Experimental Investigations on Flexural Behavior of Partially Replaced LWAC Beams

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Abstract:- In this study evaluation of the structural performance and characteristics of normal concrete (NC) and light weight aggregate concrete (LWAC) was done through a series of experimental tests. And bond strength, interfacial shear strength and flexural behaviour are essential for assessing the suitability of LWAC in construction. The bond strength between concrete and steel reinforcement is determined using pull-out tests. interfacial shear strength at the concrete-to-concrete interface is evaluated using push-off tests, where L-shaped specimens are tested for vertical load failure. The flexural behaviour of reinforced concrete control beams made of fully NC and NC-LWAC double layered beams were examined through tests on beams through four-point loading, focusing on pure flexural failure. Various flexural parameters, such as load at first crack, yield load, ultimate load and deflection are measured and analysed. The results compare the performance of fully NC beams with NC-LWAC beams, evaluating load versus deflection curves, cracking behaviour, stiffness degradation, ductility indices, energy absorption, and moment capacities. The study also documents failure patterns to understand crack propagation and overall behaviour under loading, providing insights into the advantages and limitations of NC and LWAC in structural applications.

Keywords: *EPS, cinder, LWAC, RC beams, flexure.*

1. Introduction

Experimental studies of different kinds have been done in an attempt to reduce the density of the concrete which has led to the innovation of lightweight aggregate concrete. Present studies on Lightweight aggregate concrete is composed of EPS beads and cinder as replacement for natural coarse aggregate at different proportions from 0 to 20% and cement is also replaced by Silica fume 10% of total cement quantity after testing all different mixes for both mechanical strength and physical durability optimum mix obtained was containing EPS beads 10% and Cinder 90% , whose density is 1874 kg/m3and compressive strength was 24.85 MPa, in the present study optimum mix was used as sacrificial concrete below neutral axis in double layered (NC-LWAC)RC beams with varying reinforcement ratios and are subjected to the pure flexural loading and the results were compared with fully normal concrete RC beams with similar reinforcement ratios, along with the flexural tests preliminary tests like bond tests and interfacial shear tests were also done for better understanding of flexural behavior of double layer RC beams.

2. Pull-Out tests

The bond strength between concrete and steel, essential for assessing the bond behavior of Lightweight Aggregate Concrete (LWAC), was tested using a pull-out method as per IS 2770 (Part I)-1967. For this, 150 mm cubes with an embedded HYSD steel bar were cast and cured for 28 days, after which the steel bar was pulled to measure bond strength. Results, shown in Table 1.1, reveal that LWAC specimens attain around 85% of the bond strength of Normal Concrete (NC) due to their lighter weight and unique aggregate composition. This reduced bond strength, visualized in Figures 1.1(a)-(c) through the test setup, initial state, and post-test condition, should be considered in the design of structures using LWAC.

(a)Experiment set up (b) specimen before test (c) specimen after test

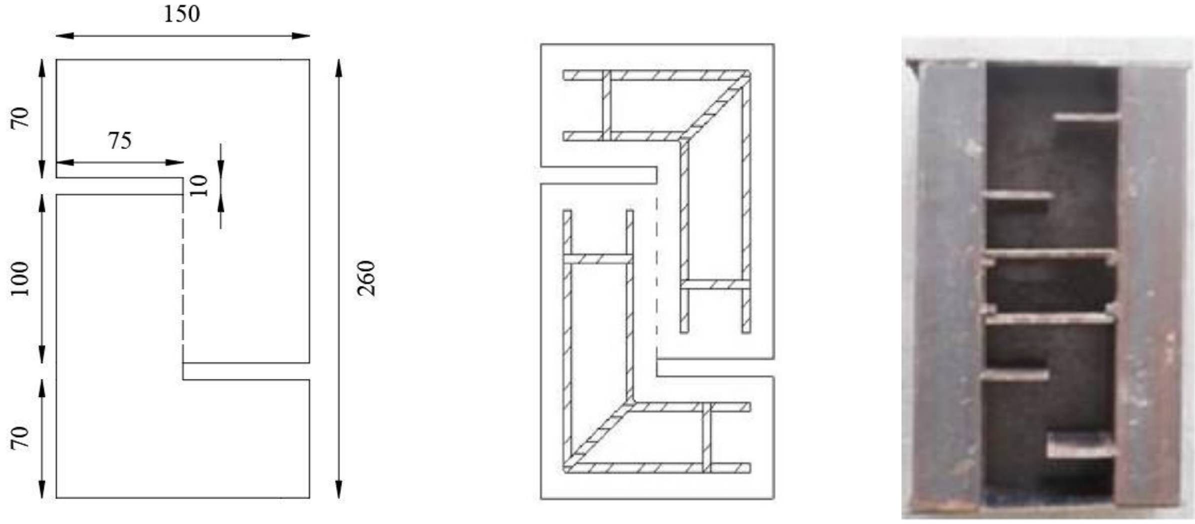
Figure 1.1 Pull-out test specimen and experimental setup

Table 1.1 Pull-out test results

Test sample	Normal Concrete Strength (MPa)	Lightweight Concrete Strength (MPa)
1	9.02	7.9
2	9.51	7.4
3	8.75	7.74
Average	9.09	7.68

3. Push-Off Test

The push-off test, a common method for assessing the shear strength at concrete interfaces, was conducted using two L-shaped concrete sections joined at an interface, with gaps at both ends. Each push-off sample measured 150 × 150 × 260 mm with a 10 mm notch, as shown in Figure 2.1(a), and included reinforcement positioned within the mould as in Figure 2.1(b). Steel moulds were used to cast two samples simultaneously as shown in Figure 2.1(c). Three different interface types NC to NC, NC to LWAC, and LWAC to LWAC were tested, as illustrated in Figure 2.3. After casting and 28 days of curing, the samples were tested in a Compression Testing Machine (CTM). Table 2.1 present the direct shear strength values: NC-NC interfaces showed the highest average shear strength at 9.3 MPa, while LWAC-LWAC had the lowest at 3.2 MPa. The NC-LWAC combination achieved an intermediate shear strength of 5.4 MPa, approximately 60% of NC-NC's strength, indicating that although LWAC's shear performance improves with NC, it does not reach NC's full capacity. This study suggests that while NC remains superior in shear strength, combining it with LWAC enhances LWAC's shear performance, though still below that of pure NC.



