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Flexural Strength of Hybrid Beams Containing Reactive Powder Concrete and Conventional Concrete

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Abstract

This paper presents an experimental investigation consisting of casting and testing in flexure twenty four rectangular simply supported reinforced concrete beams.Three of the tested beams are made with conventional concrete (CC), five with reactive powder concrete (RPC) and sixteen as hybrid beams of the two concretes. RPC is used in tension in ten hybrid beams and in compression in the other six beams. Experimental results have generally shown that higher ultimate loads (P_u) are obtained with the increase of RPC layer thickness (h_R/h), steel fibers volumetric ratio (V_f) and longitudinal steel ratio (ρ) for hybrid beams with RPC in tension as well as in compression. However, the effect of (ρ) is more pronounced than the other factors. Using RPC in compression is found to be more effective than using RPC in tension. The increasing ratios for ultimate loads of hybrid beams with RPC in compression, ρ=3.36% and V_f= 1% (compared to CC beams) are 47.13% and 71.97% for (h_R/h) of 0.25 and 0.5, respectively. These ratios are higher than those for hybrid beams with RPC in tension, ρ=3.36% and V_f= 1%, for h_R/h of 0.25 and 0.5 by 35.67% and 37.58%, respectively.

Key Words: Reactive Powder Concrete, flexural strength, hybrid beams.

مقاومة الانثناء للعتبات الهجينة المتكونة من خرسانة المساحيق الفعالة و الخرسانة التقليدية

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الخلاصة

يقدم هذا البحث تحريا مختبريا يتضمن الصب و الفحص (تحت الانثناء) لأربع و عشرين عتبة خرسانية مسلحة مستطيلة المقطع و بسيطة الاسناد. ثلاث عتبات كانت مصنعة من الخرسانة التقليدية و خمس من خرسانة المساحيق الفعالة و ست عشرة كعتبات هجينة من الخرسانتين. استخدمت خرسانة المساحيق الفعالة في منطقة الشد في عشر عتبات هجينة و في منطقة الانضغاط في الست الاخريات. اظهرت النتائج المختبرية عموماً انه بالامكان الحصول على

احمال قصوى اعلى عند زيادة كل من سمك طبقة خرسانة المساحيق الفعالة ، نسبة الياف الحديد و نسبة الحديد الطولي للعتبات الهجينة ذات خرسانة المساحيق الفعالة في منطقة الشد كما في منطقة الانضغاط. وجد ان استخدام خرسانة المساحيق الفعالة في منطقة الانضغاط يؤثر اكثر من استخدامها في منطقة الشد. ان نسب الزيادة للاحمال القصوى للعتبات الهجينة ذات خرسانة المساحيق الفعالة في منطقة الانضغاط، $\rho=3.36$ % و $V_f=1$ % (مقارنة مع العتبات ذات الخرسانة التقليدية)، كانت 47.13 % و 71.97 % لقيم h_R/h المساوية لـ 0.25 و 0.5 على التوالي. هذه النسب اعلى من تلك الخاصة بالعتبات الهحينة ذات خرسانة المساحيق الفعالة في منطقة الشد ، $\rho=3.36$ % و $V_f=1$ %، لقيم h_R/h المساوية لـ 0.25 و 0.5 بمقدار 35.67 % و 37.58 % على التوالي.

الكلمات المرشدة: خرسانة المساحيق الفعالة،مقاومة الانثناء،العتبات الهجينة.

1. Introduction

Reactive powder concrete (RPC), which is now more generally described as ultra-high performance concrete (UHPC) [1], has attracted the attention of researchers and practitioners since its introduction in the 1990s, not only because of its high compressive strength but also because of its excellent environmental resistance (durability). The addition of fibers to UHPC further improves tensile cracking resistance, post cracking strength, ductility and energy absorption capacity [2].

RPC is a cement based composite material formulated by combining cement, silica fume, fine sand, high range water reducer, water and steel or organic fibers. It is a special concrete in which the microstructure is optimized by precise gradation of all particles to yield maximum density [3,4,5].

RPC mixes are characterized by high silica fume content and very low water-cement ratio. Coarse aggregate is eliminated to avoid weaknesses of the microstructure and heat treatment is applied to achieve high strength [6,7]. RPC is composed of particles of similar moduli and size which helps in increasing the homogeneity thereby reducing the differential tensile strain in the concrete and consequently increasing the ultimate load carrying capacity of RPC [4].

Owing to the fineness of silica fume and the increased quantity of hydraulically active components, it has been called reactive powder concrete [8].

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[9].

RPC was first developed by *Richard and Cheyrezy (1995)*[6] in the early 1990s. They reported achieving compressive strength in the range 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.

Wille et al. (2011) [1] developed an UHPC of 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.
5. Add fibers, if applicable, and mix for an additional 2 minutes.

It should be mentioned, here, that nearly all local researches on RPC used heat curing (with or without presetting pressure) to develop the desired mechanical properties. Based on the information obtained from previous works, the present study is the first local study (with other simultaneously and independently performed studies at the University of Mustansiriya / College of Engineering) to produce RPC of compressive strength more than 120 MPa using 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. Use of RPC in Hybrid Elements

Design criteria of hybrid elements is based on the concept that the use of the materials of improved performance (such as HSC, HPC and UHPC), which are relatively expensive materials, should be limited to parts in the structure subjected to severe environmental conditions and/or when stiffness or resistance of the structural element must be increased without increasing the dead weight or at points of concentrated load application, while other parts of the structure consist of conventional concrete[10].

Denarie et al. (2003)[11] tested a composite UHPFRC and conventional reinforced concrete (RC) beams to ultimate flexural strength. These composite beams comprised of an UHPFRC overlay to replace the standard tensile reinforcing bars in a RC beam and exhibited an ultimate force comparable to the standard RC beams.

Alaee and Karihaloo (2003) [12] used UHPFRC as bonded strips applied to the tensile face to rehabilitate and improve existing reinforced concrete beams. The rehabilitated composite beams behaved monolithically until fracture with ultimate force equal to or higher than the reference concrete member, but experienced a softening phase after reaching the ultimate force.

Habel et al. (2007) [13] investigated the flexural behavior of composite beams. The beams composed of RC substrates and UHPFRC layers in the tension face as shown in **Figure (1).** They concluded that applying UHPFRC layer to form a composite beam increases stiffness, minimizes deformations for given imposed loads, reduces crack widths and crack spacing and delays the formation of localized macrocracks as compared to the original conventionally reinforced concrete beams. They found also that the composite beams behaved monolithically and debonding only occurred near the ultimate load for beams without reinforcing bars in UHPFRC layer whereas the presence of such bars in UHPFRC prevents debonding.

Raj and Jeenu (2010)[3] investigated the flexural behavior of composite beams whose top (compression) layers were made of UHPC of compressive strength greater than 80 MPa and the lower (tension) layers are of 25 MPa compressive strength normal concrete. They concluded that the ultimate load of composite beams with 5 cm and 10 cm UHPC layer (beam overall depth is 20 cm) increases by 38% and 62% respectively compared to normal strength concrete beams. Energy absorption was also increased using composite beams.

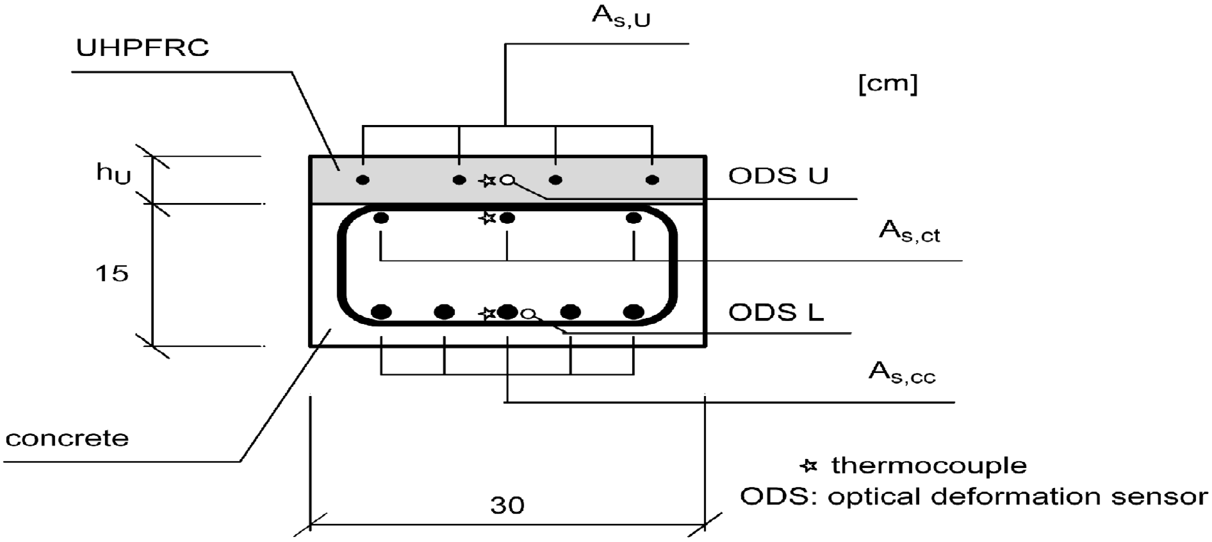

Fig .(1) Cross-section of the composite “UHPFRC-concrete” beams[13]

