0.19 m^3 capacity. Mixing procedure proposed by Wille et al. (2011) [9] was adopted in this study to produce RPC and MRPC in a simple way without any accelerated curing regimes. Fine sand, coarse aggregate (in MRPC mixes) and silica fume were first mixed for 4 minutes, then cement was added and the dry components were mixed for 5 minutes. Superplasticizer was added to the water, then the blended liquid was added to the dry mix during the mixer rotation and the mixing process continued for another 3 minutes. Finally, steel fibers were added during mixing within 2 minutes. The total mixing time was about 15 minutes.

Table 1. Mix proportions of RPC and MRPC

Concrete Type	RPC		MRPC		
Cement (C) (kg/m^3)	900		900		
Sand (S) (kg/m^3)	900		450		
Gravel (G) (kg/m^3)	-		450		
Silica Fume (SF) (kg/m^3)	225*		225*		
Super-plasticizer (SP) (kg/m^3)	56.25**		56.25**		
Water (W) (kg/m^3)	180		180		
W/C	0.2***		0.2***		
Steel Fibers (kg/m^3)	78	156	0	78	156
V_f (%)	1	2	0	1	2

*SF/C = 25%, **SP/(C+SF) = 5%, ***W/(C+SF) = 0.16

Casting of RPC and MRPC beams was done by placing the specific concrete into molds continuously in three layers with each layer being vibrated using a table vibrator to obtain a more compacted concrete. With each mix, control specimens were cast to determine the mechanical properties of concrete. Control specimens involve 3 cylinders (100 mm×200 mm) for compressive strength and 3 prisms (100 mm×100 mm×500 mm) for flexural strength (modulus of rupture). After casting, all specimens were covered with a nylon sheet for 24 hours to prevent loss of moisture.

3- 4- Curing of Specimens

After 24 hours from casting, all specimens were demolded and placed in water containers in the laboratory to be cured at room temperature for 28 days. In the previous works, RPC was always produced using accelerated curing methods such as heat curing at elevated temperature or presetting pressure. Any of these methods was not used in this study in order to gain an advantage of producing RPC of exceptional mechanical properties (compressive strength up to 120 MPa) using conventional curing method without any additional provisions. This was proved to be successful as will be seen in this paper. However, this normal curing was proposed by Wille et al [9] as part of their proposed simpler way to produce RPC and the mixing procedure used in this research was the main part of their proposal.

3- 5- Details and Designation of Beams

Seven beams of dimensions of 110 mm×150 mm×1200 mm were cast and tested in shear. Two of these beams are made with RPC and five with MRPC. Three volumetric steel fiber ratios (V_f =0%, 1% and 2%) and three longitudinal reinforcement ratios (ρ= 1.1%, 1.58% and 2.37%) were used in the tested beams. No shear reinforcement (stirrups) was used in all beams as shown in Figure 1. Shear span to effective depth ratio (a/d) of 3.27 was kept constant in all beams.

To designate the tested beams accurately and briefly taking into account the main variables mentioned above, the following symbols were used: Letter R or letters MR refer to the beams that made with RPC or MRPC, respectively. The first number (1, 2, or 3) following letter(s) refers to the longitudinal steel ratio (ρ= 1.1%, 1.58% or 2.37%), respectively. The second number (0, 1, or 2) following first number refers to the steel fiber ratios (V_f =0%, 1% and 2%), respectively. Details of beam specimens are presented in Table 2.