(a)Dimensions (b)Reinforcements (c)Mould

Figure 2.1 Push-off test specimen

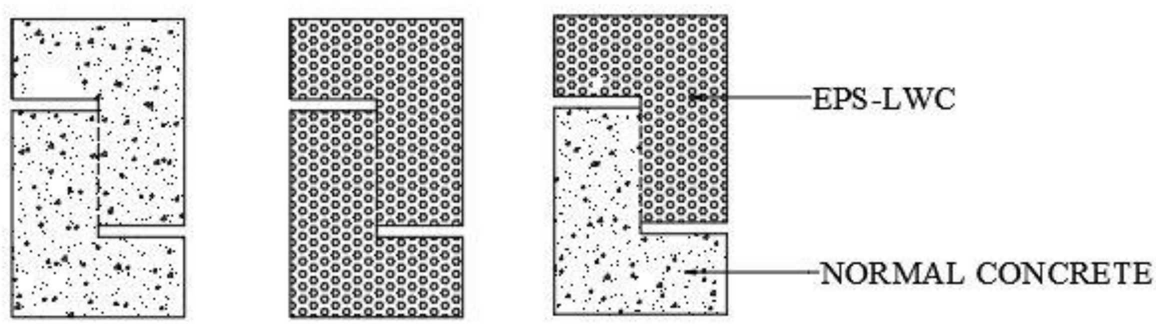
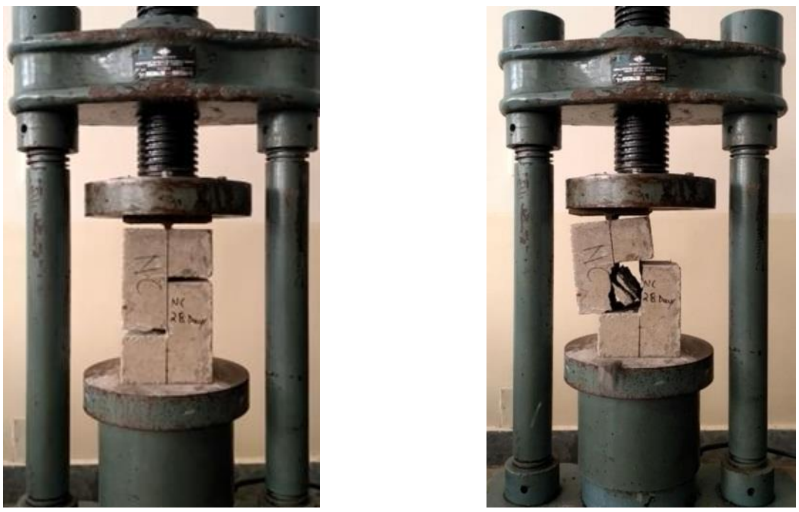


Figure 2.2 Push-off test specimen (a) NC-NC (b) LWAC-LWAC (c) LWAC-NC in



(a) Before test (b) After test

Figure 2.3 Push-off test set up in CTM.

Table 2.1 Push-off test results

Specimen	Push-Off Test Results NC Strength (MPa)	LWAC Strength (MPa)	LWAC-NC Strength (MPa)
1	12.7	3.0	5.3
2	8.7	3.3	5.3
3	6.7	3.2	5.7
Mean	9.3	3.2	5.4

4. Beam specimens

RC beams with specific dimensions were designed and tested under controlled conditions. Figure 3. illustrates the beam cross sectional dimension and depth of LWAC, and Figure 3. shows test set up where beams are supported on rollers and centrally loaded using a hydraulic loading system to maintain a consistent four-point loading condition. And

Table 3. details the properties of the both conventional and double layered beam specimens with varying reinforcement ratios, where the concrete below the NA acts as sacrificial material primarily providing sufficient bonding with the embedded steel bars to generate adequate resistive bending moment. This design is based on a balanced section and is also supported by the findings of Hayder Kadhem et al. (2021).

