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Load-Deflection Behavior of Hybrid Beams Containing Reactive Powder Concrete and Conventional Concrete

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Abstract :

This paper presents an experimental investigation consist of casting and testing of twenty four rectangular simply supported reinforced concrete beams. Three of the tested beams were made with conventional concrete (CC), five with reactive powder concrete (RPC) and sixteen as hybrid beams of the two types of concrete. RPC is used in tension zone (at the bottom) in ten hybrid beams and in the compression zone in the other six beams. Experimental results show that the stiffer load-deflection behavior is 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 that of the other factors. Using RPC in compression is found to be more effective than using RPC in tension.

Key Words: Reactive Powder Concrete, load, deflection, hybrid beams.

سلوك الحمل- الأود للعتبات الهجينة المتكونة من خرسانة المساحيق الفعالة و الخرسانة التقليدية

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الخلاصة:

يقدم هذا البحث تحريا مختبريا يتضمن صب و فحص أربع و عشرين عتبة خرسانية مسلحة مستطيلة المقطع و بسيطة الاسناد. ثلاث عتبات كانت مصنوعة من الخرسانة التقليدية و خمس من خرسانة المساحيق الفعالة و ست عشرة كعتبات هجينة مصنوعة من كلا النوعين. استخدمت خرسانة المساحيق الفعالة في منطقة الشد في عشر عتبات هجينة و في منطقة الانضغاط في الست الاخريات. اظهرت النتائج المختبرية ان سلوك الحمل-الهطول يصبح اكثر صلادة عند زيادة سمك طبقة خرسانة المساحيق الفعالة و نسبة الالياف الحديدية و نسبة الحديد الطولي للعتبات الهجينة ذات خرسانة المساحيق الفعالة في منطقة الشد كما في منطقة الانضغاط. كما اظهرت النتائج ان استخدام خرسانة المساحيق الفعالة في منطقة الانضغاط يؤثر اكثر من استخدامها في منطقة الشد.

الكلمات المرشدة: خرسانة المساحيق الفعالة،الحمل، الأود، 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.

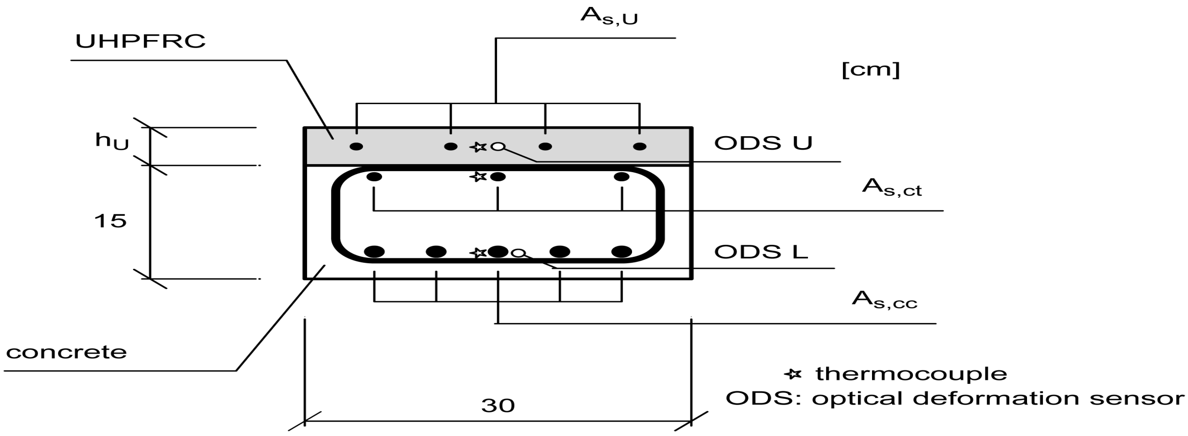

Fig .(1) Cross-section of the composite "UHPFRC-concrete" beams [13]

3. Experimental Work

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

3.1 Materials

3.1.1 Cement

Ordinary Portland cement (type I) manufactured by the united cement company (UCC) in Iraq is 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].

3.1.2 Fine Aggregate

Natural sand is used for CC mixes while fine sand with maximum particle size of 600μm is 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 (1).**

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 (2).**

Table (1) 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.

Table (2) 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 is 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 (3).**

Table (3) Chemical Composition 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 is used as an admixture to produce RPC in this study. Properties of the superplasticizer are given in **Table (4).**

Table (4) 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

* According to manufacturer editions.

3.1.6 Steel Fibers

Hooked end steel fibers with aspect ratio (L/d) of 80 are used in RPC mixes. Sample of the used steel fibers is shown in **Figure (2)** and their properties are listed in **Table (5).**

Fig .(2) Sample of the used steel fibers

Table (5) Properties of 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.

3.1.7 Steel Reinforcement

Deformed steel bars with three nominal diameters of 12, 16 and 20mm are used as main flexural reinforcing bars in tension, while the 8mm diameter deformed steel bars are used as shear reinforcement (stirrups). **Table (6)** gives the tensile test results performed on samples of the used steel bars.

Table (6) 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 is used for mixing of both CC and RPC mixes and curing of all specimens.

3.2 Mix Proportions

Table (7) 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) are adopted in this study.

Table (7) 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, 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 are used to pour the tested 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 is 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 is added and the dry components are mixed for about 3 minutes to obtain a homogeneous dry mix, then water is 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] is adopted in this study to produce RPC in a simple way without any accelerated curing regimes. Fine sand and silica fume are first mixed for 4 minutes, then cement is added and the dry components are mixed for 5 minutes. Superplasticizer is added to the water, then the blended liquid is added to the dry mix during the mixer rotation and the mixing process continued for another 3 minutes. Finally, steel fibers are added during mixing within 2 minutes. The total mixing time of RPC is about 15 minutes.

Casting of CC and RPC beams is 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 is mixed and placed first, then, the top layer (RPC or CC) is mixed and placed above the first one. The time period between the placing of the two layers is about 30 minutes. It may be noted that the top surface of the bottom layer is left rough to ensure good interaction between the two layers.

With each mix control specimens are cast to determine the mechanical properties of concrete. Control specimens involve three cylinders (100mm×200 mm) for compressive strength, three cylinders (100mm×200mm) for splitting tensile strength, three cylinders (150mm×300mm) for modulus of elasticity and three prisms (100mm×100mm×500mm) for flexural strength (modulus of rupture).

After casting, all specimens are 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 are demolded and placed in water containers in the laboratory to be cured at room temperature. This normal curing method is applied for CC as well as RPC.

In the previous works, RPC is always produced using accelerated curing methods such as heat curing at elevated temperature or presetting pressure. Any of these methods is 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 is proved to be successful as will be seen in this paper. However, this normal curing is proposed by Wille et al [1] as part of their proposed simpler way to produce RPC and the mixing procedure used in this study is the main part of their proposal.

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

3.5 Details and Designation of Tested Beams

Twenty four beams of dimensions (110mm×200mm×1500mm) are 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 is 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%) are used in the tested beams. Shear reinforcement (stirrups) are 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).**

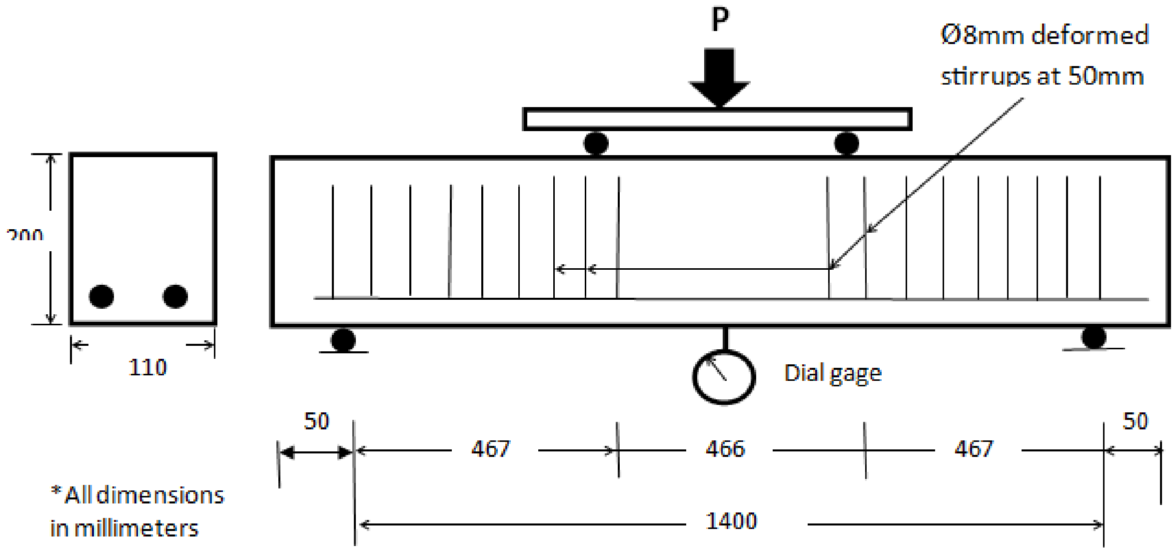

Fig .(3) Details and setup of the tested beams

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

(Letter) (1^{st} No.) – (2^{nd} No.)