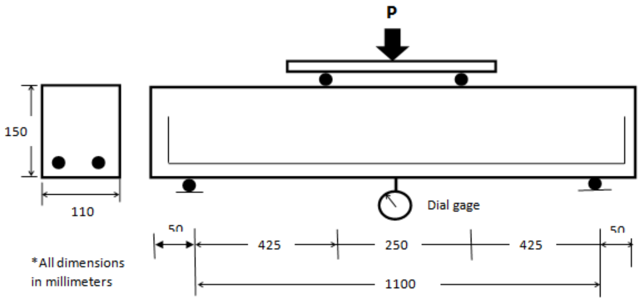

Figure 1. Details and setup of the tested beams

Table 2. Details of the tested beams

Beams	Concrete type	A_s (%)	ρ	V_f (%)
MR1-1	MRPC	2Ø10	1.1	1
MR2-1	MRPC	2Ø12	1.58	1
MR3-1	MRPC	3Ø12	2.37	1
MR2-0	MRPC	2Ø12	1.58	0
MR2-2	MRPC	2Ø12	1.58	2
R2-1	RPC	2Ø12	1.58	1
R2-2	RPC	2Ø12	1.58	2

3- 6- Testing of Beams in Shear

All beams were tested as simply supported beams over a span of 1100 mm under two point loads using a universal testing machine of 3000 kN capacity (Figures 2 and 3). The load was applied gradually in small increments up to failure. Mid-span deflection of the tested beam was recorded every 5 kN using a dial gage of 0.01 mm accuracy and 30 mm capacity attached to the bottom face of beam mid-span (Figure 1). Also cracking developments of the beam were observed during the test and crack patterns were mapped.

4- Results and Discussions

4- 1- Mechanical Properties of RPC and MRPC

Tests results of mechanical properties of RPC and MRPC are shown in Table 3. Mechanical properties reach compressive strength of 121 and 118 MPa, modulus of elasticity of 57.31 and 54.16 GPa, flexural strength of 17.63 and 13.11 MPa, and splitting tensile strength of 12.98 and 13.91 MPa, for RPC and MRPC respectively. These values were obtained without using any accelerated curing regime as mentioned before. It is shown from these results that the use of coarse aggregate in RPC resulted in comparable mechanical properties to RPC without coarse aggregate. Furthermore, splitting tensile strength of MRPC was higher than that of RPC, may be because the contribution of aggregate interlock in arresting cracks, which is an effective component in shear strength of concrete beams.

Results also showed that when steel fibers ratio increases from 0 to 2%, compressive strength, modulus of elasticity, flexural strength and splitting tensile strength of MRPC increase by 40.89, 41.15, 162.2 and 117.34%, respectively. Similar general trend was observed for RPC. It is clearly shown that the effect of steel fibers on flexural strength and splitting tensile strength is higher than that on compressive strength and modulus of elasticity. This assures that steel fibers are used mainly to improve tensile properties of RPC and MRPC.

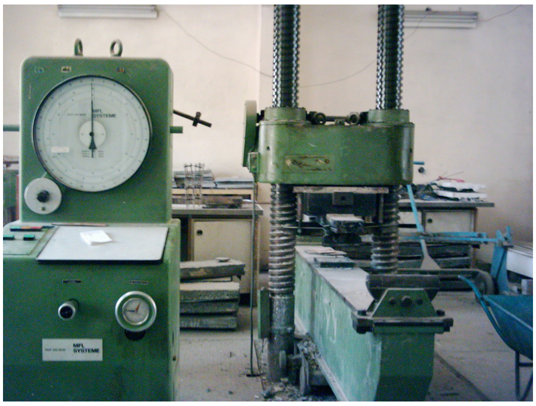

Figure 2. Testing machine

Figure 3. One of the beams under testing

Table 3. Mechanical properties of RPC and MRPC.

Type of Concrete	Steel Fibers Ratio (V_f) (%)		Cylinder Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Flexural Strength (MPa)	Splitting Tensile Strength (MPa)
RPC	1	Test result	105.7	49.95	10.44	10.5
		Increasing ratio (%)	0	0	0	0
	2	Test result	121	57.31	17.63	12.98
		Increasing ratio (%)	14.47	14.73	68.86	23.61
MRPC	0	Test result	83.75	38.37	5	6.4
		Increasing ratio (%)	0	0	0	0
	1	Test result	97	48.65	9	10.1
		Increasing ratio (%)	15.82	26.79	80	57.81
	2	Test result	118	54.16	13.11	13.91
		Increasing ratio (%)	40.89	41.15	162.2	117.34

4- 2- Ultimate Loads of the Tested Beams

Table 4 lists the ultimate loads results of the tested beams. The results generally show that ultimate loads (P_u) increase with the increase of steel fibers volumetric ratio (V_f) and longitudinal steel ratio (ρ), while including coarse aggregate in RPC (as 50% replacement of fine sand) did not decrease the ultimate loads, instead it slightly increases shear strength. Detailed discussions of the effects of the above parameters on ultimate loads results of the tested beams are given in the following sections.

