Journal of Engineering and Development
www.jead.org
Vol. 20, No.02, March2016
ISSN 1813-7822

BEHAVIOR OF HYBRID REINFORCED CONCRETE BEAMS COMBINING REACTIVE POWDER CONCRETE AND VARYING TYPES OF LIGHTWEIGHT CONCRETE

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(Received: 06/12/2015; Accepted: 26/01/2016)

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 12 simply supported reinforced concrete beams. The dimensions of (12) 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 and 100) mm, volumetric steel ratios (V_f=1%) in LWC and type of LWC (porecilenite aggregate, polystyrene and sawdust). The results showed that the characteristic strength (first and ultimate loads) was increased when the thickness of RPC layer was increased; this increased percentage were (7-100) % and (32-133) % respectively for first cracking loads and ultimate loads. In addition to that, these parameters were decreased the values of deflection from (1-17) %. However that it can be seen from the experimental results, the concrete with steel fiber and porecilenite had more effective than the concrete with other types of aggregate (sawdust and polystyrene). Also the concrete with porecilenite type reflected more number of cracks than sawdust and polystyrene, respectively. 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.

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

سلوك الانثناء للعتبات الخرسانية المسلحة الهجينة المتكونة من خرسانة عالية المقاومة وأنواع مختلفة من الخرسانة خفيفة الوزن

الخلاصة: يستعرض البحث الحالي دراسة عملية لسلوك الانثناء للعتبات الهجينة المتكونة من خرسانة عالية المقاومه والخرسانة خفيفة الوزن. يتضمن العمل المختبري صب وفحص أثنتا عشر عتبه خرسانية مسلحة بسيطة الاسناد (simply supported).كانت أبعاد (12)عتبه متماثلة هندسيا، ذو مقطع عرضي مستطيل ،وبأبعاد mm(125×200×1600). أما المتغيرات الرئيسة لهذا البحث فهي نوع

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حيث تم استخدام خرسانة المساحيق الفعالة والخرسانه خفيفة الوزن,سمكطبقةخرسانةالمساحيقالفعالة mm (100 and 50 ,0= h_R), تم استخدام نسبه (1%) لألياف الحديد في طبقه الخرسانه الخفيفة الوزنونوع خرسانه خفيفة الوزن (حجر البورسلنايت , كرات الفلين ونشارة الخشب).أظهرت النتائج المختبرية أن خصائص المقاومة (الشقوق الأولى و الاحمال القصوى) تزداد عند زياده ارتفاع طبقة خرسانة المساحيق الفعالة, هذه الزيادة المؤية كانت تتراوح مابين (7-100)% و (32-133) بالتتابع لأحمال الشقوق الاولى والأحمال القصوى. بالأضافه الى ذالك هذه المتغيرات نقصت من قيمة الهطول بمقدار (1-17)%. بينما تمت الملاحظة من خلال النتائج المختبرية أن الخرسانة مع الياف الحديد و البورسلنايت تكون أكثر فعالية من خرسانة الأنواع الأخرى من الركام (كرات الفلين ونشارة الخشب). كذلك الخرسانة المكونة من البورسلنايت تظهر أكثر تأثيرا في عدد الشقوق من الفلين ونشارة الخشب تتابعا. كل العتبات قد فشلت بالأنثناء بدون اضهار أي شقوق قص أي حديد التسليح الحد الأقصى. كذلك لكل العتبات الهجينة, لم يظهر الانزلاق بين طبقات الخرسانة.

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 (12) beams were geometrically similar, having rectangular cross-section of dimensions (125×200×1600) mm were casted and tested in flexure.

Four of these beams were made with full lightweight concrete (LWC) and others as hybrid beams of two concrete layers. 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), three thicknesses for RPC layer (h_R =0, 50 and 100) mm, one volumetric steel ratios (V_f =1%) in LWC and type of LWC (Porecilenite aggregate, polystyrene and sawdust). These specimens were divided into four groups, each group had three specimens one of the them was reference with same type if LWC that used in group, the others were hybrid specimens with two type of concrete (LWC and 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).

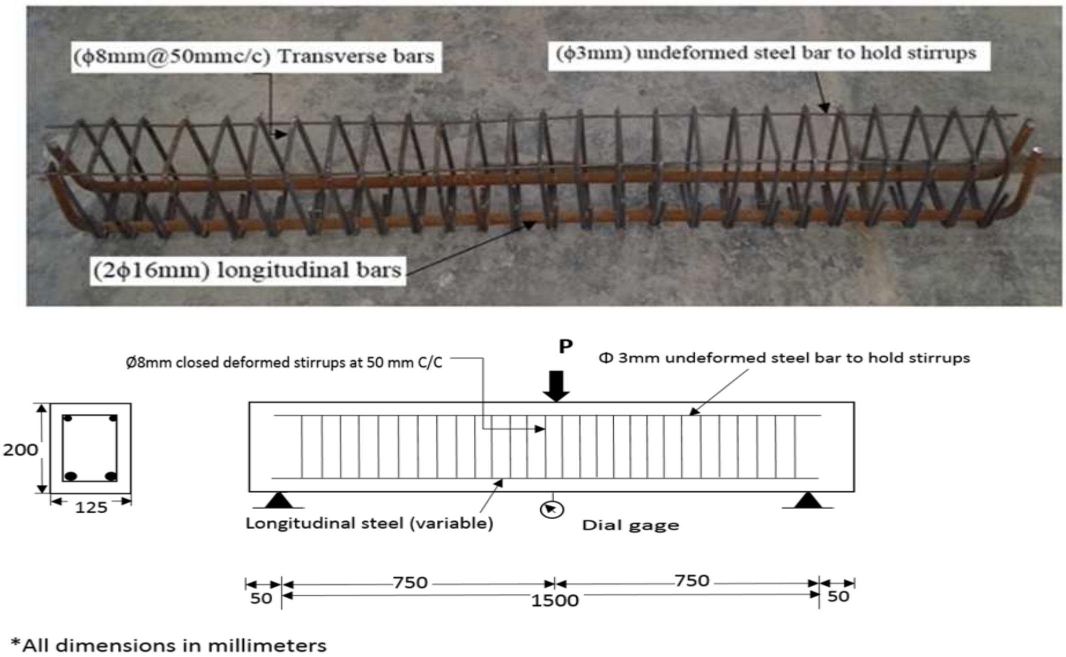

Figure (1): Setup of the Tested Beams.