Definitions of designation symbols are given in **Table (8).** "Asterisk" mark (*) was used with the 1^{st} No. (and h_R/h value) to indicate that RPC is in compression as shown in **Figure (4).**

Table (8) Definition of beams designation symbols

<table>
<tr><th rowspan="2">Letter</th><th colspan="2">Corresponding Value</th><th rowspan="2">1^{st} No.</th><th colspan="2">Corresponding Value</th><th rowspan="2">2^{nd} No.</th><th>Corresponding Value</th></tr>
<tr><th>ρ (%)</th><th>A_s</th><th>h_R (cm)</th><th>h_R/h</th><th>V_f (% of RPC)</th></tr>
<tr><td rowspan="2">A</td><td rowspan="2">1.21</td><td rowspan="2">2Ø12</td><td>1</td><td>0</td><td>0</td><td rowspan="2">0</td><td rowspan="2">0</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">5</td><td rowspan="2">0.25</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">2.15</td><td rowspan="2">2Ø16</td><td rowspan="2">1</td><td rowspan="2">1</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">10</td><td rowspan="2">0.5</td></tr>
<tr><td rowspan="2">C</td><td rowspan="2">3.36</td><td rowspan="2">2Ø20</td><td rowspan="2">2</td><td rowspan="2">2</td></tr>
<tr><td>4</td><td>20</td><td>1</td></tr>
</table>

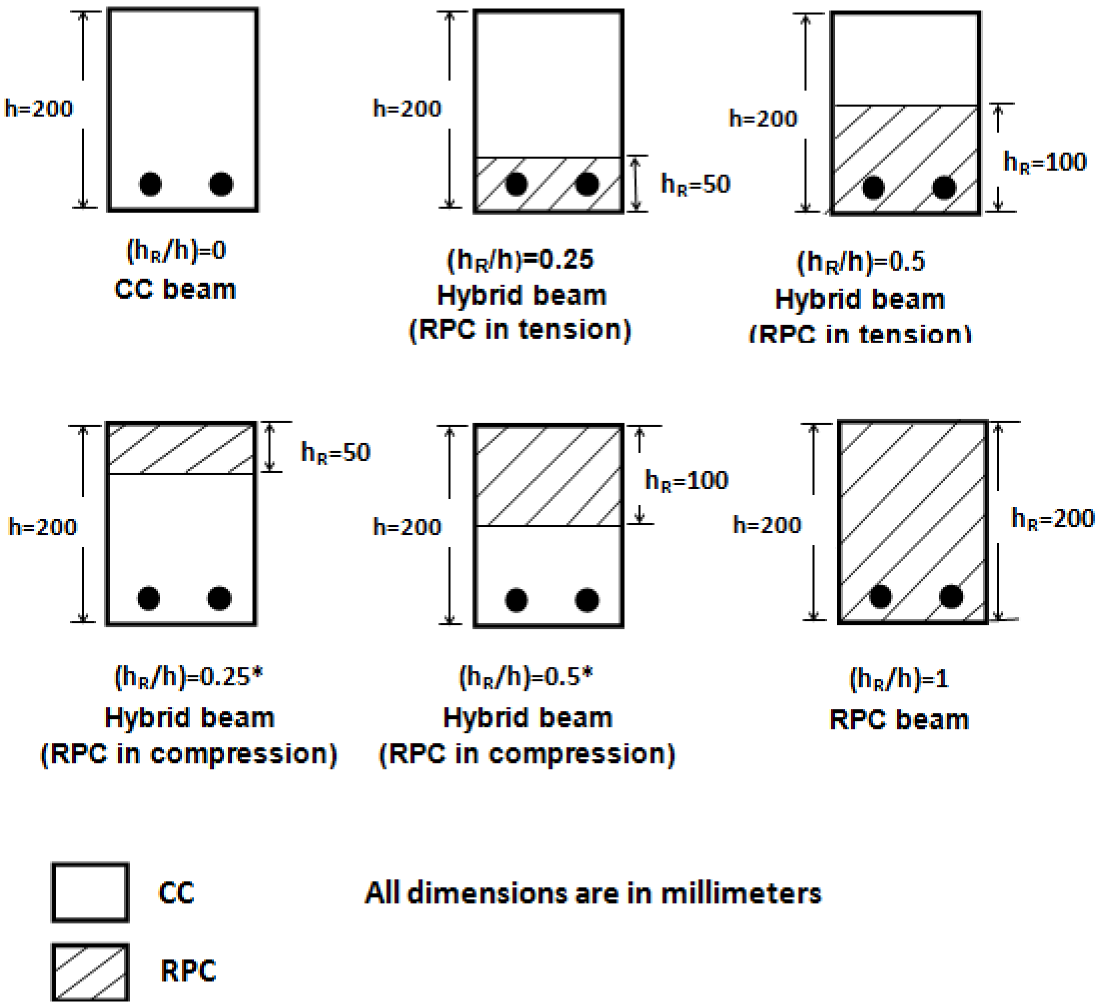

Fig .(4) Types of tested beams

However, details of all 24 beams are presented in **Table (9).**

Table (9) 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 is 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 is 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 is 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 is calculated as follows:

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

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 is 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 is calculated as follows:

$$f_r = \frac{3PL}{2bh^2} \quad \text{……..(2)}$$

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 is 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 is 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 is calculated as follows:

$$f_s = \frac{2P}{\pi DL} \quad \text{…….(3)}$$

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 is used to determine the splitting tensile strength for CC as well as RPC mixes.

3.7 Testing of Beams in Flexure

All beams are 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 is applied gradually in small increments up to failure. Midspan deflection of the tested beam is recorded every 5kN using a dial gage of 0.01mm accuracy and 30mm capacity attached to the bottom face of beam midspan, **Figure (3).**

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 (10)** 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 are 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.

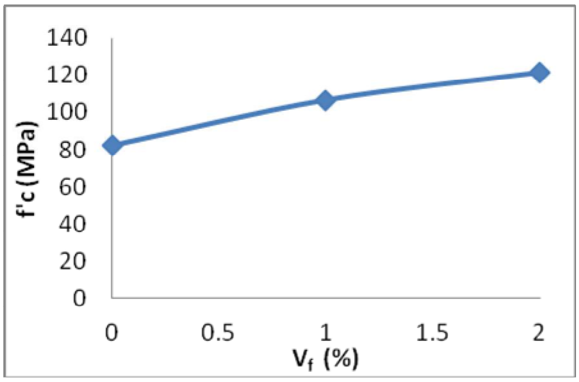

Fig .(11) Effect of steel fibers ratio on compressive strength of RPC.

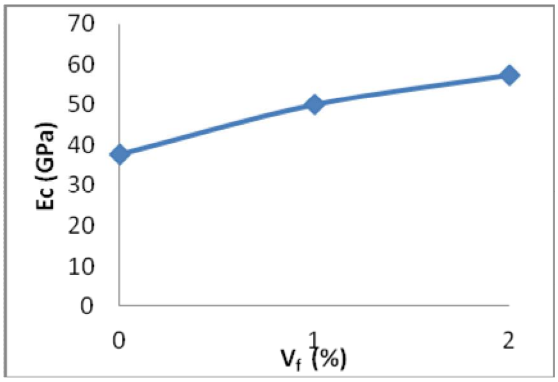

Fig .(12) Effect of steel fibers ratio on modulus of elasticity of RPC.

