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Research Article

Shear and flexural strength of pumice lightweight concrete beams with silica fume

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Abstract

Recently, many types of research in Iraq have had the properties of lightweight concrete beams utilizing both artificial and normal aggregate for economic reasons. Very limited works have been implemented to investigate the resistance of flexural and shear behavior of structural lightweight aggregate concrete; therefore, it is important to study the properties and their structural behavior. The present work is to investigate the shear and flexural strength of lightweight concrete beams made of pumice with silica fume admixture. The lightweight concrete has been made by partial replacement of crushed gravel with 75% pumice and 7% silica fume. The value of compressive force strength is 29 MPa within twenty-eight days. A total of ten reinforced concrete beams is used, with dimensions of (150 x 150 x 750) mm, with and without silica fume, and with varying ratios of transverse reinforcement (stirrups). The deflection at mid-span was also measured using a mechanical dial gauge. Normal-weight concrete beams are also used for comparison with the lightweight concrete beams. Beam behavior was assessed in terms of ultimate deflection, failure mode, and crack pattern. According to the experimental results, the prepared concrete's weight and strength met the LWC requirements. The results showed a significant effect of the transverse reinforcement ratio (stirrups), where the values of the shear and resistance of flexural rose when the amount of reinforcement increased. Furthermore, the appearance of the first crack has been significantly delayed as the reinforcement ratio rose.

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1. Introduction

The Romans used lightweight concrete a long time ago as a construction material in walls and domes [1]. After that, lightweight concrete was used in the construction of ships and barges during World War [2]. Nowadays, the use of lightweight concrete is very common in many structures for several benefits, such as reducing the dead load value, enhancing the properties of fire and thermal resistance, reducing wood formwork, etc. One of the ways to produce lightweight structural concrete is by using lightweight aggregate such as pumice [3]. To get high-strength lightweight concrete, mineral admixtures may be used, like fly ash or silica fume [4, 5, 6]. Kumar and Raju [7], studied the properties of reinforced concrete beams made from lightweight aggregate. They used two types of aggregate to produce lightweight concrete, partially substituting coarse aggregate with pumice and palm oil shells. They concluded that palm oil shell concrete has sufficient strength compared to pumice aggregate. Pravallika and Rao [8] studied the strength force of lightweight concrete produced by replacing coarse material with pumice at percentages of 0%, 10%, 20%, 30%, 40%, and 50%. They observed that the concrete specimens showed good results in lightweight for 50% partial substitution of normal aggregate compared to pumice stone. Yang, K. H., et al. [9] investigated the significant influence of the size of the aggregate on the shear behavior. The microphotograph is used to compare the typical failure surface characteristics along the inclined

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beam cracks. They observed that the maximum aggregate size enhanced the shear strength of continuous lightweight concrete (LWC) beams. However, compared to normal weight concrete (NWC) continuous beams, the growth rate was lower. Asamoah et al. [10] used steel bars made from recovered scrap metal to study the response and applicability of the technique for recycled concrete; they studied the flexural behavior and shear behavior of concrete beams with 50% of materials that have been recycled. R. Saravanakumar et al. [11] focused on developing lightweight concrete by replacing normal coarse aggregates with pumice stone. The main goal of their study was to achieve better compressive strength while maintaining a low density, thereby reducing the structure's self-weight, which reduces the possibility of seismic damage. They compared mechanical properties (compressive and flexural capacity) between normal concrete and lightweight pumice concrete to validate its structural ability for earthquake-resistant construction. Mohamed A. Khafaga [12] investigated the shear behavior of reinforced reduced-weight concrete beams by using lightweight expanded clay aggregate in place of normal aggregates. He examined the effects of several variables, like concrete type based on its weight, the ratio of span of shear to the depth of beam (a/d), grade of concrete, and the number of stirrups. His findings were then compared with the Egyptian code. He concluded that, in spite of the results from experimental tests demonstrating that the reduced concrete beams exhibited diminished stiffness, ductility, and carrying capacity load in comparison to the natural weight concrete beams. The present work was twofold: firstly, to produce lightweight concrete using pumice as a partial replacement of coarse aggregate, and secondly, to study the behavior of the resistance of flexural and shear resistance behavior of lightweight concrete for its importance in structures.

2. Material used

2.1. Cement

Ordinary Portland Cement (OPC), type I, was the cement utilized in this research, which was produced by the Badoosh cement factory (Mosul). The mechanical and physical properties of the cement are shown in Table 1, and its chemical compositions are given in Table 2, which agrees with ASTM C150/C150M [13].

