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Flexural BEHAVIOR OF HYBRID REINFORCED CONCRETE BEAMS COMBINING ULTRA HIGH STRENGTH CONCRETE AND PORECILENITE AGGREGATE LIGHTWEIGHT CONCRETE

Yaarub G. Abtan[1], Hind T. Jaber[2*]

1) Assistant Prof., Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq.
2) M.Sc.Student., Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq.

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Abstract: The main objective of this research was studied the flexure behavior of hybrid reinforced concrete beams combining reactive powder concrete (RPC) and lightweight concrete (LWC). The experimental work consists of casting and testing in flexure seven simply supported reinforced concrete beams. The dimensions of (7) beams were geometrically similar, having rectangular cross-section, of dimensions (125×200×1600) mm. Lightweight concrete was used in tension layer and reactive powder concrete was used in compression layer for all hybrid concrete beams. The main variables were; type of concrete (LWC and RPC), thicknesses of RPC layer (h_R =0, 50, 100 and 200) mm and longitudinal reinforcement ratios (ρ= 0.0033 and 0.0227). The type of LWC used in the experimental work was porecilenite aggregate. The results showed that the characteristic strength (first and ultimate loads) was increased when the thickness of RPC layer was increased. In addition to that, these parameters were decreased the values of deflection. All beams failed by flexure mode without any shear cracks which achieved by yielding of tensile steel in the tension zone. Also, for all hybrid beams, the slip was absent between the concrete layers. Finally, the reinforcement ratio (ρ) had more effective factor of all parameter used to increase the stiffness value of the beams which increased the characteristic strength and reduced the deflection values.

Keywords: *RPC, LWC, Hybrid beam, Steel Fiber, Flexure*

سلوك الانثناء للعتبات الخرسانية المسلحة المتكونة من خرسانة عالية المقاومة خرسانة بورسلنايت خفيفة الوزن

الخلاصة: يستعرض البحث الحالي دراسة عملية لسلوك الانثناء للعتبات الهجينة المتكونة من خرسانة عالية المقاومه و الخرسانة خفيفة الوزن. يتضمن العمل المختبري صب وفحص سبعة عتبات خرسانية مسلحة بسيطة الاسناد(simply supported). كانت أبعاد (7) عتبات متماثلة هندسيا، ذو مقطع عرضي مستطيل ،وبأبعاد (125×200×1600) mm . أما المتغيرات الرئيسة لهذا البحث فهي نوع الخرسانة حيث تم استخدام خرسانة المساحيق الفعالة والخرسانه خفيفة الوزن،سمك طبقة خرسانة المساحيق الفعالة (h_R =0, 50,100 and 200) mm و نسب حديد التسلح الطولي (ρ =0.0033 and 0.0227), . نوع الخرسانه خفيفة الوزن المستخدم في العمل المختبري كان حجر البورسلنايت .أظهرت النتائج المختبرية أن خصائص المقاومة (الشقوق الأولى و الاحمال القصوى) تزداد عند زياده ارتفاع طبقة خرسانة المساحيق الفعالة. بالأضافه الى ذالك هذه المتغيرات نقصت من قيمة الهطول. كل العتبات قد فشلت بالأنثناء بدون اضهار أي شقوق قص أي بوصول حديد التسليح الحد الأقصى. كذلك لكل العتبات الهجينة، لم يظهر الانزلاق بين طبقات الخرسانة. أخيرا حديد التسليح الطولي كان أكثر المتغيرات المستخدمة تأثيرا في زيادة صلاده العتبات أي زيادة كل من خصائص المقاومة ونقصان قيمة الهطول.

*Corresponding Author: hindalmgoter@gmail.com

1. Introduction

In civil engineering construction, the objective of using or selecting any material is to make full use of its properties in order to get the best performance for the formed structure. The merits of a material are based on factors such as availability, structural strength, durability, workability and cost. As it is difficult to find a material, which possesses all these properties to the desired level, the engineer's problem consists of an optimization involving different materials and methods of construction [1].

Hybrid layered systems of various strength materials can be used in civil engineering construction. The hybrid concrete structure under flexural as consists of two layers; as example the compressive layer, which is made of high compressive material, and the tension layer, which is made of lightweight material to get the best performance of this structure with lower cost and weight.

The term "Lightweight concrete" is generally used for concrete of density lesser than 2200 Kg/m^3. The use of lightweight concrete is ruled primarily by economic considerations. There are several types of lightweight concrete such as no-fines concrete, aerated concrete, and lightweight aggregate concrete [2].

Lightweight concrete (LWC) with compressive strength ranging between (17 to 27) MPa is defined as low-strength concrete (LSC). For compressive strength ranging from (27 to 41) MPa, LWC is defined as medium-strength concrete (MSC). However, for compressive strength greater than 41 MPa, it is defined as high-strength concrete (HSC) [3].

Reactive powder concrete (RPC) is one of the modern and most important developments in concrete technology, it has established great attention in recent years in the world due to its superior mechanical properties such as; high strength, high ductility, high durability, limited shrinkage, high resistance to corrosion and abrasion [4,5] .

Many research studied the hybrid structural element [6-13]. However, through the literature review of this study, cannot find any investigation on hybrid beam with LWC at its tension layer. So, the present investigation concerned on studying the behavior of this type of layered system.

2. Experimental Work

2.1 Experimental Program

The dimensions of (7) beams were geometrically similar, having rectangular cross-section of dimensions (125×200×1600) mm were casted and tested in flexure. Two of these beams were made with full lightweight concrete (LWC), one with full reactive powder concrete (RPC) and others as hybrid beams of two concrete layer. Lightweight concrete was used in tension zone and reactive powder concrete was used in compression zone for all hybrid concrete beams. The variables were type of concrete (LWC and RPC), four thicknesses for RPC layer (h_R =0, 50, 100 and 200) mm and two longitudinal reinforcement ratios (ρ= 0.0033and 0.0227). The type of LWC used in the experimental work was porecilenite aggregate. These specimens were divided into two groups, the first group had three specimens one of the them was reference with LWC, the others were hybrid specimens with two type of concrete (LWC and RPC), the second group had four specimens, slimily to the first group but the fourth specimen was another reference in this group with full RPC. The beams were tested simply supported over (1500mm) clear span under one point loading. Shear reinforcement (stirrups) were kept constant in all beams with sufficient quantity (8mm closed stirrups at 50mm center to center spacing) to ensure that all beams failed in flexure as shown in Figure (1). Also figure (2) showed details of the tested beams. All details of specimens were shown in Table (1).