3. Experimental Work

The experimental work of this study consists of casting and testing in flexure twenty four rectangular simply supported reinforced concrete beams. Three of these beams are made with conventional concrete (CC), five with reactive powder concrete (RPC) and sixteen as hybrid beams of the two concretes. RPC is used in tension in ten hybrid beams and in compression in the other six beams. Details of all experimental work stages are presented in the following .

3.1 Materials

3.1.1 Cement

Ordinary Portland cement (type I) manufactured by the United Cement Company (UCC) in Iraq was used throughout the experimental work of this study for both CC and RPC. This cement conforms to the *Iraqi Standard Specification No.5/1984*[14] and its chemical analysis and physical properties are shown in **Tables (1) and (2),** respectively.

3.1.2 Fine Aggregate

Natural sand was used for CC mixes while fine sand with maximum particle size of 600µm was used for RPC mixes. The gradings of the used natural and fine sand conform to the *Iraqi Standard specification No. 45/1984* [15] as shown in **Table (3).**

Table .(1) Chemical Analysis of Cement*

Compound Composition	Chemical Composition	Percent by weight	Iraqi specification No. 5/1984
Lime	CaO	61.19	-
Silica	SiO_2	21.44	-
Alumina	Al_2O_3	4.51	-
Iron Oxide	Fe_2O_3	3.68	-
Magnesia	MgO	2.31	Maximum 5
Sulfate	SO_3	2.7	Maximum 2.8
Loss on ignition	L.O.I	2.39	Maximum 4.0
Insoluble residue	I.R	1.18	Maximum 1.5
Lime saturation factor	L.S.F	0.87	0.66-1.02
Tricalcium aluminates	C_3A	6.06	-

*All tests were made at the National Center for Construction Laboratories and Research.

Table .(2) Physical Properties of Cement*

Physical Properties	*Test Results*	*Iraqi specification No. 5/1984*
Fineness using Blaine air permeability apparatus(cm^2/gm)	4050	Minimum 2300
Soundness using autoclave method	Not available	Minimum 0.8%
Setting time using Vicat's instruments Initial (min.) Final (hr)	135 3:25	Maximum 45 Minimum 10
Compressive strength for cement Paste Cube(70.7mm) at: 3days (MPa) 7days (MPa) 28days (MPa)	24.4 32.3 47.2	Minimum 15 Minimum 23

*All tests were made at the National Center for Construction Laboratories and Research.

Table .(3) Grading of Fine Aggregate*

Sieve size (mm)	Natural sand (for CC)		Fine sand (for RPC)	
	Cumulative passing %	Limits of Iraqi specification No.45/1984 for zone 2	Cumulative passing %	Limits of Iraqi specification No.45/1984 for zone 4
10	100	100	100	100
4.75	95	90-100	100	95-100
2.36	81	75-100	100	95-100
1.18	69	55-90	100	90-100
0.600	50	35-59	88	80-100
0.300	19	8-30	20	15-50
0.150	3	0-10	5	0-15

*The test was performed in the constructural Materials Laboratory of College of Engineering /Al-Mustansiriya University.

3.1.3 Coarse Aggregate

Crushed river gravel with maximum particle size of 10mm was used as coarse aggregate for CC mixes only. RPC in this study was made without coarse aggregate to improve its homogeneity. The grading of the used coarse aggregate conforms to the *Iraqi Standard specification No. 45/1984* [15] as shown in **Table (4).**

Table .(4) Grading of Coarse Aggregate*

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No.45/1984 for size 10 mm
14	100	100
10	94	85-100
5	16	0-25
2.36	0	0-5

*The test was performed in the constructural Materials Laboratory of College of Engineering /Al-Mustansiriya University.

3.1.4 Silica Fume

A grey colored densified silica fume was used as an admixture in RPC mixes to enhance its properties. The fineness of the used silica fume is 200 000 m^2/kg and its chemical composition is given in **Table (5).**

Table .(5) Chemical Analysis of Silica Fume*

Chemical Composition	Percent %
SiO_2	98.87
Al_2O_3	0.01
Fe_2O_3	0.01
CaO	0.23
MgO	0.01
K_2O	0.08
Na_2O	0.00

*According to manufacturer editions.

3.1.5 Superplasticizer

A superplasticizer commercially named Sika Visco Crete PC-20 was used as an admixture to produce RPC in this study. Some properties of this superplasticizer are given in **Table (6).**

3.1.6 Steel Fibers

Hooked end steel fibers with aspect ratio (L/d) of 80 were used in RPC mixes. Sample of the used steel fibers is shown in **Figure (2)** and their properties are listed in **Table (7).**

Table .(6) Properties of Sika Visco Crete PC-20*

Main action	Concrete superplasticizer
Appearance/Colures	Light brownish liquid
Chemical base	Modified polycarboxylates based polymer
Density	1.09 kg/l, at 20 °C
PH	7
Chloride ion content%	Free
Effect on setting	Non-retarding
Storage life	12 months from date of productionif stored properly in original, at temperatures between +5°C and +35°C. Protect from direct sunlight and frost.

*According to manufacturer editions.

Table .(7) Properties of the used steel fibers*

Type of steel	Hooked
Relative Density	7860 kg/m^3
Yield strength	1130 MPa
Modulus of Elasticity	200 000 MPa
Strain at proportion limit	5650*10^{-6}
Poisson's ratio	0.28
Average length (L)	30 mm
Nominal diameter (d)	0.375
Aspect Ratio(L/d)	80

*According to manufacturer editions.

Fig .(2) Sample of the used steel fibers

3.1.7 Steel Reinforcement

Deformed steel bars with three nominal diameters of 12, 16 and 20mm were used as beams flexural main reinforcing bars in tension, while the 8mm diameter deformed steel bars were used as shear reinforcement (stirrups). **Table (8)** gives the tensile test results performed on samples of the used steel bars.

Table .(8) Tensile test results of steel bars*

Nominal diameter (mm)	**Measured diameter (mm)**	**Yield stress, f_y (MPa)**	**Ultimate strength, f_u (MPa)**
8	8.03	428	537
12	12.09	532	715
16	16.18	528	707
20	20.16	521	695

*The tests were performed in the constructural Materials Laboratory of College of Engineering /Al-Mustansiriya University.

3.1.8 Water

Tap water was used for mixing of both CC and RPC mixes and curing of all specimens.

3.2 Mix Proportions

Table (9) gives mix proportions of CC and RPC mixes used in different beams. Based on several trial mixes, one CC mix and three RPC mixes that differ from each other only in volumetric steel fibers ratio (V_f) were adopted in this study.

Table .(9) Mix proportions of CC and RPC

Concrete Type	CC	RPC		
Cement (C) (kg/m^3)	400	900		
Sand (S) (kg/m^3)	600	900		
Gravel (G) (kg/m^3)	1200	-		
Silica Fume (SF) (kg/m^3)	-	225*		
Super-plasticizer (SP) (kg/m^3)	-	56.25**		
Water (W) (kg/m^3)	200	180		
W/C	0.5	0.2***		
Steel Fibers (kg/m^3)	-	0	78	156
V_f (%)	-	0	1	2

*SF/C = 25%

**SP/(C+SF) = 5%

***W/(C+SF) = 0.16

RPC mixes are characterized by the high cement content and the use of steel fibers to improve tensile properties of RPC, and admixtures such as silica fume to increase strength and superplasticizer to enhance RPC workability.