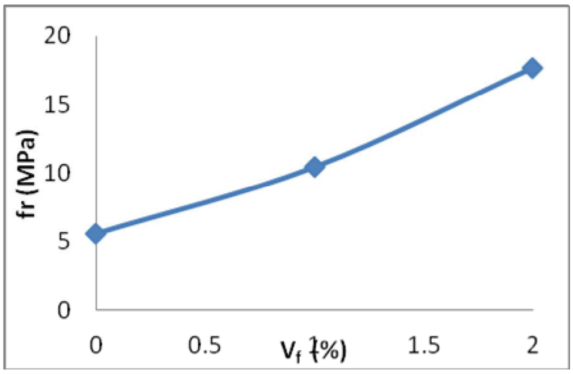

Fig .(13) Effect of steel fibers ratio on flexural strength of RPC.

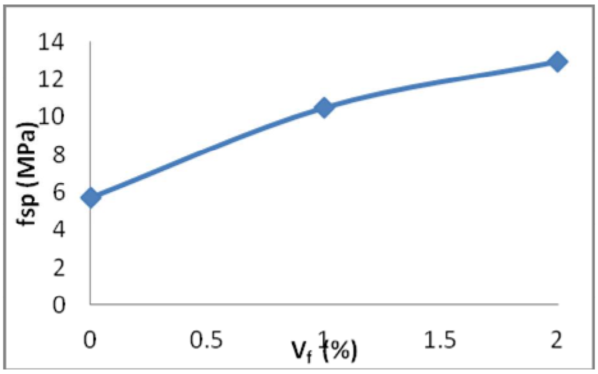

Fig .(14) Effect of steel fibers ratio on splitting tensile strength of RPC.

Table (10) 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 Load-Deflection Behavior

Load-deflection behavior of the tested beams is illustrated in **Figures (15 to 21). Table (11)** lists maximum deflections (deflections at failure) of the tested beams. It is generally shown that increasing RPC layer thickness; steel fibers ratio or longitudinal steel ratio has a positive effect on general load-deflection behavior of the tested beams, leading to significantly small deflections.

4.2.1 Effect of RPC Layer Thickness (h_R/h)

4.2.1.1 Under-reinforced Beams (ρ=1.21%)

Hybrid beams exhibit a stiffer behavior than the CC beam (A1) especially when using steel fibers ratio of 2% (**Figure (18)).** Only a slight increase in stiffness was observed when (h_R/h) increases from 0.25 to 0.5 while RPC beams show slightly lower stiffness than hybrid beams as may be shown in **Figures (15 to 18).** This lower stiffness of RPC beams may be attributed to the absence of coarse aggregate and to the presence of shrinkage cracking caused by rapid drying which may occur because of the very low water to cement ratio in RPC. A slight increase in stiffness is also observed when RPC is used in compression (A2*-0) as compared to hybrid beam with RPC in tension (A2-0) as shown in **Figure (16).**

Maximum midspan deflections of hybrid beams with RPC in tension (10.5mm-17.2mm) were lower than that of CC beams (19.55mm) as shown in **Figure (4-24)** because of the greater stiffness of them, while maximum deflection of RPC beams (>22mm) were higher than that of CC beams because RPC beams sustained higher ultimate load and this allows them to withstand larger deflections (higher energy absorption).

Table (11) Maximum midspan deflections of the tested beams.

Beam	ρ (%)	V_f (% of RPC)	h_R/h	P_u (kN)	Δ_{max} (mm)§
A1	1.21	_	0	81	19.55
A2-0	1.21	0	0.25	88	16.3
A2*-0	1.21	0	0.25*	93	17.2
A3-0	1.21	0	0.5	90	13.6
A4-0	1.21	0	1	102	23.03
A2-1	1.21	1	0.25	98	14.94
A3-1	1.21	1	0.5	105	15.5
A4-1	1.21	1	1	112	22.3
A2-2	1.21	2	0.25	108	10.5
A3-2	1.21	2	0.5	113	13.8
A4-2	1.21	2	1	118	22.75
B1	2.15	_	0	111	12.5
B2*-0	2.15	0	0.25*	185	13.78
B2-1	2.15	1	0.25	115	11.1
B3-1	2.15	1	0.5	148	17.5
B4-1	2.15	1	1	198	23.5
C1	3.36	_	0	157	10.4
C2-1	3.36	1	0.25	175	11.4
C2*-0	3.36	0	0.25*	196	12.9
C2*-1	3.36	1	0.25*	231	15.3
C3-1	3.36	1	0.5	211	15.6
C3*-0	3.36	0	0.5*	215	16.9
C3*-1	3.36	1	0.5*	270	19.3
C4-1	3.36	1	1	277	21.25

§At ultimate load P_u

*RPC in compression

4.2.1.2 Over-reinforced Beams (ρ=2.15% or 3.36%)

No large differences can be observed in stiffnesses of CC, hybrid and RPC beams until pre-failure stage of CC beams where CC and hybrid beams with RPC in tension started to fail while RPC beams and hybrid beams with RPC in compression continue to resist higher loads and consequently higher deflections (higher energy absorption), **Figures (19) to (21).** However, hybrid beams with RPC in compression show a stiffer behavior than hybrid beams with RPC in tension (**Figures 19 and 21).** These similar initial stiffnesses may be attributed to the greater effect of steel reinforcement in confining beams at pre-failure stage.

Hybrid beams as well as CC beams failed by crushing of concrete in the compression zone (brittle failure). This explains the lower maximum midspan deflection of these beams (10.4mm-17.55mm) when compared to RPC beam B4-1 (23.6mm) which failed by yielding of tension steel allowing it to withstand larger deflection (ductile failure). However, hybrid beams with RPC in tension and (h_R/h) of 0.5 show higher maximum deflections (17.55mm and 15.6mm) than those for (h_R/h) of 0.25 (11.1mm and 11.4mm) due to the significant increase in ultimate loads (and consequently in maximum deflections) when (h_R/h) increases from 0.25 to 0.5.

Figure (23) shows that hybrid beams with RPC in compression exhibit larger deflections than those for hybrid beams with RPC in tension. This may be attributed to the higher flexural strength of these beams which allows them to withstand larger deflections before failure (higher energy absorption).

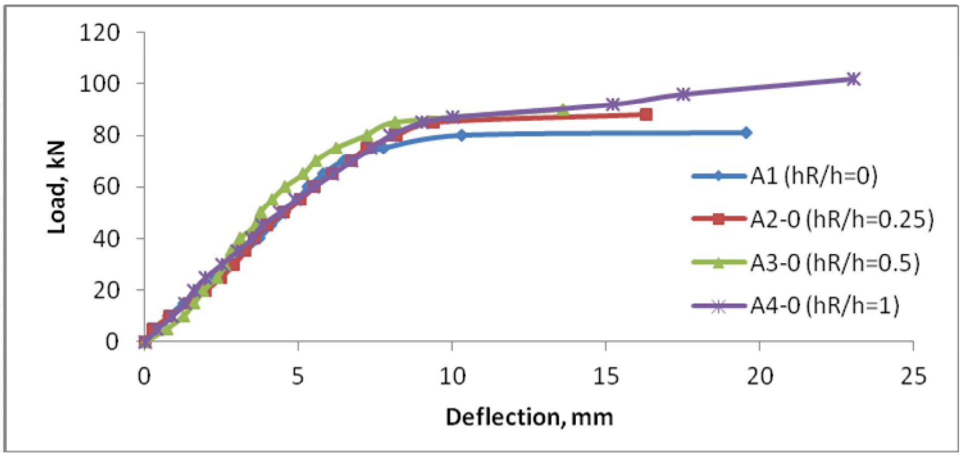

Fig .(15) Load-deflection curves for beams with ρ=1.21%, V_f=0% and RPC in tension.

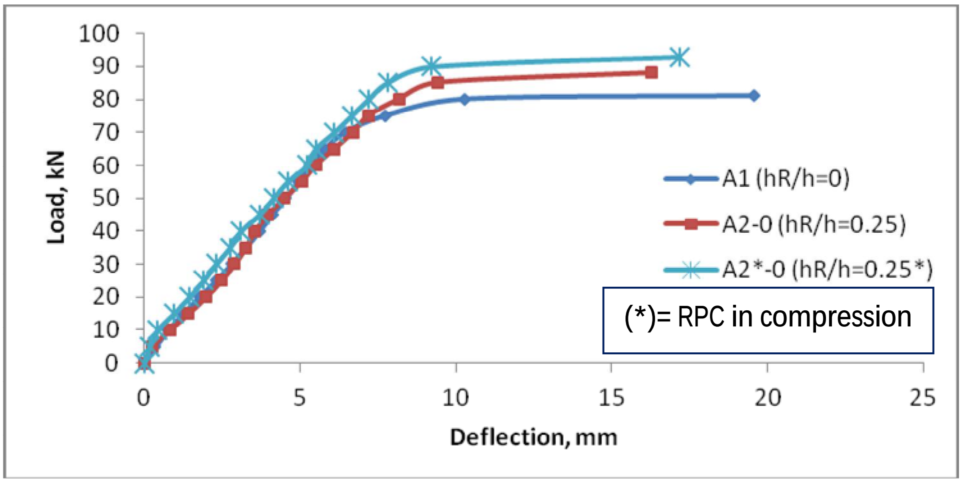

Fig .(16) Load-deflection curves for hybrid beams with RPC in tension and in compression (ρ=1.21% and V_f=0%).