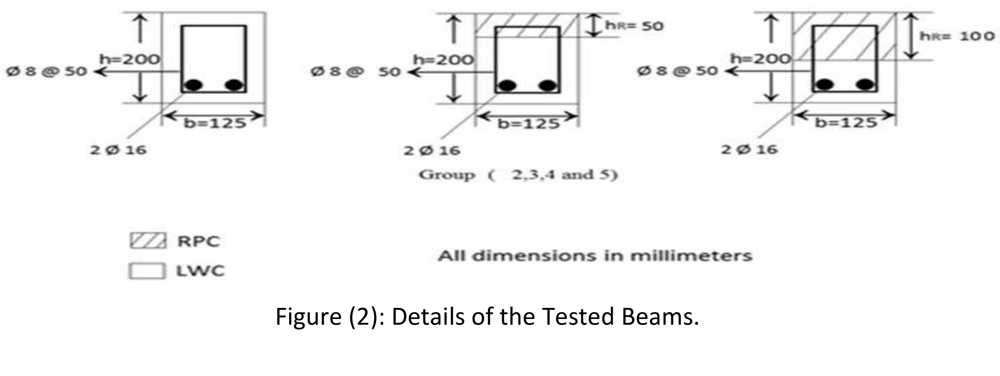

Figure (2): Details of the Tested Beams.

Table (1): Beam Specimens Detail.

Group Name	Beam Name	Concrete Type	Height of RPC h*	Type of LWC	Main Reinforcement (ρ%)
G2	B4	LWC	0 h	Porecilenite Aggregate	2 φ16
	B5	RPC+ LWC	0.25 h		
	B6	RPC+ LWC	0.5 h		
G3	B7	LWC	0 h	Polystyrene	2 φ16
	B8	RPC+ LWC	0.25 h		
	B9	RPC+ LWC	0.5 h		
G4	B10	LWC	0 h	Sawdust	2 φ16
	B11	RPC+ LWC	0.25 h		
	B12	RPC+ LWC	0.5 h		
G5	B13	LWC	0 h	Porecilenite Aggregate With steel fiber of 1%	2 φ16
	B14	RPC+ LWC	0.25 h		
	B15	RPC+ LWC	0.5 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. 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].

Polystyrene [17] with density of 20 Kg/m^{3}and sawdust with density of 1900Kg/m^3 were used in this study as light weight aggregate. "Glenium 51" was used as super plasticizer 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. Hooked short steel fibers were used through the experimental program and this type was manufactured by the SPI fiber force Company, Turkey. The concrete mix proportions used in this study were; (1:1:0), (1:1.12:0.84), (1:4.5:0.02) and (1:1.5:0.15) by weight for reactive powder concrete, lightweight aggregate concrete, low strength concrete with polystyrene and low strength concrete with sawdust, 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).

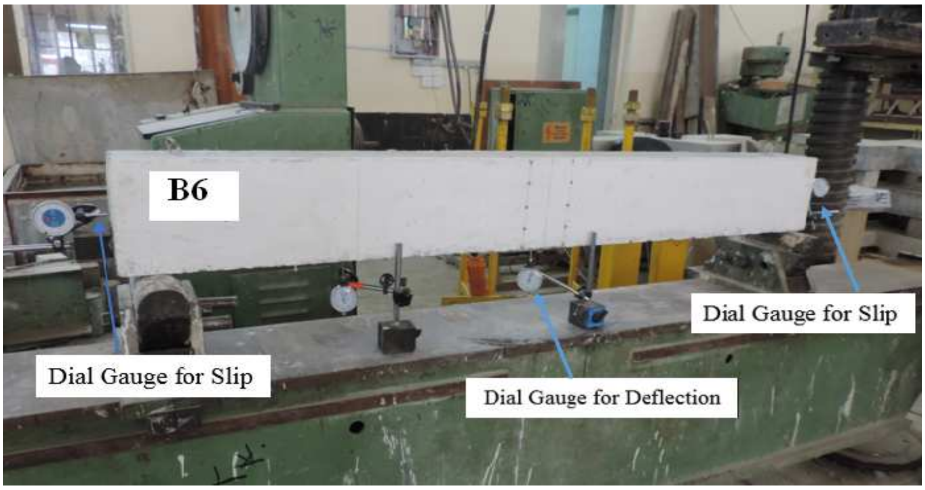

Figure (3): Beams under Testing.

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 (2and 5) where LWC type with porecilenite, where this number were (12,12,11) for group 2 (Porecilenite) and (9,9,13) for group 5 (Porecilenite with 1% steel fiber) for beams (B4 , B5 ,B6 ,B13 ,B14 and B15) ,respectively. 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 B4 to B15).