Table 4. Ultimate loads of the tested beams

Beams	Concrete type	ρ (%)	V_f (%)	P_u (kN)	Mode of Failure
MR1-1	MRPC	1.1	1	53	Flexural
MR2-1	MRPC	1.58	1	68	Shear
MR3-1	MRPC	2.37	1	115	Shear
MR2-0	MRPC	1.58	0	43	Shear
MR2-2	MRPC	1.58	2	98	Flexural
R2-1	RPC	1.58	1	65	Shear
R2-2	RPC	1.58	2	88	Flexural

4- 2- 1- Effect of Longitudinal Steel Ratio

Increasing longitudinal steel ratio (ρ) from 1.1% to 1.58% and 2.37% increases ultimate loads of MRPC beams from 53 kN in beam MR1-1 to 68 kN in beam MR2-1 (28.3% increase) and 115 kN in beam MR3-1 (117% increase), respectively as shown in Table 5 and Figure 4.

Table 5. Effect of Longitudinal Steel Ratio (ρ) on ultimate loads of MRPC beams

Beams	Concrete type	ρ (%)	V_f (%)	P_u (kN)	% increase in P_u
MR1-1	MRPC	1.1	1	53	0*
MR2-1	MRPC	1.58	1	68	28.3*
MR3-1	MRPC	2.37	1	115	117*

*Compared to Pu of MR1-1.

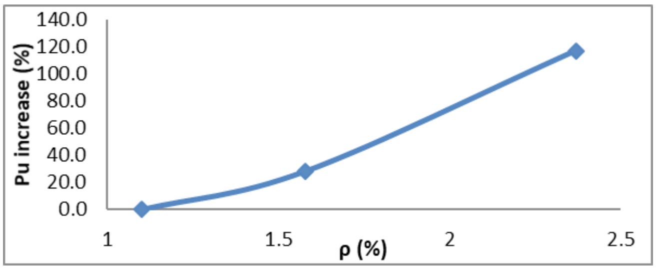

Figure 4. Effect of Longitudinal Steel Ratio (ρ) on ultimate loads of MRPC beams (V_f=1%).

This response is expected and may attributed to that increasing ρ reduces the penetration of the flexural cracks which reduces the principal stresses for a given applied load, and consequently greater load is required to cause the principal stresses that will result in diagonal tension cracking. Also increasing ρ increases the dowel capacity of the beam and reduces cracks widths which results in increasing friction along the diagonal crack surface.

4- 2- 2- Effect of Steel Fibers Volumetric Ratio

Table 6 and Figure 5 show that increasing steel fibers volume ratio (V_f) from 0% to 1% and 2% increases ultimate loads (P_u) of MRPC beams from 43 kN in beam MR2-0 to 68 kN in beam MR2-1 (58.1% increase) and 98 kN in beam MR2-2 (127.9% increase), respectively. Latter increasing ratio (127.9%) for MRPC approaches the corresponding ratio (132.4%) reported by Ridha [14] for RPC, as mentioned before.

Table 6. Effect of steel fibers ratio (V_f) on ultimate loads of RPC and MRPC beams

Beams	Concrete type	ρ (%)	V_f (%)	P_u (kN)	% increase in P_u
MR2-0	MRPC	1.58	0	43	0*
MR2-1	MRPC	1.58	1	68	58.1*
MR2-2	MRPC	1.58	2	98	127.9*
R2-1	RPC	1.58	1	65	0**
R2-2	RPC	1.58	2	88	35.3**

* Compared to P_u of MR2-0, ** Compared to P_u of R2-1.