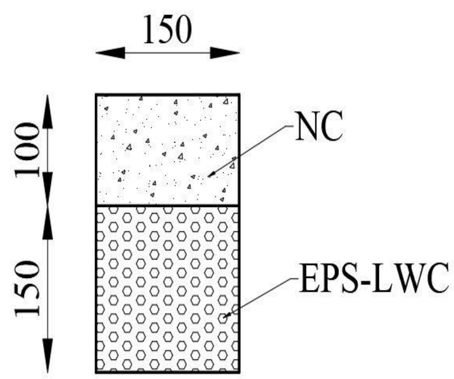


Figure 3.1 Cross section of beam indicating the depth of replacement

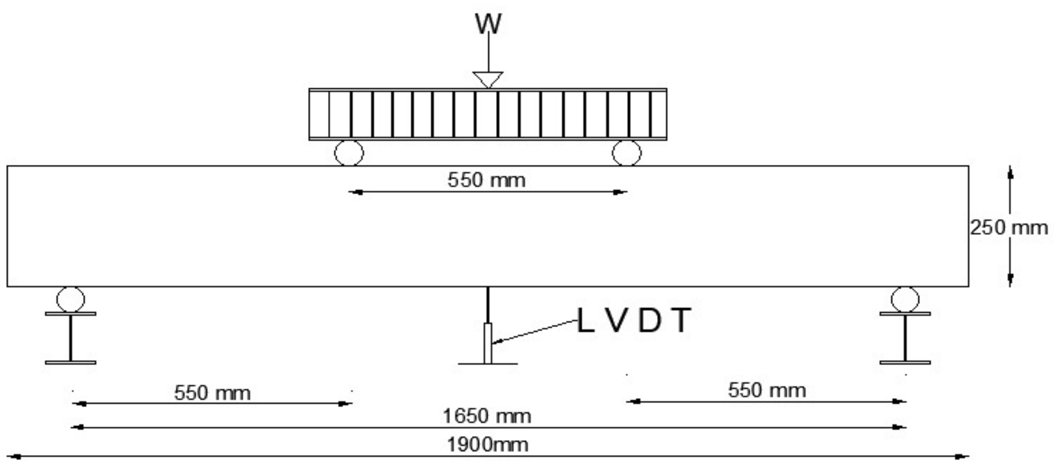


Figure 3.2 Graphical representation of beam test set up

Table 3.1 Detailing of beam specimens

Beam	Tension reinforcement	Compression reinforcement	reinforcement ratio
NC/R1/1.37	2Φ10 +1Φ16	2Φ10	1.37
NC/R2/1.14	2Φ10 +1Φ12	2Φ10	1.14
NC/R3/1.05	3Φ10	2Φ10	1.05
NC-LWAC/R1/1.37	2Φ10 +1Φ16	2Φ10	1.37
NC-LWAC/R2/1.14	2Φ10 +1Φ12	2Φ10	1.14
NC-LWAC/R3/1.05	3Φ10	2Φ10	1.05

5. Casting of Beams

Casting reinforced concrete beams is essential to ensure specimen consistency and quality, directly affecting the reliability of experimental results. First, reinforcing cages are constructed according to specifications in Table 3.1, with handles attached for easier handling. The formwork is then meticulously prepared, free of defects, and coated with a de-bonding agent like oil for easy removal after setting. Cover blocks are used to maintain correct reinforcement cover depth, ensuring precise positioning within the beam. Once formwork and reinforcement are in place concrete mixing begins. Cement, silica fume, cinder, EPS beads, sand, and admixtures are measured and mixed in a 100-litre pan mixer, with water added gradually to achieve the desired workability. Admixtures are added in the final stage, with mixing continuing for 2-3 minutes. The concrete is then layered into the formwork, with thorough compaction to prevent segregation. With the help of GI wires two layers of standard concrete and LWAC was established Figure 4.1. After casting, beams are covered with damp gunny sacks and cured for 28 days to ensure proper hydration. Once cured, the formwork is removed, and beams are whitewashed with lime-based paint to aid in crack observation during testing as in Figure 4.2.

Figure 4.1 Using GI wire to differentiate concrete layers

Figure 4.2 White-washed beams

6. Beam Testing Setup and procedure

The beam testing setup, illustrated in Figure 5.1, was designed to evaluate the flexural behavior of RC beams under controlled loading conditions. Each beam was positioned on a loading frame with roller supports providing a 125 mm bearing, and a four-point loading condition was established with an I-section frame centrally aligned for uniform load distribution. A loading ram was lowered to contact the center of the I-section, while a Linear Variable Differential Transformer (LVDT) was positioned at the mid-span to record deflection data, which was fed into a data acquisition system. Loading was applied gradually using a hydraulic system, and the appearance of the first crack was noted, with crack widths measured via a crack scope. Cracks were marked for visibility, and loading continued until reaching the beam's ultimate load. All NC and NC-LWAC beams were tested similarly, with results tabulated in Table 5.1, detailing key metrics like load at first crack (Pcr), yield load (Py), ultimate load (Pu), and corresponding deflections (δcr, δy, δu). These data points reveal critical aspects of the beams' flexural performance, such as the onset of cracking (Pcr), reinforcement yielding (Py), and maximum load capacity (Pu), along with associated deflections that shed light on deformation characteristics. Ratios like Pcr/Pu and Py/Pu illustrate ductility and crack resistance, while additional metrics such as crack width, stiffness, ductility index, and energy absorption provide a thorough assessment of the beams' flexural performance.