Table 1. Mechanical and physical properties of cement

physical properties	Result	ASTM C150/C150M [13]
Specific gravity	3.026	----------
Blaine specific surface (m^2/kg)	291.0	≥ 260
Loss on ignition (%)	2.18	≤ 3%
Soundness (mm)	1.4	----------
Initial setting time (minutes)	123.0	≥ 45 Minutes ≤ 375 Minutes
Final setting time (hours)	4.01	----------
Compressive strength (MPa) at 28 days	36.0	----------

Table 2. Cement chemical compositions

Component	Test results (%)	ASTM C150/C150M [13]
SiO_2	21.33	----------
Al_2O_3	5.432	----------
Fe_2O_3	2.326	----------
CaO	60.3	----------
MgO	3.8864	≤ 6%
SO_3	0.1821	≤ 3%
C_3S	35.68	----------
C_2S	36.73	----------
C_3A	7.9	----------
C_4AF	10.6	----------

2.2. Silica Fume

Silica fume was used with grey color and at a fixed replacement ratio of 7% by cement weight. The specific gravity was 2.172, and the value of Loss on Ignition (LOI) was 2.87% and was compatible with ASTM C1240 [14]. Table 3 illustrates the silica fume's chemical composition.

Table 3. Chemical compositions of silica fume

Component	Test results (%)	ASTM C1240-15 (%) [14]
SiO_2	87.14	Min. 85
Al_2O_3	1.149	------
Fe_2O_3	0.148	------
CaO	0.85	------
MgO	0.5722	------
SO_3	0.4731	------

2.3. Aggregate

Natural sand was used as a fine aggregate, which was obtained from Mosul–Kanhash in Iraq, with a fineness modulus of 2.8. The specific gravity of the sand used was 2.65, and the sieve analysis for sand, which agrees with ASTM C136/C136M-14 [15], is shown in Table 4. Natural crushed aggregate was utilized as coarse aggregate and was obtained from Zakho in the north of Iraq with a 12.5 mm maximum size of aggregate; the specific gravity was 2.65, and its absorption was 1.2%. The sieve analysis for gravel to ASTM C136/C136M-14 [15] is shown in Table 5. Pumice stone was used as an aggregate for producing the lightweight concrete. The sieve analysis for pumice to C330/C330M [16] is given in Table 6, while Table 7 displays the pumice's physical properties according to ASTM.

Table 4. Sieve analysis of fine aggregate

Size of sieve (mm)	Passing %	ASTM C136/136M - 14 [15]
9.5	100	100
4.75	100	95 - 100
2.36	85	80 - 100
1.18	72	50 - 85
0.6	48.6	25 - 60
0.3	13.4	5 - 30
0.15	2.4	0 - 10

Table 5. Sieve analysis of crushed aggregate

Size of sieve (mm)	Passing %	ASTM C136/136M - 14 [15]
37.5	100	100
25	98.94	90 - 100
19	53.24	35 - 80
12.5	34.14	20 - 55
9.5	2.14	0 - 10
4.75	1	0 - 5

Table 6. Sieve analysis for pumice

Size of sieve (mm)	Passing %	Limit of ASTM C330/330M-14 [16]
12.5	100	90 - 100
9.5	80	40 - 80
4.75	20	0 - 20
2.36	6	0 - 10

Table 7. Physical properties of pumice

Property	Results	Limit of ASTM
Bulk SSD Specific gravity	1.28	ASTM, C127-14, 2014 [17]
Absorption%	20	ASTM, C127-14, 2014 [17]
Dry loose unit weight (kg/m^3)	477	ASTM, C29/C29M – 09 [18]
Dry rodded unit weight (kg/m^3)	511	ASTM, C29/C29M – 09 [18]

2.4. Superplasticizer

Superplasticizer (type G) was used as an admixture to improve the workability of the mix by giving rheoplastic properties. The properties of superplasticizer (chemical and physical) are given in Table 8 according to ASTM C 494 [19].

Table 8. Properties of superplasticizer

Color	Brown
Density	1.148 – 1.208 Kg/liter
Chloride content %	< 0.1
Alkaline content %	< 5

2.5. Reinforced Steel

Deformed bars were used for both main reinforcing and stirrups. The results of using reinforcing steel are shown in Table 9.

Table 9. Reinforcing steel lab. results

Diameter of bar (mm)	Yielding stress (MPa)	Tensile stress (MPa)	Elongation %
8.0	359	561	24.3
10.0	379	629	18.9

3. Experimental Program

3.1. Mix Proportion

Table 10 displays the proportions of the lightweight concrete mixture. The coarse aggregate was divided into two parts (75% pumice and 25% crushed aggregate). Silica fume has been replaced by a constant value of 7% by weight of cement. Normal weight concrete (NC) was produced with a ratio (1:1.5:3) for comparison with lightweight concrete. The values of workability and slump were 120 mm $\mp$ 5 and 85 mm $\mp$ 5 for the normal weight and the lightweight concrete (LWC), respectively.