3.3 Mixing and Casting

Wooden molds were used for beams with inner dimensions of 110mm in width, 200mm in depth and 1500mm 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 of 0.19m^3 capacity. CC was mixed in a classical procedure where gravel and sand were mixed first for 2 minutes then cement was added and the dry components were mixed for about 3 minutes to obtain a homogeneous dry mix, then water was added during the mixing process which continued for another 3 minutes or until obtaining a homogeneous mixture.

Mixing procedure proposed by *Wille et al. (2011)* [1] was adopted in this study to produce RPC in a simple way without any accelerated curing regimes. Fine sand 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 of RPC was about 15 minutes.

Casting of CC and RPC 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.

For hybrid beams (two layers beams), bottom layer which may be CC or RPC was mixed and placed first, then the top layer (RPC or CC) was mixed and placed above the first one. The time period between the placing of the two layers was about 30 minutes where the top surface of the bottom layer was left rough to ensure good interaction between the two layers.

With each mix control specimens were prepared to determine the mechanical properties of concrete. Control specimens involve 3 cylinders (100mm×200 mm) for compressive strength, 3 cylinders (100mm×200mm) for splitting tensile strength, 3 cylinders (150mm×300mm) for modulus of elasticity and 3 prisms (100mm×100mm×500mm) 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. This normal curing method was applied for CC as well as for RPC.

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 [1] as part of their proposed simpler way to produce RPC and the mixing procedure used in this study was the main part of their proposal.

Specimens were taken out of containers after 28 days of water curing and kept in the laboratory until testing.

3.5 Details and Designation of Beams

Twenty four beams of dimensions (110mm×200mm×1500mm) were cast and tested in flexure in this study. Three of these beams are made with CC, five with RPC and sixteen as hybrid beams of two layers with different thicknesses. RPC was used in tension in ten hybrid beams and in compression in the other six. Four thicknesses for RPC layer (h_R =0, 5cm, 10 and 20cm), three volumetric steel ratios (V_f =0%, 1% and 2%) and three longitudinal reinforcement ratios (ρ= 1.21%, 2.15% and 3.36%) were used in the tested beams. Shear reinforcement (stirrups) were kept constant in all beams with sufficient quantity (8mm stirrups at 50mm spacing) to ensure that all beams will fail in flexure as shown in **Figure (3).**

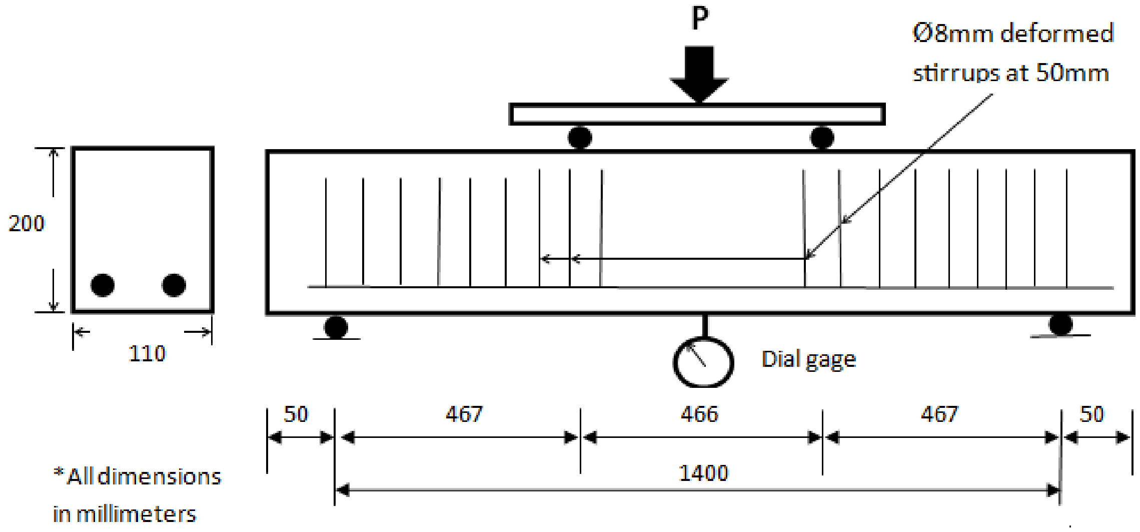

Fig .(3) Details and setup of the tested beams

To designate the tested beams accurately and briefly taking into account the main variables mentioned above, the following general form was used:

(Letter) (1st No.) – (2nd No.)

Definitions of designation symbols are given in Table (10). "Asterisk" mark (*) was used with the 1st No. (and h_R/h value) to indicate that RPC was in compression as shown in **Figure (4).**

Table .(10) Definition of beams designation symbols

Letter	Corresponding Value		1st No.	Corresponding Value		2nd No.	Corresponding Value
	ρ (%)	A_s		h_R (cm)	h_R/h		V_f (% of RPC)
A	1.21	2Ø12	1	0	0	0	0
			2	5	0.25		
B	2.15	2Ø16				1	1
			3	10	0.5		
C	3.36	2Ø20				2	2
			4	20	1		

