FLEXURAL BEHAVIOUR OF REINFORCED LIGHTWEIGHT FOAMED CONCRETE BEAMS

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ABSTRACT

This paper presents the experimental results of a study on flexural behaviour of reinforced lightweight foamed concrete beams. The main objective of this research is to explore flexural behaviour of reinforced lightweight foamed concrete beams with compressive strength of 25 N/mm^2 at 28-days of age. The hardened density of lightweight foamed concrete was controlled at 1750 ± 50 kg/m^3. A total of three reinforced concrete beams were cast, where it consisted of two lightweight foamed concrete beams and a normal weight concrete beam which acted as control specimen. Two type of lightweight foamed concrete with cement to sand ratio of 3:1 and 2:1 respectively were produced in order to achieve targeted compressive strength of 25 MPa. The average oven dried density of 1676 kg/m^3 were obtained for both lightweight foamed concrete. The constituents of the lightweight foamed concrete consisted of Type 1 Ordinary Portland Cement (OPC), quartz sand, silica fume, water and pre-foamed foam. All beams were designed as under-reinforced beams with singly reinforced of 2T10. The results of the laboratory test showed that the reinforced lightweight foamed concrete beams sustained lower ultimate load as compared to normal weight concrete beam by 22% to 24%. Nevertheless, it manages to exceed the design capacity as much as 54% for LW-1 and 49% for LW-2 respectively. Besides, the reinforced lightweight foamed concrete beams tended to deflect 13% to 20% more than of that the reinforced normal weight concrete beam. On the other hand, the reinforced lightweight foamed concrete beams showed lower displacement ductility ratio than that of the reinforced normal weight concrete beam. Apart from that, it was observed that the reinforced lightweight foamed concrete beams were weak in resisting shear forces nonetheless flexural failure cannot be ignored entirely due to the presence of excessive yielding of the steel strain data.

Keywords: Flexural behaviour, reinforced concrete beams, lightweight foamed concrete, displacement and ductility

1 INTRODUCTION

Concrete, a mixture of sand, cement, aggregate and water, is one of the most used substances on the planet as stated by (Lomborg, 2001). Over the years, extensive researches have been conducted and as a result, different types of concrete had emerged to deal with the variety of demands for different types of construction projects. One of the commonly researched types is lightweight concrete. As the name implies, lightweight concrete is low in density and yet capable of delivering the same physical properties as normal weight concrete. Concrete is classified as lightweight when the density ranges between 300 kg/m^3 and 1850 kg/m^3 (Neville, 2006). First recorded structural usage of lightweight concrete is The Pantheon which was developed by the Roman civilization at year 126. This signifies that lightweight structures are technologically and practically feasible.

The dead weight induced by normal weight concrete increases construction cost since the structural element has to carry its own weight plus the applied load. By having a lighter structural element, the cost saving will be more effective. The reduction in dead weight reflects to a smaller column loads which directly leads to a reduction in applied loads on the foundation. The overall cost saving in terms of material usage is huge and the structure will be less problematic when it comes to design and construction. The higher strength to weight ratios of reinforced lightweight foamed concrete beams also contributes to the possibility of having longer spanning beams as well as opening up more free spaces by having lesser intermediate columns. Consecutively, steel reinforcements usage will be reduce together with the reduction in member sizes.

The main objective of this research is to explore flexural behaviour of reinforced lightweight foamed concrete beams with compressive strength of 25 N/mm^2 at 28-days of age. The hardened density of lightweight foamed concrete was controlled at 1750 ± 50 kg/m^3. After numerous trials, the required properties of the lightweight foamed concrete could be obtained with a mixture of cement, sand, silica fumes, water and synthetic foam. Two type of lightweight foamed concrete with cement to sand ratio of 3:1 (LW-1) and 2:1

(LW-2) respectively were produced in order to achieve targeted compressive strength of 25 MPa.