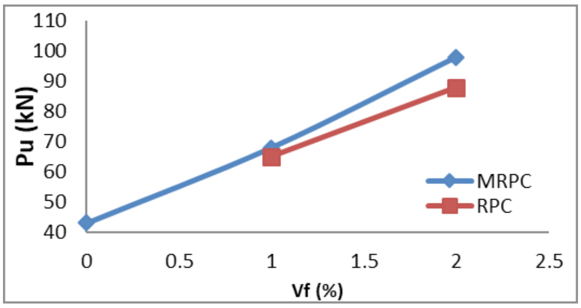

Figure 5. Effect of steel fibers ratio on ultimate loads of RPC and MRPC beams (ρ=1.58%)

This improving effect may be attributed to the bridging effect of steel fibers across the diagonal crack which restricts the crack propagation through the shear span and tends to tie up the crack sides toward each other. Similar effect with lower ultimate loads was recorded in RPC beams (65 kN and 88 kN for V_f of 1% and 2%, respectively with increasing ratio of 35.3%) as compared to ultimate loads of MRPC beams (68 kN and 98 kN for V_f of 1% and 2%, respectively with increasing ratio of 44.1%) (Table 6 and Figure 5). This reflects the positive effect coarse aggregate on ultimate shear loads as will be discussed in the next section.

Three beams (MR1-1, MR2-2 and R2-2) were failed in flexure rather than diagonal shear although they had no transverse shear reinforcement (stirrups), while the nonfibrous beam MR2-0 (ρ=1.58%, V_f=0%) was failed in shear with the lower ultimate load of 43 kN among all tested beams. The above results show the effectiveness of steel fibers as shear reinforcement instead of the traditional stirrups.

4- 2- 3- Effect of Coarse Aggregate

The use of coarse aggregate with 8 mm maximum size as partial replacement (50%) of fine sand increases the ultimate load from 65 kN in beam R2-1 to 68 kN in beam MR2-1 (4.6% increase) and from 88 kN in beam R2-2 to 98 kN in beam MR2-2 (11.36% increase) for V_f of 1% and 2%, respectively as shown in Table 7 and Figure 6.

Table 7. Effect of Coarse Aggregate on ultimate loads of MRPC beams

Beams	Concrete type	ρ (%)	V_f (%)	P_u (kN)	% increase in P_u
R2-1	RPC	1.58	1	65	0*
MR2-1	MRPC	1.58	1	68	4.6*
R2-2	RPC	1.58	2	88	0**
MR2-2	MRPC	1.58	2	98	11.36**

* Compared to Pu of R2-1, ** Compared to Pu of R2-2.

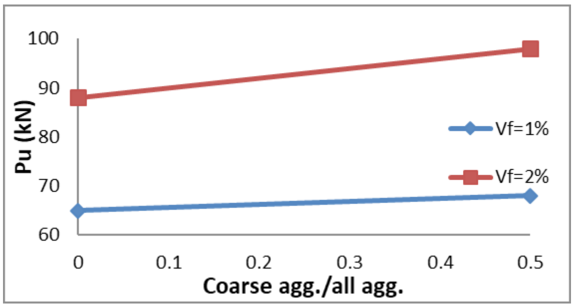

Figure 6. Effect of Coarse Aggregate on ultimate loads of MRPC beams (ρ = 1%)

This behavior may be attributed to the greater modulus of elasticity of coarse aggregate as compared to cement matrix and to the aggregate interlock across the cracks interfaces which provides more restriction to the widening of the cracks under increasing load and delays the failure. The above results show that RPC can be produced without the limitation of removing all coarse aggregate with mechanical properties and structural behavior (shear and flexural) maintained in their high levels. Furthermore, MRPC beams gave better results than RPC beams as mentioned above.