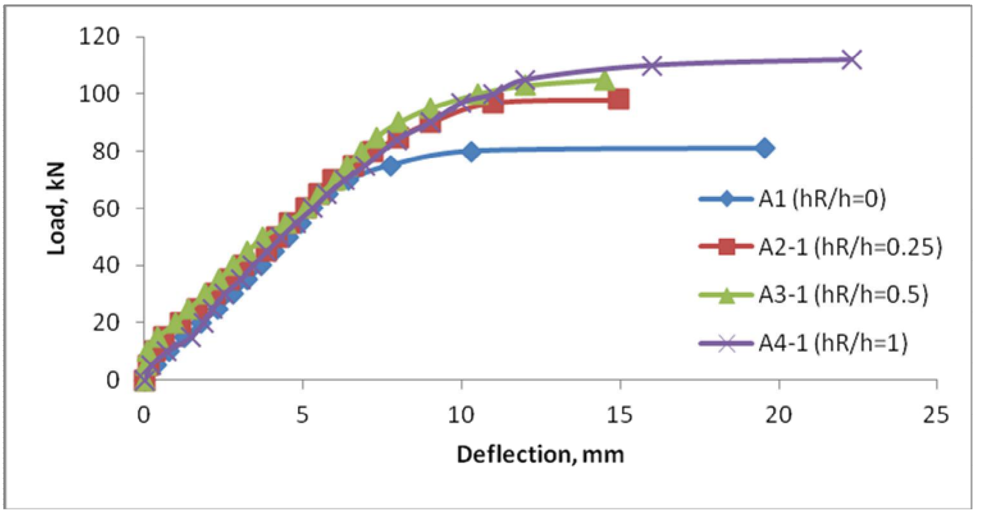

Fig .(17) Load-deflection curves for beams with ρ=1.21%, V_f=1% and RPC in tension.

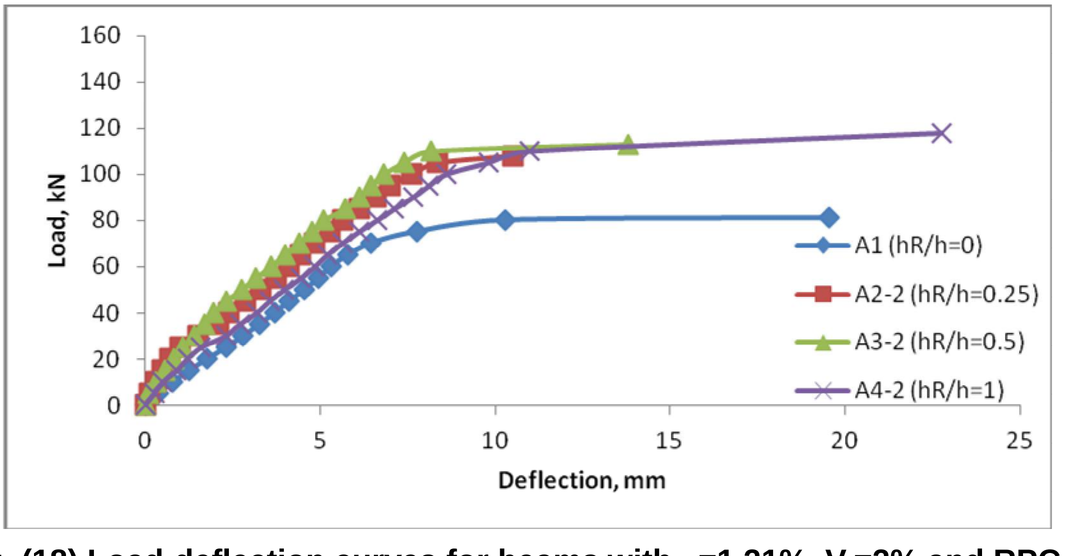

Fig .(18) Load-deflection curves for beams with ρ=1.21%, V_f=2% and RPC in tension.

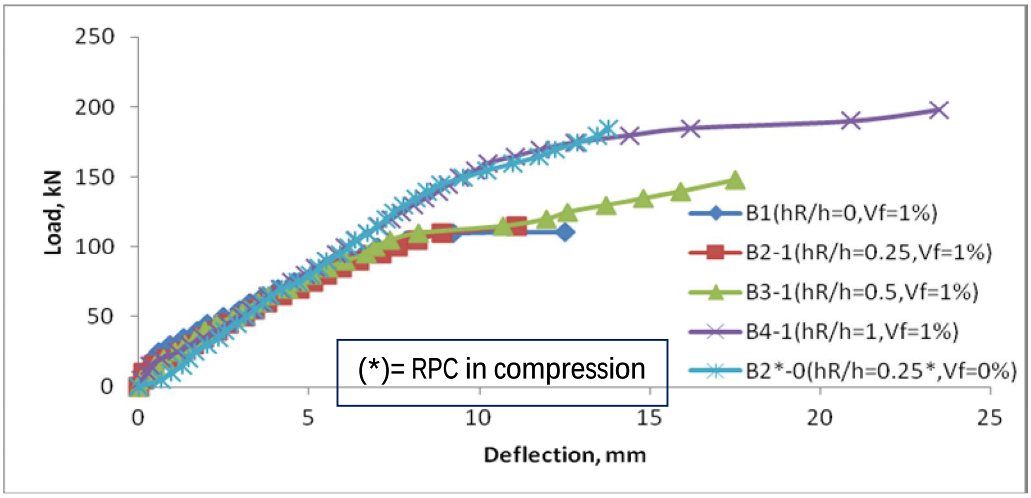

Fig .(19) Load-deflection curves for beams with ρ=2.15% and and RPC in compression.

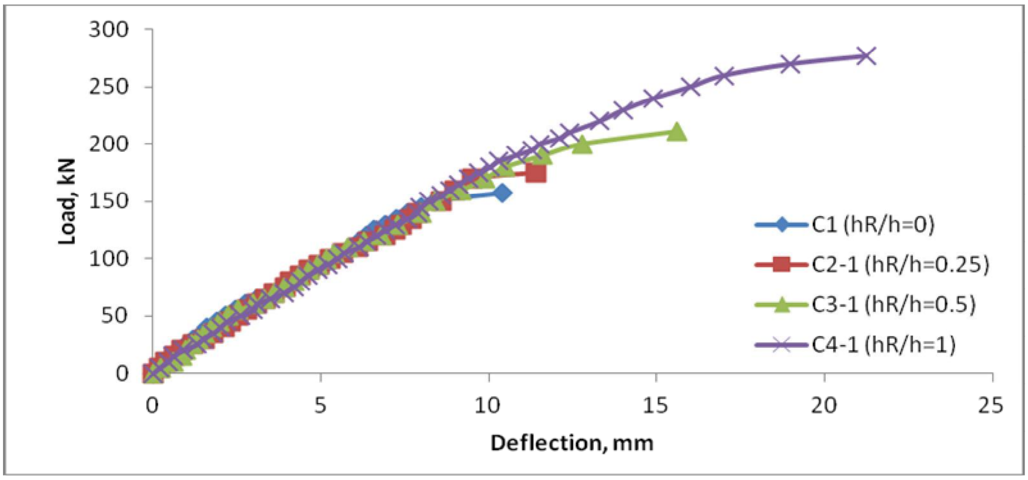

Fig .(20) Load-deflection curves for beams with ρ=3.36%, V_f=1% and RPC in tension.