Also, lightweight concrete with porecilenite aggregate had homogeneity compared with other types of LWC, so, concrete beams with porecilenite aggregate had more number of cracks than other types of aggregate (Sawdust and Polystyrene) where this number were (7,9,12) for group 4 (Sawdust)and (7,9,12) for group 3 (Polystyrene) for beams (B10 , B11 ,B12 ,B7 ,B8 and B9), respectively. 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***	*Type of LWC*	*Load (kN)*		*Maximum Mid Deflection (mm)*	$\frac{P_{cr}}{P_u}$ %	$\frac{P_{cr}}{(P_{cr})^*}$ %	$\frac{P_u}{(P_u)^*}$ %
					Pcr	Pu				
G2 (2φ16)	B4*	LWC	0 h	Porecilenite Aggregate	22.5	47.5	5.11	0.473	1	1
	B5	RPC+ LWC	0.25 h		24	62.5	5	0.384	1.06	1.31
	B6	RPC+ LWC	0.5 h		25	97.5	4.85	0.256	1.11	2.05
G3 (2φ16)	B7*	LWC	0 h	Polystyrene	15	30	6.21	0.500	1	1
	B8	RPC+ LWC	0.25 h		20	42.5	6	0.471	1.33	1.41
	B9	RPC+ LWC	0.5 h		25	55	5.4	0.454	1.66	1.83
G4 (2φ16)	B10*	LWC	0 h	Sawdust	20	37.5	6.14	0.533	1	1
	B11	RPC+ LWC	0.25 h		30	52.5	5.45	0.571	1.5	1.4
	B12	RPC+ LWC	0.5 h		40	87.5	5.09	0.457	2	2.33
G5 (2φ16)	B13*	LWC	0 h	Porecilenite Aggregate + 1% Steel Fibers	35	55.5	4.6	0.631	1	1
	B14	RPC+ LWC	0.25 h		47.5	70	4.35	0.678	1.35	1.26
	B15	RPC+ LWC	0.5 h		55	117.5	4.05	0.468	1.57	2.11

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

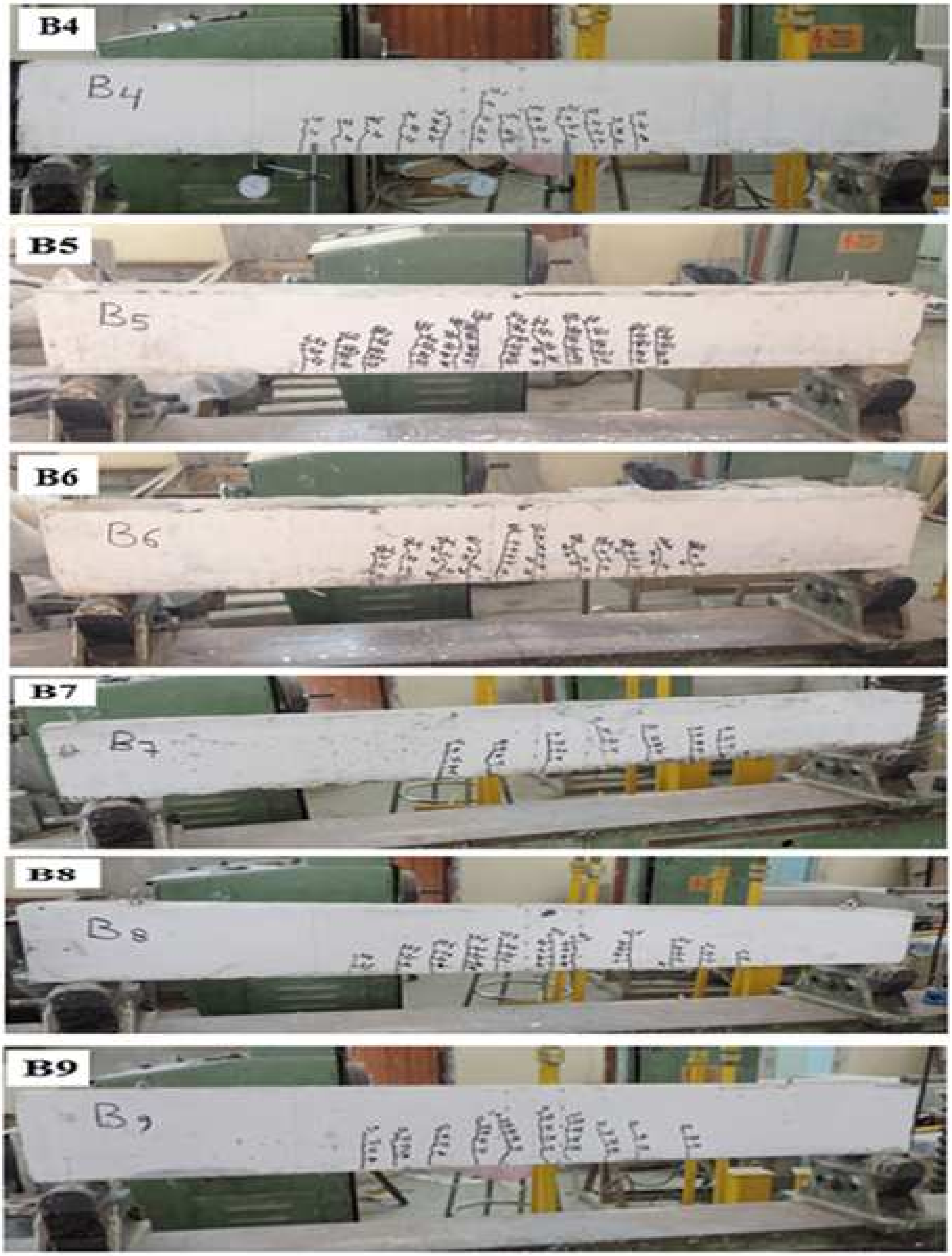

Figure (4): Crack Patterns for Tested Beams.