2 EXPERIMENTAL PROGRAM

2.1 MATERIALS AND CONSTITUENT PROPORTIONS

A total of three reinforced concrete beams were cast, where it consisted of two lightweight foamed concrete beams and a normal weight concrete beam which acted as control specimen. The average oven dried density of 1676 kg/m^3 were obtained for both lightweight foamed concrete. The constituents of the lightweight foamed concrete consisted of Type 1 Ordinary Portland Cement (OPC), quartz sand, silica fume, water and pre-foamed foam. The pre-formed foam was produced by diluted a synthetic foaming agent with tap water in a ratio of 1:30 based on volume.

Tables 2.1 and 2.2 depict the design mix proportions of lightweight foamed concrete and normal weight concrete respectively.

Table 2.1: Mix Proportions of Lightweight Foamed Concrete (LW)

Reference Name	LW-1	LW-2
Cement to sand ratio	3:1	2:1
Water-cement ratio	0.6	0.6
Cement (kg/m^3)	861	796
Sand (kg/m^3)	287	398
Silica Fume (kg/m^3)	86.1	79.6
Water (kg/m^3)	517	478
Foam (kg/m^3)	3	3

Table 2.2: Mix Proportion of Normal Weight Concrete (NW)

Reference Name	NW
Water-cement ratio	0.6
Cement (kg/m^3)	400
Water (kg/m^3)	240
Sand 600µm – 5mm (kg/m^3)	1000
Aggregate 5 – 10mm (kg/m^3)	230
Aggregate 10 – 20mm (kg/m^3)	455

2.2 BEAM DETAILS

A total of three beams were fabricated and tested. All beams were designed as under-reinforced beams with singly reinforced of 2T10. The cross sectional area of the testing beams was fixed as 115 mm width x 181 mm depth.

The effective span length of the beams was determined by the designed failure mode. For this research, it is pre-decided to obtain flexural failure. In order to achieve this, the length of the loading point to the nearest support should be at least 6 times correspondent to the effective depth, ie: 6 x 145 = 870 mm (Kong et al., 1987). Therefore, 900 mm was chosen from the loading point to the nearest support. The length between two point loads was 300 mm and allocating an additional 100mm each side after the supports. Thus, the total length of the beam is 2300mm, as shown Figure 2.1. Table 2.3 depicts the summary of the beam design. The design was carried out according to the design code of BS 8110: 1997.

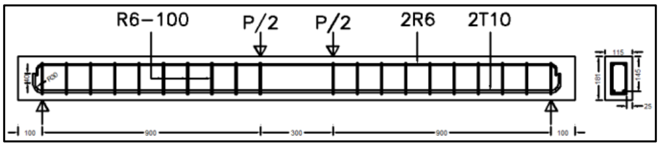

Figure 2.1: Detailing of Beam

Table 2.3: Summary of Beam Design

Reference Name	All Beam
A_s provided for 2T10 (mm^2)	157.1
M_{Design} (kNm)	8.448
P_{Design} (kN)	9.36
A_{sv} provided for R6-100 (mm^2)	56.6

2.3 BEAM FABRICATION AND INSTRUMENTATION

There are two types of steel bars namely R6 mild steel round bar and T10 high tensile steel bar that were used throughout this study. In this research, the belt driven band saw was used to cut the steel bars. This machine allows precise cut to be executed on any specified length to an accuracy of milli meters.

Next, manual bending of stirrups was done at the bending platform. In addition, high tensile steel bars were bended by the bar bending machine. A total of sixty numbers of stirrup was required for this study. In order to obtain the steel reinforced cage, it was necessary to tie the shear links and the main reinforcement steel bars together. On the other hand, waterproof plywood were cut and nailed to create the formwork for the beams. After the steel reinforced cage were done, electrical resistance strain gauges with series name of TML FLK-6-11 were applied to the steel reinforcements. The placement location of the gauges were grind smooth to provide an even grip distribution of the adhesive material. After the strain gauge was applied, it was coated by a layer of silicone gel and covered with vinyl 3M tape for water proofing purpose. The beams casting were done accordingly. No compaction was allowed for reinforced lightweight foamed concrete beams except the reinforced normal weight concrete beam.

