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Full Length Research Paper

An investigation of the flexural behaviour of reinforced lightweight concrete beams

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This paper presents an investigation of the flexural behaviour of reinforced lightweight concrete beams made from lightweight expanded clay aggregate (LECA). Nine reinforced concrete beams were fabricated and tested using the symmetrical two-point loads test. The concrete strength and steel bar reinforcement were two important parameters examined during the beam tests. The paper compares flexural performance of the tested beams for example failure modes, load deflection response, and ultimate moment capacity with those of the theoretical analysis. The experimental results suggest that the ultimate moment of beams made with LECA lightweight concrete could be predicted satisfactorily using the equation provided by the ACI 318 building code. However, the maximum section bars for restraining brittle compression failure should be reduced in the beams.

Key words: Lightweight concrete, reinforced concrete beam, flexural behaviour, failure mode, ultimate moment.

INTRODUCTION

In concrete structures, the concrete imposes a huge amount of the total load of the structure. Lighter concrete offers design flexibility and substantial cost savings by providing less dead load, improved seismic structural response, longer spans such as long-span bridges, low-heat conductivity, smaller size structural members, decreased storey height, less steel reinforcement, and lower foundations costs when applied to structures and high-rise buildings. In high-rise buildings, in most cases, the structure is affected during earthquakes due to the higher unit weight of concrete (Ilker and Burak, 2008). In recent years, due to the numerous advantages of using lightweight aggregate concrete (LWAC) in construction, there has been an increasing interest in production and also investigation of properties of this material (Sari and Pasamehmetoglu, 2005; Yasar et al., 2003; Kilic et al., 2003; Rossignolo et al., 2003; Kan and Demirbog, 2009; Gennaro et al., 2008; Hossain, 2004; Demirbog and Gu, 2003; Babu et al., 2005; Teo et al., 2007; Subasi, 2009; Alengaram et al., 2010). However, many authors have reported that although lightweight concrete (LWC) has good insulation and mechanical properties, it needs further investigation of their structural behaviour for use as structural members. Teo et al. (2006) have shown that lightweight oil palm shell (OPS) concrete (1950 kg/m^3 dry density, 26 MPa compressive strength) beams (3000 mm length, 250 mm depth by 150 mm width) have good ductility behaviour and ultimate moments predicted using BS 8110 (1985) provides a conservative estimate for OPS concrete beams up to a reinforcement ratio of 3.14%. Also, for beam with a 3.90% reinforcement ratio, BS 8110 underestimates the ultimate moment capacity by about 6%.

Experimental results of a study made by Jumaat et al. (2009) indicate that the shear capacities of oil palm shell foamed concrete (OPSFC) beams without shear links are higher than those of normal weight concrete (NWC) beams and exhibit more flexural and shear cracks. Another study (Alengaram et al., 2008) showed that, flexural behaviour of reinforced palm kernel shell

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Nomenclature: b, Web width; **d,** effective depth; A_s, area of tension reinforcement; f_c, cube compressive strength; f'_c, cylinder compressive strength; f_y, yield strength of steel; **P,** ultimate load; **Mn,** nominal moment carried by the section; **ρ,** percentage of tension reinforcement (As/bd).

Table 1. Chemical composition of cement, silica fume, leca and limestone (%).

Oxide composition	Cement	Silica fume	LECA	Limestone powder
Sio_2	22	95.5	66.05	0.50
Fe_2O_3	23	0.87	7.10	-
Al_2O_3	4.44	1.32	16.57	0.50
CaO	64.92	0.49	2.46	55.4
Mgo	1.42	0.97	1.99	0.0
Na_2O	0.27	0.31	0.69	-
K_2O	0.58	1.01	2.69	-
P_2O	-	0.16	0.21	-
SO_3	1.67	0.10	0.03	-
LOI	1.30	-	0.84	43.13
Cl	-	-	-	0.02

concrete (PKSC) beams closely resembles that of equivalent beams made by NWC. In a study, Tang et al. (2006) stated that beams made with lightweight polystyrene aggregate (PA) concrete with near-surface mounted (NSM) GFRP bars showed a reduction in ultimate deflection and an improvement in flexural stiffness and bending capacity, depending on the PA content of the beams. Furthermore, Omar and Mohamed (2002) conducted an experimental research on the behaviour of prestressed concrete beams made from Clinker lightweight aggregate, (44.4 MPa compressive cube strength, and 1980 kg/m^3 dry density). They reported that the prestressed lightweight concrete beams could resist loading up to 90% of the normal prestressed concrete beams. In addition, they found the clinker lightweight aggregate concrete exhibits good performance and is suitable for use in prestressed concrete beams. In this study, the flexural behaviour of four groups (A, B, C and CL) of reinforced lightweight concrete LECA beams of grades 30, 40, 50 and 60 were compared with the flexural prediction of the ACI equation (Equation 1). Additional parameters including deflection and type of failure were also studied.