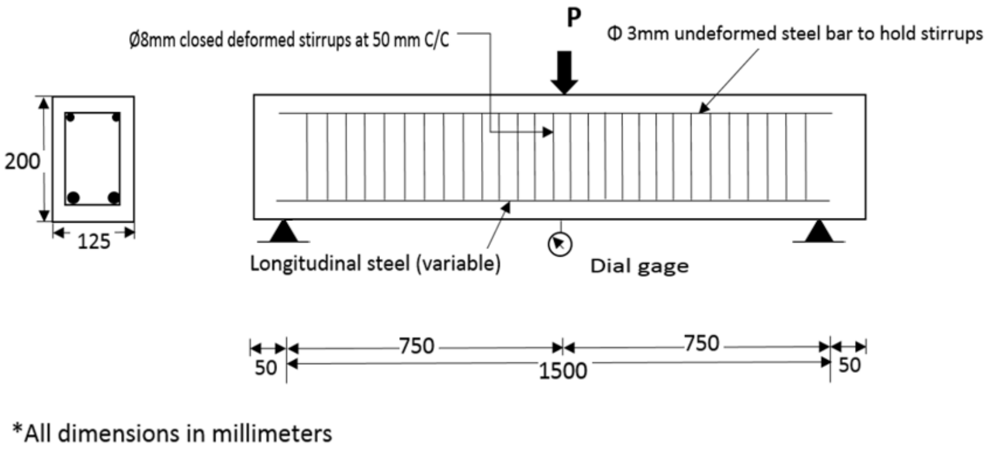


Figure (1): Setup of the Tested Beams.

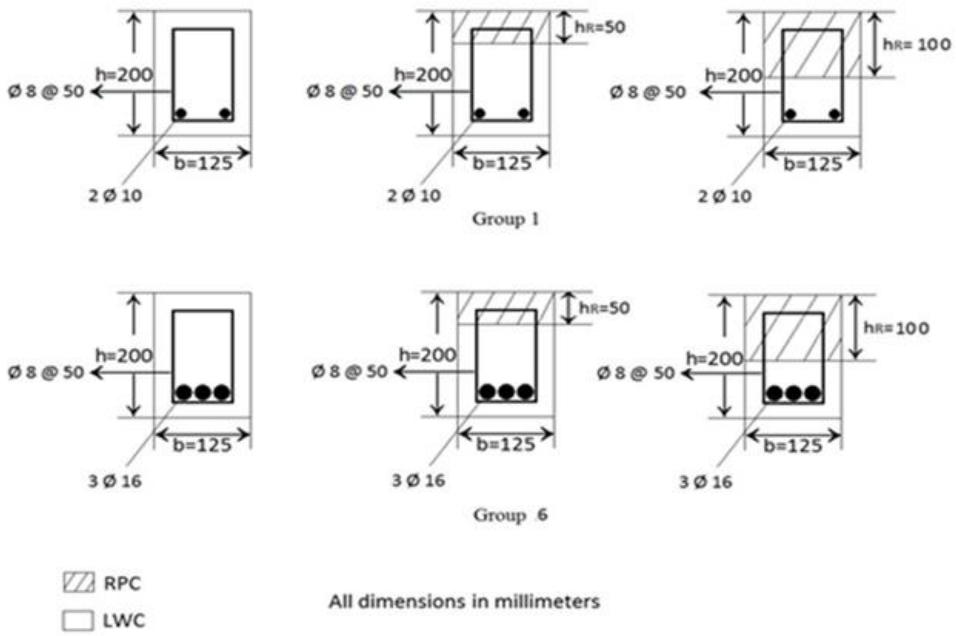


Figure (2): Details of the Tested Beams.

Table (1): Beam Specimens Details.

Group Name	Beam Name	Concrete Type	Height of RPC h*	Type of LWC	Main Reinforcement (ρ%)
G1	B1	LWC	0 h	Porecilenite Aggregate	2 φ10 (0.0033)
	B2	RPC+ LWC	0.25 h		
	B3	RPC+ LWC	0.5 h		
G6	B16	LWC	0 h	Porecilenite Aggregate	3 φ16 (0.022117)
	B17	RPC+ LWC	0.25 h		
	B18	RPC+ LWC	0.5 h		
	B19	RPC	h		

* h: 200 mm height of beam.

2.2 Materials

Ordinary Portland cement (Type I) was used throughout the experimental work of this study for both RPC and LWC. The chemical analysis and physical test results of the cement used conform to the specification No.5/1984 [14]. Al-Ekhaider natural sand of 4.75mm maximum size was used as fine aggregate. For RPC, very fine sand with maximum size 600µm was used. This sand which was used for concrete mixes, were within the requirements of the Iraqi Specification No.45/1984 [15]. Local naturally lightweight aggregate of Porcelanite stone (from Alrutba region in Iraq) was used as coarse aggregate in LWC. Grading of the Porcelanite coarse aggregate falls in the size designation of 19 to 4.75 mm and density of 830 Kg/m^3 and conformed by ASTM C 330-05 [16]. "Glenium 51" was used as superplasticizer throughout present work. A grey colored densified silica fume (manufactured by BASF Construction Chemicals, Jordan) was used as an admixture in RPC mix. The fineness of the used silica fume was 20000 m^2/kg. The concrete mix proportions used in this study were (1:1:0) and (1:1.12:0.84) by weight for reactive powder concrete and lightweight aggregate concrete, respectively.

