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BEHAVIOR OF SEMI LIGHTWEIGHT REINFORCED CONCRETE BEAMS UNDER THE INFLUENCE OF FLEXURAL LOADS

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ABSTRACT

The presented study involves an experimental investigation into the influence of semi-lightweight concrete on the structural response of reinforced concrete beams. In this research, six beam specimens with specific dimensions of 100x200x1800 mm were subjected to testing. The research involves the creation of lightweight concrete, achieved by replacing a portion of the conventional fine and coarse aggregates in the concrete mixture with polystyrene foam granules. To enhance the concrete's strength, properties, and workability, a superplasticizer and silica fume additives were incorporated. The experimental program made trial mixtures with different proportions of replacing a mixture of aggregates with polystyrene foam granules, and then lightweight concrete was obtained with a strength of 22.5Mpa and density of 1750 kg per cubic meter by replacing 40% of the mixed aggregate by weight with polystyrene foam granules by volume. Then, six semi-lightweight concrete beams were cast with different reinforcing models. The beams were studied and examined during casting, treatment, and testing in terms of bending, flexural, and strain of the lower reinforcing steel and compression zone concrete, determining the deflection, modulus of elasticity, effective moment of inertia, crack pattern, and knowledge of Type of failure for each beam to compare it with the different codes for designing concrete structures. Through this study, it was found that The values of failure moments for lightweight reinforced concrete (LWRC) obtained from test results are lower than theoretical calculations of moments for normal concrete (fcu = 22.5 MPa) by a rate ranging between 10 to 25 %, according to the percentage mentioned by the American code. The values of failure moments for lightweight reinforced concrete obtained from test results are lower than theoretical calculations of moments for normal concrete (fcu = 40.0 MPa) by a rate ranging from 20 to 35%. From the compression test of the cylinders, it was found that the modulus of elasticity of semi-lightweight concrete using polystyrene foam granules was less than the Egyptian Code calculations for the modulus of elasticity of ordinary concrete by 10%. Still, it was 10% higher than the American Code calculations.

KEYWORDS: Lightweight concrete, polystyrene foam particles, flexural loads, stress-strain curve, deflection.

سلوك الكمرات الخرسانية المسلحة الخفيفية الوزن تحت تاثير احمال العزوم

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الملخص

البحث المقدم يدرس بشكل عملي تأثير الخرسانه الخفيفه الوزن على سلوك الانحناء للكمرات الخرسانيه المسلحه. في هذا البحث تم اختبار ٦ كمرات بأبعاد ١٠٠×٢٠٠ و طولها ١٨٠٠ مم. في هذه الدراسه تم انتاج خرسانه خفيفة الوزن باستبدال خليط من الركام الناعم و الخشن

بحبيبات البوليسترين فوم , تم اضافة ملدنات فائقه للخلطه و سيليكا فيوم لتحسين المقاومه, الخواص و قابلية التشغيل . قام البرنامج العملي بعمل خلطات تجريبيه باختلاف نسب استبدال خليط من الركام بحبيبات البوليسترين فوم و من ثم تم الحصول على خرسانه خفيفة الوزن مقاومتها 22.5 ميجاباسكال و كثافتها ١٧٥٠ كجم لكل متر مكعب باستبدال ٤٠٪ من الركام الخليط بالوزن بحبيبات البوليسترين فوم بالحجم. ثم تم صب ست كمرات خرسانيه خفيفة الوزن بنماذج تسليح مختلفه و تم دراسة و فحص الكمرات اثناء الصب و المعالجه والاختبار من حيث الانحناء و انفعال حديد التسليح السفلي و انفعال الخرسانه في منطقة الضغط و تحديد الهبوط و معامل المرونه و عزم القصور الذاتي الفعال و نمط الشروخ و معرفة نوع الانهيار لكل كمره لمقارنتها بالكود المصري و الأمريكي لتصميم المنشآت الخرسانيه. ومن خلال ما قمت بدراسته تبين أن قيم عزم الإنهيار للخرسانة المسلحة خفيفة الوزن المتحصل عليها من نتائج الاختبار أقل من الحسابات النظرية للخرسانة العادية (f_{cu} = 40.0 MPa) بنسبة تتراوح بين ١٠٪ إلى ٢٥٪ بينما تقل عن حسابات الخرسانة العادية (f_{cu} = 22.5 MPa) بنسبة تتراوح من ٢٠٪ إلى ٣٥٪. ومن اختبار الضغط للأسطوانات تبين أن معامل المرونة للخرسانة شبه خفيفة الوزن باستخدام حبيبات رغوة البوليسترين كان أقل من حسابات الكود المصري لمعامل المرونة للخرسانة العادية بنسبة ١٠%. بخلاف ذلك، كانت أعلى بنسبة ١٠% من حسابات الكود الأمريكي.

الكلمات المفتاحية : خرسانة خفيفة الوزن ، حبيبات البوليسترين فوم، أحمال الانحناء، منحنى الاجهاد و الانفعال، الهبوط.

1. INTRODUCTION

Concrete is one of the most essential elements used in structural engineering, so researchers are interested in obtaining the best types of concrete in terms of use and improving properties. Among the most important of these types is lightweight concrete, which is of great importance in construction, building, and construction because it reduces the dead load and foundation loads and lowers the concrete mass, which helps to reduce the lateral load affected during an earthquake.