Table 10. Concrete mixture design

Mix type	Cement	Normal Sand	Crushed Gravel	pumice	w/c	Silica Fume %	Sp.% Weight of Cement	Density kg/m^3
LWC	435	652.5	326	475	0.28	7	1	1915
NC	397	596	1191	-----	0.50	7	1	2400

3.2. Geometry and Properties of The Test Beams

The beams were tested cast in steel molds that have a rectangular cross-section of 150 x 150 mm and a length of 750 mm. The machine that was used for this test contains three parts: frame, hydraulic jack, and dial gauge (see Figure 1). The frame was manufactured locally from I-section steel beams at a suitable dimension. Also, the hydraulic jack is a device that uses a maximum pressure of 700 bar. The dial gauge was used for measuring the deflection at the mid-span of beams.

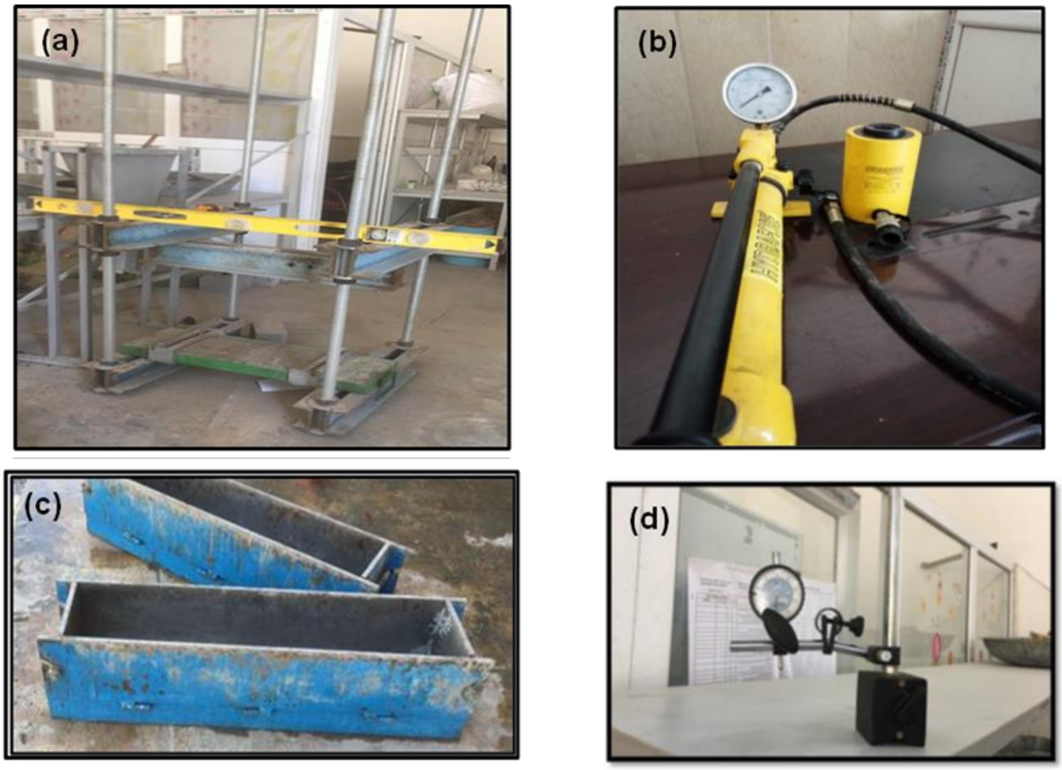
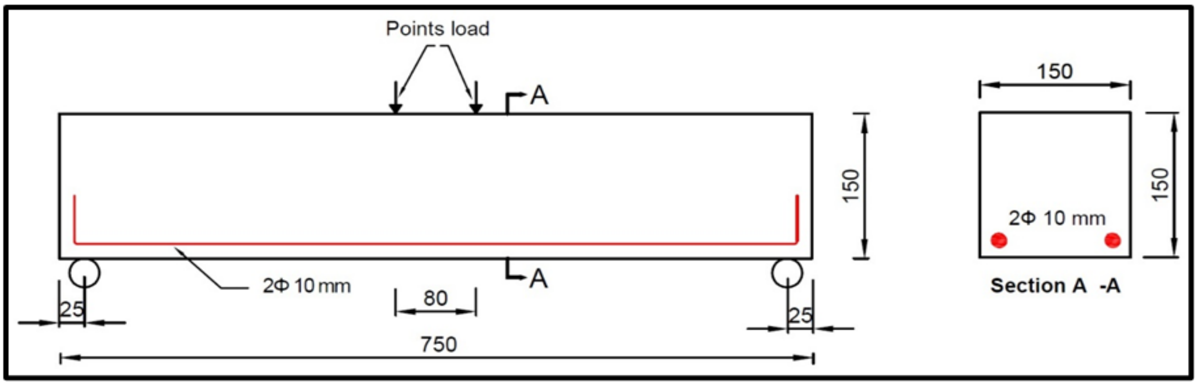
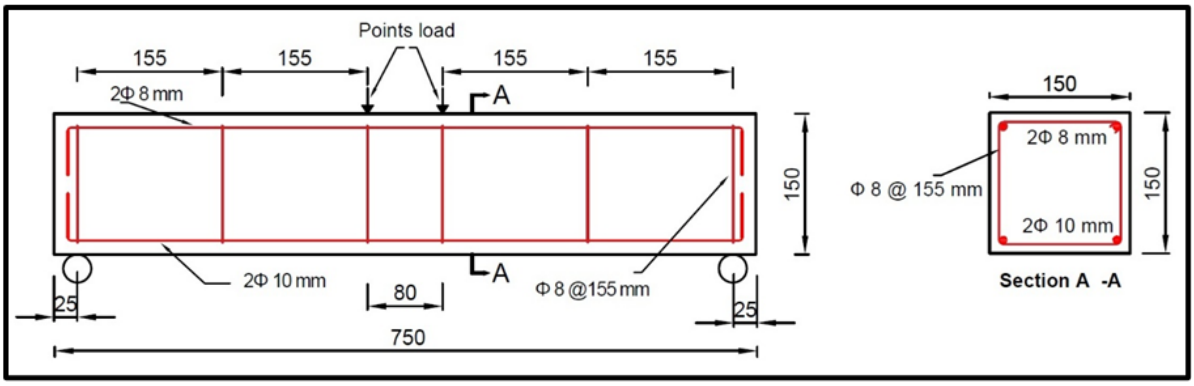