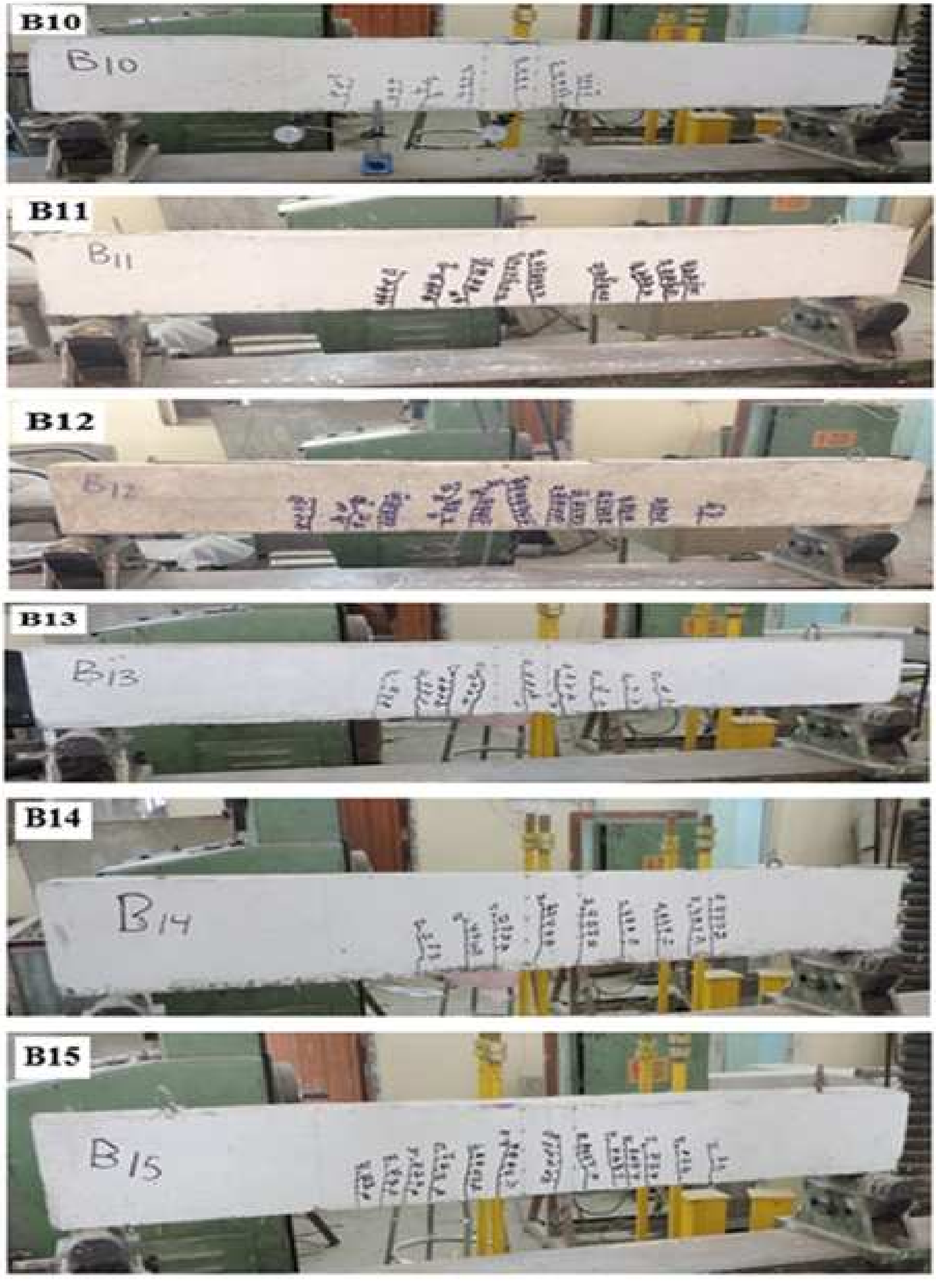

Figure (4): (Continued).

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 Tables (2) to (4) and shown in Figures (5) to (11).

The first cracking loads of the beams varied from (25.6%) to (67.8%) 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*
G2 (2ϕ16)	B4*	LWC	Porecilenite Aggregate	0 h	22.5	47.5	-	-
	B5	RPC+ LWC		0.25h	24	62.5	7	32
	B6	RPC+ LWC		0.5 h	25	97.5	11	105
G3 (2ϕ16)	B7*	LWC	Polystyrene	0 h	15	30	-	-
	B8	RPC+ LWC		0.25h	20	42.5	33	42
	B9	RPC+ LWC		0.5 h	25	55	67	83
G4 (2ϕ16)	B10*	LWC	Sawdust	0 h	20	37.5	-	-
	B11	RPC+ LWC		0.25h	30	52.5	50	40
	B12	RPC+ LWC		0.5 h	40	87.5	100	133
G5 (2ϕ16)	B13*	LWC	Porecilenite Aggregate + 1% Steel Fibers	0 h	35	55.5	-	-
	B14	RPC+ LWC		0.25h	47.5	70	36	26
	B15	RPC+ LWC		0.5 h	55	117.5	57	112

* Reference beam of this group.

Table (4): Increasing Percentage of First Cracking and Ultimate Loads of Different LWC Type.