To reduce the weight of concrete, some aggregate can be replaced with lightweight materials with a lower density than the aggregate. This replacement should not negatively affect the concrete mixture, harm its properties, or reduce its quality.

Polystyrene foam is one of the new materials used in concrete to relatively reduce the weight of concrete.

This research aims to use polystyrene foam as a substitute for part of the aggregates and to study the behavior of lightweight reinforced concrete beams under the influence of moment loads through laboratory experiments conducted to determine the amount of foam replaced by the aggregate mixture and to obtain a homogeneous concrete mixture with the help of superplasticizers and silica fume and then Casting six reinforced concrete beams with different ratios of lower and upper reinforcement. These experiments include patterns and locations of different cracks for beams during loading, determining the type of failure and deflection in the middle of the span, studying the stress and strain curve, the load curve with deflection, and knowing the effective moment of inertia.

Flexural strength is a way of measuring the tensile strength of concrete. To measure flexural strength, concrete beams are loaded, and it's important that the span length is at least three times their depth. Flexural strength quantified as the Modulus of Rupture (MR), is typically approximated to be 10 to 20 percent of the concrete's compressive strength, as per its properties. It can be determined by standard test methods ASTM C 78 [1] (Third-Point Loading) or ASTM C 293[2] (Center-Point Loading).

Design of reinforced concrete elements for flexure based on the Strength Design Method of American Concrete Institute ACI 318-05 [3] and the Ultimate Strength Limit State in the Egyptian Code of Practice ECP 203 [4].

According to ACI 213R-87 [5] Structural lightweight concrete is defined as concrete made with lightweight aggregate; the air-dried unit weight at 28 days is usually 14.4 to 18.5 KN/m^3, and the cylinder compressive strength is more than 17.2 MPa. However, according to EURO code 2 (EN 1992-1-1:2004) [6]. Lightweight aggregate concrete is characterized by its closed structure and a density not exceeding 22 KN/m^3. It comprises or includes artificial or natural lightweight aggregates with a particle density of less than 20 KN/m^3.

According to the ACI 318-11[7]., modulus of elasticity Ec for LWC shall be permitted to be taken as ($\rho^{1.5} \times 0.043\sqrt{f'_c}$) for values of ρ between 14.40 KN/m^3 and 24.80 KN/m^3, where ρ is the unit weight of concrete and f'c is its ultimate compressive strength of concrete cylinder.

The strength of the LWA controls the upper strength limit of the LWAC, which should obtain a minimum compressive strength for a concrete cylinder of 17.2 MPa according to ACI 213R-03 [8].

The bond strength between lightweight concrete and reinforcing steel is one of the most important properties of concrete. the Analytical and experimental investigation for bond behavior of newly developed polystyrene foam particles' lightweight concrete was studied [9].

One of the most widely used materials in light concrete is foam, whether insulation concrete, structural concrete, or decorative concrete. The researcher conducted an experimental study on the flexural behavior of reinforced polystyrene blocks in concrete beams [10].

The flexural characteristics of reinforced concrete beams containing lightweight aggregate in the tensile zone was studied [11].

Lightweight reinforced concrete beams have been studied, All beams were detailed according to the Egyptian Code of Design and Construction of Reinforced Concrete Structures, ECP 203–2018 (ECP, 2018) [12, 13].

The Structural Behavior of Reinforced Concrete Beams with Embedded Polystyrene Spheres has been studied [14], the researcher investigated the feasibility of reducing the weight of reinforced concrete beams by incorporating polystyrene spheres and its impact on structural performance.

2. EXPERIMENTAL PROGRAM

2.1 Mix Design

Initial mixtures were created using traditional concrete components while incorporating superplasticizers and silica fume to achieve high-strength concrete. However, when foam was introduced as a partial substitute, it reduced concrete strength. Subsequently, three distinct lightweight concrete mixtures were prepared by substituting coarse and fine aggregates with polystyrene foam granules. Importantly, these substitutions were made at varying ratios of 20%, 30%, and 40%, as outlined in **Table 1.** It's worth noting that these ratios are represented in terms of volume units.

Table 1: Properties of concrete mixes/m^3

Concrete mix	Cement	Silica fume	Coarse Aggregate	Sand	Polystyrene Foam	Super Plasticizer	Water (kg) % W/C	Density
NWC	450 kg	22.5 kg	1350 kg	650 kg	-	6.75 kg	135 kg (30%)	2600 kg/m^2
LWC-1	450 kg	22.5 kg	1100 kg	580 kg	200 liters	6.75 kg	135 kg (30%)	2300 kg/m^3
LWC-2	450 kg	22.5 kg	950 kg	510 kg	320 liters	6.75 kg	135 kg (30%)	2050 kg/m^3
LWC-3	450 kg	22.5 kg	700 kg	440 kg	440 liters	6.75 kg	135 kg (30%)	1750 kg/m^3

The concrete mix utilized for casting the six beams is labeled as "LWC-3" because it substantially reduces the weight of normal concrete, lowering it from 2600 kg to 1750 kg per cubic meter. This reduction is primarily achieved through the substitution of 40% of the volume of the mixture of coarse and fine aggregates with polystyrene foam.