Fig. 1. a) Frame test, b) Hydraulic Jack, c) Steel molds, and d) Dial gauge

The details of the steel reinforcement of the beams are shown in Figure 2. The main bars for tensile reinforcing of the beams were 2 Ø12, whereas the beams' compression reinforcement for all the beams was 2 Ø8. Shear reinforcements (stirrups) of an 8 mm diameter were used with a spacing of (155, 77.5, and 55) mm to estimate the effect of the transverse reinforcement ratio on the beams.



(a)



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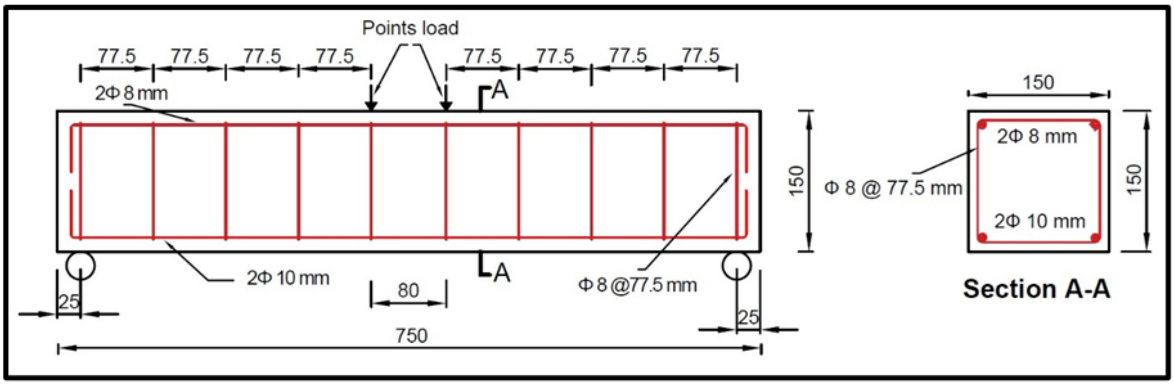

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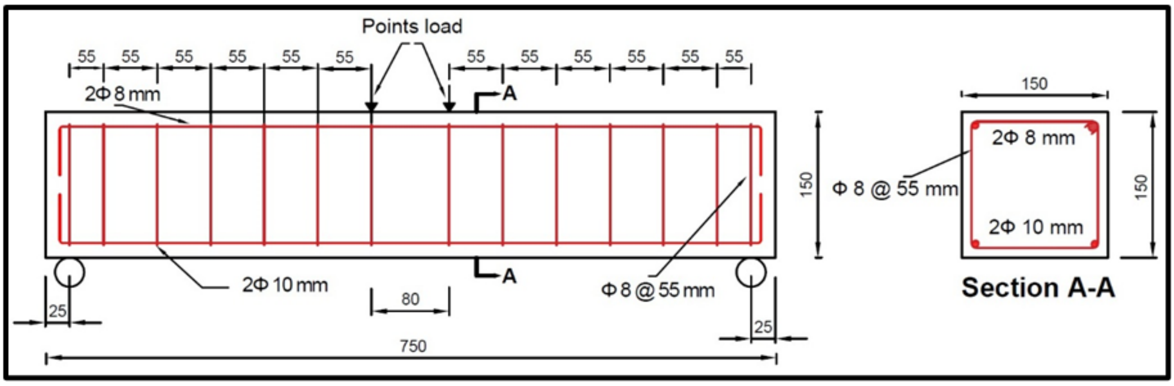