Beam No.	Group No.	Concrete Type	Thickness of RPC	Variable Used: Type of LWC	Load (kN)		Increased Percentage %	
					Pcr	Pu	Pcr	Pu
B4*	G2	LWC	0 h	Porecilenite Aggregate	22.5	47.5	-	-
B7	G3			Polystyrene	15	30	33**	37**
B10	G4			Sawdust	20	37.5	11**	21**
B13	G5			Porecilenite Aggregate + 1% Steel Fibers	35	55.5	56	17
B5*	G2	RPC+ LWC	0.25h	Porecilenite Aggregate	24	62.5	-	-
B8	G3			Polystyrene	20	42.5	17**	32**
B11	G4			Sawdust	30	52.5	25	16**
B14	G5			Porecilenite Aggregate + 1% Steel Fibers	47.5	70	98	12
B6*	G2	RPC+ LWC	0.5 h	Porecilenite Aggregate	25	97.5	-	-
B9	G3			Polystyrene	25	55	0	44**
B12	G4			Sawdust	40	87.5	60	10**
B15	G5			Porecilenite Aggregate + 1% Steel Fibers	55	117.5	120	21

*Reference beam to comparison

** Represent decrees

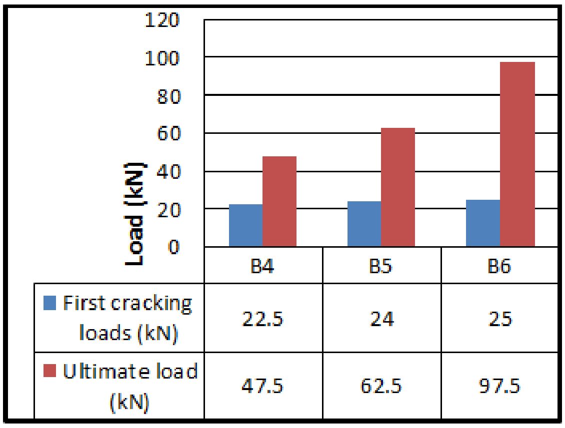

Figure (5): First Cracking and Ultimate Loads for Group No.2 with Porecilenite Aggregate (2Ø16).

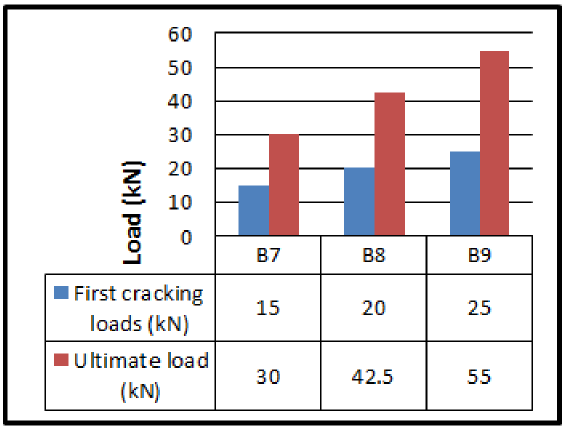

Figure (6): First Cracking and Ultimate Loads for Group No.3 with Polystyrene (2Ø16).

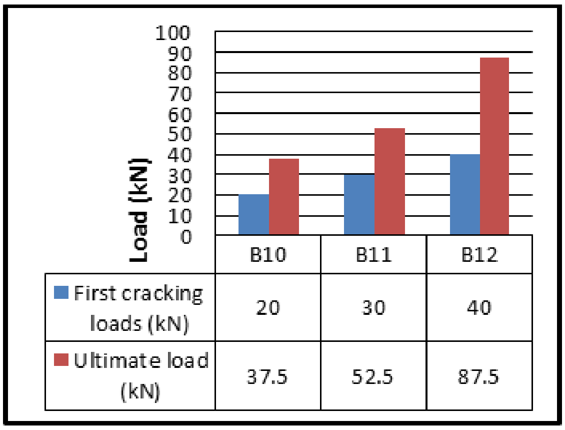

Figure (7): First Cracking and Ultimate Loads for Group No.4 with Sawdust (2Ø16).

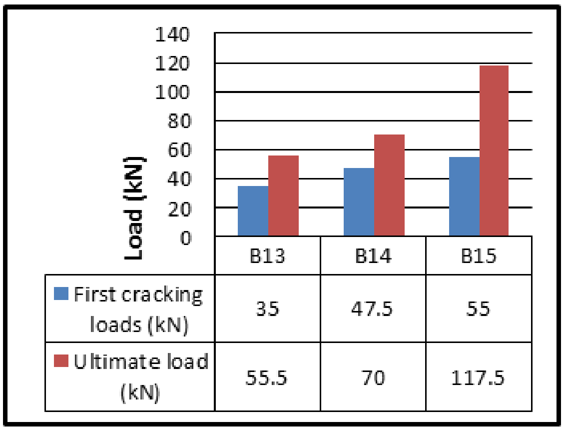

Figure (8): First Cracking and Ultimate Loads for Group No.5 with Porecilenite Aggregate Contains Steel 1% Fiber (2Ø16).

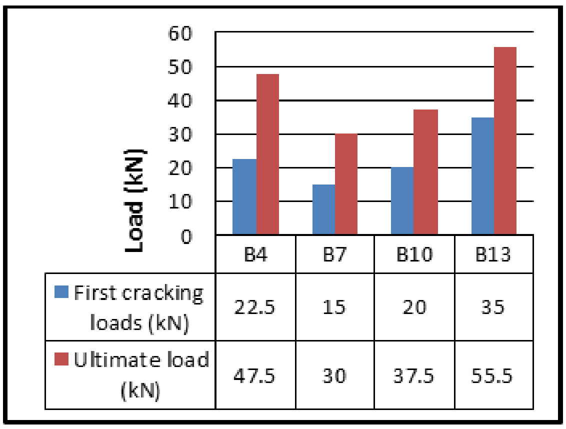

Figure (9): First Cracking and Ultimate Loads for Different LWC Type and (0h) RPC and (2ϕ16).