2.1.1. Coarse Aggregate

The coarse aggregate utilized in the mixture was sourced from natural deposits and consisted of dolomite. It exhibited a density of 1900 kg/m^3. It featured particle diameters ranging from 10 mm to 15 mm. Thorough measures were taken to guarantee its cleanliness, absence of impurities, and a comprehensive washing process with water.

2.1.2. Fine Aggregates

The fine aggregate used in the lightweight concrete mix was clean, natural sand devoid of organic matter. It possessed a density of 1950 kg/m^3, contributing to the composition of the concrete mixture.

2.2. Mixing

In the concrete mixing process, the coarse aggregate was combined with the fine aggregate, followed by the addition of cement, silica, and polystyrene foam granules. Subsequently, water was added. The sequence of steps is as follows:

Mixing of coarse and fine aggregates.
Addition of cement and silica.
Incorporation of polystyrene foam granules.
Addition of water with subsequent inclusion of superplasticizer.
Mixing for a minute to initially blend the components.
Continued mixing for 8 minutes to achieve a homogeneous concrete mixture. as shown in **Fig. 1.**

Fig. 1. Fresh lightweight concrete mix.

2.2.1. Polystyrene foam

In this study, polystyrene foam was introduced as a viable alternative material to conventional aggregates, reducing the weight of the concrete block and producing semi-lightweight concrete. This polystyrene foam was employed as small granules with a diameter ranging from 0.5 mm to 0.8 mm and appearing white, as illustrated in Fig. 2. Notably, the actual density per 1 m^3 amounted to a mere 30 kg/m^3, resulting in virtually negligible weight compared to the aggregates typically used in normal-weight concrete.

Fig. 2. polystyrene foam granules.

2.3. Reinforcement Steel

During this study, high-strength steel reinforcement bars with a diameter of 10 mm and mild smooth steel bars with diameters of 6 mm and 8 mm were used. A tensile test was conducted on all diameters and the actual yield stress was known and the maximum tensile stress that each diameter could bear in the laboratory. The results were as in **Table 2.**

Table 2. Properties of Reinforcing Steel Bars.

Bar Diameter (mm)	**Cross Sectional Area (mm^2)**	**Yield/Ultimate Strength (MPa)**	**Yield/Ultimate Strength laboratory (MPa)**	**Yield/Ultimate Strain laboratory**	**Modulus of elasticity of steel Laboratory (MPa)**
6	28.28	240/350	330/425	0.0016/0.0021	198500
8	50.26	240/350	350/490	0.0018/0.0025	197000
10	78.53	360/520	570/710	0.0030/0.0037	188000

2.4. Description of Test Specimens:

The tested samples are detailed in **Table 3**., consisting of six concrete beams with varying proportions of lower and upper reinforcement. To address the limited compression zone area, additional compression steel was incorporated to maintain the equilibrium of the concrete section.

Table 3: Specimens Details.

Specimen	Dimension (mm)	Lower Steel	Upper Steel	Vertical Stirrups	f_{cu} (MPa)	Type of section
B-1	100x200x2000	3Y10	2Y6	10Φ8/m	22.56	Over Reinf.
B-2	100x200x2000	2Y10	2Y6	10Φ8/m	22..62	Balanced Section
B-3	100x200x2000	4Y10	2Y10	10Φ8/m	22.66	Over Reinf.
B-4	100x200x2000	3Y10	2Y8	10Φ8/m	22.48	Over Reinf.
B-5	100x200x2000	2Y10	2Y8	7Φ8/m in the middle 10Φ8/m At shear zone	22.51	Balanced Section
B-6	100x200x2000	2Y10	2Y6	7Φ8/m in the middle 10Φ8/m At shear zone	22.55	Balanced Section

2.5. Casting

The casting process for the concrete beams occurred in four distinct stages:

1. First Stage: In this stage, the normal concrete mixture was determined without replacing the aggregate. Three different models with varying proportions of water and cement were prepared. Each model resulted in six cubes and three cylinders, as shown in **Fig. 3.**
2. Second Stage: After determining the appropriate normal concrete mixture, the second stage involved creating three lightweight concrete mixtures with different proportions of polystyrene foam replacing a combination of coarse and fine aggregates, as shown in **Fig. 4.**
3. Third Stage: Two lightweight concrete beams were cast using the concrete mixture obtained in the previous stage. However, different proportions of the lower reinforcement steel and stirrups were used, as shown in **Fig. 5.**
4. Fourth Stage: The final stage involved casting four reinforced lightweight concrete beams. These beams had variations in both the lower and upper reinforcing steel quantities. This stage aimed to enhance the results and make comparisons with established codes, as shown in **Fig. 6.**

Fig. 3. Stage 1: Three models of ordinary concrete

Fig. 4. Stage 2: Three lightweight concrete mixes

Fig. 5. Stage 3: Two lightweight concrete beams

Fig. 6. Stage 4: Four lightweight concrete beams

2.6. Measuring Devices

There are three types of measuring devices used in conducting tests as shown in **Fig. 7., 8. And 9.**

Fig. 7. Deflection Measurement

Fig. 8. Steel Strain Measurement

Fig. 9. Concrete Strain

2.7. Conducting the test on concrete beams and loading

In this study, the tested beams measured 2000 mm in length. The testing procedure involved placing the beam on two supports, maintaining a 1800 mm distance between them. Subsequently, all measuring devices were appropriately connected. The beams were subjected to loading using two concentrated loads, each positioned at a distance of 600 mm from their respective supports. **Fig. 10.** illustrates the setup and procedure for testing the concrete beams under loading.