(d)

Fig. 2. Reinforcement details for beams with shear stirrups (a) Reinforcement for NC2 and LWC2 beams, (b) Reinforcement for NC3 and LWC3 beams, (c) Reinforcement for NC4 and LWC4 beams and (d) Reinforcement for NC5 and LWC5 beams

3. Results and discussion

3.1. Slump Test

This test gives a visualization about the degree of workability of concrete in the field. The test was performed according to ASTM C143-15 [20]. A cone of a slump has dimensions (300 mm high, 200 mm diameter at the upper end, and 100 mm diameter at the lower end). Table 11 explains the results of the slump test for both normal concrete and lightweight pumice concrete.

Table 11. Slump cone test on concrete

Concrete type	Slump (mm)
Normal concrete	150
Lightweight pumice concrete	98

4.2. Density Test

The density of concrete was calculated using ASTM 567-14 [21] and ASTM 138-14 [22]. For lightweight pumice aggregate concrete, the density ranged from (1854 to 2012) kg/m^3. Undoubtedly, the type and weight of aggregate had a major effect on the concrete's density. Where the density of the concrete decreased with the increasing ratio of pumice aggregate replacement.

4.3. Compressive Strength

Table 12 lists the compressive strength results for normal concrete and lightweight pumice concrete at 7 and 28 days. By showing a notable rise in strength concerning the curing age, it is possible to observe that the compressive strength development for both normal concrete and lightweight pumice concrete is similar. However, the compressive strength of normal concrete is higher than lightweight pumice concrete by about 47.8% and 47.7% at 7 and 28 days, respectively.

Table 12. Compressive Strength of Normal and Lightweight Concrete

Concrete type	Compressive strength (MPa)	
	7 days	28 days
Normal concrete	38.7	55.4
Lightweight pumice concrete	20.2	29.0

4.4. First Crack Load And Failure Load

Table 13 shows the first load crack and the load failure for both lightweight and normal concrete for various ratios of transverse reinforcement; from the table, it can be concluded that the maximum flexural load is obtained for the lightweight concrete beams with the transverse reinforcement ratio of 1.22%. It is seen that there is a significant increase in the values of the shear behavior and flexural strength when the ratio of transverse reinforcement (stirrups) rises. As well as the appearance of the first crack, it has been significantly delayed by about 20% when the reinforced ratio rose.

Table 13. Reinforcement details, Beams' initial crack load, and load failure

Beam type	Reinforcement details	Initial crack load kN	Load failure kN	Failure mode of
NC1	Without reinforcement	16.5	16.5	Flexural failure
NC2	2 of 10 mm bottom	24.75	52.25	Shear failure
NC3	2 of 8 mm top 2 of 10 mm bottom 6 stirrups of 8mm	30.25	71.5	Shear-flexural failure
NC4	2 of 8 mm top 2 of 10 mm bottom 10 stirrups of 8mm	30.25	74.25	Flexural failure
NC5	2 of 8 mm top 2 of 10 mm bottom 14 stirrups of 8mm	33.0	77.0	Flexural failure
LWC1	Without reinforcement	6.875	6.875	Flexural failure
LWC2	2 of 10 mm bottom	22.0	41.25	Shear failure
LWC3	2 of 8 mm top 2 of 10 mm bottom 6 stirrups of 8mm	24.75	44.0	Shear-flexural failure
LWC4	2 of 8 mm top 2 of 10 mm bottom 10 stirrups of 8mm	24.75	49.5	Flexural failure
LWC5	2 of 8 mm top 2 of 10 mm bottom 14 stirrups of 8mm	27.5	49.5	Flexural - failure

Figures 3 and 4 show the relation between the first load crack and load failure with the ratio of transverse reinforcement % for various ratios of reinforcement (0.0, 0.43, 0.86, 1.22) % of both normal and lightweight concrete, and it is seen that the onset of the first crack and the failure load were delayed significantly when the ratio of reinforcement increased.