2.3 Test Procedure and Measurements

All beams were tested as simply supported beams over a clear span of 1500mm under one point load using hydraulic universal testing machine (MFL system) with ultimate load capacity (3000 kN). Mid span deflection of the tested beam was recorded every 5kN using a dial gage of 0.01mm accuracy and 30mm capacity attached to the bottom center of the beam were fixed in its correct location, In addition, two dial gauges with (0.001mm/div.) accuracy were used to measure the slip of all hybrid beams, see Figure (3).

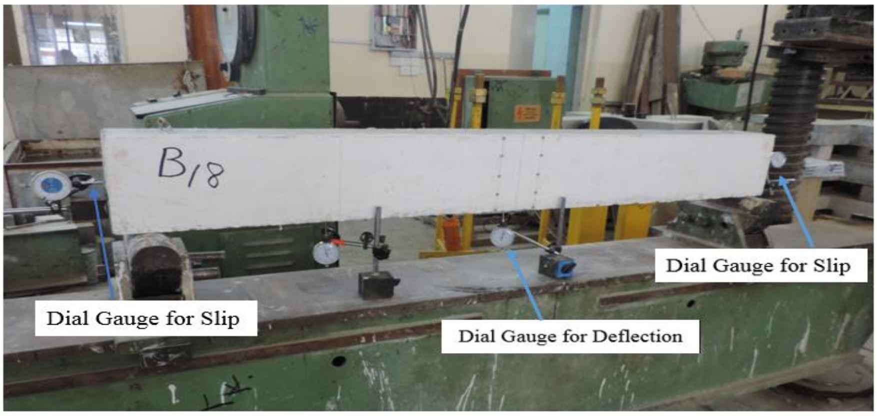


Figure (3): Beams under Testing.

3. Result and Discussion

As mentioned previously, the main objective of this study was to investigate the structural behavior of hybrid reinforced concrete beams combining reactive powder concrete (RPC) and lightweight concrete (LWC).

The experimental results of rectangular beam specimens including; general behavior and crack pattern, first cracking loads, ultimate loads ,load-deflection response at mid span and load-slip at interface layer were presented and discussed.

3.1 General Behavior and Crack Pattern

Photographs of the crack patterns at failure stage of all project tested beams were shown in Figure (4).The numbers shown beside the cracks indicated the load when the crack had reached that position. The test results of load characteristics and deflection were given in Table (2). The general behavior of the tested beams can be described as follows:

At early stages of loading, the tested beams were free of visible cracks and then the first crack was appeared at bottom of mid span in the tension zone. The load at which crack appears refers as cracking load (P_{cr}). Gradually, several cracks initiated in the tension zone at the constant moment region, with increasing the loads, these cracks extended upwards and became wider. In the final stages of loading, the cracks were developed and extend faster, some of them reached the compression zone until the failure occurred at ultimate load capacity (P_u).

It can be noticed that the number of cracks was approximately equal for groups (1and 6) where LWC type with porecilenite. The number of cracks increased when the strength of the section was increased, therefore; this number was increased by increasing the thickness of RPC gradually to (0.5 h) in the hybrid section beams (from B1 to B18) and this was explained the reason of higher cracks number (20) in B19 which had the maximum strength with uniform RPC section. This may be due to the strength of the beam section was increased with increased the thickness of RPC layer, thereby, the ultimate load capacity of the section was increased, so, the number of cracks was increased. Another note can be observed that in each group of beams when the number of cracks increased, its height in middle span of the beam (pure flexure region) was increased also. When the height of cracks increased, it led to rise the neutral axis upward and reduce the area of the compression zone.

Table (2): Experimental Results of Tested Beams.

Group No.	Beam No.	Concrete Type	Height of RPC h**	Load (kN)		Maximum Mid Deflection (mm)	$\frac{P_{cr}}{P_u}$ %	$\frac{P_{cr}}{(P_{cr})^*}$ %	$\frac{P_u}{(P_u)^*}$ %
				Pcr	Pu				
G1 (2φ10)	B1*	LWC	0 h	22.5	42.5	6	0.529	1	1
	B2	RPC+ LWC	0.25 h	32.5	51.5	5.14	0.631	1.44	1.21
	B3	RPC+ LWC	0.5 h	40	78	5.05	0.512	1.78	1.83
G6 (3φ16)	B16*	LWC	0 h	40	62.5	4.05	0.640	1	1
	B17	RPC+ LWC	0.25 h	50	78.5	4.05	0.636	1.25	1.25
	B18	RPC+ LWC	0.5 h	60	120	3.88	0.500	1.5	1.92
	B19	RPC	h	115	260	4.15	0.442	2.88	4.16

* Reference Beams of this group.
** h: 200 mm height of beam.