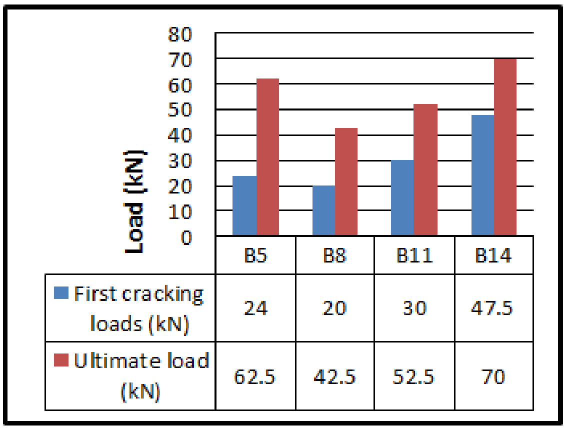

Figure (10): First Cracking and Ultimate Loads for Different LWC Type and (0.25h) RPC and (2ϕ16).

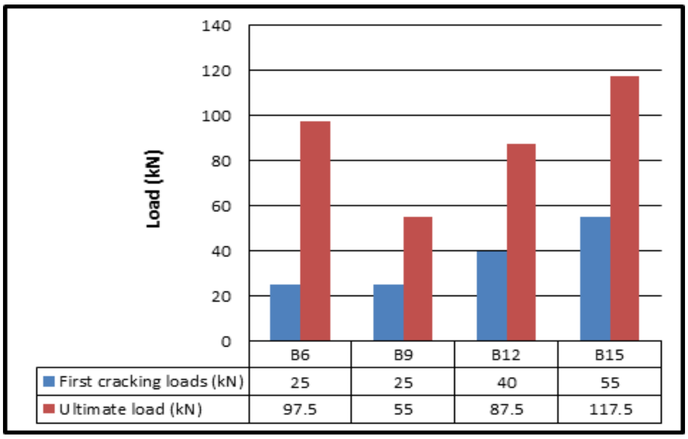

Figure (11): First Cracking and Ultimate Loads for Different LWC Type with (0.5h) RPC and (2ϕ16).

3.2.1 First Cracking Load (Pcr)

The first cracking loads were presented in Table (2) and Figures (5) to (11), as well as the crack patterns for all tested beams was shown in photographs of Figure (4).

For each group of tested beams, from Figures (5) to (8), the value of the cracking load was increased with increasing the RPC thickness. For example the values of cracking loads in group 2 were (22.5, 24 and 25) kN for (B4, B5 and B6) 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.

Figures (9) to (11) clarify the effect of LWC type on the cracking load of the beams in case of constant depth of RPC layer and reinforcement ratio in groups (2, 3, 4 and 5). These figures revealed that the type of LWC layer affects the cracking load value of the beam. The beams with porecilenite and 1% steel fibers (B13, B14 and B15) had the highest cracking load values in comparison with other beams without steel fibers. This result was confirmed the effective resistance of steel fibers against tensile stresses. Therefore, using steel fibers in the mix leads to increase the tensile strength of concrete which increased the cracking load value of the beam. Table (4) showed the increasing percentage of the first cracking loads of different LWC type.

The results revealed that increasing the cracking load value can be increased by increasing the depth of RPC layer, using steel fibers to improve the strength of the LWClayer. 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 1.58 when the RPC layer was increased gradually to (0.5 h).

3.2.2 Ultimate Load (Pu)

The ultimate loads were presented in Table (2) and Figures (5) to (11). For each group of tested beams, from Figures (5) to (8), the value of the ultimate load was increased with increasing the RPC thickness. For example these values of ultimate loads in group 2 were (47.5, 62.5 and 79.5) kN for (B4, B5 and B6) 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.

Figures (9) to (11) clarify the effect of LWC type on the ultimate load of the beams in case of constant depth of RPC layer and reinforcement ratio in groups (2, 3, 4 and 5). These figures revealed that the type of LWC layer affects the ultimate load value of the beam. The beams with porecilenite and 1% steel fibers (B13, B14 and B15) had highest ultimate load values in comparison with other groups because the steel fibers contributed in resisting the cracking and this led to increase the concrete strength against the applied loads. Table (4) showed the increasing percentage of the ultimate loads of different LWC type.

It is noticeable that the behavior of tested groups of beams was similar in both cracking and ultimate loads. Beside that the porecilenite can be strengthened by steel fibers to improve the strength of the beam. Also, the porecilenite had better effect than the sawdust which was better than the polystyrene.

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. As well as, this result can be noticed when using steel fibers to improve the strength of the LWC layer. 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 2.08 when increasing the RPC layer gradually to (0.5 h) because of increasing moment capacity of the section.

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 Tables (2), (5) and (6) and Figures (12) to (18).

In general, all 12 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 (12) to (18), 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 type of LWC materials.

For each group of tested beams, it can be seen from Figures (12) to (15) 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 2 (5.11, 5 and 4.85) mm were reduced through (B4, B5 and B6) where the depth of RPC zone were (0h, 0.25h and 0.5h), respectively, as shown in Figure (12). 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. Table (5) showed the decreasing percentage of maximum deflection for groups of different thickness of RPC.

Figures (16) to (18) clarify the effect of LWC type on the stiffness of the beams in case of constant thickness of RPC layer and reinforcement ratio in groups (2, 3, 4 and 5). These figures revealed that the type of LWC layer affects deflection values of the beam. The beams with porecilenite and 1% steel fibers (group 5) had higher stiffness and lower deflections. As well as, the beams with polystyrene (group 3) had lower stiffness and higher deflection. This behavior reflected the effect of the modulus of elasticity of used type of LWC in the section. Table (6) showed the decreasing percentage of maximum deflection of different LWC type.

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. Beside that the porecilenite can be strengthened by steel fibers to improve the stiffness of the beam as well as its strength because the concrete in this case became more strength in compression to resist the applied loads as well as deflections and more strength in tension to resist cracking.