4- 3- Load-Deflection Behavior

The load-midspan deflection behavior of the tested beams is illustrated in Figures 7 to 11. Generally, the load-deflection curve was linear (or elastic) in the first stage with constant slope until the flexural cracks in the maximum moment region appeared and widen causing a change in the curvature with elasto-plastic behavior. The curve continues in this form until the sudden shear failure occurs after a short time from the appearance of diagonal cracks in the shear span. In beams that failed in flexure, the flexural cracks continue to propagate toward the compression zone under increasing load, then longitudinal steel yielded before the complete formation of diagonal cracks. This graduated failure mechanism was accompanied with increasing deflections under low load increment causing the load-deflection curve to change into flat curve until failure.

Increasing ρ from 1.1% (beam MR1-1) to 1.58% (beam MR2-1) and 2.37% (beam MR3-1) generally increases the initial stiffness of the load-deflection curves of MRPC beams as shown in Figure 7. Also stiffer behavior (leading to smaller deflections) was observed when steel fibers ratio increased from 0% (beam MR2-0) to 2% (beam MR2-2) and from 1% (beam R2-1) to 2% (beam R2-2) for MRPC and RPC beams as shown in Figures 8 and 9, respectively. This behavior is due to that increasing ρ or V_f increases stiffness and arrests cracks and consequently reduces deflection.

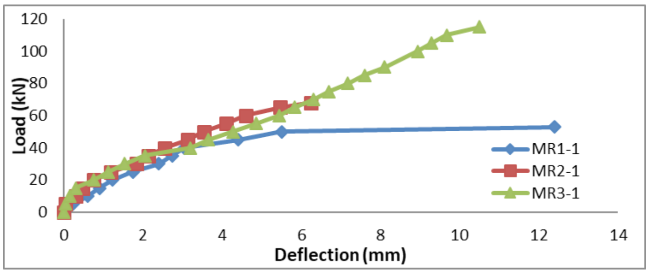

Figure 7. Load-deflection curves of MRPC beams with different ρ (V_f=1%)

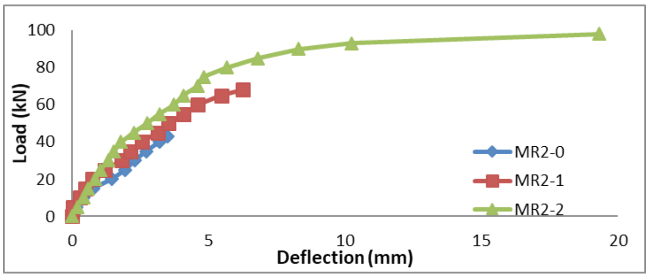

Figure 8. Load-deflection curves of MRPC beams with different V_f (ρ =1.58%)

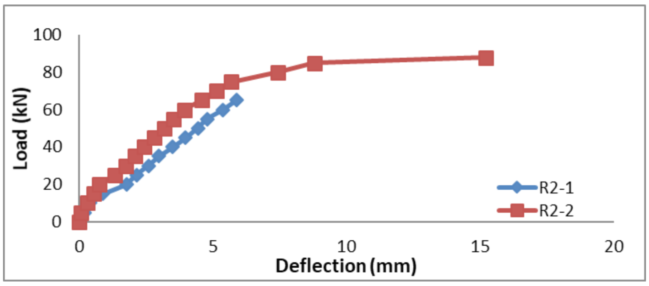

Figure 9: Load-deflection curves of RPC beams with different V_f (ρ =1.58%)

The use of coarse aggregate in MRPC beams gives a higher stiffness (lower deflections) to the load-deflection curves as shown in Figures 10 and 11, because of the fact that coarse aggregate has higher elastic modulus than cement matrix. This again proves not only the possibility of using coarse aggregate in RPC, but also its better results than using only fine sand in RPC.