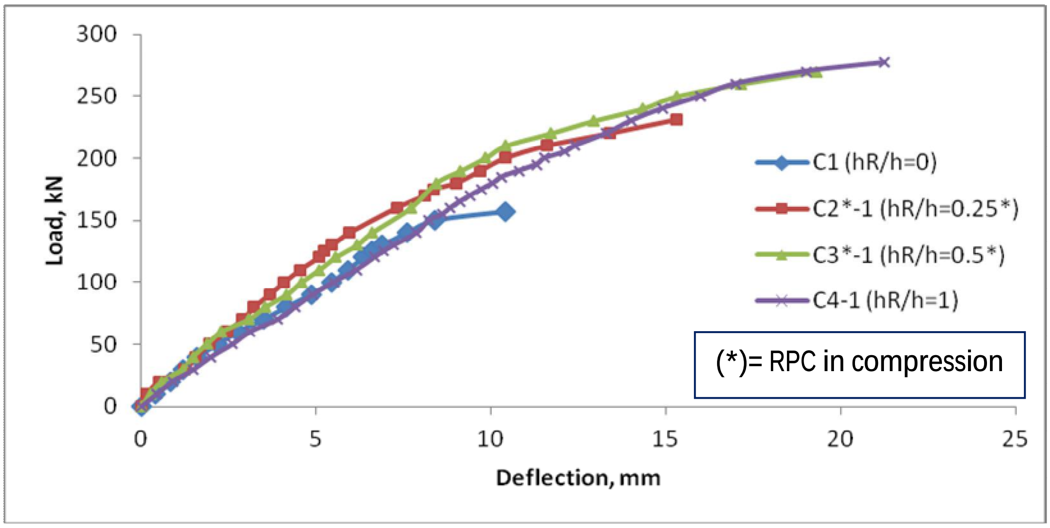

Fig .(21) Load-deflection curves for beams with ρ=3.36%, V_f=1% and RPC in compression.

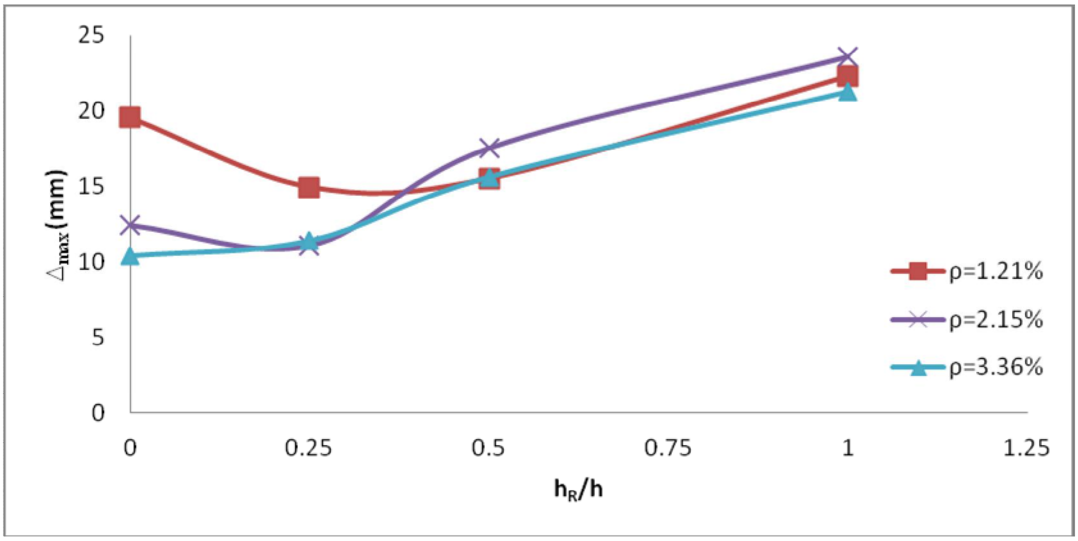

Fig .(22) Effect of RPC layer thickness on maximum deflections of beams with RPC in tension (V_f=1%).

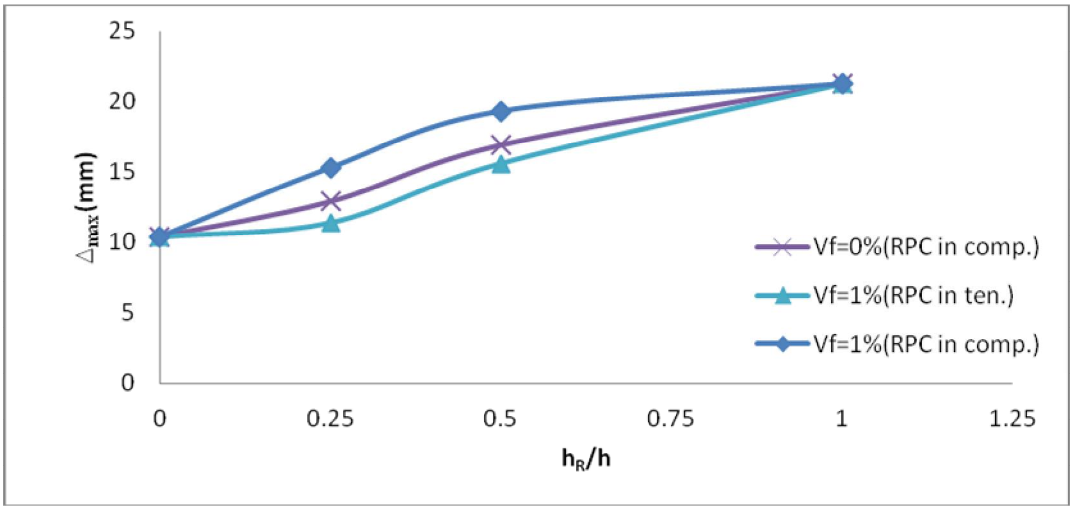

Fig .(23) Effect of RPC layer thickness on maximum deflections of beams with RPC in compression (ρ=3.36%).

4.2.2 Effect of Steel Fibers Ratio (V_f)

Generally, when steel fibers ratio increases from 0% to 2%, the stiffness of hybrid beams with RPC in tension and RPC beams increases too with very clear effect of 2% steel fibers as shown in **Figures (24 to 26).** For hybrid beams with RPC in compression, increasing (V_f) from 0% to 1% increases stiffness of these beams. This effect is more pronounced in hybrid beams with (h_R/h) of 0.25* **(Figures 27 and 28).**

Maximum midspan deflections of hybrid beams with RPC in tension were lower than CC beams for different ratios of steel fibers, while RPC beams show higher maximum deflections than CC because of their high ductility as mentioned before (**Figure 29).**

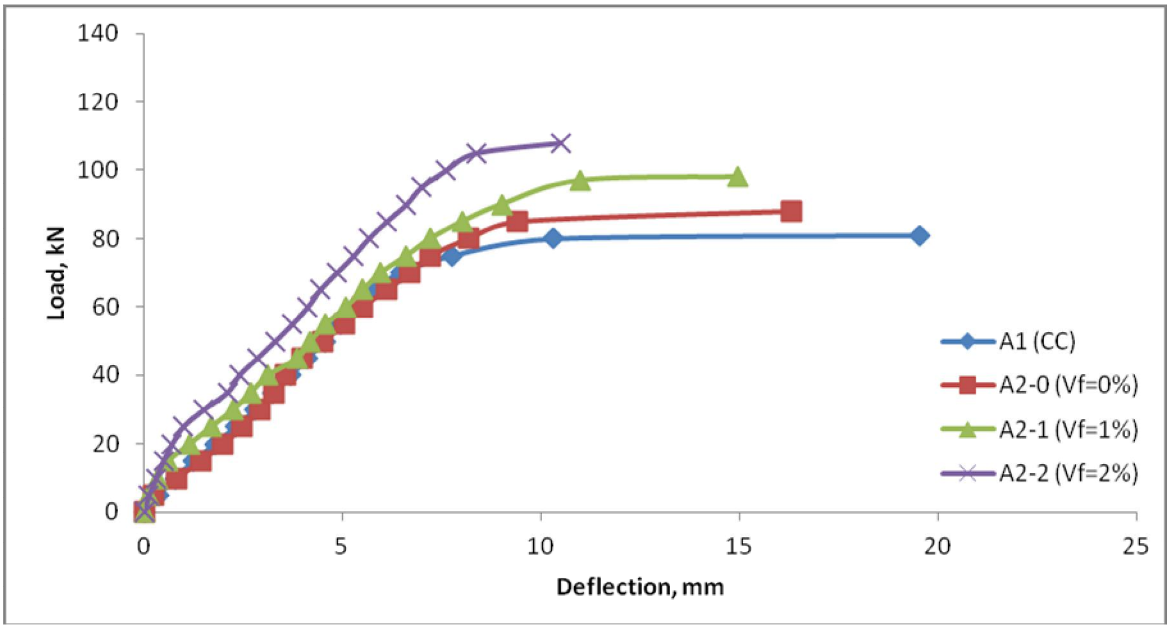

Fig .(24) Load-deflection curves for hybrid beams with ρ=1.21% and h_R/h=0.25 (RPC in tension).