Table (5): Decreasing Percentage of Maximum Deflection for Groups of Different Thickness of RPC

Group No.	*Beam No.*	*Concrete Type*	*Type of LWC*	*Variable Used: Thickness of RPC*	*Maximum Deflection (mm)*	*Decreasing Percentage %*
G2 (2φ16)	B4*	LWC	Porecilenite Aggregate	0 h	5.11	1
	B5	RPC+ LWC		0.25h	5	2
	B6	RPC+ LWC		0.5 h	4.85	5
G3 (2φ16)	B7*	LWC	Polystyrene	0 h	6.21	1
	B8	RPC+ LWC		0.25h	6	3
	B9	RPC+ LWC		0.5 h	5.4	13
G4 (2φ16)	B10*	LWC	Sawdust	0 h	6.14	1
	B11	RPC+ LWC		0.25h	5.45	11
	B12	RPC+ LWC		0.5 h	5.09	17
G5 (2φ16)	B13*	LWC	Porecilenite Aggregate + 1% Steel Fibers	0 h	4.6	1
	B14	RPC+ LWC		0.25h	4.35	5
	B15	RPC+ LWC		0.5 h	4.05	12

* Reference beam of this group.

Table (6): Decreasing Percentage of Maximum Deflection of Different LWC Type.

Beam No.	Group No.	Concrete Type	Thickness of RPC	Variable Used: Type of LWC	Maximum Deflection(mm)	Decreasing Percentage %
B4*	G2	LWC	0 h	Porecilenite Aggregate	5.11	1
B7	G3			Polystyrene	6.21	22**
B10	G4			Sawdust	6.14	20**
B13	G5			Porecilenite Aggregate + 1% Steel Fibers	4.6	10
B5*	G2	RPC+ LWC	0.25h	Porecilenite Aggregate	5	1
B8	G3			Polystyrene	6	20**
B11	G4			Sawdust	5.45	9**
B14	G5			Porecilenite Aggregate + 1% Steel Fibers	4.35	13
B6*	G2	RPC+ LWC	0.5 h	Porecilenite Aggregate	4.85	1
B9	G3			Polystyrene	5.4	11**
B12	G4			Sawdust	5.09	5**
B15	G5			Porecilenite Aggregate + 1% Steel Fibers	4.05	16

*Reference beam to comparison

** Represent increase

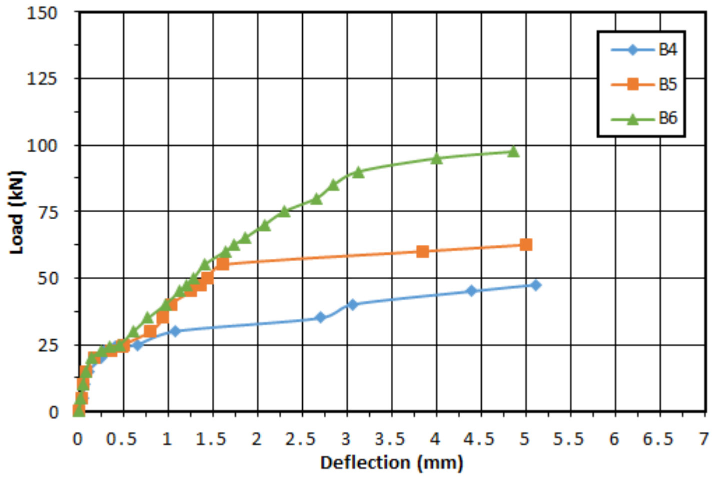

Figure (12): Load-Deflection Curves for Group No.2 with Porecilenite Aggregate (2Ø16).

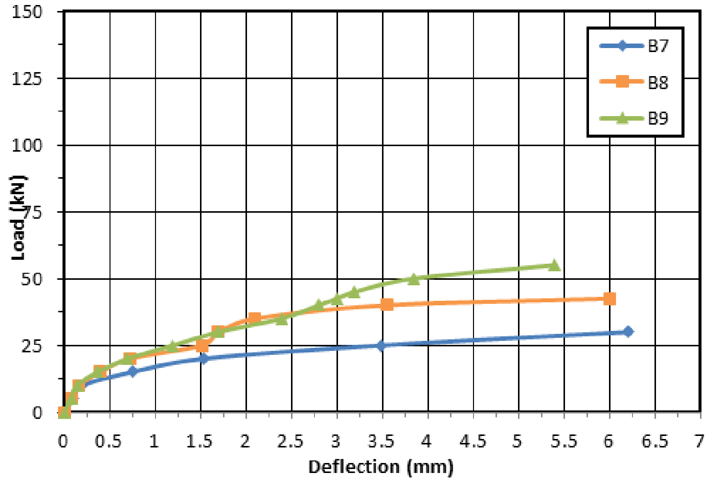

Figure (13): Load-Deflection Curves for Group No.3 with Polystyrene (2Ø16).

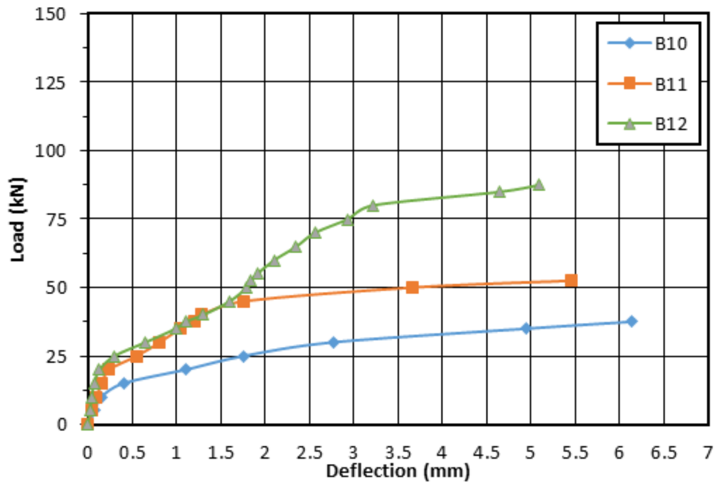

Figure (14): Load-Deflection Curves for Group No.4 with Sawdust (2Ø16).