Fig. 10. Conducting the test on concrete beams and loading.

2.8. Compression Strength Test (for cubes)

The compressive strength of concrete was evaluated by testing three cubes for each mix after 28 days using a compression testing machine. The results are presented in **Table 4.**

Table 4: Compression Strength Results of cubes after (28) days.

Mix Name	Specimen Number	Polystyrene foam ratio	Compression Strength (MPa)	Average Compression Strength (MPa)
NWC	1	0%	40	40
	2		38.5	
	3		41.2	
LWC-1	1	20%	31.6	33.1
	2		34.6	
	3		33.2	
LWC-2	1	30%	29.1	28.6
	2		29	
	3		27.8	
LWC-3	1	40%	23.1	22.8
	2		23	
	3		22.56	

3. RESULTS AND DISCUSSION

This chapter will delve into the outcomes and analysis of the tests conducted on six semi-lightweight reinforced concrete beams. The results and analysis encompass various aspects such as crack patterns, failure loads, mid-span deflections of the beams shown in **Fig. 11.**, concrete strain, lower steel strain, stirrup strain, failure modes, ductility assessment, concrete modulus of elasticity, stress-strain relationships, and compelling moment of inertia. Summarized Results for all Tested Beams shown in **Table 5.**

Table 5: Summarized Results for all Tested Beams.

Specimen	At First crack		At Failure		Type of Failure
	P_{CR} (kN)	Δ_{CR} at middle (mm)	P_F (kN)	Δ_F at middle (mm)	
B-1	11.0	1.18	48.0	10.87	Compression failure
B-2	10.0	2.15	42.6	12.10	Compression failure
B-3	16.0	1.90	68.0	11.10	Compression failure
B-4	12.0	1.98	34.6	6.24	Compression failure
B-5	10.0	1.59	42.0	10.01	Compression failure
B-6	10.9	2.21	36.2	11.77	Compression failure

The analytical study of the results aimed to understand the behavior of reinforced lightweight concrete beams under moment loads. This study involved calculating the moment at failure and the first crack based on the test results of the beams. Additionally, the modulus of elasticity was determined from the results of the cylinder tests, and the moment of inertia was calculated using stress equations. The impact of the ratio of reinforcement steel to concrete was also assessed. Comparative analyses were conducted between experimental and theoretical deflection data. Furthermore, a comparison was made between the experimental and theoretical results based on Egyptian and American codes.