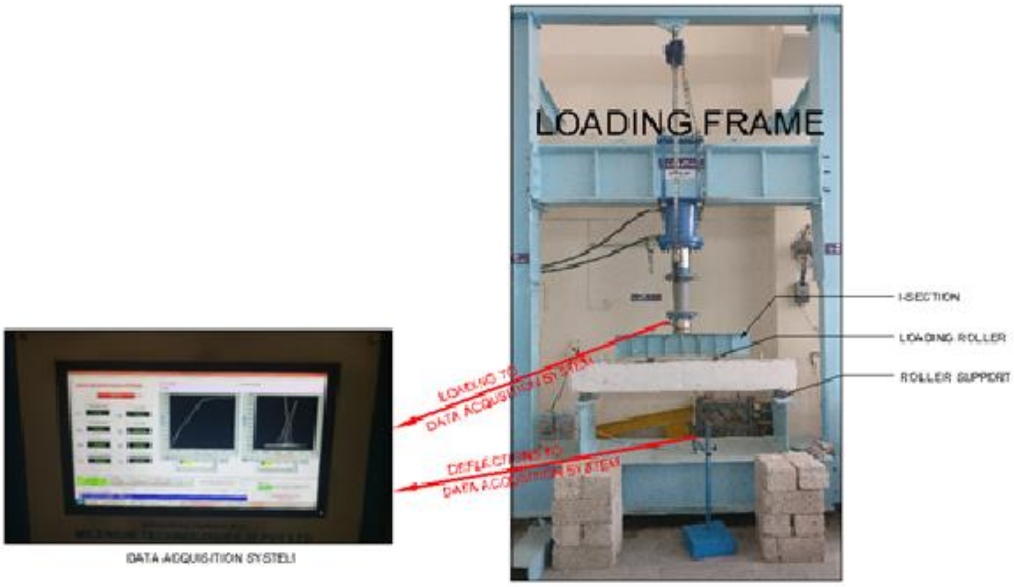


Figure 5.1 Beam testing setup

Table 5.1 Beam test results

Beam ID	Pcr kN	δcr mm	Py kN	δy mm	Pu kN	δu mm	Pw kN	δw mm	Pcr/Pu	py/pu
NC-R1-1.37	13.87	1.95	108.3	6.8	115.4	24.16	76.93	16.11	12.02	93.84
NC-R2-1.14	12.85	2.13	88.1	9.7	95.5	30.25	63.67	20.17	13.46	92.28
NC-R3-1.05	11.96	2.54	75.8	10.4	83.4	31.64	55.60	21.09	14.34	90.84
NC-LWAC-R1-1.37	12.78	0.97	102.63	10.9	112.4	27.27	74.93	18.18	11.37	91.31
NC-LWAC-R2-1.14	11.14	1.18	82.76	16.8	90.6	33.12	60.40	22.08	12.30	91.34
NC-LWAC-R3-1.05	10.43	1.76	75.12	21.2	81	34.34	54.00	22.89	12.88	92.74

Crack width mm	Initial stiffness kN/mm	service stiffness kN/mm	Ductility index mm/mm	Energy absorbtion kN-mm	Mcr (cal) kN-m	Pcr/2 kN	Mcr (exp) kN-m	Mcr(exp) /Mcr(cal)	Mu (cal) kN-m	Pu/2 kN	Mu (Exp) kN-m	Mu (exp)/ Mu(cal)
0.1	27.96	12.9	3.57	2973.12	4.786	6.935	3.814	0.80	30.47	57.7	31.74	1.04
0.1	12.33	8.92	3.12	2556.61	4.786	6.425	3.534	0.74	22.99	47.8	26.26	1.14
0.15	8.84	6.14	3.04	2283.02	4.786	5.98	3.289	0.69	20.05	41.7	22.94	1.14
0.2	9.4	7.18	2.51	2729.62	4.193	6.39	3.515	0.84	30.47	56.2	30.91	1.01
0.2	6.3	4.52	1.97	2445.07	4.193	5.57	3.064	0.73	22.99	45.3	24.92	1.08
0.25	4.45	3.65	1.62	2188.35	4.193	5.215	2.868	0.68	20.05	40.5	22.28	1.11

7. Flexural Test Results

Load-displacement curves were generated to understand the relationship between applied load and deflection for NC beams with various reinforcement ratios Figure 6.1. Initially, these curves are linear, indicating elastic behavior with a proportional relationship between load and deflection; however, as the load increases, the curves deviate from linearity, marking the onset of cracking and the transition to plastic behavior, with each beam reaching an ultimate load before failure. These curves provide insights into the stiffness, load-carrying capacity, and deformation characteristics of NC beams under flexural loading. All specimens exhibited bilinear behavior, with reduced load capacity as reinforcement ratios decreased. Similarly, Figure 6.2 shows load-deflection curves for partly NC-LWAC beams, where the initial linear segment indicates elastic behavior, and the overall trend demonstrates that partial LWAC replacement does not significantly reduce flexural performance. The ultimate load and deflection for NC-LWAC beams reveal that adequate structural performance is maintained, suggesting weight reduction can be achieved by using LWAC below the Neutral Axis (NA) without compromising integrity. In both beam types, the reinforcement ratio is a key factor in determining flexural behavior.