All beams were tested at 28 days of age. The electrical resistance strain gauges with series name of TML PL-60-11 were applied at the mid span of beam, as shown in Figure 2.2. Similar with steel strain gauges, the placement location of the gauges were grind smooth to provide an even grip distribution of the adhesive material.

2.4 METHOD OF TESTING

2.4.1 Compressive Strength Test

The compression test of concrete for this study was conducted by using a hydraulically operated universal tester. The axial loading rate was fixed at 0.2 kN/s constantly. The dimensions of specimens were measured prior to the testing. The compressive strength was computed by using Equation 1.

$$F_c = \frac{P}{A_c} \quad (1)$$

where;
F_c = Compressive strength, N/mm^2
P = Maximum load applied, N
A_c = Cross sectional area of specimen, mm^2

2.4.2 Structural Beam's Flexural Test

The flexural test of beams was conducted by using a Magnus Frame, namely STF-8 with a capacity of 300kN. 4 point loading tests were conducted on the beam specimens. Concrete and steel strain gauges, and LVDTs that attached to the tested beam were connected to data logger to obtain concrete and steel strains as well as deflection at different loading respectively at during the entire testing period.

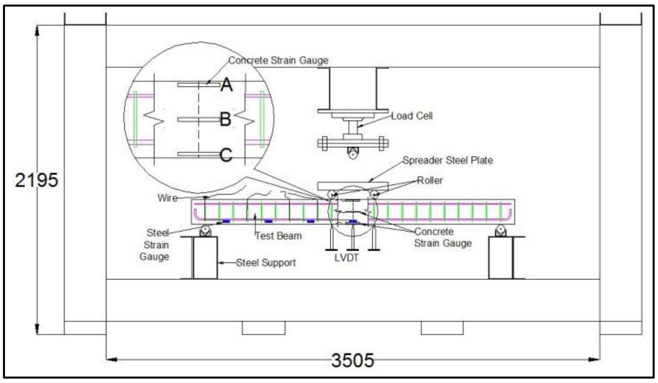

Figure 2.2: Depiction of Beam on Magnus Frame and Location of Concrete Strain Gauges

3 RESULTS AND DISCUSSIONS

3.1 COMPRESSIVE STRENGTH OF CONCRETE

Table 3.1 shows the compressive strength of lightweight foamed concrete at 28-days of age.

Table 3.1: Lightweight Foamed Concrete Properties

Reference Name	LW-1	LW-2
Fresh Density (kg/m^3)	1770	1770
Hardened Density (kg/m^3)	1704	1732
Oven-Dried Density (kg/m^3)	1659	1692
Average 28-day Strength of Five Specimens (N/mm^2)	27.07	26.26

Table 3.1 shows that LW-2 obtained lower average 28 days strength as compared to that of LW-1. Nonetheless, both lightweight foamed concrete obtained strength of 25 N/mm^2. Table 3.2 depicts the result of the normal weight concrete with the compressive strength of 28.6 N/mm^2 at 28 days of age.

Table 3.2: Normal Weight Concrete Properties

Reference Name	NW
Slump Value (mm)	51
Hardened Density (kg/m^3)	2175
Oven-dried Density (kg/m^3)	2145
Average 28-day Strength of Five Specimens (N/mm^2)	28.6

3.2 STRUCTURAL BEAM'S FLEXURAL TEST

3.2.1 Bending Moments

Table 3.3 compares the experimental ultimate moment ($M_{Ultimate}$) and theoretical design moment (M_{Design}). The theoretical design moment of the beams was predicted using the rectangular stress block analysis as recommended by BS8110. The moment of LW-1 and LW-2 obtained from the experiment were approximately 45% to 97% higher as compared to the theoretical design moment. However, the both reinforced lightweight foamed concrete beams showed lower capacity ratio as compared to that of reinforced normal weight beam. This might due to the early failure of tensile for the lightweight foamed concrete. This trend had also been shown by another researcher (McCarthy, 2005).