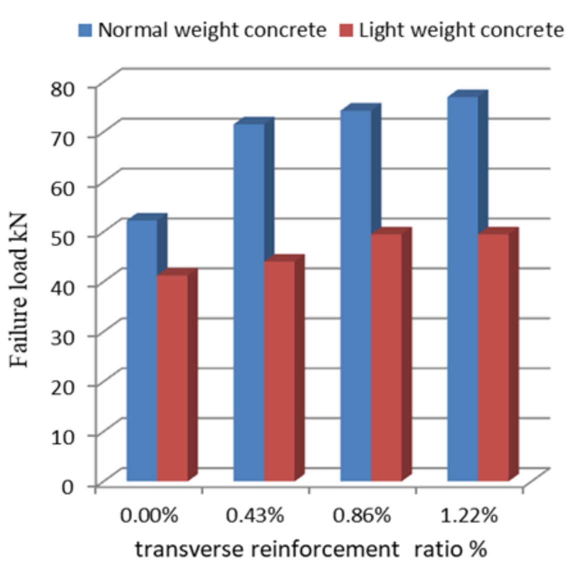


Fig. 3. First load crack vs transvers reinforcement

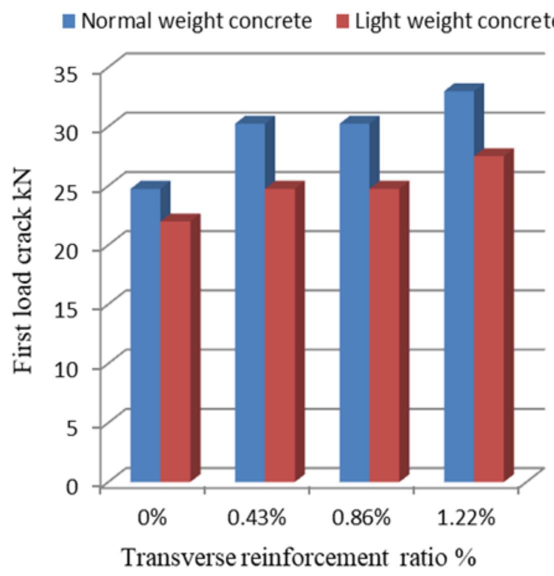


Fig. 4. Failure load vs transvers reinforcement

4.5. Load-deflection Relationship

The magnitudes of deflections for concrete members can be very important. As loads increase, the deflection value of beams and slabs increases, and this causes sagging floors on flat roofs and excessive vibrations. Perhaps the ideal approach to diminishing deflections is by increasing member thickness. Yet designers are constantly compelled to keep members as shallow as could be allowed [23].

The moment of inertia (I) of an RC beam depends upon the degree of the member's cracking. When the load is smaller than the cracking load, the deflection can be calculated using the concrete section's gross moment of inertia, I_g, without taking reinforcing into account. However, the member cracks at specific intervals throughout the span when the load extends greater than the cracking load. The section's flexural stiffness is reduced by the neutral axis vicissitude across the cracks, which results in a change in curvature throughout the length of the member. The amount of (I) modifications along the span of the beam from a high amount of I_g for the uncracked (gross) section to a low amount of I_{ce} for the completely cracked (transformed) section Accurately determining deformation using moment-curvature relationships in the elastic range is challenging due to the difference of (I) along the length of the span, which delays the deflection calculation. Hence, in a cracked member, it is desirable to use an effective moment of inertia (I_e) that will have a value between those derived for cracked and uncracked sections.

The theoretical (Ie) is calculated according to ACI 318M-14 [23] from the following equation:

$$I_e = (\frac{M_{cr}}{M_a})^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \quad \leq \quad I_g \tag{1}$$

Where; Ma: The member's maximum moment that is calculated at the deflection stage (N.mm), Mcr: Beam cracking moment $= \frac{f_{cr}\, I_g}{y_t}$ (N.mm), Icr: Moment of inertia of cracked, transformed section (at yield), Ig: Moment of inertia of gross section – neglect (mm^4), fr: Modulus of rupture of concrete = $0.62\ \lambda\sqrt{f_{c'}}$ (MPa), λ: Factor for the type of concrete, and y_t: Distance from neutral axis to the face of tension (mm).

While the experimental deflections were measured at mid-span using a mechanical dial gauge having an accuracy of 0.01mm (loading is done by using a hydraulic jack), as shown in Figure 5.

Fig. 5. Dial Gauge and Loading Points Locations

The theoretical deflection is calculated according to ACI 318M-14[23], using the following formula:

$$\delta = \frac{pa}{24EI}(3L^2 - 4a^2) \quad (2)$$

Where; δ: Midspan deflection, A: Distance between point load and support, E: Modulus of elasticity of concrete = $w_c^{1.5}\ 0.043\sqrt{f_{c'}}$, I: Effective moment of inertia, and L: Effective span.