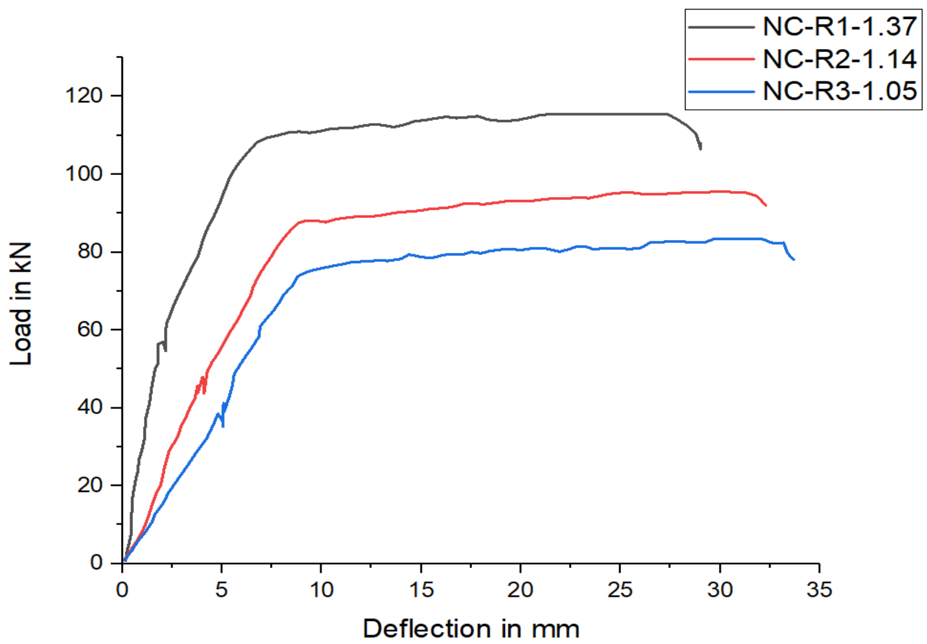


Figure 6.1 Load vs deflection curve of fully NC beams

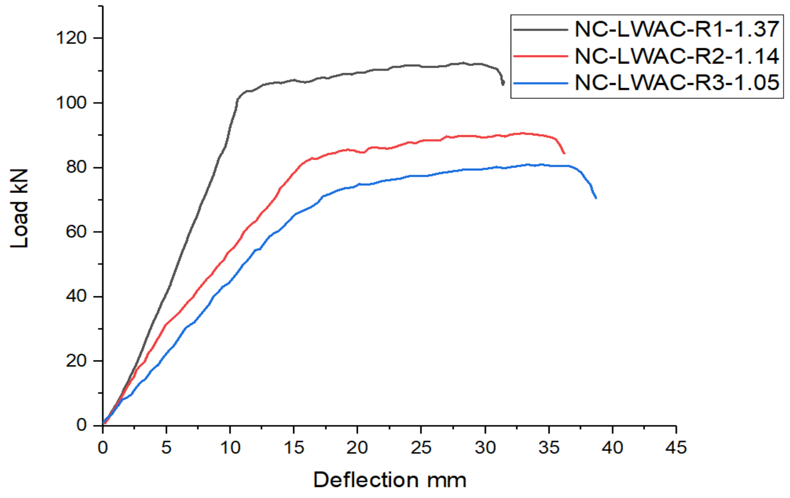


Figure 6.2 Load vs deflection curve of partially NC-LWAC beams

8. Deflection At Different Phases of Loading

The deflection at different phases of loading for various RC beam specimens is as shown in Figure 7.1 which reveals that deflections in partially LWAC beams are comparatively higher than those in fully NC beams across different reinforcement ratios. This indicates that the incorporation of LWAC, despite its benefits in reducing weight, results in increased deflections under loading. The higher deflection in LWAC beams suggests that while they offer weight savings, there is a trade-off in terms of increased flexibility and potentially reduced stiffness.

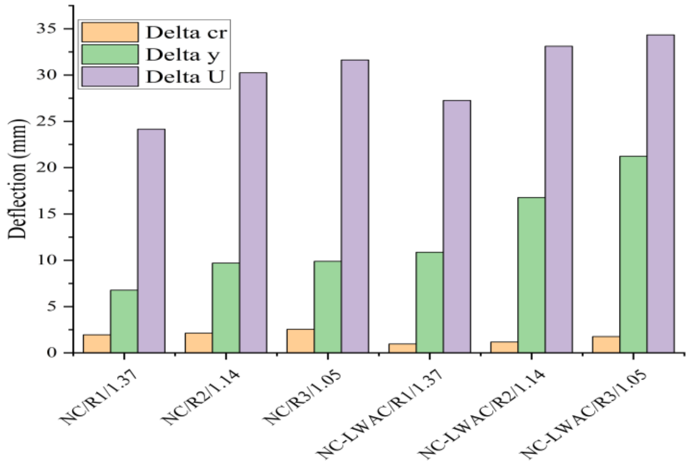


Figure 7.1Deflection at different phases of loading

9. Post Cracking Behavior

Understanding the post-cracking performance of various RC beams requires knowledge of their performance ratios, Pu/Pcr and Pu/Py. Pu/Pcr represents the ratio of the ultimate load (Pu) to the yield load (Py), and Pu/Py represents the ratio of the ultimate load to the load at the first crack (Pcr). Higher values of these ratios indicate better performance after cracking, suggesting that the beam can carry a higher load beyond the initial cracking and yielding points. The experimental results depicted in Figure 8. demonstrate that the post-cracking actions of NC-LWAC beams are marginally superior to completely NC beams. for the respective reinforcement ratios. This suggests that NC-LWAC beams can sustain higher loads and demonstrate better resilience after cracking compared to fully NC beams. The improved performance of NC-LWAC show that the post-cracking behaviours of combination of lightweight aggregate concrete, which helps in reducing the overall weight, and normal concrete, which provides the necessary strength and stiffness.

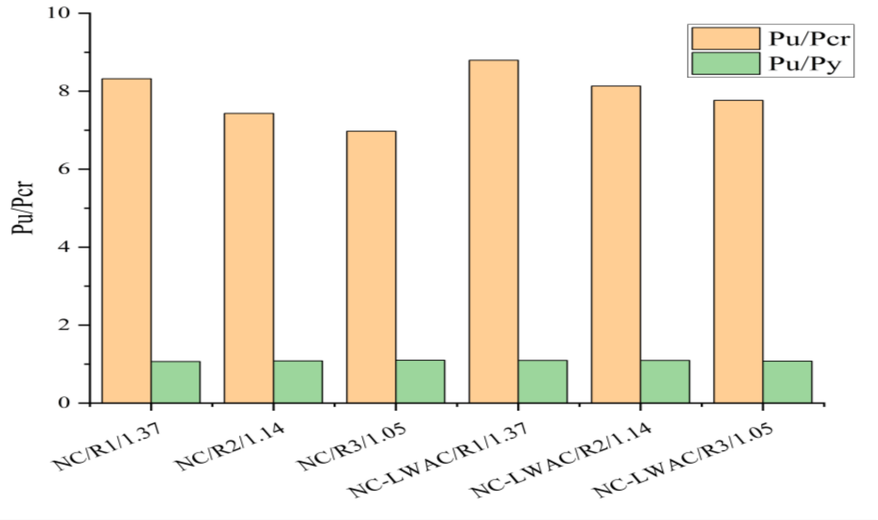


Figure 8.1 post-cracking behavior of beams

10. Stiffness Calculation

The initial and service stiffness of different RC beams provides great insights into their performance of the structure under various loading scenarios. Initial stiffness, as shown in Figure 9. is determined by the slope of the linear part. load-deflection curve prior to the initial flexural crack forming Hayder Kadhem et.al, (2021), This measure reflects the beam's ability to resist deformation under initial loading, indicating the elastic behaviour of the material. Service stiffness, depicted in Figure 9.1 is determined by calculating the load-deflection curve's slope at 50% and 80% of the ultimate load capacity. Hayder Kadhem et.al, (2021),. This metric provides an understanding of the beam's performance under service loads, representing its stiffness during typical operational conditions rather than just at the initial loading phase. The outcomes of the experiment demonstrate that completely NC beams exhibit higher initial stiffness brought on by the inherent strength and rigidity of normal concrete. However, NC-LWAC beams demonstrate comparable service stiffness. Research by Hayder Kadhem et.al, (2021) supports these findings as well, highlighting the significance of assessing both initial and service stiffness in order to fully understand how RC beams behave under different loading conditions.