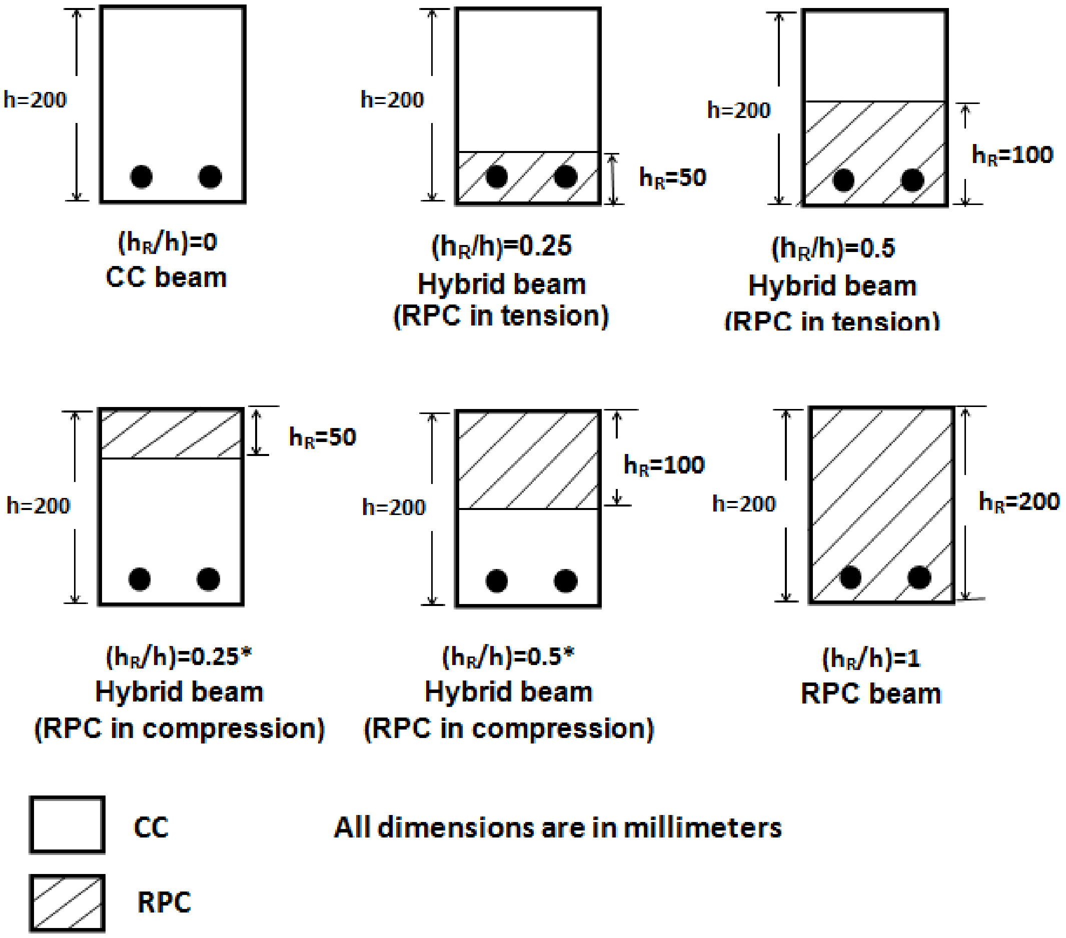

Fig .(4) Types of the tested beams

However, details of all 24 beams are presented in **Table (11).**

Table .(11) Details of the tested beams

Beams	**A_s**	**ρ (%)**	**h_R (cm)**	**h_R/h**	**V_f (% of RPC)**	**Type of beam**
A1	2Ø12	1.21	0	0	-	CC beam
A2-0	2Ø12	1.21	5	0.25	0	Hybrid beam (RPC in tension)
A3-0	2Ø12	1.21	10	0.5	0	Hybrid beam (RPC in tension)
A4-0	2Ø12	1.21	20	1	0	RPC beam
A2-1	2Ø12	1.21	5	0.25	1	Hybrid beam (RPC in tension)
A3-1	2Ø12	1.21	10	0.5	1	Hybrid beam (RPC in tension)
A4-1	2Ø12	1.21	20	1	1	RPC beam
A2-2	2Ø12	1.21	5	0.25	2	Hybrid beam (RPC in tension)
A3-2	2Ø12	1.21	10	0.5	2	Hybrid beam (RPC in tension)
A4-2	2Ø12	1.21	20	1	2	RPC beam
B1	2Ø16	2.15	0	0	-	CC beam
B2-1	2Ø16	2.15	5	0.25	1	Hybrid beam (RPC in tension)
B3-1	2Ø16	2.15	10	0.5	1	Hybrid beam (RPC in tension)
B4-1	2Ø16	2.15	20	1	1	RPC beam
C1	2Ø20	3.36	0	0	-	CC beam
C2-1	2Ø20	3.36	5	0.25	1	Hybrid beam (RPC in tension)
C3-1	2Ø20	3.36	10	0.5	1	Hybrid beam (RPC in tension)
C4-1	2Ø20	3.36	20	1	1	RPC beam
A2*-0	2Ø12	1.21	5	0.25*	0	Hybrid beam (RPC in compression)
B2*-0	2Ø16	2.15	5	0.25*	0	Hybrid beam (RPC in compression)
C2*-0	2Ø20	3.36	5	0.25*	0	Hybrid beam (RPC in compression)
C3*-0	2Ø20	3.36	10	0.5*	0	Hybrid beam (RPC in compression)
C2*-1	2Ø20	3.36	5	0.25*	1	Hybrid beam (RPC in compression)
C3*-1	2Ø20	3.36	10	0.5*	1	Hybrid beam (RPC in compression)

3.6 Testing of Control Specimens

3.6.1 Compressive Strength Test

The compressive strength test was performed according to *ASTM C 39/C39M-01*[16] on 100mm×200mm cylinders for both CC and RPC using a compression machine of 2000 kN capacity as shown in **Figure (5).** Average of three specimens was used to determine the compressive strength for CC as well as RPC mixes.

Fig .(5) Compressive strength test

Fig .(6) Modulus of elasticity test

3.6.2 Modulus of Elasticity Test

The modulus of elasticity test was performed according to *ASTM C469-02*[17] on cylinders of 150mm×300mm for both CC and RPC loaded uniaxially by a universal testing machine of 3000kN capacity with the strain-measuring equipment attached to the cylinder as shown in **Figure (6).**

Modulus of elasticity for each specimen was calculated as follows:

$$\mathbf{E_c} = \frac{S_2 - S_1}{\epsilon_2 - 0.000050} \qquad \text{………..…… (1)}$$

Where:
E_c= chord modulus of elasticity, MPa.
S_2= stress corresponding to 40% of ultimate load, MPa.
S_1= stress corresponding to a longitudinal strain, Є1, of 50 millionths, MPa.
ϵ_2= longitudinal strain produced by stress S2.

3.6.3 Flexural Strength Test

The flexural strength (modulus of rupture) test was performed according to *ASTM C 293-02*[18] on prismatic specimens of 100mm×100mm×500mm for both CC and RPC with center-point loading using a hydraulic testing machine (ELE) of 50 kN capacity as shown in **Figure (7).**

Flexural strength of each specimen was calculated as follows:

$$f_r = \frac{3PL}{2bh^2} \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

Fig .(7) Flexural strength test

Fig .(8) Splitting tensile strength test

where:

f_r = flexural strength (modulus of rupture), MPa.

P= applied load at failure, N.

L= span length, mm.

b= width of specimens, mm.

h= depth of specimens, mm.

Average of three specimens was used to determine the flexural strength for CC as well as RPC mixes.

3.6.4 Splitting Tensile Strength Test

The splitting tensile strength test was performed according to *ASTM C496/C496M-04*[19] on 100mm×200mm cylinders for both CC and RPC using a testing machine of 2000 kN capacity as shown in **Figure (8).**

Splitting tensile strength for each specimen was calculated as follows:

$$f_s = \frac{2P}{\pi DL} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where:

f_s= splitting tensile strength,MPa.

P= applied load at failure, N.

D= diameter of cylinder specimen, mm.

L= length of cylinder specimen, mm

Average of three specimens was used to determine the splitting tensile strength for CC as well as RPC mixes.

3.7 Testing of Beams in Flexure

All beams were tested as simply supported beams over a span of 1400mm under two point loads using a universal testing machine of 3000kN capacity, **Figures (9) and (10).**

The load was applied gradually in small increments up to failure. First crack load was recorded as the load at which the first visible crack was detected.

Fig .(9) Flexure testing machine

Fig .(10) One of the beams under testing

4. Results and Discussions

4.1 Mechanical Properties of CC and RPC

Tests results of mechanical properties (compressive strength, modulus of elasticity, flexural strength and splitting tensile strength) of CC and RPC are shown in **Table (12)** and **Figures (11) to (14).**

For CC, compressive strength, modulus of elasticity, flexural strength and splitting tensile strength were 30.56MPa, 24.88GPa, 3.91MPa and 3.32MPa, respectively.

For RPC, compressive strength, modulus of elasticity, flexural strength and splitting tensile strength reach 121.25MPa, 57.31GPa, 17.63MPa and 12.98MPa, respectively. These values were obtained without using any accelerated curing regime as mentioned before.

Results show that when steel fibers ratio increases from 0% to 2%, compressive strength, modulus of elasticity, flexural strength and splitting tensile strength increase by 46.57%, 52.09%, 213.7% and 128.12%, respectively.

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.

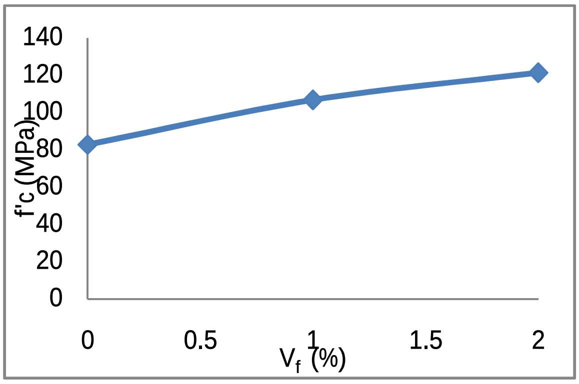

Fig.(11) Effect of steel fibers ratio on compressive strength of RPC.

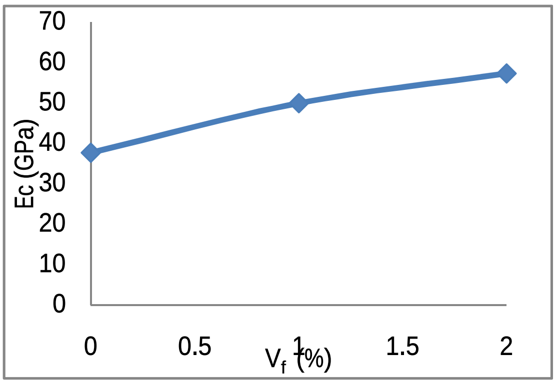

Fig .(12) Effect of steel fibers ratio on modulus of elasticity of RPC.

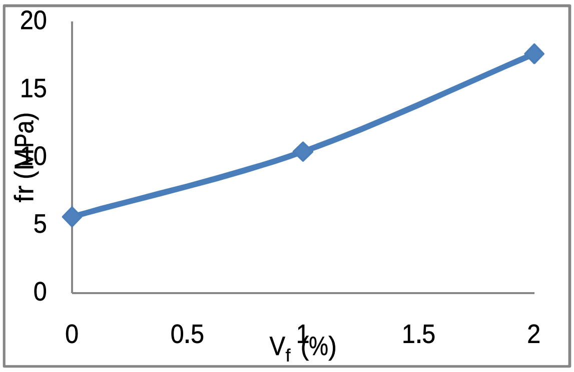

Fig .(13) Effect of steel fibers ratio on flexural strength of RPC.