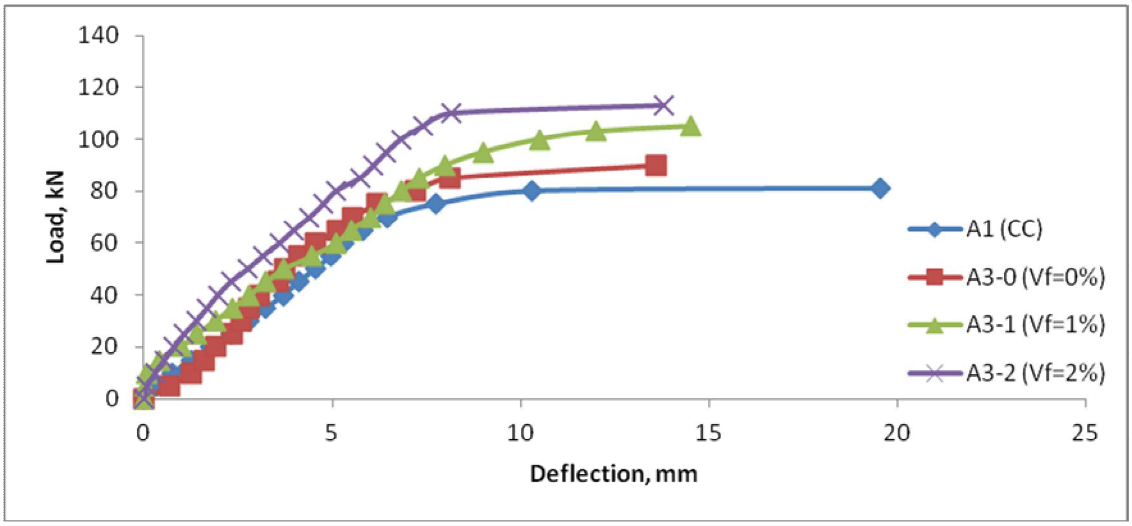

Fig .(25) Load-deflection curves for hybrid beams with ρ=1.21% and h_R/h=0.5 (RPC in tension).

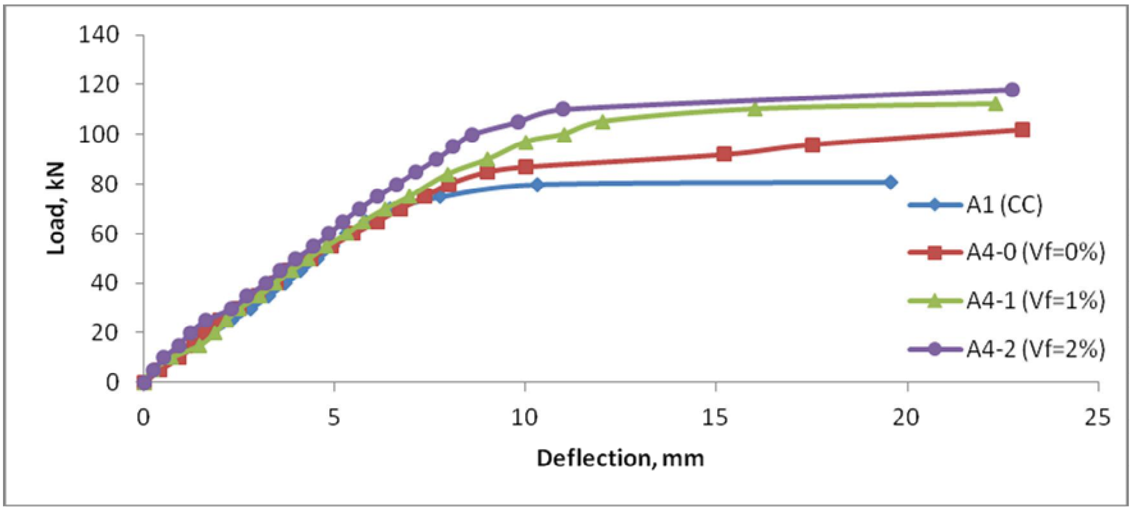

Fig .(26) Load-deflection curves for RPC beams ($h_R/h=1$) with ρ=1.21%.

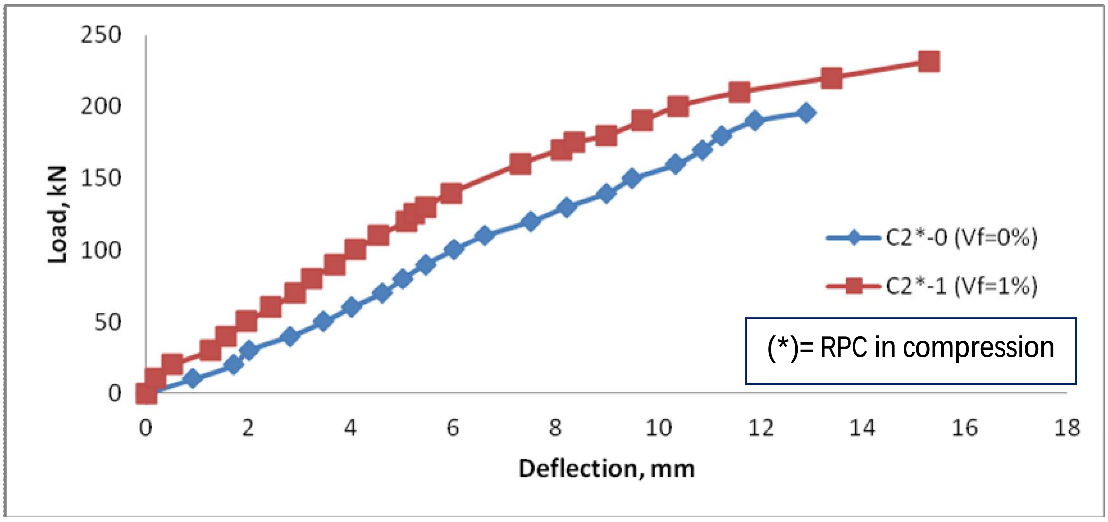

Fig .(27) Load-deflection curves for hybrid beams with ρ=3.36% and h_R/h=0.25* (RPC in compression).

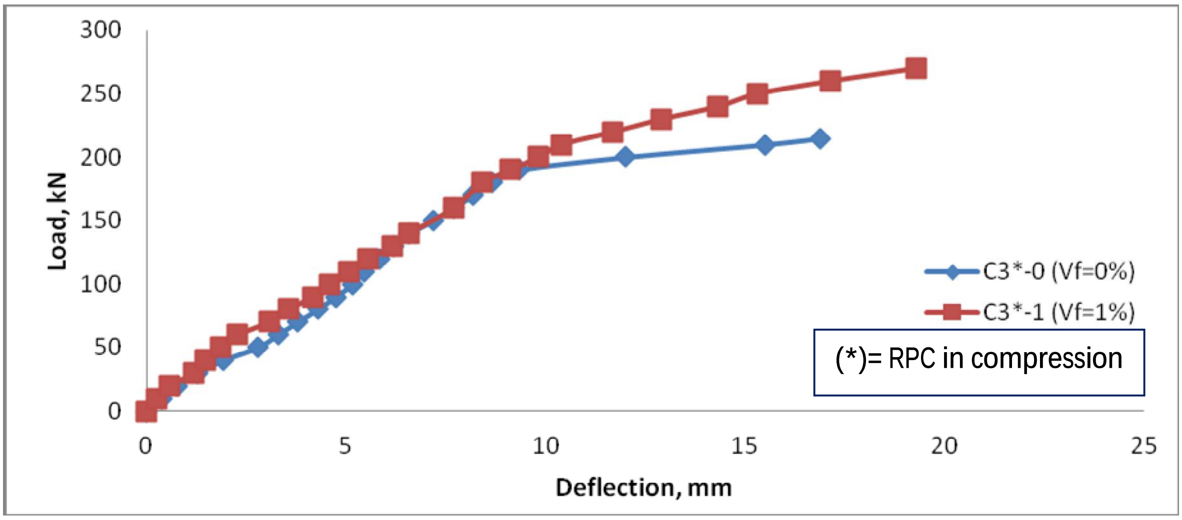

Fig .(28) Load-deflection curves for hybrid beams with ρ=3.36% and h_R/h=0.5* (RPC in compression).