It was seen that the deflection obtained from the experiment at the service moments compares reasonably well to the theoretical deflection calculated by ACI 318M-14 [23]. After cracking, the slope of the curve alteration indicates a drop in the rigidity of the beam until the steel yields. The comparison between the theoretical and experimental deflection values at mid-span of the beam is shown in Table 14.

Table 14. Experimental and theoretical deflection of beams

Beam type	Exp. Defl. $\delta_{ex.}$ (mm)	Theor. defl. $\delta_{the.}$ (mm)	$\frac{\delta_{ex.}}{\delta_{the.}}$
NC1	------	------	------
NC2	1.96	0.89	2.20
NC3	4.27	1.26	3.39
NC4	4.30	1.31	3.28
NC5	6.33	1.35	4.69
LWC1	------	------	------
LWC2	1.31	1.07	1.22
LWC3	1.34	1.14	1.18
LWC4	1.6	1.29	1.24
LWC5	1.6	1.29	1.24

4.6. Effect of Vertical Reinforcement

The beams without shear reinforcement have linear load-deflection curves up to failure, while the beams with shear reinforcement (stirrups) have a slight load-deflection curve after cracking. The curves explain the influence of the stirrup ratio (ρ_v) within the same group of beams, as well as comparing it with the different groups. It is apparent that as the (ρ_v) grew, the ultimate load increased while the deflection decreased at the ultimate load. The load-deflection curves show clearly that the pre-cracking portion was nearly a straight line for all beams; see Figures 6 and 7. After cracking, the curve changes from a straight line to a slope, indicating a decrease in the stiffness of the beam. It is essential to note that reinforcing a concrete beam only in the tension zone (bottom of the beam) exhibited high deflection. However, the use of stirrups reduced the ultimate deflection. However, with an increasing stirrup ratio, the deflection begins to rise, and this means that the stirrups have improved the beams in terms of an increase in shear strength, but in terms of deflection, there has been no improvement. The reason for the increased deflection is the lack of tension reinforcement.