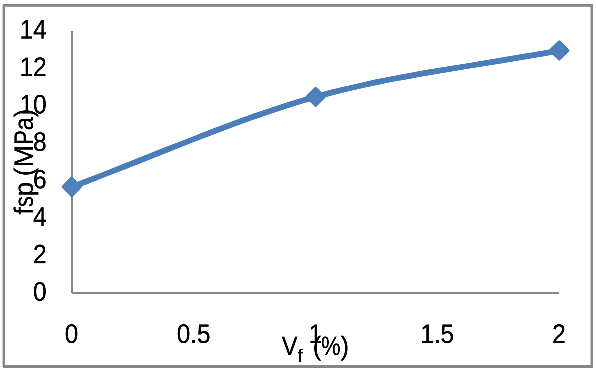

Fig .(14) Effect of steel fibers ratio on splitting tensile strength of RPC.

Table .(12) Mechanical properties of CC and RPC.

Type of Concrete	Steel Fibers Ratio (V_f) (%)		Cylinder Compressive Strength (MPa)	Modulus of Elasticity (GPa)	Flexural Strength (MPa)	Splitting Tensile Strength (MPa)
CC	-	Test result	30.56	24.88	3.91	3.32
RPC	0	Test result	82.72	37.68	5.62	5.69
		Increasing ratio (%)	0	0	0	0
	1	Test result	105.7	49.95	10.44	10.5
		Increasing ratio (%)	28.98	32.56	85.76	84.53
	2	Test result	121.25	57.31	17.63	12.98
		Increasing ratio (%)	46.57	52.09	213.7	128.12

4.2 Ultimate Loads of the Tested Beams

The ultimate loads results of the tested beams are listed in **Table (13).** The results generally show that the ultimate loads (P_u) increase with the increase of RPC layer thickness expressed as the ratio of RPC layer thickness to the beam depth (h_R/h), steel fibers volumetric ratio (V_f) and longitudinal steel ratio (ρ). Hybrid beams with RPC in compression show generally higher ultimate loads than those of hybrid beams with RPC in tension. However, the effect of (ρ) is more pronounced than that of the other factors. Detailed discussions of the ultimate loads results are given in the following sections.

4.2.1 Hybrid beams with RPC in tension

4.2.1.1 Effect of RPC layer thickness

Tests results show that the increase in RPC layer thickness increases ultimate loads as shown in **Table (13) and Figure (15).**

The ultimate loads for under-reinforced beams (ρ=1.21%) were 20.98%, 29.62% and 38.27% higher than those of reference CC beam (beam A1) for h_R/h of 0.25, 0.5 and 1 (RPC beam), respectively.

Table .(13) Ultimate loads of the tested beams

Beam	ρ (%)	V_f (% of RPC)	h_R/h	P_u (kN)
A1	1.21	_	0	81
A2*-0	1.21	0	0.25*	93
A2-0	1.21	0	0.25	88
A3-0	1.21	0	0.5	90
A4-0	1.21	0	1	102
A2-1	1.21	1	0.25	98
A3-1	1.21	1	0.5	105
A4-1	1.21	1	1	112
A2-2	1.21	2	0.25	108
A3-2	1.21	2	0.5	113
A4-2	1.21	2	1	118
B1	2.15	_	0	111
B2*-0	2.15	0	0.25*	185
B2-1	2.15	1	0.25	115
B3-1	2.15	1	0.5	148
B4-1	2.15	1	1	198
C1	3.36	_	0	157
C2*-0	3.36	0	0.25*	196
C2*-1	3.36	1	0.25*	231
C2-1	3.36	1	0.25	175
C3*-0	3.36	0	0.5*	215
C3*-1	3.36	1	0.5*	270
C3-1	3.36	1	0.5	211
C4-1	3.36	1	1	277

*RPC in compression

For higher ρ, ultimate loads were 3.6%, 33.33% and 78.37% higher than those for reference CC beam (beam B1, ρ=2.15%) and 11.46%, 34.4% and 76.43% higher than those for reference CC beam (beam C1, ρ=3.36%) for (h_R/h) of 0.25, 0.5 and 1, respectively.

The above values indicate that the effect of h_R/h is greater for higher ρ than that for lower ρ for h_R/h values of 0.5 and 1. This behavior may be attributed to the combined contribution of higher ρ and greater (h_R/h) in increasing the beams stiffness which allows such beams to sustain higher loads before failure that are characterized by crushing in concrete in compression zone, which is not the case in under reinforced beams which failed by yielding of steel in the tension zone.

Table .(14) Effect of RPC layer thickness (h_R/h) on ultimate loads of beams with RPC in tension*.

Beam	ρ (%)	h_R/h	P_u (kN)	$P_u/P_{u\,(CC)}$ (%)
A1	1.21	0	81	100
A2-1		0.25	98	120.98
A3-1		0.5	105	129.62
A4-1		1	112	138.27
B1	2.15	0	111	100
B2-1		0.25	115	103.6
B3-1		0.5	148	133.33
B4-1		1	198	178.37
C1	3.36	0	157	100
C2-1		0.25	175	111.46
C3-1		0.5	211	134.4
C4-1		1	277	176.43

*V_f=1% of RPC in all beams

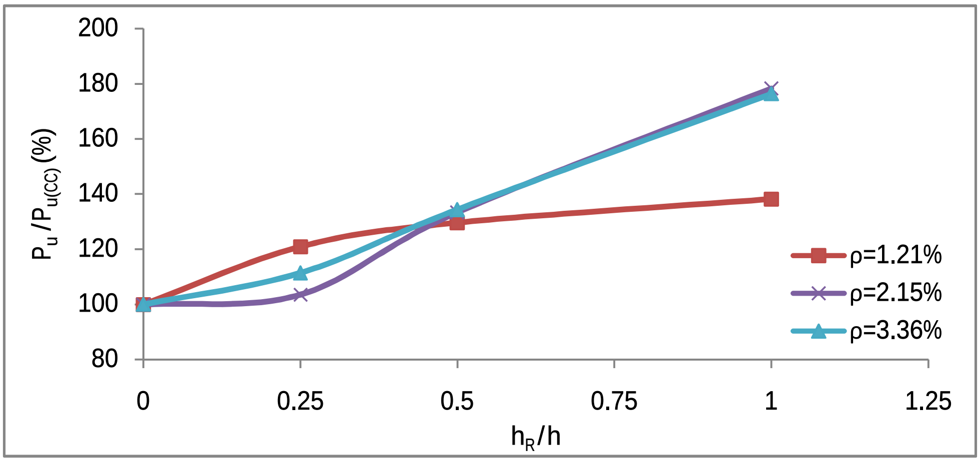

Fig .(15) Effect of RPC layer thickness on ultimate loads of beams with RPC in tension (V_f=1%).

4.2.1.2 Effect of Steel Fibers Volumetric Ratio (V_f)

Table (15) and Figure (16) show the effect of steel fibers volume ratio (V_f) on ultimate loads (P_u) of the tested beams. Results show that ultimate loads increase as (V_f) increases from 0% to 2% for hybrid and RPC beams.

When (V_f) increases from 0% to 2%, the maximum increase in (P_u) reaches 22.72%, 25.55% and 15.68% for hybrid beams with h_R/h of 0.25,0.5 and 1 (RPC beam), respectively.

The above results indicate that the effect of (V_f)on increasing (P_u) (within the range of (V_f) used) is still in a secondary importance (maximum increase of 25.55% for hybrid beams) as compared to the effect of h_R/h as shown previously and the effect of longitudinal steel ratio ρ as will be seen in the next section. This lesser effect of steel fibers on flexural strength of reinforced concrete members assures that the main aim of using steel fibers in reinforced concrete is to improve ductility and toughness properties.

Table (15) Effect of steel fibers ratio (V_f) on ultimate loads of beams with RPC in tension*.