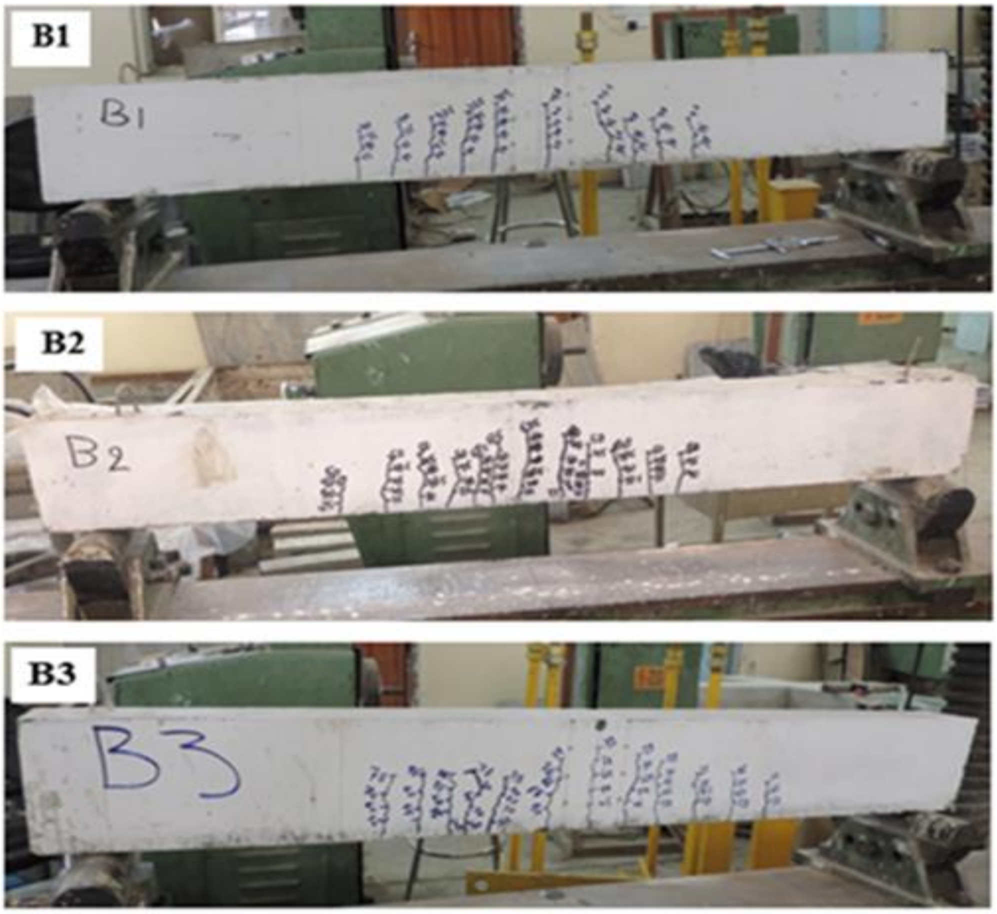


Figure (4): Crack Patterns for Tested Beams.

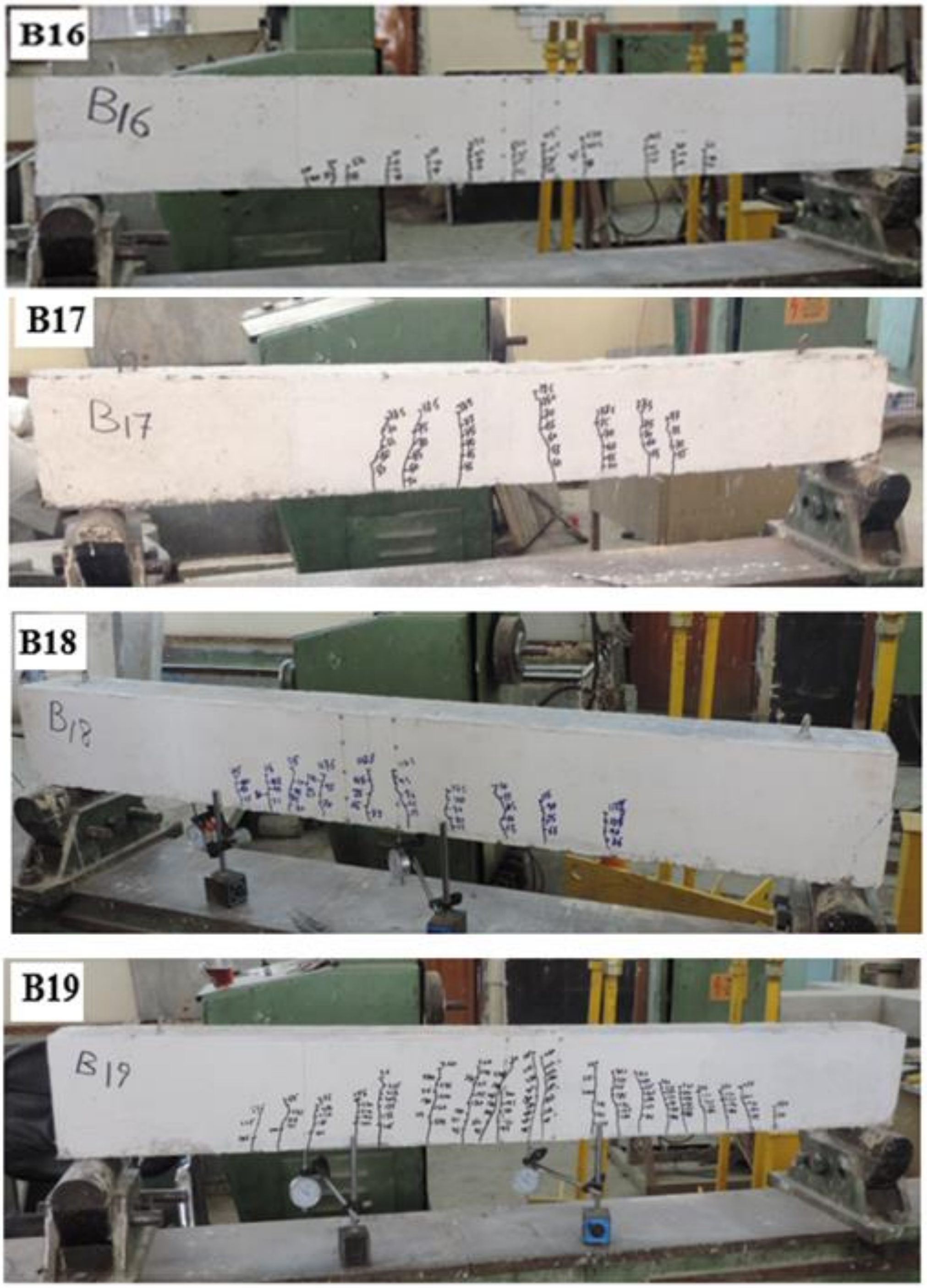


Figure (4): (Continued).

3.2 Strength Characteristics

In this part, first cracking and ultimate loads were presented and discussed for all the tested beams. The obtained data were listed in Table (2) to (4) and shown in Figures (5) to (9).

The first cracking loads of the beams varied from (44.2%) to (64%) of the experimental ultimate loads, and all first cracks were distributed throughout the constant moment region.

Table (3): Increasing Percentage of First Cracking and Ultimate Loads for Groups of Different Thickness of RPC.