Table 3.3: Comparison between Experimental and Theoretical Moments

Reference Name	LW-1	LW-2	NW
Experimental Ultimate Moment, $M_{Ultimate}$ (kNm) (1)	13.05	12.60	16.65
Theoretical Design Moment M_{Design} (kNm) (2)	8.448	8.448	8.448
Capacity ratio (1)/(2)	1.54	1.49	1.97

3.2.2 Deflection Behaviour

Table 3.4 depicts the mid-span deflection of the beams at experimental ultimate moment. It can be noted that the mid-span deflections of the reinforced lightweight foamed concrete beams are higher than that of the reinforced normal weight concrete beam. The deflections of LW-1 and LW-2 were approximately 20% and 13% higher corresponded to that of NW respectively. Figure 3.1 shows that the LW-1 and LW-2 tends to deform more at any given loads as compared to the normal weight concrete. It is suggested that additional reinforcements have to be provided if the normal weight concrete was replace by the lightweight foamed concrete. In addition, LW-2 showed lower ultimate load resistance as compared to LW-1. The results revealed that higher compressive strength of LW-1 promoted stronger structural member.

Table 3.4: Deflection of Beams at Experimental Ultimate Moment

Reference Name	LW-1	LW-2	NW
Mid-span Deflection at Ultimate Failure, Δ (mm)	27.02	25.40	22.44
Δ/Δ_{NW}	1.20	1.13	1.00

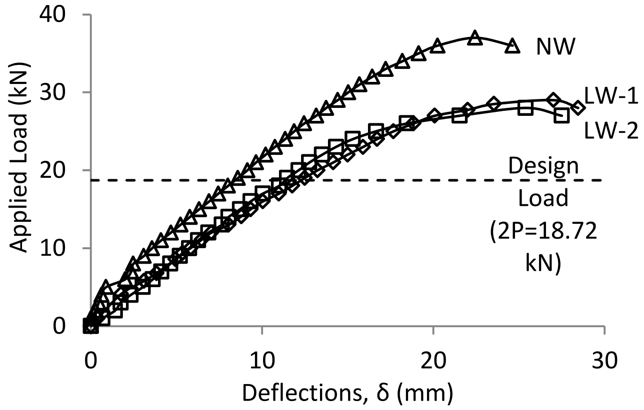

Figure 3.1: Applied Load vs Deflections

Figure 3.1 shows a slight kink at the loading level at about 3 to 5 kN for all specimens. This is the point where the first crack occurs. The concrete was sustaining the tensile stress before the first crack occurred. The tensile stress was transferred to the steel reinforcement bars after the first crack occurred. The first crack of concrete occurred was due to the force applied exceeded the concrete's tensile capacity. This response was in-line when failure criterion of limiting tensile strain of plain concrete, which ranges between 0.0001 to 0.0002 ε was exceeded as a strain greater than 0.002 ε was detected from the readings of the concrete strain gauge C (refer to Figures 3.2 and 3.3). This response triggered a sudden reduction of the applied load vs deflection where the stress had been transferred over to the steel reinforcements at the load range of 3 to 5 kN.

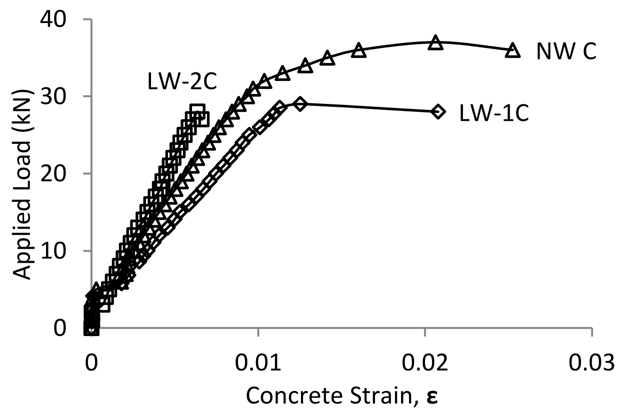

Figure 3.2: Applied Load vs Tensile Strains of Concrete

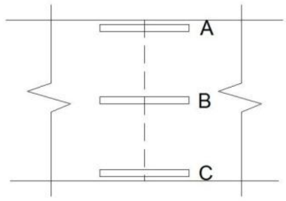

Figure 3.3: Concrete Strain Gauge at Mid-span beam (A) Top Gauge (1cm offset from top), (B) Center Gauge (Height/2), (C) Bottom Gauge (1cm offset from bottom)

Referring to Figure 3.4, it can be noted that the steel strains prior to the yield point of the reinforced lightweight foamed concrete beams behave similarly to that of the reinforced normal weight concrete beam.