Beam	h_R/h	V_f(%)	P_u (kN)	$P_u/P_{u\,(V_{f=0\%})}$ %
A2-0	0.25	0	88	100
A2-1		1	98	111.36
A2-2		2	108	122.72
A3-0	0.5	0	90	100
A3-1		1	105	116.66
A3-2		2	113	125.55
A4-0	1	0	102	100
A4-1		1	112	109.8
A4-2		2	118	115.68

***** ρ=1.21% for all beams.

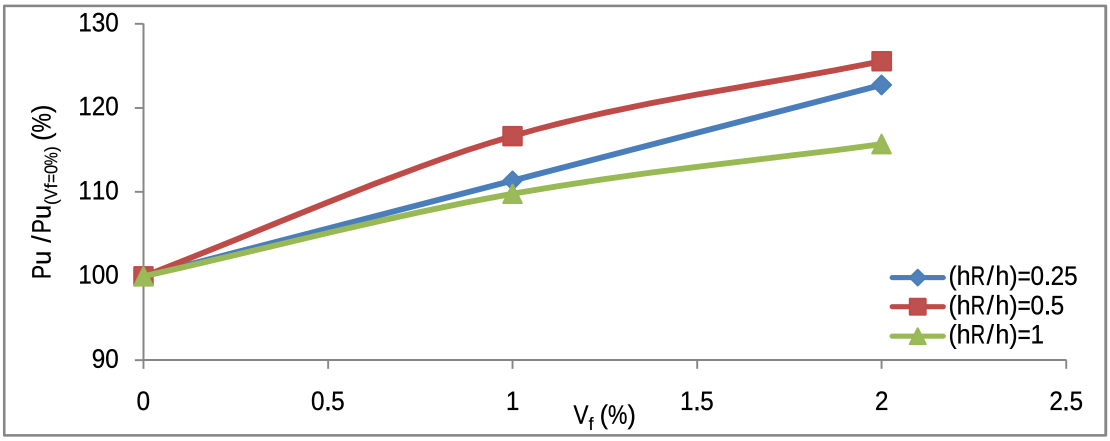

Fig .(16) Effect of steel fibers ratio on ultimate loads of beams with RPC in tension(ρ=1.21%).

4.2.1.3 Effect of Longitudinal Steel Ratio (ρ)

The effect of longitudinal steel ratio (ρ) on ultimate loads of the tested beams is shown in **Figure (17) and Table (16).** Unlike the other two factors (RPC layer thickness and steel fibers ratio), longitudinal steel has the greatest effect on ultimate loads. Results show that when (ρ) increases from 1.21% to 3.36%, the ultimate load increases by 78.57%, 100.95%

and 147.32% for (h_R/h) equal to 0.25, 0.5and 1, respectively. These results clearly indicate that the increases in (P_u) become larger when (h_R/h) increases.

These results give an important guide to the improvement of CC beams using RPC layer, where this process should take longitudinal steel ratio into account as the major parameter. Similar conclusion was reached by Habel et al.[13]. This important conclusion can be illustrated when comparing the increase in (P_u) of beams A4-2 and C1 considering the CC beam A1 as a reference. Beam A4-2, which is a RPC beam (h_R/h=1) with 2% steel fibers and (ρ) equal to 1.21% (same as ρ of beam A1), achieves an increase in (P_u) of 45.67%, while the increase in (P_u) of beam C1, which is a CC beam (h_R/h=0 and no steel fibers used) with (ρ) of 3.36%, reaches 93.82%.

Table .(16) Effect of longitudinal steel ratio (ρ) on ultimate loads of beams with RPC in tension*.

Beam	h_R/h	ρ (%)	P_u (kN)	$P_u/P_{u\,(\rho=1.21\%)}$ (%)
A2-1	0.25	1.21	98	100
B2-1		2.15	115	117.34
C2-1		3.36	175	178.57
A3-1	0.5	1.21	105	100
B3-1		2.15	148	140.95
C3-1		3.36	211	200.95
A4-1	1	1.21	112	100
B4-1		2.15	198	176.78
C4-1		3.36	277	247.32

*V_f=1% of RPC in all beams.

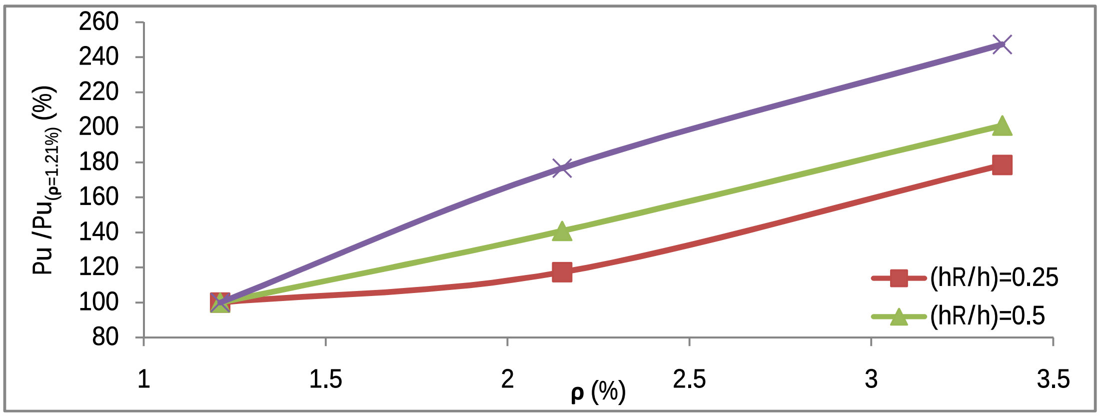

Fig .(17) Effect of longitudinal steel ratio on ultimate loads of beams with RPC in tension(V_f=1%).

4.2.2 Hybrid Beams with RPC in Compression

4.2.2.1 Effect of RPC layer thickness

Ultimate loads of beams with RPC in compression increase with the increase in h_R/h as shown in **Table (17) and Figure (18).** The increasing ratios for ultimate loads of such beams (compared to CC beams) are 47.13% and 71.97% for (h_R/h) of 0.25* (beam C2*-1) and 0.5*(beam C3*-1), respectively. These ratios are clearly higher than those for hybrid beams with RPC in tension (11.46% and 34.39% for (h_R/h) of 0.25 (beam C2-1) and 0.5 (beam C3-1) respectively, (**Table 17).**

The increasing ratios of hybrid beams A2*-0 (ρ=1.21%), B2*-0 (ρ=2.25%) and C2*-0 (ρ=3.36%) are 14.81%, 66.66% and 24.84% compared to CC beams A1, B1 and C1, respectively (**Table 17).**

All above results indicate that using RPC in compression is more effective than using RPC in tension. This is especially true in over reinforced beams (ρ=2.25% and ρ=3.36%) which failed by crushing of RPC in the compression zone. In contrast, under reinforced beam A2*-0 records an increasing ratio of only 6.17% greater than the ultimate load of beam A2-0 (both beams failed by yielding of tension steel).

Table (17) Effect of RPC layer thickness (h_R/h) on ultimate loads of beams with RPC in compression.

Beam	ρ (%)	V_f (% of RPC)	h_R/h	P_u (kN)	$P_u/P_{u\,(CC)}$ (%)
A1	1.21	_	0	81	100
A2*-0	1.21	0	0.25*	93	114.81
A4-0	1.21	0	1	102	125.92
B1	2.15	_	0	111	100
B2*-0	2.15	0	0.25*	185	166.66
B4-1	2.15	1	1	198	178.37
C1	3.36	_	0	157	100
C2-1	3.36	1	0.25	175	111.46
C2*-0	3.36	0	0.25*	196	124.84
C2*-1	3.36	1	0.25*	231	147.13
C3-1	3.36	1	0.5	211	134.39
C3*-0	3.36	0	0.5*	215	136.94
C3*-1	3.36	1	0.5*	270	171.97
C4-1	3.36	1	1	277	176.43

*RPC in compression

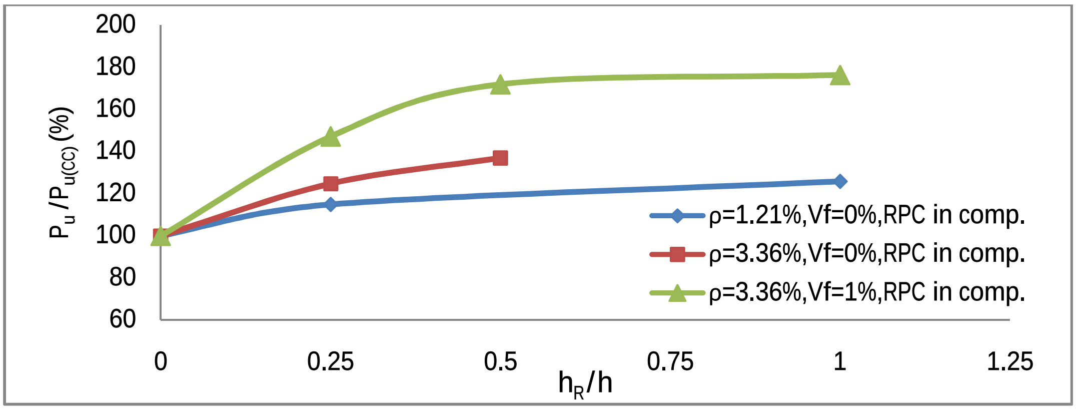

Fig . (18) Effect of RPC layer thickness on ultimate loads of beams with RPC in compression.