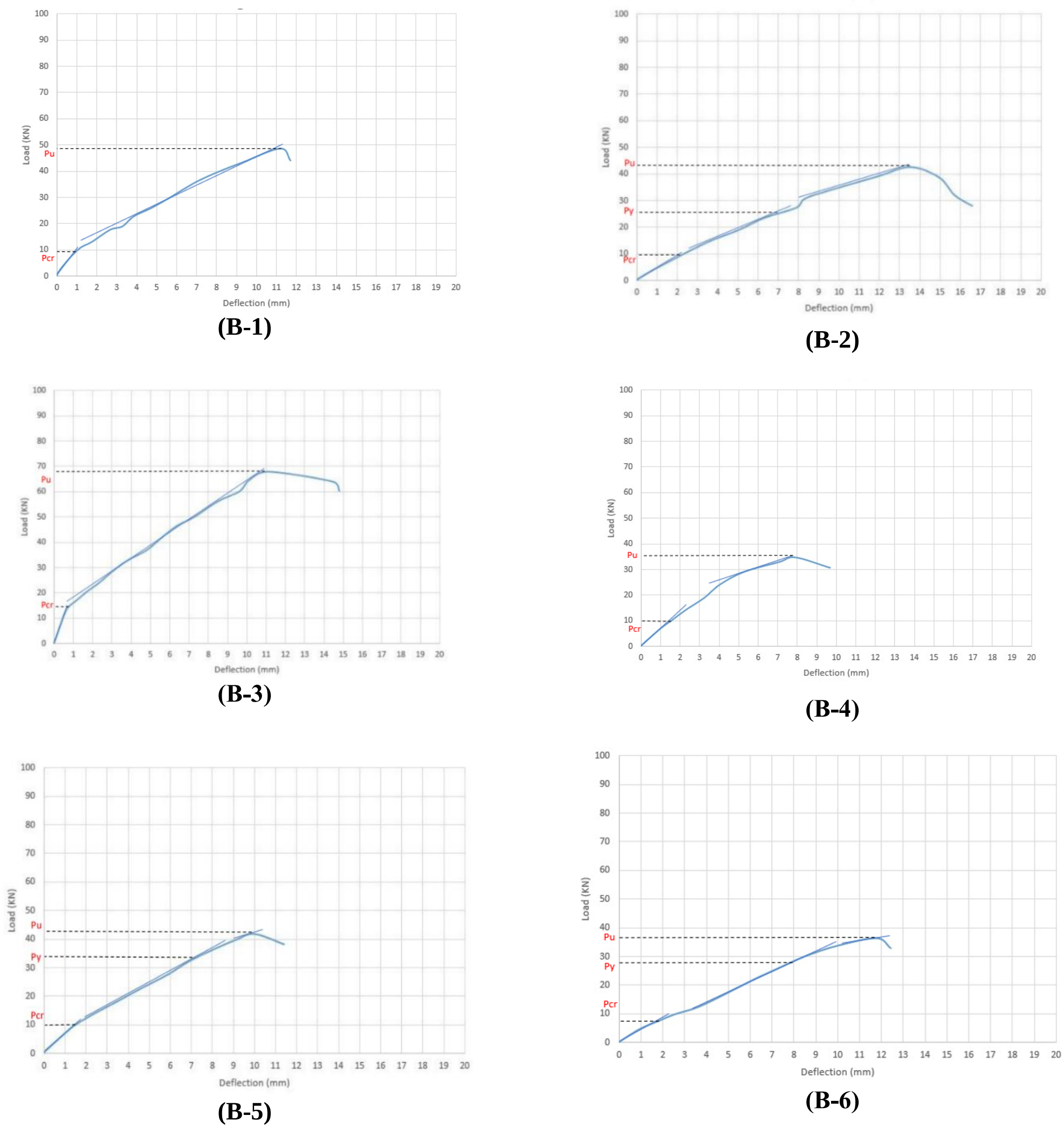


Fig. 11. Load Deflection Curve at the middle Span for all tested beam.

3.1. Load deflection and crack pattern behavior.

3.1.1. Load deflection behavior.

The concrete sections in beams B-2, B-5, and B-6 were balanced, resulting in ductile failure where the steel reached the yielding stage. These beams exhibited three distinct stages in their load-deflection curves. A linear relationship was initially observed until the first crack appeared (stage one). Subsequently, the slope of the curve increased after the first crack (stage two), and in the third stage, the steel reinforcement reached the yield stress, causing a non-linear relationship. Ultimately, failure occurred in the beam.

On the other hand, beams B-1, B-3, and B-4 had over-reinforced concrete sections, resulting in brittle failure. The steel reinforcement did not reach the yielding stage in these beams, leading to only two stages in the load-deflection curve. Initially, a linear relationship was noted until the first crack in the beam (stage one). The second stage involved an increased slope of the curve after the first crack, culminating in a sudden failure of the beam due to the reinforcing steel not reaching the yielding stage. For a visual representation, please refer to **Fig. 12.** depicting load-deflection curves at the middle span for all tested beams.

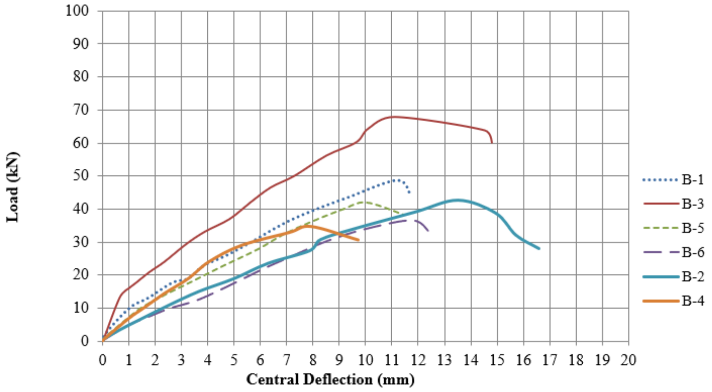
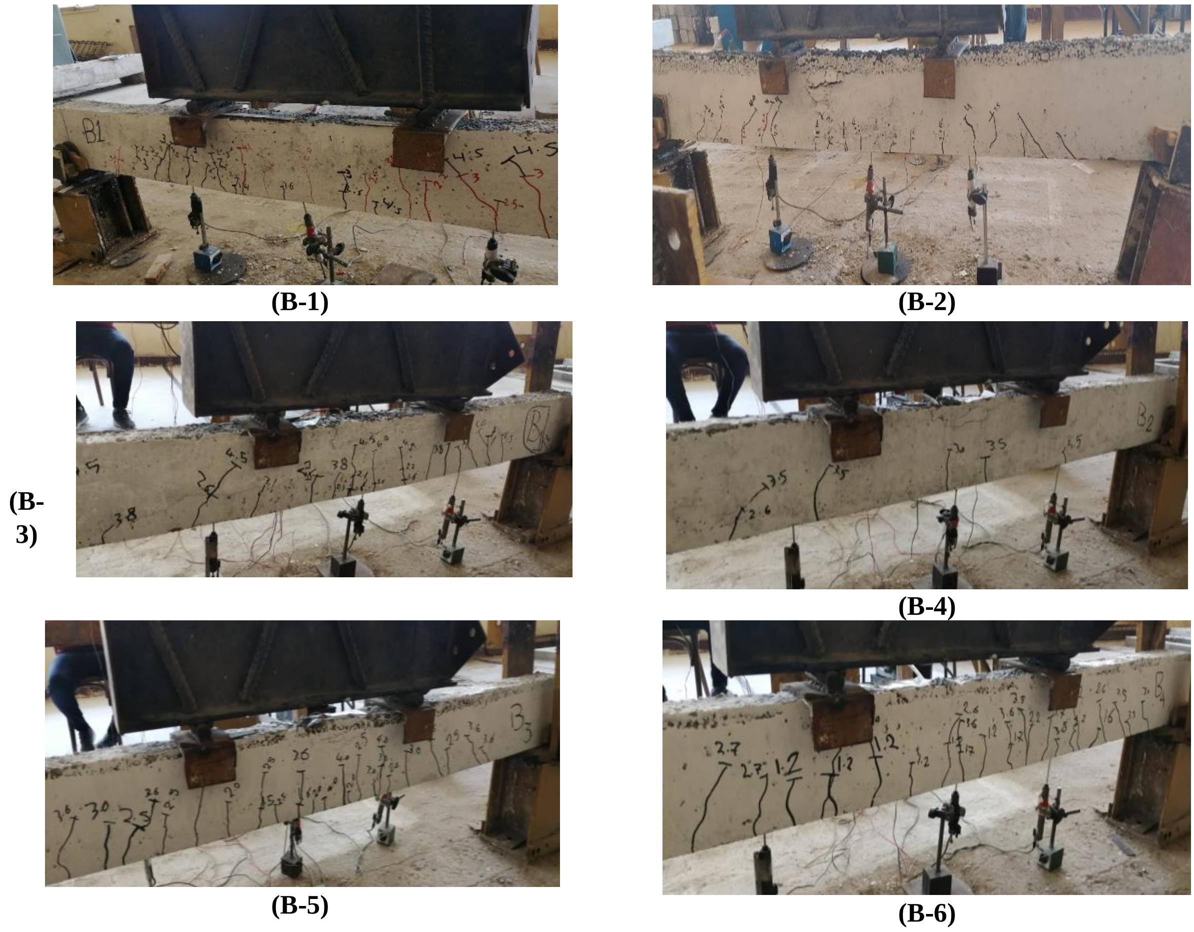