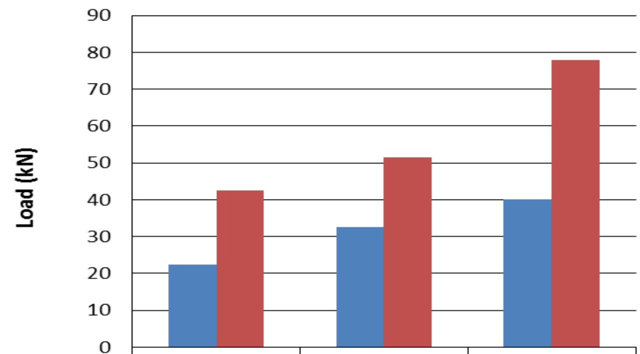
Group No.	Beam No.	Concrete Type	Type of LWC	Variable Used: Thickness of RPC	Load (kN)		Increased Percentage %	
					Pcr	Pu	Pcr	Pu
1 **(2φ10)**	B1*	LWC	Porecilenite Aggregate	0 h	22.5	42.5	-	-
	B2	RPC+ LWC		0.25h	32.5	51.5	44	21
	B3	RPC+ LWC		0.5 h	40	78	78	84
6 **(3φ16)**	B16*	LWC	Porecilenite Aggregate	0 h	40	62.5	-	-
	B17	RPC+ LWC		0.25h	50	78.5	25	26
	B18	RPC+ LWC		0.5 h	60	120	50	92
	B19	RPC		h	115	260	188	316

* Reference beam of this group.

Table (4): Increasing Percentage of First Cracking and Ultimate Loads of Different Reinforcement Steel Ratio.

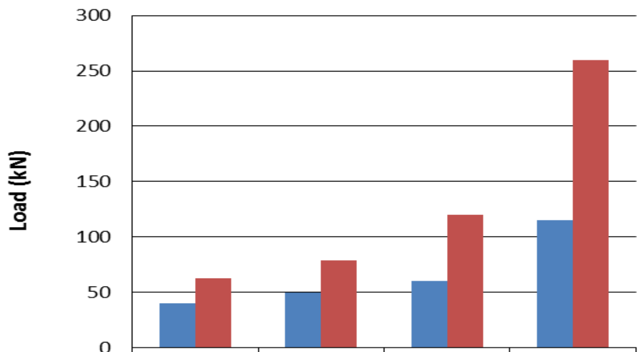
eam No.	Group No.	Concrete Type	Type of LWC	Thickness of RPC	Variable Used: Reinforcement Steel Ratio	Load (kN)		Increased Percentage %	
						Pcr	Pu	Pcr	Pu
31*	G1	LWC	Porecilenite Aggregate	0 h	2φ10	22.5	42.5	-	-
316	G6				3φ16	40	62.5	78	47
32*	G1	RPC+LWC		0.25h	2φ10	32.5	51.5	-	-
317	G6				3φ16	50	78.5	54	52
33*	G1	RPC+LWC		0.5 h	2φ10	40	78	-	-
318	G6				3φ16	60	120	50	54

*Reference beam to comparison.
** represent decrees.



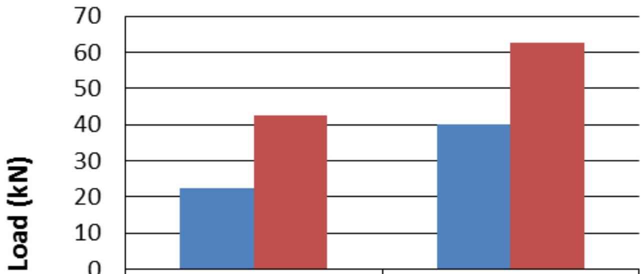
	B1	B2	B3
First cracking loads (kN)	22.5	32.5	40
Ultimate load (kN)	42.5	51.5	78

Figure (5): First Cracking and Ultimate Loads for Group No.1 with Porecilenite Aggregate (2Ø10).



	B16	B17	B18	B19
First cracking loads (kN)	40	50	60	115
Ultimate load (kN)	62.5	78.5	120	260

Figure (6): First Cracking and Ultimate Loads for Group No.6 with Porecilenite Aggregate (3Ø16).



	B1	B16
First cracking loads (kN)	22.5	40
Ultimate load (kN)	42.5	62.5

Figure (7): First Cracking and Ultimate Loads for Different Reinforcement Steel Ratio with Porecilenite Aggregate and (0h) RPC.

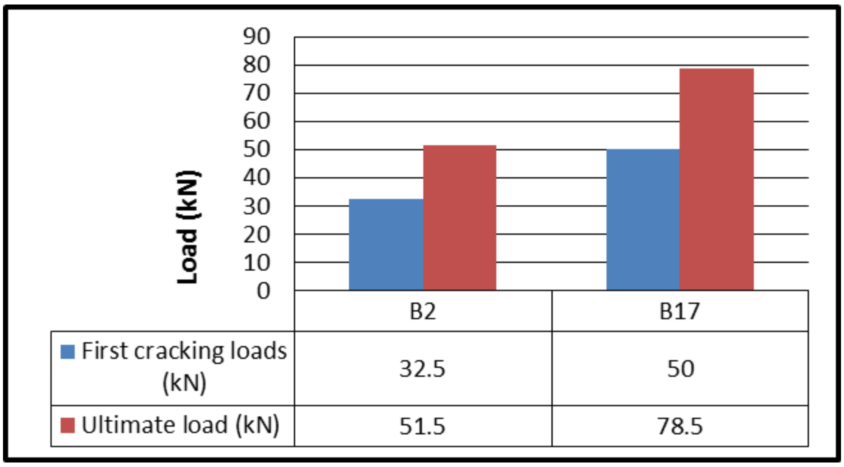


Figure (8): First Cracking and Ultimate Loads for Different Reinforcement Steel Ratio with Porecilenite Aggregate and (0.25h) RPC.