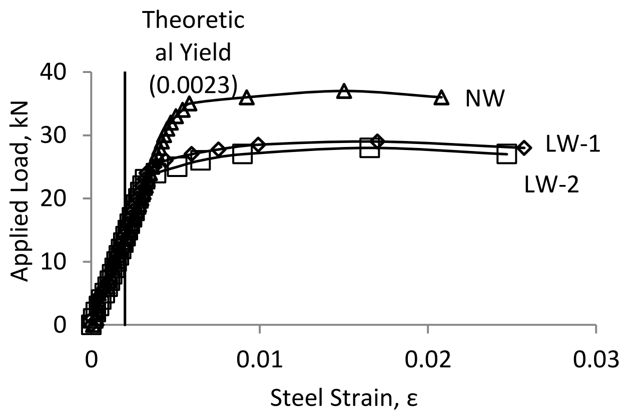

Figure 3.4: Applied Load vs Steel Strains of Steel Reinforcement Bars at Mid-span Beam

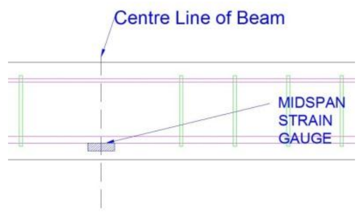

Figure 3.5: Location of Steel Strain Gauge at Mid-span Beam

The theoretical yield limit is calculated based on Equation 2.

$$\mathit{Theoretical\ Yield}\ \text{Strain} = \frac{\mathit{Theoretical\ Stress\ Limit}}{\mathit{Young's\ Modulus\ of\ Steel}} = \frac{460\ N/mm^2}{200\ GPa} = 0.0023 \qquad (2)$$

Where the stress is the theoretical yield value of 460 N/mm^2 in accordance with BS 8110. The beam was capable of sustaining higher stresses, up to about 28 to 37 kN corresponded to the design load of 18 kN. The steel reinforcement bars might contribute substantially towards the strength gain. The concrete compression zone began to crush whence excessive yield of steel reinforcement bars.

Figure 3.6 shows the compressive strain for the both reinforced lightweight foamed concrete beams increased consistently till the ultimate strain of 0.0036. Clarke (1993) stated a similar finding which maximum concrete strain of 0.0035 had been obtained. On the other hand, the concrete strain of reinforced normal weight concrete beam had not reached the theoretical strain. The steel reinforcement bars might be reached the ultimate yield prior to the crushing of the concrete could be a reason of this phenomena.

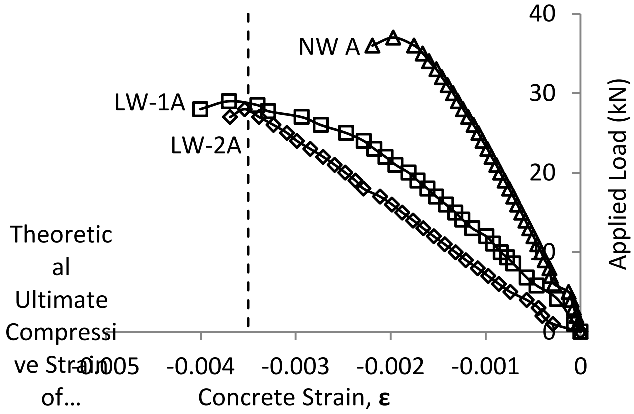

Figure 3.6: Applied Load vs Compressive Strains of Concrete

3.2.3 Ductility Behaviour

Referring to Table 3.5, the reinforced lightweight foamed concrete beams showed a lower ductility ratio as compared to that of the reinforced normal weight concrete beam.