Fig. 12. load deflection curves at middle span for all tested beams.

3.1.2. Crack pattern behavior.

In beams where the steel reinforcement yielded, the resulting cracks were wide and distributed across the beam's perimeter. Conversely, the cracks were more localized and specific in beams with brittle failure. These variations in crack patterns are depicted in **Fig. 13.**, illustrating the crack patterns for all the tested beams.



(B-1) (B-2) (B-3) (B-4) (B-5) (B-6)

Fig. 13. Crack Pattern for all tested beams.

3.2. Comparison Between Experimental and Theoretical Moment at the First Crack and at Failure.

The moments were determined experimentally using the loading method illustrated in **Fig. 14.**, and the calculations were based on the following equation:

$$\text{Moment(M) exp.} = \frac{\text{Pexp. x 0.6}}{2} \ \text{(Kn.m)}$$

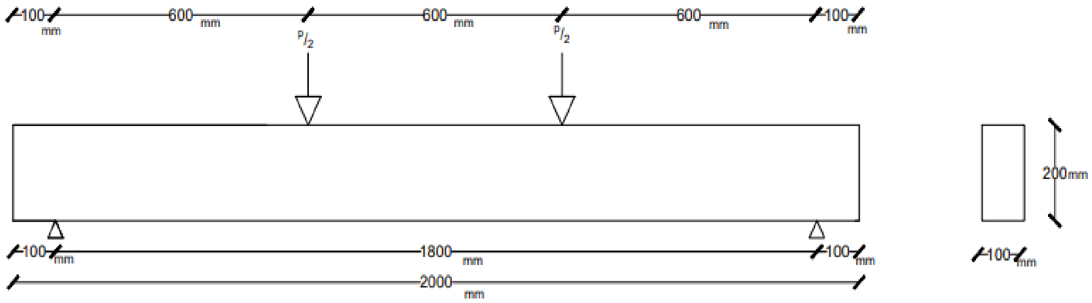


Fig. 14. The Loading Method.

Table 6. analyses the forces observed in the concrete section. Notably, the c\d values for the lightweight reinforced concrete section were consistently lower than those c\d values for normal reinforced concrete, showcasing a reduction of approximately (10-15) %.

Note: F_s values recorded by strain gauges.

Table 6.: analysis of the results of the forces that occurred in the concrete section.

Specimen	Type of section	f_{cu} (MPa)	F_s (MPa)	$F_s^{\backslash}$ (MPa)	a (mm)	c = 1.25a (mm)	d (mm)	c/d
B-1	Over Reinforced	22.56	540	48.25	69.17	86.46	185	0.467
B-2	Balanced Section	22..62	580	0.00	50.60	63.25	185	0.342
B-3	Over Reinforced	22.66	555	38.60	93.50	116.875	185	0.630
B-4	Over Reinforced	22.48	565	51.18	71.10	88.875	185	0.480
B-5	Balanced Section	22.51	585	0.00	51.10	63.875	185	0.345
B-6	Balanced Section	22.55	570	0.00	49.70	62.125	185	0.336

Table 7. Moment values for all beams theoretically and experimentally

Specimen	Experimental		Theoretical		Experimental		Theoretical (f_{cu} = 22.5 MPa)		Theoretical (f_{cu} = 40.0 MPa) (NWC)	
	At First crack		At First crack		At Failure		At Failure		At Failure	
	P_{CR} (kN)	M_{CR} at middle (KN.M)	P_{CR} (kN)	M_{CR} at middle (KN.M)	P_F (kN)	M_F at middle (KN.M)	P_F (kN)	M_u at middle (KN.M)	P_F (kN)	M_u at middle (KN.M)
B-1	11.0	3.3	5.08	1.524	48.0	14.4	64.00	19.20	71.67	21.50
B-2	10.0	3.0	5.08	1.524	42.6	12.78	48.46	14.54	51.80	15.54
B-3	16.0	4.8	5.08	1.524	68.0	20.4	81.00	24.30	93.33	28.00
B-4	12.0	3.6	5.08	1.524	34.6	10.38	66.67	20.00	73.53	22.06
B-5	10.0	3.0	5.08	1.524	42.0	12.6	48.83	14.65	52.26	15.68
B-6	10.9	3.27	5.08	1.524	36.2	10.86	47.80	14.34	51.03	15.31