EXPERIMENTAL PROGRAMME

Materials and concrete mixes

The cement used was ASTM Type II Portland cement with a specific gravity of 3150 kg/m^3 and Blaine specific surface area 0.306 m^2/g. Initial and final setting times of the cement were 175 and 230 min, respectively. 10% silica fume on cement weight was used as a cement substitute. The silica fume had a specific gravity and surface area of 2200 kg/m^3 and 20.2 m^2/g, respectively. Natural river sand of size 0.15 to 5 mm, with a fineness modulus of 3.2, and two types of LECA, fine and coarse, of size 0 to 3 mm and 4 to 6 mm, respectively, were used as aggregate. Limestone powder was also used as a filler material. Table 1 gives the chemical composition of cement, silica fume, LECA, and Limestone powder. Super plasticizer with the commercial name of Super plasticizer PCE was used for all mixes. Table 2 shows the mixture proportion for four groups of beams.

Reinforced concrete beams details

A total number of nine reinforced concrete beams in four groups (A, B, C, and CL) were fabricated and tested. Figure 1 shows the reinforcement gauge prepared for the study concerning the flexural behaviour. All of the beams were 1950 mm long, 120 mm wide, and 200 mm deep, with 160 mm effective depth. The main reinforcement for the beams consisted of hot-rolled, deformed bars with diameters of 16, 12, and 8 mm with a failure stress 658.1, 706, and 610.4 MPa and a yield stress of 500.5, 469.7, and 367.6 MPa, respectively. All of the beams were reinforced with two bars and mild steel links of 8 mm diameter bars with a failure stress of 558 MPa and a yield stress of about 301.9 MPa. The shear reinforcement for flexure was used at a close spacing of about 50 mm c/c, which was done to ensure yielding of the tension steel before crushing of the beams in shear. Table 3 and Figure 1 illustrate the beams'. All the beams and the control specimens were cast in steel moulds. For each beam, five 100 mm cubes were cast for determination of compressive strength. All the beams and the companion concrete specimens were demoulded 24 h after casting to be cured with water-saturated burlaps for 28 days (spraying the water twice a day).

Subsequently, the beams and cube specimens were air-cured with a relative humidity of 60±15 and ambient temperature of 23±3°C until the age of testing. Testing of the beams was conducted at the age of about 60 to 65 days.

Instrumentation and testing

The tests were performed using a 1000 KN hydraulic actuator and the beam specimens were tested under two-point loads, which were kept at 600 mm apart on a span of 1800 mm under a load control mode with 10 to 15 KN increments until failure. A testing machine of capacity of 500 KN with built-in load cell was used in the testing. All deflections and loads were recorded using a data logger.

TEST RESULTS AND DISCUSSION

Mode of failure

Table 4 summarizes the experimental results. All beams showed a typical structural behaviour in flexural (yielding of steel bars and then crushing of the concrete in the compression zone) except for the CL16 and B16 beam. The CL16 failed in compressive mode because it was

Table 2. Details of concrete mix (Kg/m^3).

Groups symbol	Cement	Silica fume	Limestone powder	Super plasticizer	Water	Water to binder ratio	River sand	Leca	Type of Leca
A	495	55	165	7.15	165	0.30	593.2	197.7	Fine
B	495	55	165	7.15	165	0.30	553.6	237.3	Fine
C	495	55	165	7.15	192.5	0.35	474.5	316.4	Fine
CL	495	55	165	7.15	198	0.35	474.5	316.4	Coarse