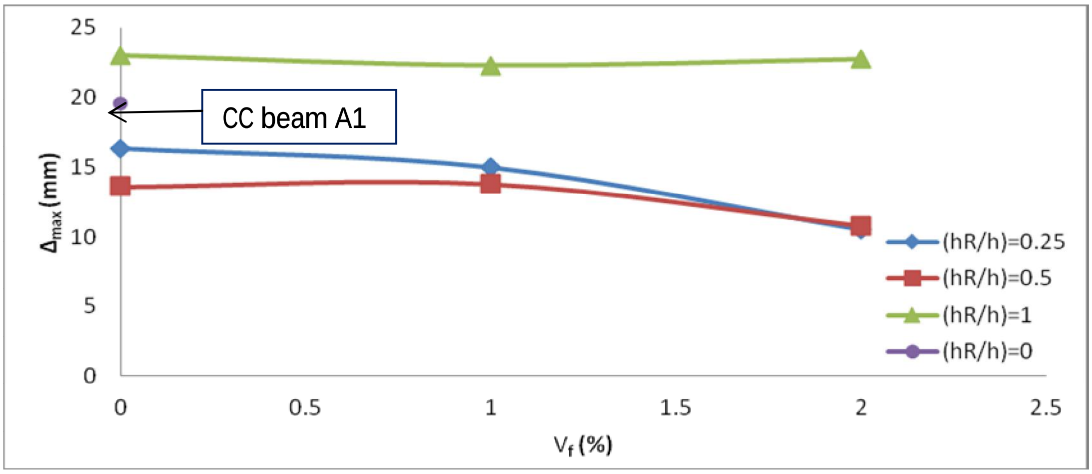

Fig .(29) Effect of steel fibers ratio on maximum deflections of beams with ρ=1.21% and RPC in tension.

4.2.3 Effect of Longitudinal Steel Ratio (ρ)

As mentioned in ultimate load results, the longitudinal steel ratio also has a significant effect on load deflection behavior of the tested beams where the stiffness of CC, hybrid and RPC beams are considerably increased when (ρ) increases from 1.21% to 3.36% as is clearly shown in **Figures (30 to 34).**

Maximum midspan deflections of CC beams and hybrid beams with (h_R/h) of 0.25 (RPC in tension) and 0.25* (RPC in compression) dropped with increasing (ρ) as shown in Figure (35). This reflects the change in mode of failure from yielding of tension steel to crushing of compression concrete with high ρ values as discussed before.

Hybrid beams with (h_R/h) of 0.5 (RPC in tension) and RPC beams (h_R/h=1) show inverse behavior where their maximum deflections at higher (ρ) were slightly higher than corresponding ones at lower ρ (**Figure (35)).** This again shows the considerable increase in ultimate loads (and consequently in maximum deflections) of hybrid beams with higher longitudinal steel ratio when (h_R/h) increases from 0.25 to 0.5 .

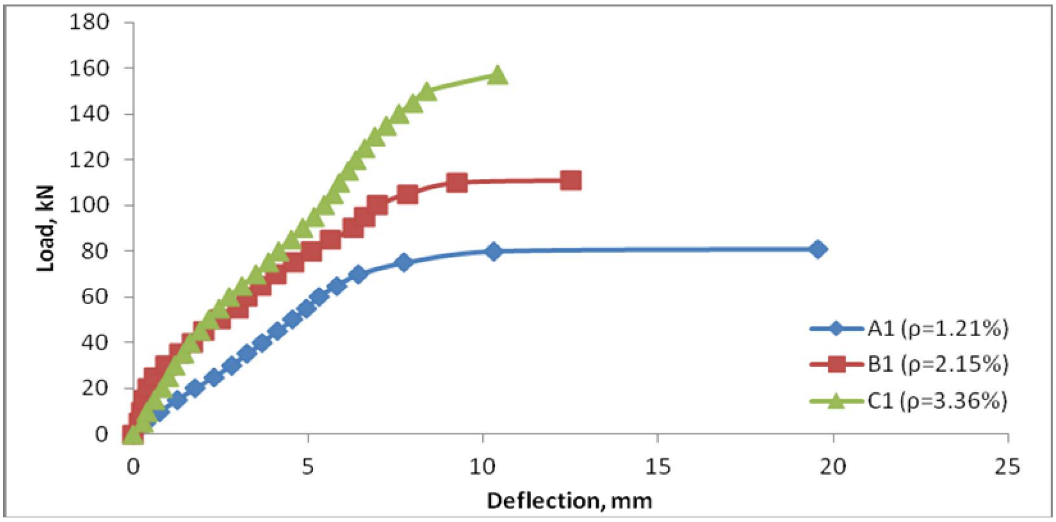

Fig .(30) Load-deflection curves for CC beams (h_R/h=0).

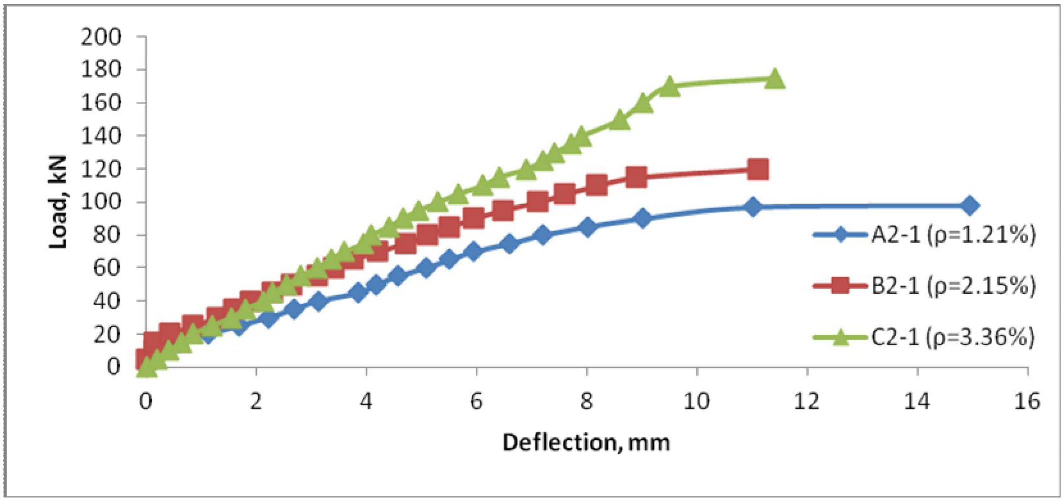

Fig .(31) Load-deflection curves for hybrid beams with V_f=1% and h_R/h=0.25 (RPC in tension).

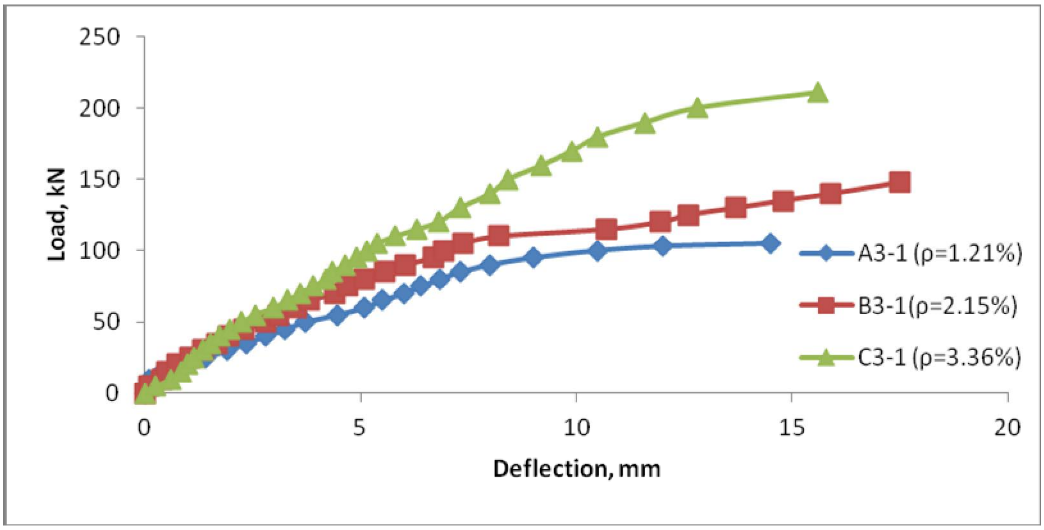

Fig .(32) Load-deflection curves for hybrid beams with V_f=1% and h_R/h=0.5 (RPC in tension).