3.3. Comparative Between Experimental and Theoretical modulus of elasticity.

The Egyptian code does not provide specific guidelines regarding utilizing lightweight concrete and its permissible properties for structural concrete. Therefore, the modulus of elasticity is computed theoretically using the subsequent equation according to the Egyptian code:

$$E_C = 4400\sqrt{f_{cu}} \quad \text{MPa} \quad \text{(the Egyptian code)}$$

$$E_C = 4400\sqrt{22.5} \quad \text{MPa}$$

$$E_C = 20871.03 \quad \text{MPa}$$

Nonetheless, the American code specifies that the modulus of elasticity for concrete with weights between 1440 kg/m^3 to 2560 kg/m3 can be theoretically computed using the following equation:

$$E_C = 4700\sqrt{f_c^{\backslash}} \quad \text{MPa} \quad \text{(the American code)}$$

$$E_C = 4700\sqrt{13.6} \quad \text{MPa}$$

$$E_C = 17332.74 \quad \text{MPa}$$

The modulus of elasticity was experimentally derived from the stress and strain tests on the cylinders. A stress-strain curve was plotted, depicted in **Fig. 15.**, and the modulus of elasticity was computed.

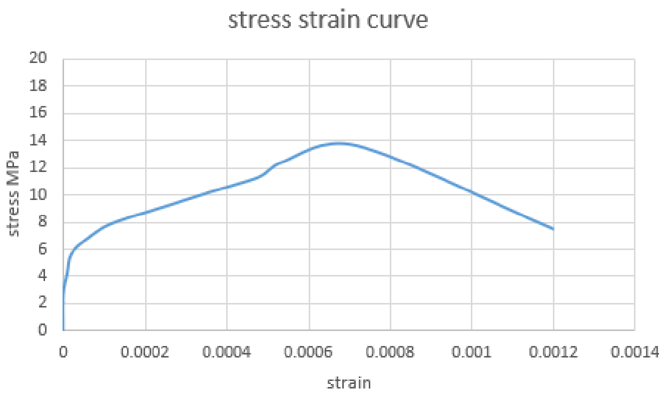


Fig. 15. Stress strain curve for (LWC-3).

And from the curve, the modulus of elasticity can be found and equal to:

$$E_{C\ exp.} = \frac{\text{stress}}{\text{strain}} \quad \text{MPa (Experimentally)}$$

$$E_{C\ exp.} = \frac{13.6}{0.00072} \quad \text{MPa}$$

$$E_{C\ exp.} = 18888.89 \quad \text{MPa}$$

3.4. Comparative Between Experimental and Theoretical deflection (Δ_f).

The experimental deflection ($\Delta_{F(exp)}$) is previously mentioned in the **Table 4**: Summarized Results for all Tested Beams and we can calculate the theoretical deflection ($\Delta_{F(Theo)}$) from this equation:

$$\Delta_{F(Theo)} = \left(\frac{23}{648} \text{ x } \frac{P_{theo.}\, L^3}{E_{theo.}\ Ie_{theo.}}\right)$$

Where:

$$P_{theo.} = \frac{ultimate\ load\ (p_f)\, N}{2} \quad \text{theoretically.}$$

$E_{theo.}$= theoretical modulus of elasticity.

$Ie_{theo.}$= theoretical effective moment of inertia (mm^4)

$\Delta_{F(Theo)}$ = Maximum Deflection (mm) at middle span theoretically.

l = clear span (1800) mm.

$\Delta_{F(exp)}$ = Maximum Deflection (mm) at middle span experimentally.

and the following **Table 8.** shows all experimental and theoretical results for all beams.

Table 8. Results for all beams theoretically and experimentally

Beam Name		B-1	B-2	B-3	B-4	B-5	B-6
Bottom steel		3Y10	2Y10	4Y10	3Y10	2Y10	2Y10
Top steel		2Y6	2Y6	2Y10	2Y8	2Y8	2Y6
P_F (KN)	Experimental	48.00	42.60	68.00	34.60	42.00	36.20
	Theoretical	64.00	48.46	81.00	66.67	48.83	47.80
M_F (KN.M)	Experimental	14.40	12.78	20.40	10.38	12.60	10.86
	Theoretical (f_{cu}=22.5 MPa)	19.20	14.54	24.30	20.00	14.65	14.34
	Theoretical (f_{cu}=40.0 MPa)	21.50	15.54	28.00	22.06	15.63	15.31
E_c (MPa)	Experimental	18888.89	18888.89	18888.89	18888.89	18888.89	18888.89
	Theoretical	20871.03	20871.03	20871.03	20871.03	20871.03	20871.03
I_E (cm^4)	Experimental	2419.61	1655.48	3356.75	3038.26	2278.56	1685.25
	Theoretical	5051.71	3786.48	6583.12	5214.50	3892.47	3786.16
Δ_F (mm)	Experimental	10.87	14.10	11.10	6.240	10.01	11.77
	Theoretical	7.42	7.29	6.78	7.20	7.10	7.29

It is evident from the presented table that a comprehensive comparison has been made between the results of laboratory tests and theoretical results as per both the Egyptian and American codes. This comparison spans across all reinforced concrete beams, encompassing varying quantities of lower and upper reinforcing steel while maintaining consistent dimensions of the concrete section.