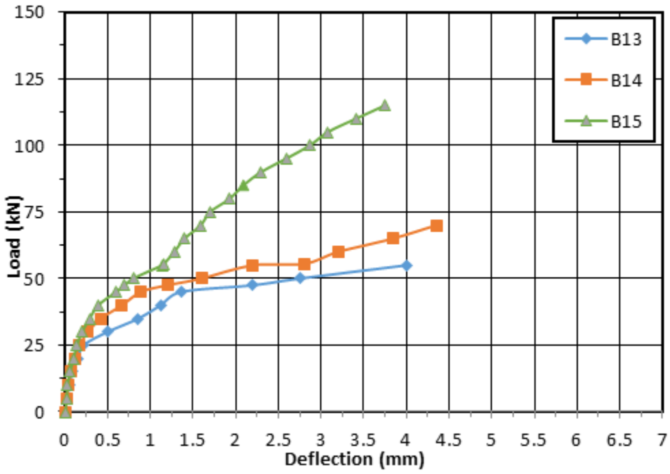

Figure (15): Load-Deflection Curves for Group No.5 with Porecilenite Aggregate Contains 1% Steel Fiber (2Ø16).

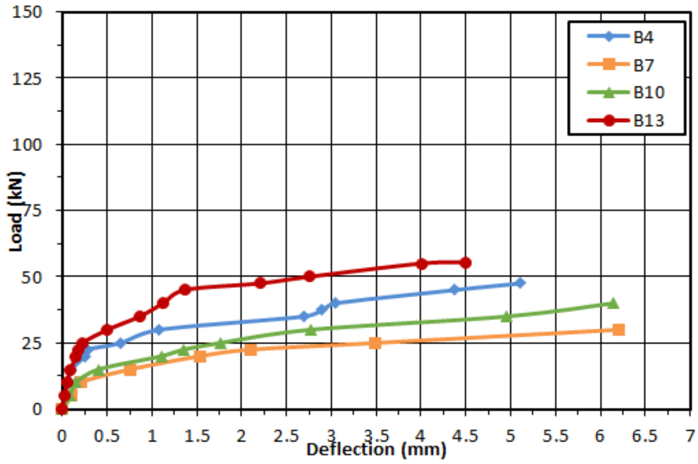

Figure (16): Load-Deflection Curves for Different LWC Type with (0h) RPC and (2Ø16).

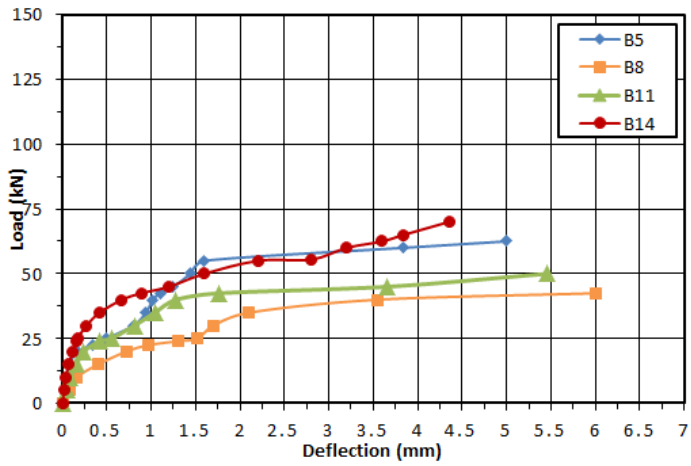

Figure (17): Load-Deflection Curves for Different LWC Type with (0.25h) RPC and (2Ø16).

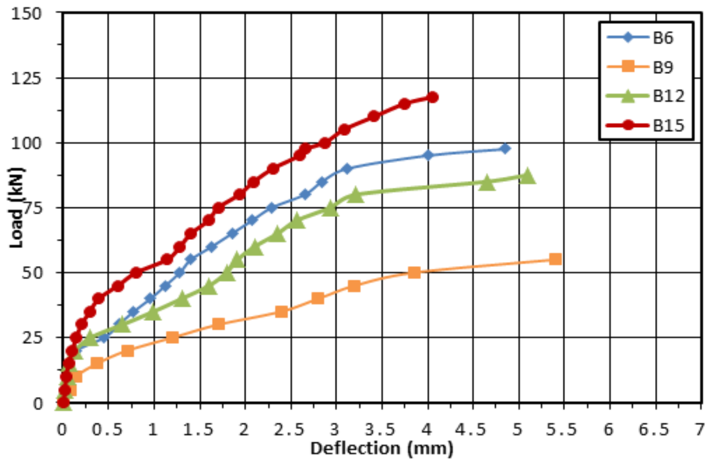

Figure (18): Load-Deflection Curves for Different LWC Type with (0.5h) RPC and (2Ø16).

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, this increased percentage were (7-100) % and (32-133) % respectively for first cracking loads and ultimate loads.
3. Increasing the cracking and ultimate loads values can be increased by using steel fibers to improve the strength of the LWC layer. Therefore, using steel fibers in

the mix leads to increase the tensile strength of concrete which increased the cracking load and the ultimate values of the beam.

4. The type of LWC layer affects deflection value of the beam. The beams with porecilenite and 1% steel fibers had higher stiffness, the decreased in values of deflection where from (10-16) % for this group (porecilenite and 1% steel fibers).
5. Increasing the RPC layer thickness leads to decrease the maximum deflection values from (1-17) % and the improvements in these properties were considerable, also, the number of cracks was increased.
6. 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
ρ_w	longitudinal reinforcement ratio
V_f	steel fiber volumetric ratio
h_R/h	layer thickness ratio
No.	number (issue)
pp.	pages

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