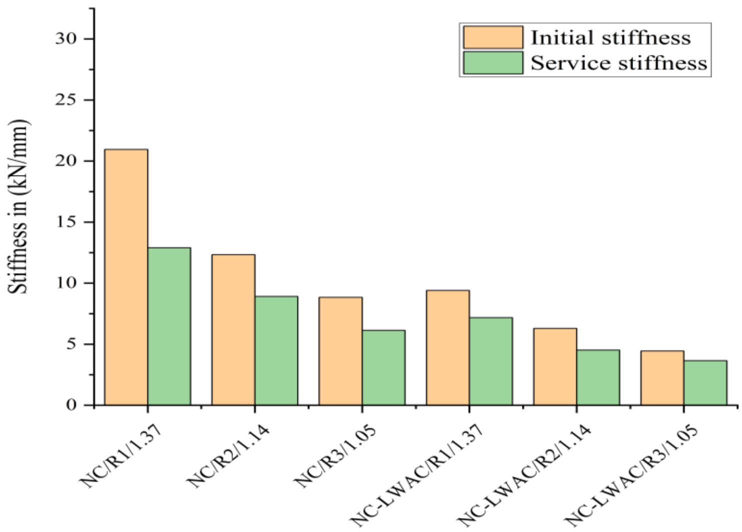


Figure 9.1 Initial and Service Stiffness of beams

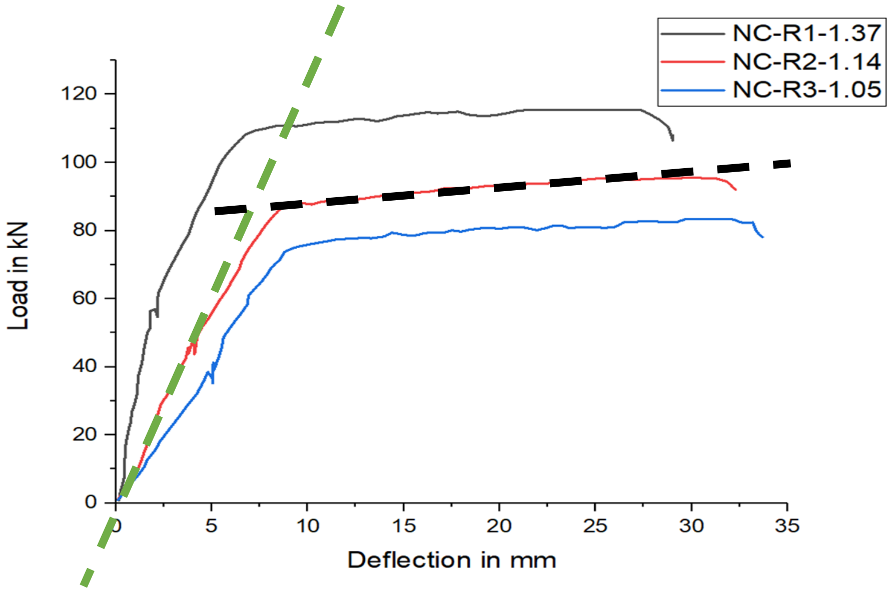


Figure 9.1 Stiffness determination of beams Hayder Kadhem et.al, (2021)

11. Displacement Ductility

Moving One important indicator of a beam's capacity to experience substantial plastic deformation prior to failure is its ductility. This is essential for evaluating the structure's overall toughness and The ratio of the final deflection to the initial yield deflection is known as the DDI. ability to absorb energy Figure 10.1 presents the Displacement Ductility Index (DDI) of various beams. The DDI is calculated as the proportion of the ultimate deflection to the first yield deflection. This ratio provides a clear indication of the beam's capacity to deform plastically under loading conditions. Higher DDI values indicate better ductility, meaning the beam can sustain more deformation without catastrophic failure. The results, as highlighted by Bernardo T. Lopes et al., (2004) demonstrate that fully NC beams are more effective than partially LWAC beams at absorbing energy via deformation by plastic. Despite being lighter, LWAC beams are less able to tolerate significant plastic deformation, as indicated by their lower DDI values.