(a) explosive crushing (V_f=0%). **(b)** non-explosive crushing (V_f=1%).

Fig .(19) Crushing of RPC in compression

4.2.2.2 Effect of Steel Fibers Ratio (V_f)

Although increasing steel fibers ratio from 0% to 1% increases ultimate loads as shown in **Table (18) and Figure (18),** this effect is still the lowest among the other factors on beams with RPC in compression as well as in tension. The main difference is that RPC in compression without steel fibers shows an explosive crushing while using steel fibers causes RPC to crush without exploding into pieces as shown in **Figure (19).** This again shows that the major role of steel fibers is to increase toughness and ductility of RPC.

Table (18) Effect of steel fibers ratio(V_f)on ultimate loads of beams with RPC in compression.

Beam	ρ (%)	h_R/h	V_f (% of RPC)	P_u (kN)	$P_u/P_{u\,(V_{f=0\%})}$ (%)
C2*-0	3.36	0.25*	0	196	100
C2*-1			1	231	117.85
C3*-0		0.5*	0	215	100
C3*-1			1	270	125.58

*RPC in compression

4.2.2.3 Effect of Longitudinal Steel Ratio

The effect of increasing longitudinal steel ratio (ρ) on increasing ultimate loads of hybrid beams with RPC in compression is greater than that on hybrid beams with RPC in tension as shown clearly in **Table (19) and Figure (20).** This is because the over-reinforced beams failed by crushing of concrete in the compression zone and the use of RPC in compression enhances the flexural strength of hybrid beams much more significantly than when RPC is used in tension.

4.3 Cracking Loads Results

Table (20) and Figures (21) to (23) show the results of cracking load (load at which the first visible crack was detected). It is clearly shown that the cracking load increases when ultimate load increases. It ranges from 8kN in beam A1 to 73kN in beam C4-1. The ratio of cracking load to ultimate load (P_{cr}/P_u) was generally between 20% and 30% for beams with RPC in tension. This ratio increases with the increase of RPC layer thickness, steel fibers ratio and longitudinal steel ratio.

Table .(19) Effect of longitudinal steel ratio(ρ)on ultimate loads of beams with RPC in compression.

Beam	h_R/h	V_f (% of RPC)	ρ (%)	P_u (kN)	$P_u/P_{u\,(\rho=1.21\%)}$ (%)
A1	0	-	1.21	81	100
B1		-	2.15	111	137.03
C1		-	3.36	157	193.82
A2-1	0.25	1	1.21	98	100
B2-1		1	2.15	115	117.34
C2-1		1	3.36	175	178.57
A2*-0	0.25*	0	1.21	93	100
B2*-0		0	2.15	185	198.92
C2*-0		0	3.36	196	210.75

*RPC in compression

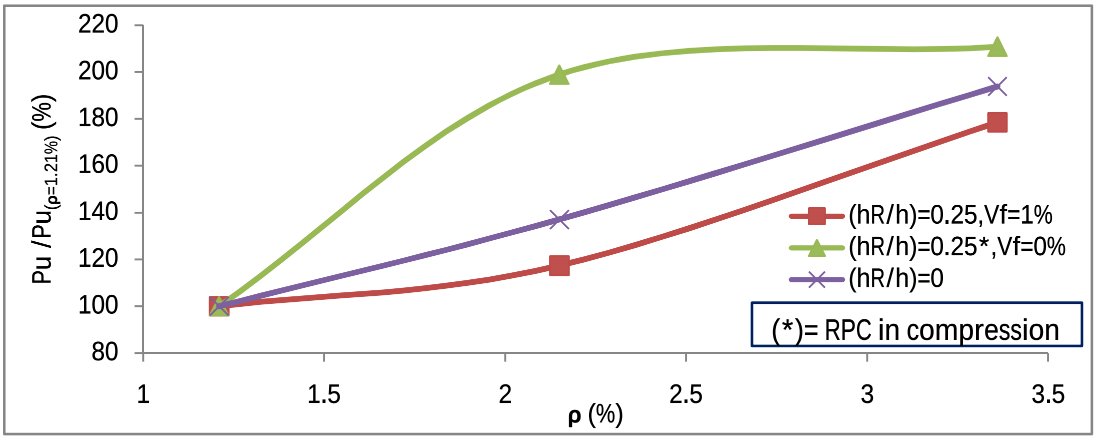

Fig . (20) Effect of longitudinal steel ratio on ultimate loads of beams with RPC in compression.

The effects of the above three parameters on the ratio of cracking load to ultimate load for beams with RPC in tension are seen to be little. This means that these parameters affect the cracking load and ultimate load in a similar way. This may be attributed to the fact that increasing RPC layer thickness, steel fibers ratio or longitudinal steel ratio will increase beam stiffness and consequently increases both the cracking load and ultimate load.

For hybrid beams with RPC in compression lower values for cracking loads (18kN to 22kN) and (P_{cr}/P_u) ratios (8.14%-19.35%) are recorded. This may be because of the fact that the tension faces of these beams are always CC which has a lower flexural strength (and consequently lower cracking load) than that of RPC.

Table .(20) Cracking loads of the tested beams.

Beam	ρ (%)	V_f (% of RPC)	h_R/h	P_{cr} (kN)	P_u (kN)	P_{cr} / P_u (%)
A1	1.21	_	0	8	81	9.87
A2-0	1.21	0	0.25	10	88	11.36
A3-0	1.21	0	0.5	20	90	22.22
A4-0	1.21	0	1	25	102	24.5
A2-1	1.21	1	0.25	20	98	20.4
A3-1	1.21	1	0.5	26	105	24.76
A4-1	1.21	1	1	30	112	26.78
A2-2	1.21	2	0.25	28	108	25.92
A3-2	1.21	2	0.5	31	113	27.43
A4-2	1.21	2	1	35	118	29.66
B1	2.15	_	0	25	111	22.52
B2-1	2.15	1	0.25	28	115	24.34
B3-1	2.15	1	0.5	40	148	27.02
B4-1	2.15	1	1	55	198	27.77
C1	3.36	_	0	38	157	24.2
C2-1	3.36	1	0.25	45	175	25.71
C3-1	3.36	1	0.5	60	211	28.43
C4-1	3.36	1	1	73	277	26.35
A2*-0	1.21	0	0.25*	18	93	19.35
B2*-0	2.15	0	0.25*	20	185	10.81
C2*-0	3.36	0	0.25*	20	196	10.2
C3*-0	3.36	0	0.5*	20	215	9.3
C2*-1	3.36	1	0.25*	21	231	9.09
C3*-1	3.36	1	0.5*	22	270	8.14

*RPC in compression

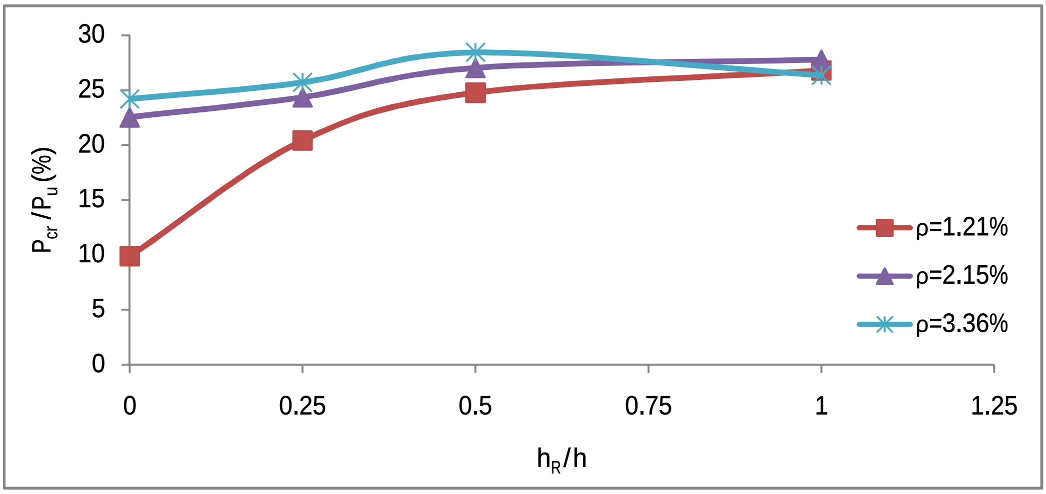

Fig .(21) Effect of RPC layer thickness on cracking loads of beams with RPC in tension(V_f=1%).