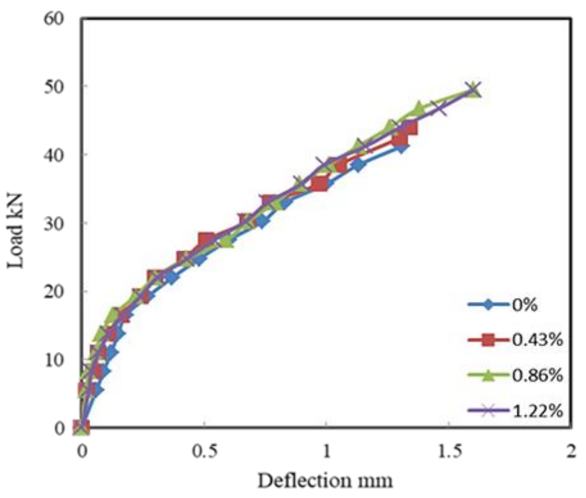


Fig. 6. Load-deflection relationship for lightweight concrete

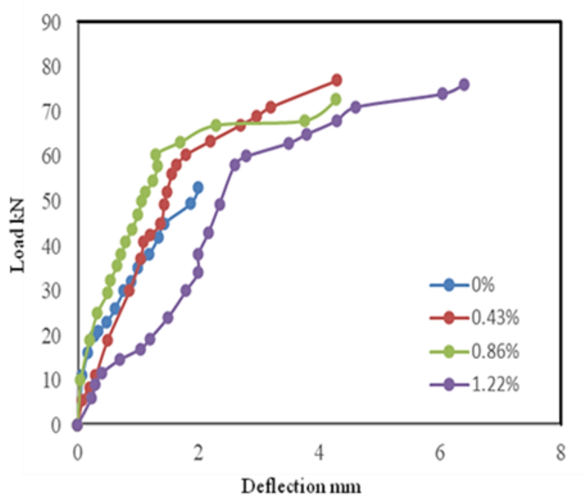
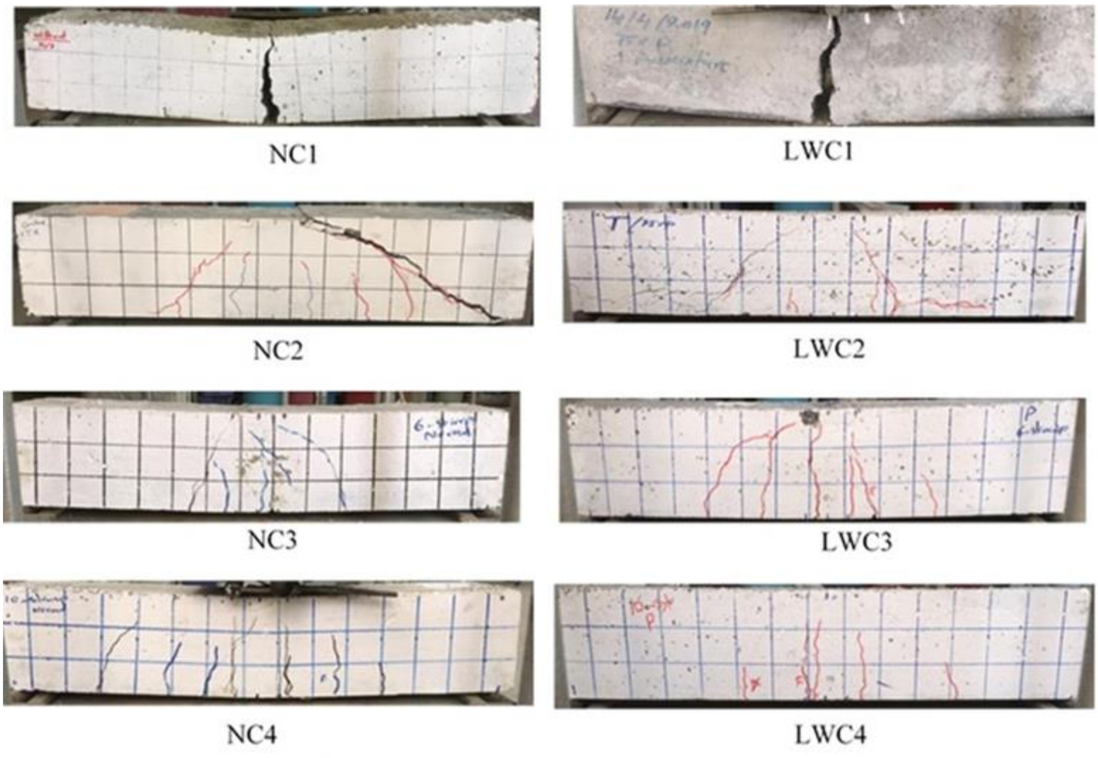


Fig. 7. Load-deflection relationship for normal-weight concrete

4.7. Mode of Failure

Cracks appeared firstly in the flexural zone for all beams at the initial phases, and with the increasing load, more cracks developed at mid-span; furthermore, vertical cracks formed in the span of shear on the reinforced beams. Figure 8 shows the beam's failure modes; it is seen that the failure of the beam without reinforcement (plain concrete) was a flexural failure that divided the beam into two symmetrical parts. The shear failure occurred in the beams without shear reinforcement (no stirrups) and also when a low ratio of transverse reinforcement was used, while the flexural failure and flexural-shear failure appeared in the beams with a high ratio of reinforcement.



NC5 LWC5

Fig. 8. Failure pattern of beams

5. Conclusion

This research investigated the flexural strength and shear behavior of pumice lightweight reinforced concrete beams with silica fume. The following is a summary of the important conclusions:

- No obvious difference in the modes of cracks between the lightweight concrete and normal concrete.
- The compressive strength of lightweight concrete containing pumice stone as a coarse aggregate is lower than that of concrete containing natural aggregate, where it is observed that the compressive strength of lightweight pumice concrete decreased by 37.6% and 37.8% at 7 and 28 days, respectively, compared to that of normal concrete at the same time. The reduction in the value of compressive strength is due to the porous nature of pumice, which has an effect on density and the cohesive strength between concrete components of the concrete mix.
- The first crack in lightweight concrete occurred at lower loads than normal concrete because it has a lesser compression strength than conventional concrete. Nevertheless, after the onset of the first cracking, before it finally failed, the lightweight concrete was able to maintain its shear resistance.
- For lightweight pumice concrete beams, the pre-cracking portion of the load-deflection curves is almost a straight line for every beam. Note that, for most beams, the practical experimental results are somewhat higher than the theoretical ones. However, as the stirrup ratio increases, the deflection starts to increase as well. This indicates that while the stirrups have enhanced the shear strength of the beams, the deflection has not improved. The small amount of tension reinforcement is the cause of the increased deflection. The small amount of reinforcement in the tension zone is what causes the increase in deflection.
- The deflection of the reinforced concrete beams depends on many points: tension reinforcement, introduction of compression reinforcement, element dimensions (make the element deeper or make the member wider), and the geometry of the structure.
- The shear capacity of the lightweight pumice concrete beams increases with the addition of the shear reinforcement (stirrups), and this prevents shear cracking from developing, allows for greater tensile stress transfer in the web zone, and reduces the danger of sudden failure modes.
- Both the failure modes and the failure load are significantly impacted by increasing the ratio of the transverse reinforcement (stirrups).

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