3.5. The effect of different ratios of lower and upper reinforcing steel on lightweight concrete beams.

When the bottom reinforcing steel of the lightweight concrete sector is increased, its resistance to loads and moments increases. However, the concrete's resistance to pressure decreases when its density decreases, so beams were reinforced with top reinforcing steel to reinforce the pressure area.

It was noted that the crack loads that were monitored in the laboratory for all beams were relatively close.

When comparing the results of the experimental and theoretical final moments, it was found that the experimental moments were less than the theoretical moments by 20% because the theoretical laws that were used were for ordinary concrete and not for lightweight concrete because there are no laws for lightweight concrete in the Egyptian code. The American code states that the lightweight concrete section's properties are less than the standard concrete section's by 15% to 25%, according to the type of aggregate replaced.

3.6. Measurement of Ductility.

The ductility index, defined as the ratio of ultimate deflection to the deflection at the yielding of the tensile reinforcement bar, is a crucial measure. This index is particularly significant for the balanced section.

Table 9. presents the measurements of ductility for (B-2), (B-5), and (B-6), offering valuable insights into the yield load derived from the test results.

Table 9. Measurement of ductility for(B-2), (B-5) and (B-6).

Specimens	Crack point		Yield point		Failure point		Ductility index
	First crack load (P_{CR})	Deflection (mm) 1/2 the span	yield load (P_Y)	Deflection (mm) 1/2 the span	Failure point (P_F)	Deflection (mm) 1/2 the span	
(B-2)	10.0 KN	2.15	26.5 KN	8.2	42.6 KN	12.1	1.475
(B-5)	10.0 KN	1.59	35.0 KN	7.6	42.0 KN	10.01	1.317
(B-6)	10.9 KN	3.12	28.0 KN	8.6	36.2 KN	11.77	1.368

3.7. Energy Absorption.

Energy absorption is critical for all specimens, assessed by calculating the area under the load-deflection curve. **Fig. 16.** vividly illustrates the energy absorption for all beams. Notably, Beam (B-3) demonstrates significantly higher energy absorption due to a substantial increase in the failure load compared to the other tested beams. It achieved a maximum deflection of 11.1 mm. This highlights the potential to enhance energy absorption by reinforcing lightweight concrete beams in line with theories specified for ordinary concrete in the relevant codes.

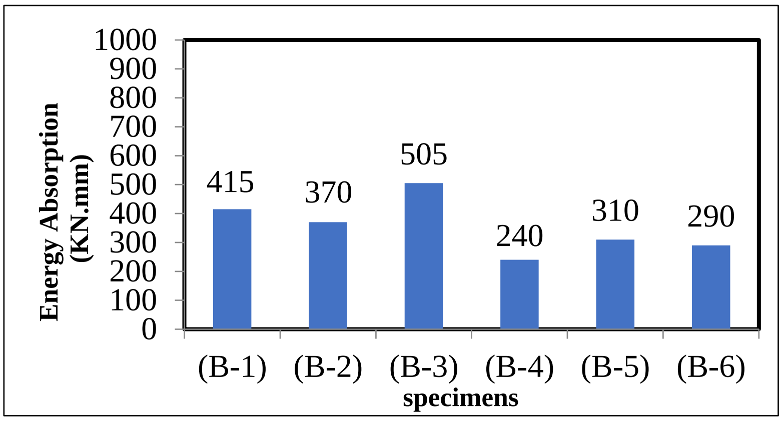


Fig. 16. Energy absorption for all beams.

CONCLUSIONS

- When the percentage of reinforcement for beams was increased by 30%, the energy absorption increased by ranging between (12-20) %.
- The c\d values of the lightweight reinforced concrete (LWRC) section were lower than the c\d values of normal reinforced concrete in codes by a percentage ranging between (10-15) %.
- The values of failure moments for lightweight reinforced concrete obtained from test results were lower than theoretical calculations of moments for normal concrete (f_{cu} = 22.5 MPa) by a rate ranging between 10% and 25 %. According to the percentage mentioned by the American code
- The values of failure moments for lightweight reinforced concrete obtained from test results were lower than theoretical calculations of moments for normal concrete (f_{cu} = 40.0 MPa) by a rate ranging between 20 and 35%.
- The modulus of elasticity of semi-lightweight concrete using polystyrene foam granules was less than the Egyptian Code (ECP) calculations for the modulus of elasticity of ordinary concrete by 10%. However, it was 10% higher than the American Code (ACI) calculations.
- Lightweight reinforced concrete can be used as a construction material in some concrete elements subject to low stresses, and it is not recommended in foundations and first floors. Due to its high-water permeability.

- When the compression steel increased by 50%, the ductility index decreased by ranging (8-12) %.

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