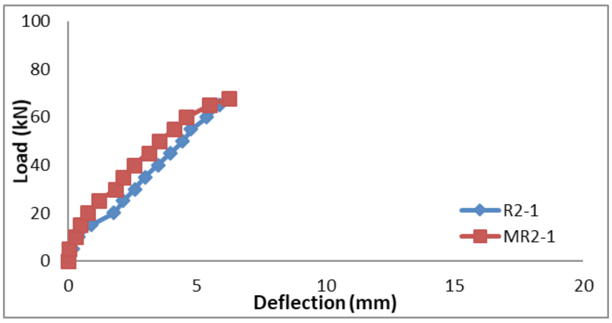

Figure 10. Load-deflection curves of RPC and MRPC beams (V_f=1%, ρ =1.58%)

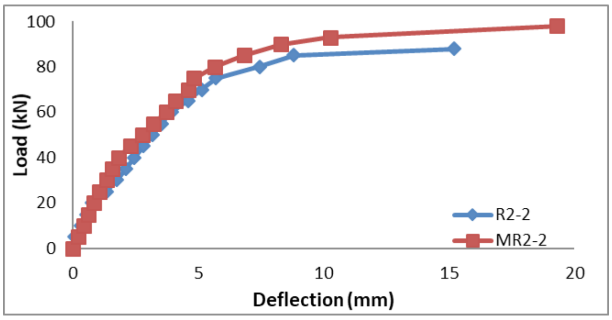

Figure 11. Load-deflection curves of RPC and MRPC beams (V_f=2%, ρ =1.58%)

Finally, as expected, beams that failed in flexure (MR1-1, MR2-2 and R2-2) show higher ductility and energy absorption since they sustained higher deflections before failure as compared to the sudden brittle shear failure with lower ultimate deflections observed in the other beams as shown in Figures 7 to 11.

4- 4- Cracking Behavior and Modes of Failure

Crack patterns and modes of failure of the tested beams are shown in Figure 12 and Table 4, respectively. The cracking behavior of beams failing in shear is as follows: At early stage of loading, several cracks were initiated in the tension face at the constant maximum moment region (middle portion of the beam between the two point loads). With further loading, these cracks extended upwards and became wider while other cracks were initiated at each of the adjacent shear spans. One (or more) diagonal crack, then, appeared in the shear spans followed by a sudden failure by a complete separation across the diagonal shear crack.

For beams failing in flexure, the cracking behavior is the same as that described before for beams failing in flexure, but before the complete formation of the diagonal crack, one (or more) of the middle region cracks propagated and widened faster than the others passing through the compression zone, then longitudinal steel yielded and consequently the beam failed. At failure, most steel fibers in the cracks pull out of the cement matrix rather than snap in all tested beams. Beam MR1-1 (ρ=1.1%, V_f=1%) was failed in flexure because of its low ρ and the presence of steel fibers which prevent shear failure by diagonal crack. Increasing ρ to 1.58% (beam MR2-1) and 2.37% (beam MR3-1) changes this failure mode to shear failure. Also, increasing ρ increases number of flexural cracks and decreases their widths as shown in Figure 12.

Beams MR2-0 (ρ=1.58%, V_f=0%), MR2-1 (ρ=1.58%, V_f=1%) and R2-1 (ρ=1.58%, V_f=1%) were failed in shear, while using V_f = 2% in beams MR2-2 and R2-2 caused them to fail in flexure which reflects the effectiveness of using steel fibers as shear reinforcement. Although using coarse aggregate as partial replacement of fine sand in MRPC beams MR2-1 (failed in flexure) and MR2-2 (failed in shear) did not change the modes of failure of the corresponding RPC beams R2-1 and R2-2, coarse aggregate raised beam stiffness and ultimate loads as mentioned before and shown in Figures 10 and 11.