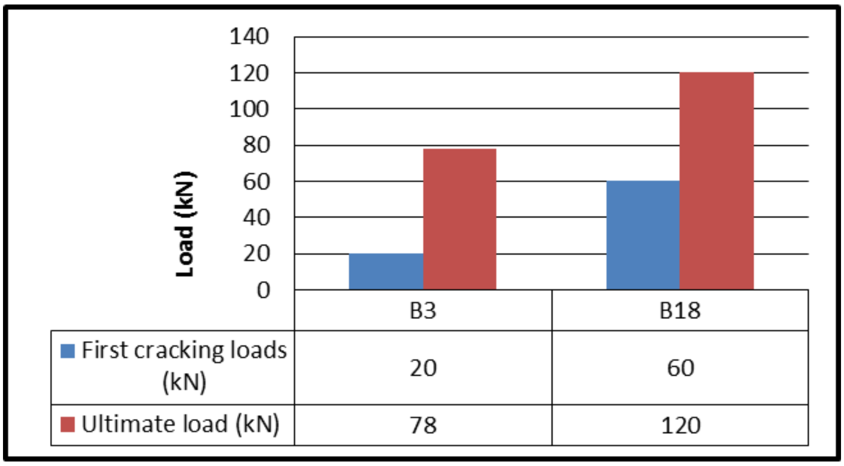


Figure (9): First Cracking and Ultimate Loads for Different Reinforcement Steel Ratio with Porecilenite Aggregate and (0.5h) RPC.

3.2.1 First Cracking Load (Pcr)

The first cracking loads were presented in Table (2) and Figures (5) to (9), as well as the crack patterns for all tested beams was shown in photographs of Figure (4).

For each group of tested beams, figures (5) and (6), the value of the cracking load was increased with increasing the RPC thickness. For example the values of cracking loads in group 1 were (22.5, 32.5 and 40) kN for (B1, B2 and B3) where the thickness of RPC zone was (0h, 0.25h and 0.5h), respectively, as shown in Figure (5). It can be seen from results, increasing the RPC thickness in the compression zone leads to increase the cracking load value of the beam, this may be due to the increase of the cracking moment value of the section. Table (3) showed the increasing percentage of the first cracking loads for groups of different thickness of RPC.

The comparison among the groups (1and 6) where the beams were similar in hybrid section (the LWC was Porecilenite) but different in reinforcement ratio revealed that increasing the reinforcement ratio (ρ) leads to increase the cracking load value. However, the cracking load values of group 6 (B16, B17 and B18) were higher than the corresponding values of groups 1 (form B1 to B3) as shown in Figures (7) to (9). This result was achieved due to the increasing of tension reinforcement ratio which led to increase the resistance of the section, thereby, increasing the cracking load value of the beams. Table (4) showed the increasing percentage of the first cracking loads of different reinforcement steel ratio.

The results revealed that increasing the cracking load value can be increased by increasing the depth of RPC layer or increasing the reinforcement ratio. Group 6 had higher values of cracking load which means that the reinforcement ratio had more effective factor on the cracking load in case of hybrid section. In addition, for each group, the ratio of cracking load of the beam to the cracking load value of its reference specimen in the entire group was increased from 1 to about 1.64 when the RPC layer was increased gradually to (0.5 h), but this value was smaller than 2.88 which was the value of (B19) with uniform section of RPC layer (h). This result may be due to that the uniform section with RPC had higher strength and higher modulus of rupture, so it had high tensile strength to resist tensile stress and cracking. Thereby, the beam (B19) in group 6 which had RPC section only and high reinforcement ratio had the greatest cracking load value among all the tested beams.

3.2.2 Ultimate Load (Pu)

The ultimate loads were presented in Table (2) and Figures (5) to (9).

For each group of tested beams, figures (5) and (6), the value of the ultimate load was increased with increasing the RPC thickness. For example these values of ultimate loads in group 1 were (42.5, 51.5 and 78) kN for (B1, B2 and B3) where the thickness of RPC zone were (0h, 0.25h and 0.5h), respectively, as shown in Figure (5). Table (3) showed the increasing percentage of the ultimate loads for groups of different thickness of RPC.

The comparison among the groups (1and 6) where the beams were similar in hybrid section (the LWC was Porecilenite) but had different reinforcement ratio revealed that increasing the reinforcement ratio (ρ) leads to increase the ultimate load value. Therefore, the ultimate load values of group 6 (B16, B17 and B18) were higher than the corresponding values of groups 1 (form B1 to B3), as shown in Figures (7) to (9). Table (4) showed the increasing percentage of the ultimate loads of different reinforcement steel ratio.

It is noticeable that the behavior of tested groups of beams was similar in both cracking and ultimate loads. Also, the results revealed that by increasing the thickness of RPC layer from (0 to 0.5) h, the ultimate load value of the beam can be increased. Group 6 had higher values of ultimate load which confirmed that the reinforcement ratio had more effective factor on the strength in case of hybrid section. While, the beam (B19) in the same group, which had RPC section only and high reinforced ratio, was the strongest one among all the tested beams, thereby, the uniform RPC section was better than the hybrid section for carrying load capacity. In addition, for each group, the ratio of ultimate load of the beam to the ultimate load value of its reference specimen in the entire group was increased from 1 to about 1.87 when increasing the RPC layer gradually to (0.5 h) because of increasing moment capacity of the section, but this value was still smaller than the value 4.16 which was the value of (B19) with uniform section of RPC layer (h) because of the uniform section with

RPC was more strength and had high moment capacity than hybrid section with lower strength concrete in the tension zone.

3.3 Load-Deflection Relationship

The load-deflection curves were graphed for the mid span deflection with the applied load. These curves reflect the deformations of the tested beams under the effect of the bending moment. The maximum deflections at ultimate load or near failure were presented in Table (2) and Figures (10) to (15).

In general, all seven tested beams exhibited similar behavior for load deflection response. At the beginning of the test for each tested beam, the curves initiated with a linear slope and it was continued approximately constant until cracking appear. After cracking, the slope of the curve decreased and continued up to yielding of the tensile reinforcement. At the last stage of the test, the curve seems to be nearly horizontal or flat. It was obvious that at all the Figures (10) to (15), the curves began with convergent values, then when cracking appears these curves spread far of other according to the differences in the beams through the depth of the RPC layer and the reinforcement ratio.