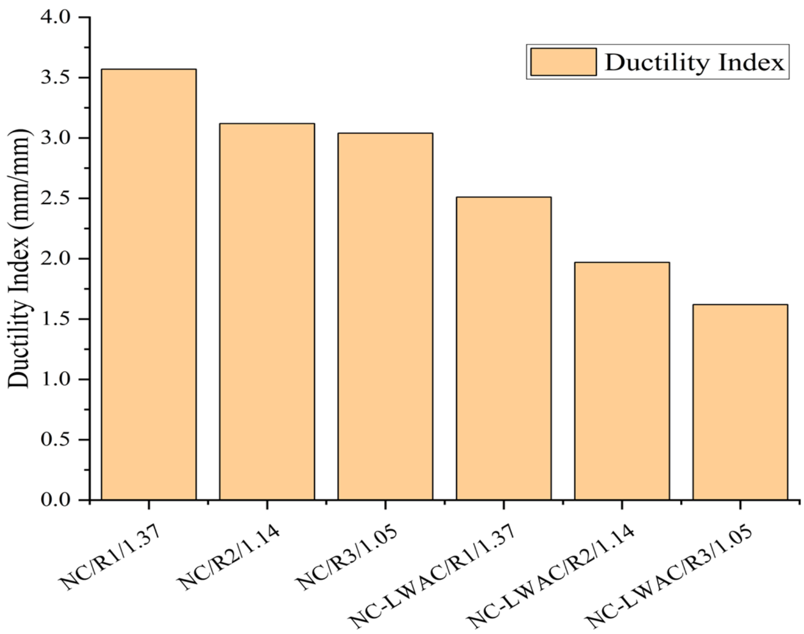


Figure 10.1 Displacement Ductility Index of beams

12. Energy Absorption

The total area under the load-deflection curve, or energy absorption, is a crucial measure that proves how well a beam can absorb and release energy when under load. The energy absorption values for several beam types are shown in Figure 11.1, emphasizing the variations in their ability to support loads and undergo plastic deformation prior to failure. It is clear from the illustration that beams composed of NC and those comprising LWAC absorb energy differently. The experimental findings show that, in comparison to fully NC beams, partially LWAC beams have lower energy absorption values. This reduced energy absorption in LWAC beams is attributed to their comparatively lower stiffness and reduced bond strength between the lightweight aggregate and the cement matrix. Consequently, partially LWAC beams are less effective in absorbing and dissipating energy through plastic deformation.

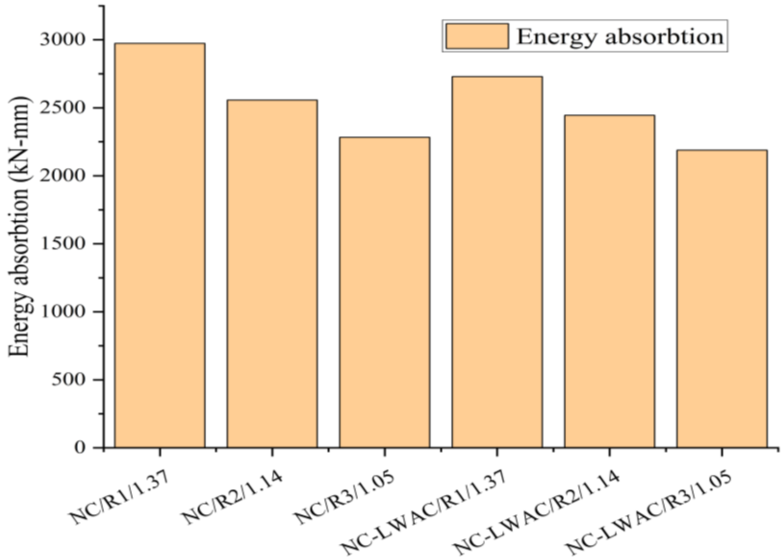


Figure 11.1 Energy absorption of beams

13. Moment Capacities

One crucial element that influences a beam's ability to withstand bending under applied stresses without failing is its moment capacity. The moment capacities of both fully NC and partial LWAC were calculated theoretically as per IS 456-2000 and also from the modified ACI 318-19 method proposed by **Hayder Kadhem et, al. (2021)**.The Modified Equation of cracking moment for Two-Layered Beam proposed by **Hayder Kadhem et, al. (2021)** For beams composed of two different concrete layers, such as those incorporating LWAC below the neutral axis, This equation accounts for the different material properties and the depth of each layer, providing a more precise calculation of the cracking moment for these complex composite sections. By considering the distinct properties of the LWAC and normal concrete layers, the modified equation offers a tailored approach to predicting the cracking moment in two-layered beams. Table 12.1 displays the comparison between the calculated and experimental moment capabilities. The findings showed that, compared to the IS 456-2000 technique, the practical data more closely matches the theoretical predictions produced by the modified ACI 318-19 method. The modified ACI 318-19 equation offers a more accurate estimate of moment capacity, closely matching the experimental results. In contrast, the IS 456-2000 formula tends to underestimate the moment capacity of the beams.

Equation of Cracking Moment of Homogenous Beam - IS 456-2000

$$M_r = \text{cracking moment, equal to } \frac{f_{cr}\, I_{gr}}{y_t}$$

Modified Equation of Cracking Moment for Non-Homogeneous Beam- ACI 318-19 by Hayder Kadhem et, al. (2021)

$$M_{cr(ACI)} = \frac{(\alpha_1 \lambda_1 f_{r1} I_{g1} + \alpha_2 \lambda_2 f_{r2} I_{g2})}{y_t}.$$

Table 12.1 Moment Capacities of Beams

Beam ID	Mcr (cal) kN-m ACI	Mcr (cal) kN-m IS	Mcr (exp) kN-m	Mcr(exp)/ Mcr(cal) ACI	Mcr(exp) /Mcr(cal) IS	Mu (cal) kN-m	Mu (Exp) kN-m	Mu (exp)/ Mu(cal)
NC-R1-1.37	4.786	7.781	3.814	0.80	0.49	30.47	31.74	1.04
NC-R2-1.14	4.786	7.781	3.534	0.74	0.45	22.99	26.26	1.14
NC-R3-1.05	4.786	7.781	3.289	0.69	0.42	20.05	22.94	1.14
NC-LWAC-R1-1.37	4.193	7.781	3.515	0.84	0.45	30.47	30.91	1.01
NC-LWAC-R2-1.14	4.193	7.781	3.064	0.73	0.39	22.99	24.92	1.08
NC-LWAC-R3-1.05	4.193	7.781	2.868	0.68	0.37	20.05	22.28	1.11

14. Failure Patterns

The crack patterns in beams subjected to flexural loads provide valuable insights into the RC beams' structural performance. Figure 13.11 shows the failure patterns in fully NC beams under loading. It is clear from the crack patterns that as the reinforcement ratio decreases the quantity of fractures in the NC beams as well decreases. Nevertheless, each crack's width increases in tandem with The reduction in the quantity of fractures. The reason for this is that there is less reinforcing available to disperse the tensile stresses across the beam. With less reinforcement, the stress is concentrated in fewer cracks, leading to wider openings. Figure 13.1 compares the crack patterns of two-layered RC beams with fully NC beams. The two-layered beams develop more cracks at lower loads, with a greater number of finer cracks, as the stiffness is reduced. Overall, the crack patterns in two-layered beams are similar to those in fully NC beams across different reinforcement ratios.