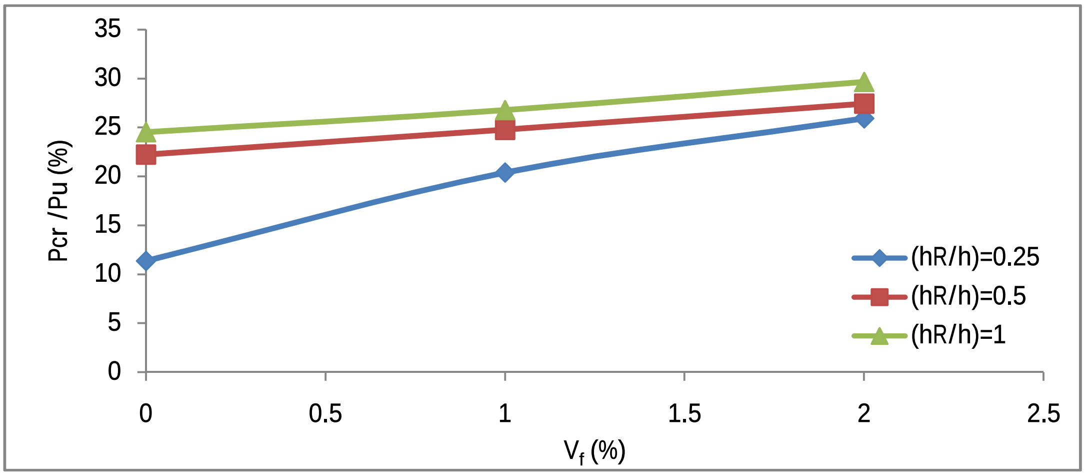

Fig .(22) Effect of steel fibers ratio on cracking loads of beams with RPC in tension (ρ=1.21%).

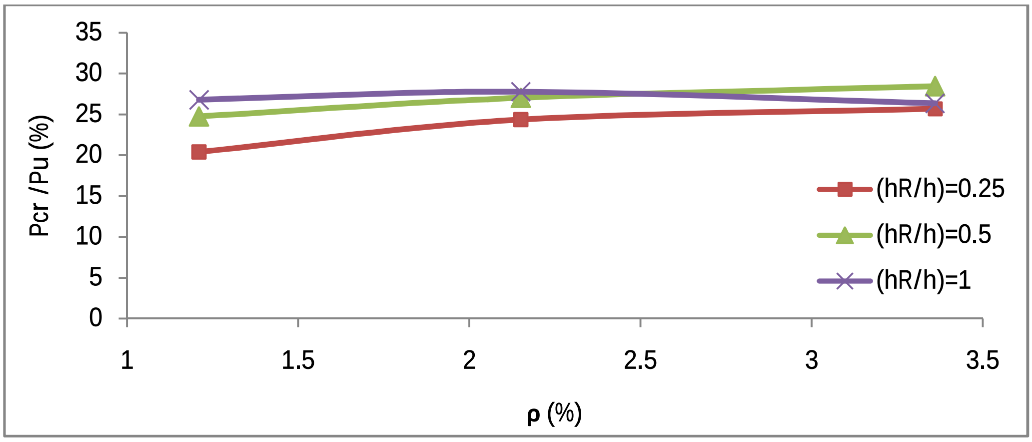

Fig .(23) Effect of longitudinal steel ratio on cracking loads of beams with RPC in tension (V_f=1%).

5. Conclusions

Based on the results obtained in the present work for the conventional, hybrid and reactive powder concrete beams, the following conclusions can be drawn :

v Mechanical Properties of RPC

1. It is possible to produce reactive powder concrete (RPC) with compressive strength of 121.25 MPa, modulus of elasticity of 57.31 GPa, flexural strength of 17.63 MPa and splitting tensile strength of 12.98 MPa using normal water curing at room temperature without the application of pressure.
2. When steel fibers ratio increases from 0% to 2%, compressive strength, modulus of elasticity, flexural strength and splitting tensile strength increase by 46.57%, 80.9%, 213.7% and 128.12%, respectively. The effect of steel fibers on flexural strength and splitting tensile strength is clearly higher than that on compressive strength and modulus

of elasticity. This assures that steel fibers are used mainly to improve tensile properties of RPC.

v Ultimate Loads of the Tested Beams

3. The increase in RPC layer thickness (h_R/h) increases ultimate loads of hybrid beams with RPC in tension. The ultimate loads for under-reinforced beams (ρ=1.21%) were 20.98%, 29.62% and 38.27% higher than those of reference CC beam (beam A1) for h_R/h of 0.25, 0.5 and 1 (RPC beam), respectively. These results lead to the conclusion that the value for h_R/h of 0.25 is better than having 0.5 for this ratio. The latter case (of 0.5) has only a marginal rise in P_u of 1.69% to 4.9%, which is insignificant considering the expensive RPC. For higher ρ, ultimate loads were 3.6%, 33.33% and 78.37% higher than those for reference CC beam (beam B1, ρ=2.15%) and 11.46%, 34.4% and 76.43% higher than those for reference CC beam (beam C1, ρ=3.36%) for (h_R/h) of 0.25, 0.5 and 1, respectively. The above results show that there is a considerable increase in (P_u) of hybrid beams with (h_R/h) of 0.5 than that of hybrid beams with (h_R/h) of 0.25. This behavior may be attributed to the combined contribution of higher ρ and greater (h_R/h) in increasing the beams stiffness which allows such beams to sustain higher loads before failure that is characterized by crushing in concrete in the compression zone. This is not the case in under-reinforced beams which failed by yielding of steel in the tension zone.
4. Using RPC in compression is more effective than using RPC in tension. This is especially true in over-reinforced beams (ρ=2.25% and ρ=3.36%) which failed by crushing of RPC in the compression zone. For example, the increasing ratios for ultimate loads (compared to CC beams) are 47.13% and 71.97% for (h_R/h) of 0.25* (beam C2*-1) and 0.5*(beam C3*-1), respectively. These ratios are higher than those for hybrid beams with RPC in tension (beam C2-1 with h_R/h of 0.25 and beam C3-1 with h_R/h of 0.5) by 35.67% and 37.58%, respectively. In contrast, under-reinforced beam A2*-0 records an increasing ratio of only 6.17% greater than the ultimate load of beam A2-0 (both beams failed by yielding of tension steel).
5. When volumetric steel fibers ratio (V_f) increases from 0% to 2%, the maximum increase in (P_u) reaches 22.72%, 25.55% and 15.68% for hybrid beams with RPC in tension and h_R/h of 0.25,0.5 and 1 (RPC beam), respectively. Increasing ratios are 17.85% and 25.58% for hybrid beams with RPC in compression and h_R/h of 0.25* and 0.5*, respectively when V_f increases from 0% to 1%. The above results indicate that the effect of (V_f)on increasing (P_u) (within the range of (V_f) used) is still of secondary importance (maximum increase of 25.58% for hybrid beams) as compared to the effect of h_R/h (conclusions 3 and 4) and the effect of longitudinal steel ratio ρ (conclusion 6).
6. The effect of longitudinal steel ratio (ρ) is the greatest on increasing ultimate loads of the tested beams. When (ρ) increases from 1.21% to 3.36%, the ultimate load of beams with RPC in tension increases by 78.57%, 100.95% and 147.32% for (h_R/h) equal to 0.25, 0.5and 1, respectively and by 110.75% for hybrid beams with RPC in compression and

h_R/h of 0.25*. This indicates that the effect of ρ is greater for hybrid beams with RPC in compression. This is because the over-reinforced beams failed by crushing of concrete in the compression zone and the use of RPC in compression enhances the flexural strength of hybrid beams much more significantly than when RPC is used in tension.

7. The effects of h_R/h, V_f and ρ on the ratio of cracking load to ultimate load for beams with RPC in tension (generally between 20% and 30%) are seen to be insignificant. This means that these parameters affect the cracking load and ultimate load in a similar way. This may be attributed to the fact that increasing these parameters will increases beam stiffness and consequently increases both the cracking load and ultimate load. Lower values are recorded for hybrid beams with RPC in compression. This may be because of the fact that the tension faces of such beams are CC which has a lower flexural strength (and consequently lower cracking load) than that of RPC.

6. References

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