For each group of tested beams, it can be seen from Figures (10) and (11) the value of the deflection was decreased with increasing RPC depth (from 0 to 0.5) h. For example, these values of maximum mid span deflection in group 1 (6, 5.14 and 5.05) mm were reduced through (B1, B2 and B3) where the depth of RPC zone were (0h, 0.25h and 0.5h), respectively, as shown in Figure (10). This result means that when increasing the depth of high strength concrete (RPC) layer in the compression zone leads to increase the flexural stiffness of the beam and improve its capability to resist deformation.

The comparison among the groups (1 and 6) where the beams had same hybrid section (the LWC was Porecilenite) but had different reinforcement ratio revealed that increasing the reinforcement ratio (ρ) leads to increase the stiffness value of the beam which reduced the deflections. Therefore, deflection values of group 6 (B16, B17 and B18) were less than the corresponding values of groups 1 (form B1 to B3), as shown in Figures (12) to (14). Group 6 had the minimum values of deflection which confirmed that the reinforcement ratio had the more effective factor on the deformability of the beam in case of hybrid section. While, the beam (B19) in the same group which had uniform section of RPC layer (h) and high reinforced ratio, had more stiffness in comparison with all the tested beams which revealed that the uniform RPC section was better than the hybrid, as shown in Figure (15).

It is noticeable that the behavior of tested beams in the property of stiffness and deformation resistance was similar to that mentioned previously in the cracking and ultimate loads. When the beam exhibited higher cracking and ultimate loads, it exhibited higher stiffness which decreased the deflection.

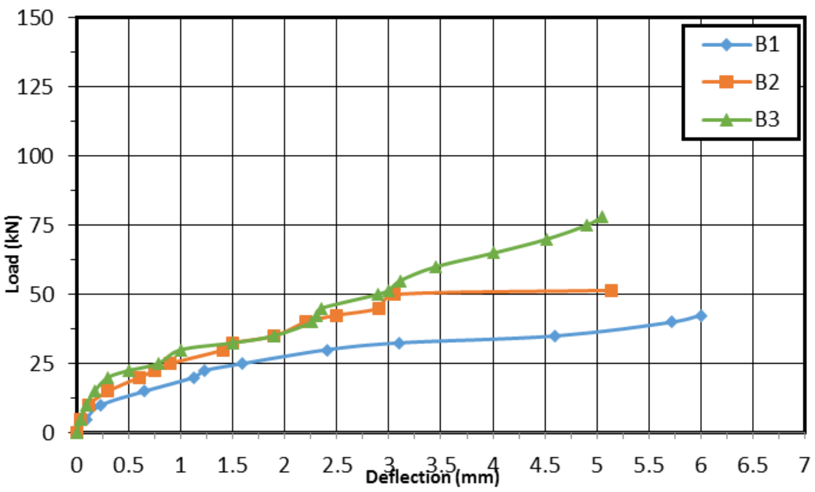


Figure (10): Load-Deflection Curves for Group No.1 Porecilenite with Aggregate (2Ø10).

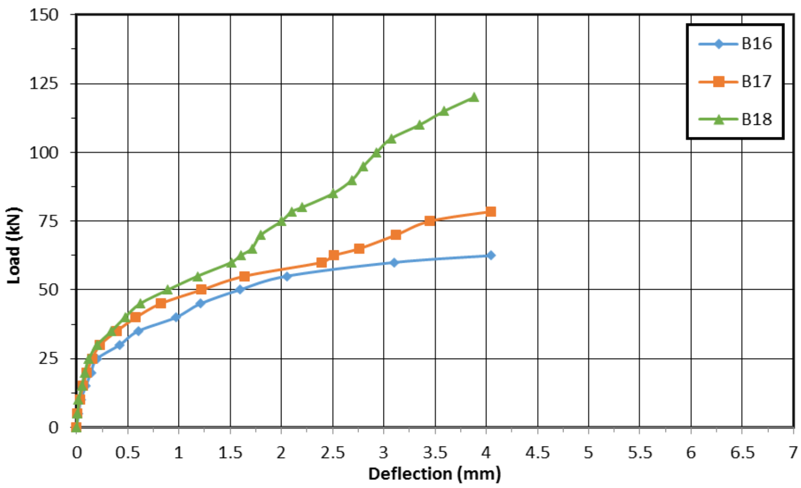


Figure (11): Load-Deflection Curves for Group No.6 with Porecilenite Aggregate (3Ø16).

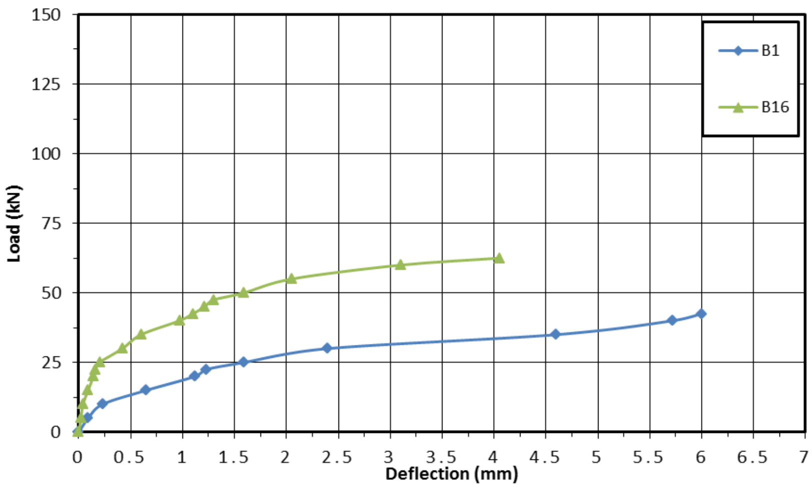


Figure (12): Load-Deflection Curves for Different Reinforcement Ratio and (0h) RPC.