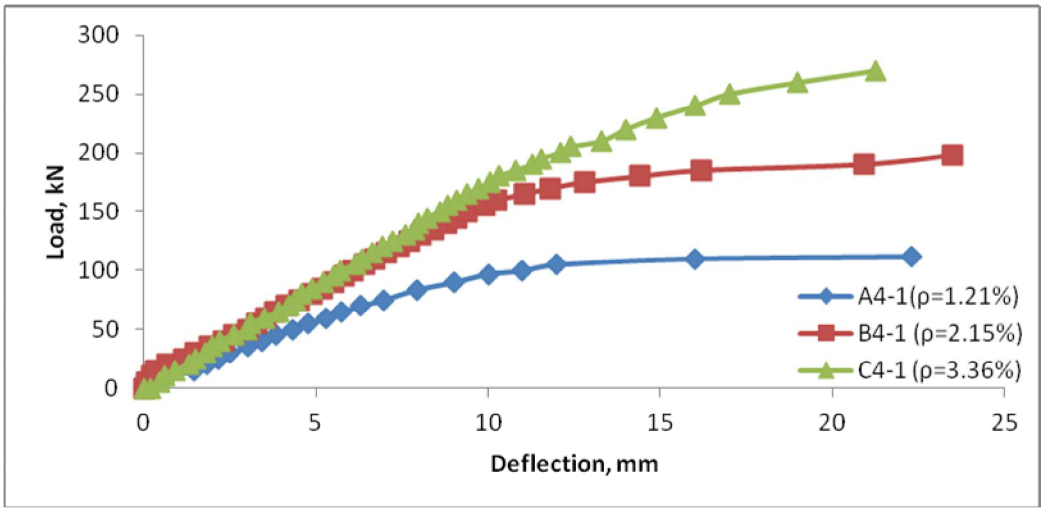

Fig .(33) Load-deflection curves for RPC beams (h_R/h=1) with V_f=1%.

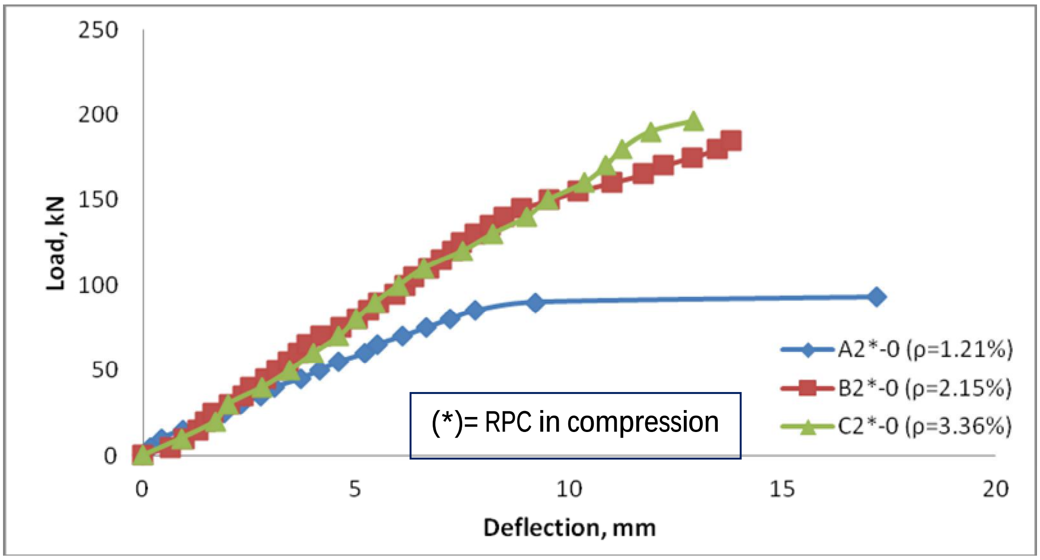

Fig .(34) Load-deflection curves for hybrid beams with V_f=0% and h_R/h=0.25* (RPC in compression).

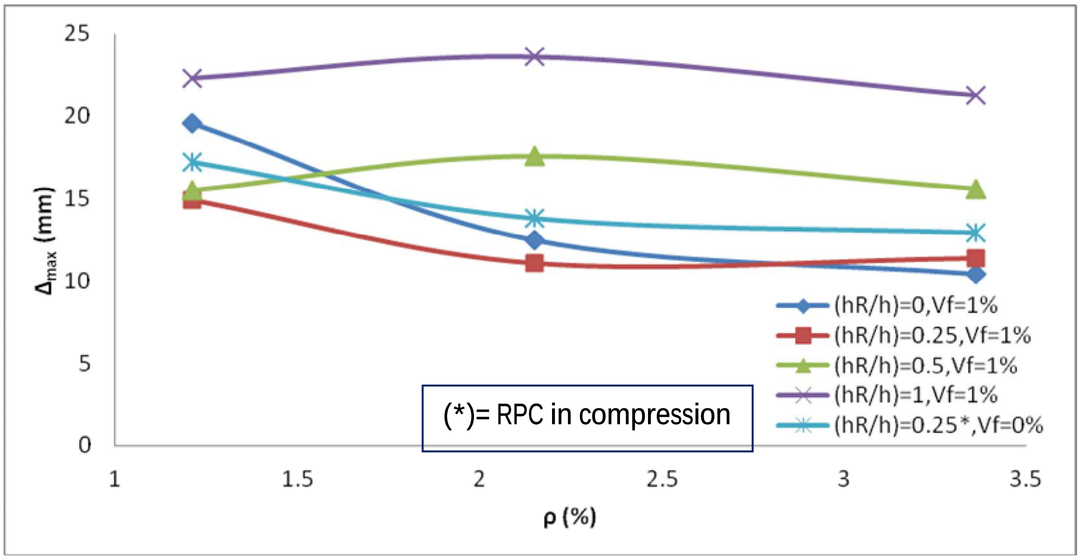

Fig .(35) Effect of longitudinal steel ratio on maximum deflections of the tested beams.

5. Conclusions

Based on the results obtained in the present work from the experimental tests 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 and 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 Load-deflection Behavior

3. Under-reinforced hybrid beams (ρ =1.21%) exhibit a stiffer behavior than the CC beam (A1) especially when using steel fibers ratio of 2%. Only a slight increase in stiffness was observed when (h_R/h) increases from 0.25 to 0.5. A slight increase in stiffness is also observed when RPC is used in compression as compared to hybrid beam with RPC in tension. For over-reinforced beams (ρ=2.15% or 3.36%), no large differences can be observed in stiffnesses of CC, hybrid and RPC beams until pre-failure stage of CC beams where CC and hybrid beams with RPC in tension started to fail while RPC beams and hybrid beams with RPC in compression continue to resist higher loads and consequently higher deflections (higher energy absorption). These similar initial stiffnesses may be attributed to the greater effect of steel reinforcement in confining beams at pre-failure stage. However, hybrid beams with RPC in compression show a stiffer behavior than hybrid beams with RPC in tension.
4. When steel fibers ratio increases from 0% to 2%, the stiffness of hybrid and RPC beams increases too with very clear effect of 2% steel fibers.
5. The longitudinal steel ratio has a significant effect on load deflection behavior of the tested beams where the stiffness of CC, hybrid and RPC beams is considerably increased when (ρ) increases from 1.21% to 3.36%.
6. Maximum midspan deflections (at ultimate loads) of hybrid beams with RPC in tension (10.5mm-17.2mm) were lower than those of CC beams (19.55mm) for different ratios of steel fibers because of the greater stiffness of them, while maximum deflection of RPC beams (>22mm) was higher than CC beams because RPC beams sustained higher ultimate load and this allows them to withstand larger deflections (higher energy absorption). Hybrid beams with RPC in compression exhibit larger maximum deflections (12.9mm – 19.3mm) than those of hybrid beams with RPC in tension (10.5mm-17.2mm). Maximum midspan deflections of CC beams, hybrid beams with RPC in tension and hybrid beams with RPC in compression dropped with increasing (ρ). This reflects the change in mode of failure from yielding of tension steel to crushing of compression concrete with high ρ values.

6. References

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