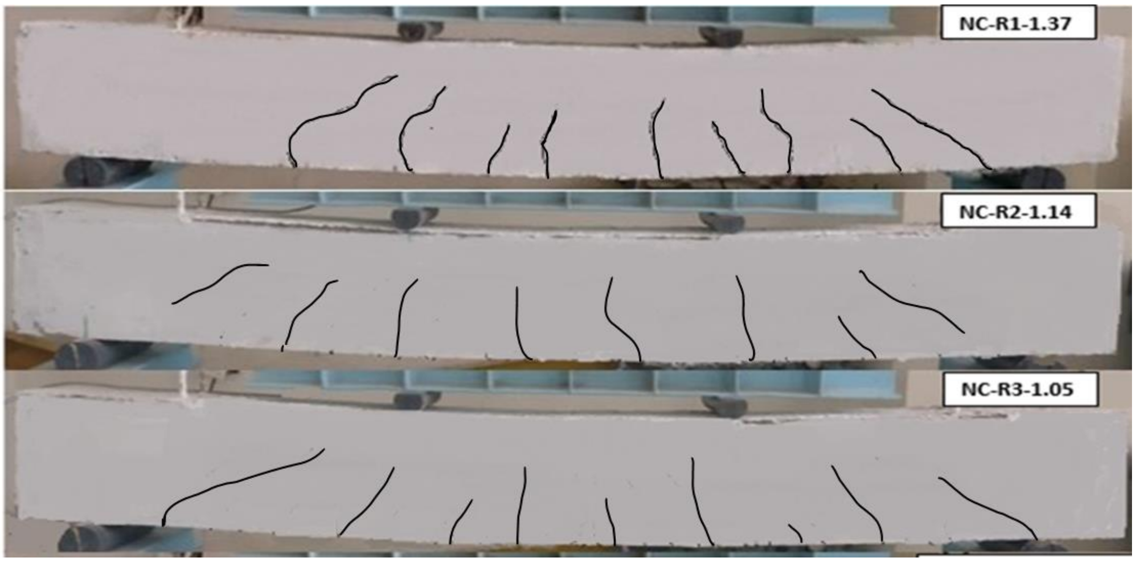


Figure 13.1 NC beam failure patterns

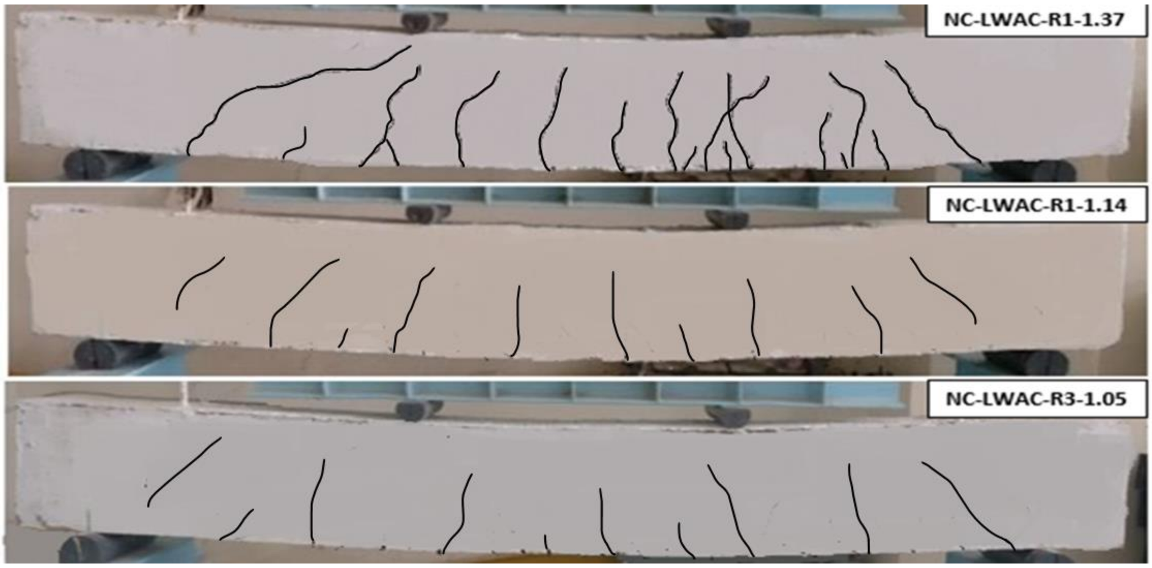


Figure 13.1 NC-LWAC beam failure patterns

15. Summary and observations

This chapter explores the flexural behavior of LWAC beams in comparison to NC beams, with an emphasis on structural performance and durability. Through a series of tests, including pull-out and push-off tests, bond strength and interfacial shear strength were evaluated. The study also investigated the flexural behavior of both fully NC and NC-LWAC beams using four-point loading, analyzing critical parameters such as load, deflection, cracking patterns, and stiffness. The results showed that while LWAC beams exhibited lower bond and shear strengths compared to NC, they demonstrated competitive flexural performance, particularly when used in combination with NC in double-layered beams. However, LWAC beams displayed higher deflections, reduced energy absorption, and lower stiffness, making them more flexible but less stiff than fully NC beams. The study concludes that while LWAC can offer significant weight reduction and is suitable for certain structural applications, it compromises some aspects of structural integrity, particularly in terms of stiffness and energy absorption. Nonetheless, NC-LWAC beams perform well under flexural loading, indicating their potential use in construction.

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