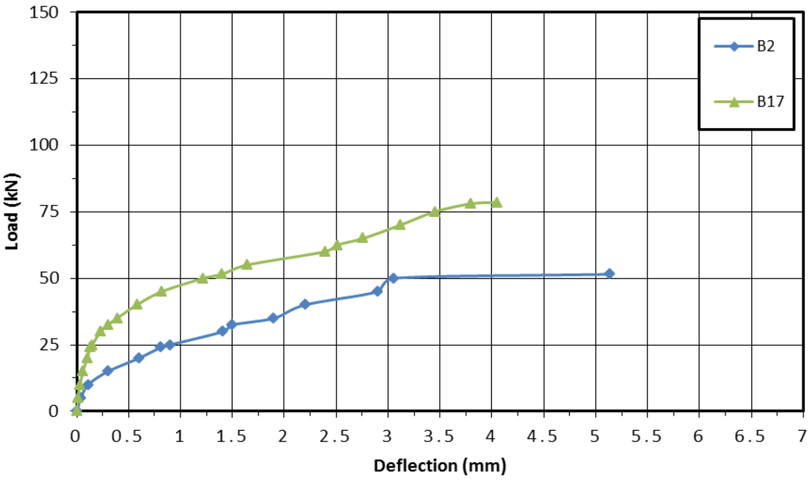


Figure (13): Load-Deflection Curves for Different Reinforcement Ratio and (0.25h) RPC.

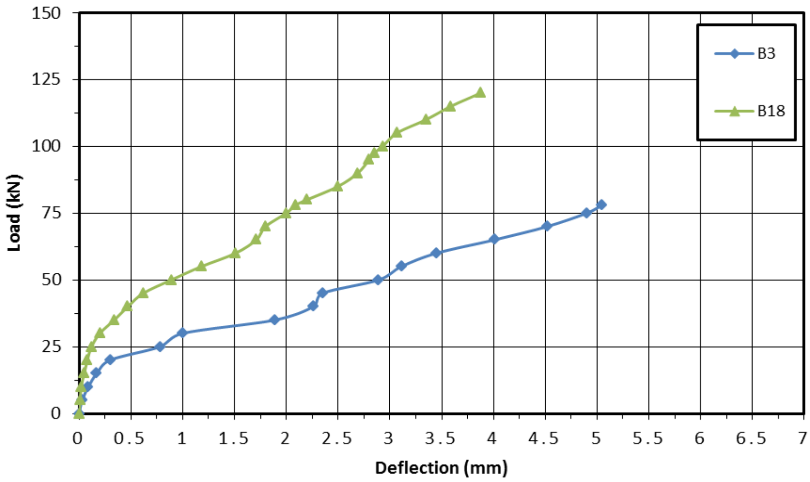


Figure (14): Load-Deflection Curves for Different Reinforcement Ratio and (0.5h) RPC.

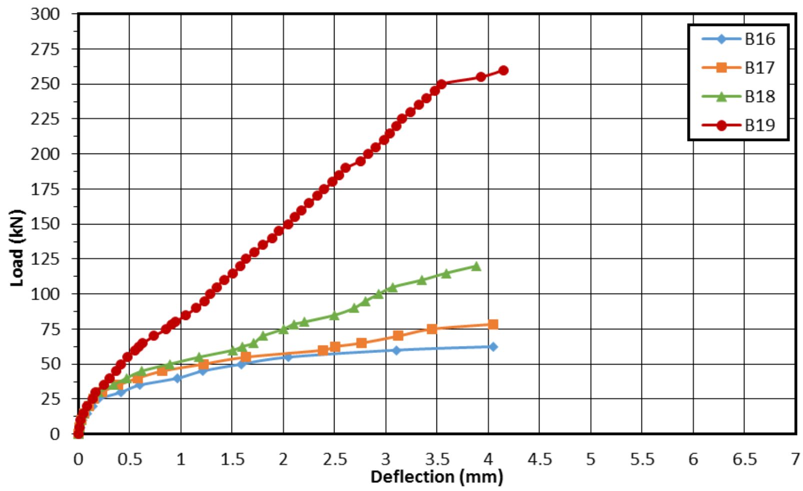


Figure (15): Load-Deflection Curves for Effect of RPC Uniform Section (B19).

3.4 Load-Slip at Interface Layer

Because of using two different types of concrete in the hybrid beams, the relative horizontal movements at the interface layer need to be checked. The dial gauges were positioned to record the slip values between the two layers with gradual increase of the applied load. During the tests, the dial gauges did not record any value of slip with the development of the applied load, and this indicated absence of the slips between the layers. Thereby, the bond between layers was enough to prevent slips. This effective bond came from three main components. One of these components was the chemical bond at the interface between layers, the other was friction between layers through contacting at interface which called mechanical bond, also. The third component was the action of the stirrups which considered as shear connectors because the stirrups extended through the compression and tension zone and bonded the layers in many position depending on spacing between stirrups. Another, but minor component, which was the hooks that used to ensure enough bond strength between the concrete in beams. These hooks extended from bottom to upper layers and crossed the interface layer in the hybrid beams and it expected contribution to reduce or prevent the slip.

4. Conclusions

Based on the results from the experimental works, the following conclusions can be drawn. It was emphasized that these conclusions were limited to the variables studied:

1. All study tested beams failed in flexure mode without any shear cracks.
2. Increasing the RPC thickness in the compression zone leads to increase the cracking and ultimate strength loads values of the beam.
3. Increasing the reinforcement ratio (ρ) had more effective factor to increase the stiffness value of the beam which reduced the deflection values.
4. Increasing the RPC layer thickness leads to decrease the maximum deflection values and the improvements in these properties were considerable, also, the number of cracks was increased.
5. During the tests, the dial gauges did not record any value of slip with the development of the applied load, and this indicated absence of the slips between the layers.

Abbreviations

UHSC	ultra high strength concrete
LWA	lightweight aggregate
RPC	reactive powder concrete
$\boldsymbol{\rho}_w$	longitudinal reinforcement ratio
h_R/h	layer thickness ratio
No.	number (issue)
pp.	pages

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