Table 3.5: Displacement Ductility Ratio

Reference Name	LW-1	LW-2	NW
Applied load at Theoretical Yield Stage (kN)	17	17	16
Deflection, Δ_y at Theoretical Yield Stage (mm)	10.99	10.04	6.91
Applied load at Ultimate Stage (kN)	29	28	37
Deflection, Δ_u at Ultimate Stage (mm)	27.02	25.40	22.44
Displacement Ductility Ratio, Δ_u/Δ_y	2.46	2.53	3.25

The study done by Ashour (2000) have shown that the displacement ductility range of 3 to 5 have sufficient ductility to sustain large displacements such as earthquakes. The displacement ductility ratio in Table 3.5 depicts that the reinforced normal weight concrete beam fulfilled the mentioned requirement.

3.2.4 Crack Pattern and Failure Mode

Figure 3.7 shows the crack pattern of all test specimens. The failure modes of the tested beams was summarized in Table 3.6.

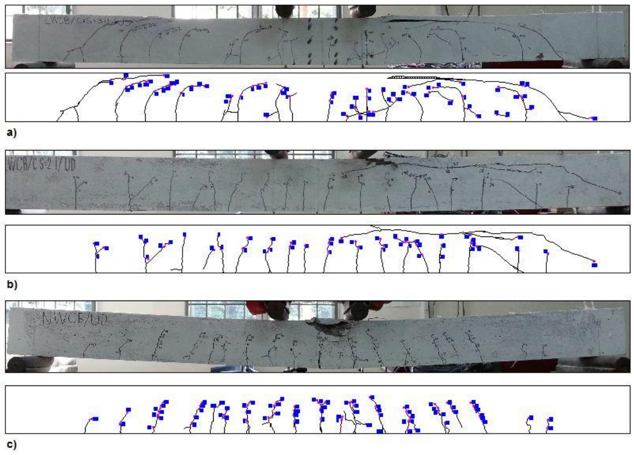

Figure 3.7: Crack Mapping Patterns (a) LW-1, C:S – 3:1 (b) LW-2, C:S – 2:1 (c) NW

Table 3.6: Failure Modes

Reference Name	Failure Mode
LW-1	Flexural + Shear
LW-2	Flexural + Shear
NW	Flexural

*Shear failure: concrete spalling at shear span.
*Flexural failure: concrete crushing at flexural zone.

The shear cracks of reinforced lightweight foamed concrete beams were presented at about 60% ultimate load onwards. This effect is probably due to the lack of coarse aggregates, in reinforced lightweight foamed concrete beams. Hence, the crack lines propagated directly without any resistance thus causing the shear failure.

Referring to Figure 3.7, it is obvious that the reinforced normal weight concrete beams failed under flexural as seen on the crushed centre portion of the beam and the almost vertical crack lines. On the other hand, the reinforced lightweight foamed concrete beams faced flexural and shear failure despite the fact that the design method was pre-decided on flexural failure.

Based on crack mapping pattern shown in Figure 3.7, it is noticeable that the reinforced lightweight foamed concrete beams experienced shear-compression failure. Shear compression failure is defined when the propagation of shear cracking reaches the compression zone but without any significant secondary cracks. Shear compression failure is actually a gradual process (Buyukozturk, 2004) which actually allows escaping time before failure occurs. It was observed that the crack lines propagated slowly at every increased loadings.

4 CONCLUSIONS

With the scope of this experimental investigation, the following conclusions can be drawn;

- The reinforced lightweight foamed concrete beams sustained lower ultimate load as compared to normal weight concrete beam by 22% to 24%. Nevertheless, it manages to exceed the design capacity as much as 54% for LW-1 and 49% for LW-2 respectively.
- The reinforced lightweight foamed concrete beams tended to deflect 13% to 20% more than of that the reinforced normal weight concrete beam.
- The reinforced lightweight foamed concrete beams showed lower displacement ductility ratio than that of the reinforced normal weight concrete beam.
- The reinforced lightweight foamed concrete beams were weak in resisting shear forces nonetheless flexural failure cannot be ignored entirely due to the presence of excessive yielding of the steel strain data.

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