5- Conclusions

Based on the results obtained in this research, the following conclusions can be drawn:

1. Reactive powder concrete (RPC) can be produced without the limitation of removing all coarse aggregate with comparable mechanical properties and structural behavior in shear and flexure. Furthermore, modified reactive powder concrete (MRPC) beams show higher ultimate loads (4.6% - 11.36%) and stiffer load-deflection behavior than RPC beams.
2. Increasing longitudinal steel ratio (ρ) from 1.1% to 1.58% and 2.37% in MRPC beams increases ultimate load by 28.3% and 117%, respectively, increases initial stiffness of load-deflection curves, increases number of flexural cracks with smaller widths and change the mode of failure from flexural to shear.
3. Increasing steel fibers ratio (V_f) from 0% to 1% and 2% in MRPC beams increases ultimate loads by 58.1% and 127.9%, respectively and increases stiffness (reduces deflections) of load-deflection curves. Similar (but lower values) trend was observed in RPC beams.
4. RPC and MRPC beams can be made without transverse shear reinforcement bars (stirrups) by exploiting the reinforcing ability of steel fibers which prevent shear failure, for example, in beam MR2-2 (ρ=1.58%, V_f=2%) while beam MR2-1 with the same ρ of 1.58% and lower V_f of 1% was failed in shear (all beams were made without stirrups).
5. Most steel fibers were failed across flexural or shear cracks by pulling out rather snap in all tested beams which contributes to the ductility and energy absorption capacity especially in beams failing in flexure.
6. Normal water curing in room temperature without pressure application can be used to produce RPC and MRPC with compressive strength of 121 MPa and 118 MPa, modulus of elasticity of 57.31 GPa and 54.16 GPa, flexural strength of 17.63 MPa and 13.11 MPa, and splitting tensile strength of 12.98 MPa and 13.91 MPa, for RPC and MRPC respectively.
7.

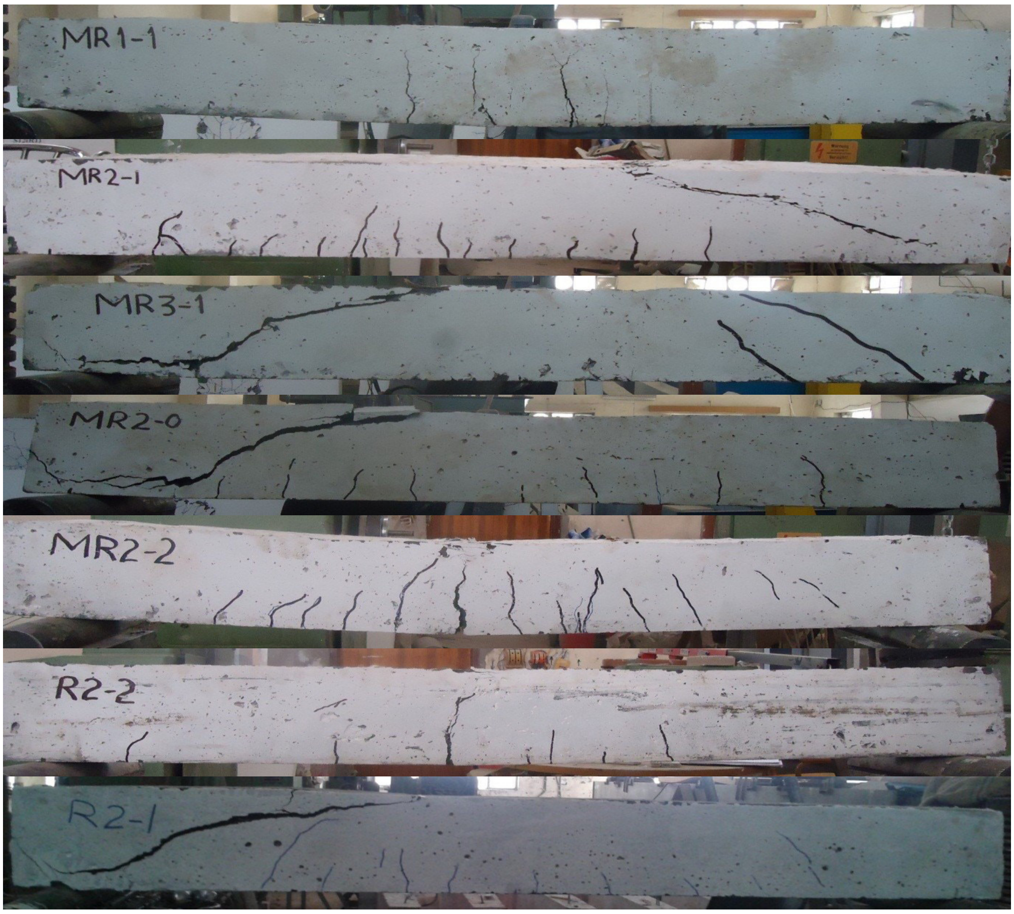

Figure 12. Crack patterns of the tested beams

References

[1] Noshiravani, T. and Bruhwiler, E., Experimental Investigation on Reinforced Ultra-High-Performance Fiber-Reinforced Concrete Composite Beams Subjected to Combined Bending and Shear , ACI Structural Journal, 110(2) (2013) 251-261.

[2] Lai, J., Sun, W., Xu, S. and Yang, C., Dynamic Properties of Reactive Powder Concrete Subjected to Repeated Impacts, ACI Materials Journal, 110(4) (2013) 463-472.

[3] Susetyo, J., Gauvreau, P. and Vecchio, F., Effectiveness of Steel Fiber as Minimum Shear Reinforcement, ACI Structural Journal, 108(4) (2011) 488-496.

[4] Wille, K., Naaman, A.E., and El-Tawil, S., Optimizing Ultra-High-Performance Fiber-Reinforced Concrete, Concrete International, (2011) 35-41.

[5] Voo, Y.L., Nematollahi, B., Said, A.M., Gopal, B.A., and Yee, T. S., "Application of Ultra High Performance Fiber Reinforced Concrete – The Malaysia Perspective", International Journal of Sustainable Construction Engineering and Technology, Vol.3, No.1, 2012, pp.26-44.

[6] Richard, P. and Cheyrezy, M., Composition of Reactive Powder Concrete, Cement and Concrete Research, 25(7) (1995) 1501-1511.

[7] Collepardi, S., Copolla, L., Troli, R. and Collepardi, M., Mechanical Properties of Modified Reactive Powder Concrete, in Proceedings of Fifth CANMET/ACI International Conference on Superplasticizers and Other Chemical Admixtures in Concrete, Rome, Italy, ACI SP-173 (1997) 1-21.

[8] Ma, J., Orgass, M., Dehn, F., Schmidt, D. and Tue, N.V., Comparative Investigation on Ultra-High Performance Concrete with and without Coarse Aggregates, in Proceedings of International Symposium on Ultra High Performance Concrete, 2004, Kassel, Germany, 205-212.

[9] Wille, K., Naaman, A. E., and Montesinos, G. J., Ultra-High Performance Concrete with Compressive strength Exceeding 150 MPa (22 ksi): A simple Way, ACI Materials Journal, 108(1) (2011) 46-54.

[10] Ashour, S., Hasanain, G. and Wafa, F., Shear Behavior of High-Strength Fiber Reinforced Concrete Beams, ACI Structural Journal, 89(2) (1992) 176-184.

[11] Kwak, Y., Eberhard, P., Kim, W. and Kim, J., Shear Strength of Steel Fiber-Reinforced Concrete Beams

without Stirrups, ACI Structural Journal, 99(4) (2002) 530-538.

[12] Minelli, F. and Vecchio, F., Compression Field Modeling of Fiber Reinforced Concrete Members under Shear Loading, ACI Structural Journal, 103(2) (2006) 244-252.

[13] Voo, Y.L., Foster, S.J. and Gilbert, R.I., Shear Strength of Fiber Reinforced Reactive Powder Concrete Prestressed Girders without Stirrups, Journal of Advanced Concrete Technology, 4(1) (2006) 123-132.

[14] Ridha, M.M.S., Shear Behavior of Reactive Powder Concrete Beams, Ph.D. Thesis, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq, (2010) 204.

Please cite this article using:

M. H. Mohammed, Shear Behavior of Reactive Powder Concrete Beams with and without Coarse Aggregate, *AUT J. Civil Eng*, 2(1) (2018) 87-96.

DOI: 10.22060/ceej.2017.12210.5145