Table 3. Test beam details

Beam determination	Tension reinforcement number and size	Beam size, b * d (mm)	Area of tensile steel, A (mm^2)	ρ = As / bd, (%)	Slump (mm)	Cube strength (MPa)	Density (kg/m^3)	
							Fresh	Air dry
A16	2Φ 16	119 * 162	402	2.09				
A12	2Φ 12	120 * 165	226	1.14	40-50	62.2	1925±25	1848±21
A8	2Φ 8	120 * 158	100	0.53				
B16	2Φ 16	120 * 161	402	2.08				
B12	2Φ 12	117 * 156	226	1.24	80-95	56.3	1845±23	1795±28
B8	2Φ 8	115 * 157	100	0.55				
CL16	2Φ 16	119 * 163	402	2.07	120	37.4	1650±29	1605±13
C12	2Φ 12	122 * 158	226	1.17	100-110	49.3	1730±23	1640±18
C8	2Φ 8	118 * 163	100	0.52				

reinforced 22% more than ρ_{max} according to the ACI 318 (2008), and this type of failure is predicted for any beam with high reinforcement ratios in this code. The mode of failure for the B16 beam was also compressive failure. However, it was designed to be under-reinforced in accordance with the ACI 318. The compressive failure mode that was observed for the CL16 and B16 beams is shown in Figures 2(a) and (b). It can be seen that the type of failure in concrete beams made of LECA lightweight concrete is different from the prediction indicated in the ACI 318. This may be due to the stress-strain relationships for lightweight aggregate concrete are more linear and brittle than for normal weight concrete (Newman and Owens, 2003). Therefore, the results from this study suggest that to prevent the brittle failure in these types of beams the maximum section bars should be reduced from:

$\rho_{max} = 0.75\rho_b$ to $\rho_{max} = 0.6\rho_b$

Design moment

Table 5 shows the moment capacity of the beams tested under two-point loading and the comparison between the experimental and theoretical ultimate moments. The flexural resistance of the beams (M_n) was calculated using the Equation 1 given in ACI 318. Following is the ACI Code's equation for nominal flexural strength design of concrete beams:

$$M_n = A_s f_y \left(d - 0.59\frac{A_s f_y}{f'_c b}\right) \quad (1)$$

The theoretical ultimate moments were calculated

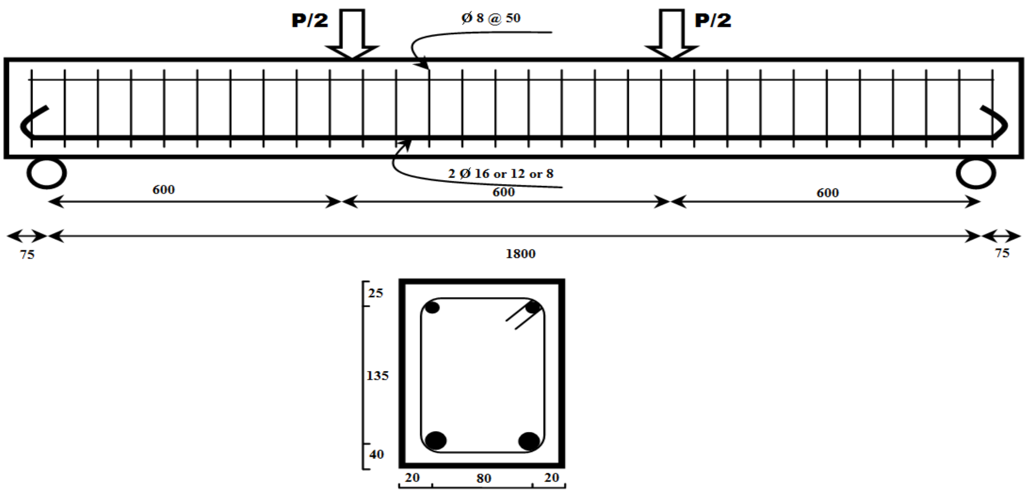

Figure 1. Reinforcement details for the test beams (sizes are in mm).

Table 4. Ultimate load and mode of failure.

Beams	Ultimate load P (KN)	$\rho = A_S / bd$	$(\rho_b)_{ACI}$	$(\rho_{max}=0.75\rho_b)_{ACI}$	$\frac{\rho}{(\rho_{max})_{ACI}}\%$	Failure mode
A16	100.48	0.0209	0.0330	0.0248	4	Steel yielding
B16	94.772	0.0208	0.0313	0.0235	89	Compressive failure
CL16	91.690	0.0207	0.0225	0.0169	2	Compressive failure
A12	64.696	0.0114	0.0362	0.0272	2	Steel yielding
B12	62.071	0.0124	0.0343	0.0257	8	Steel yielding
C12	67.986	0.0117	0.0313	0.0235		Steel yielding
A8	35.521	0.0053	0.0510	0.0382	4	Steel yielding
B8	33.768	0.0055	0.0484	0.0363	5	Steel yielding
C8	36.179	0.0052	0.0441	0.0331		Steel yielding

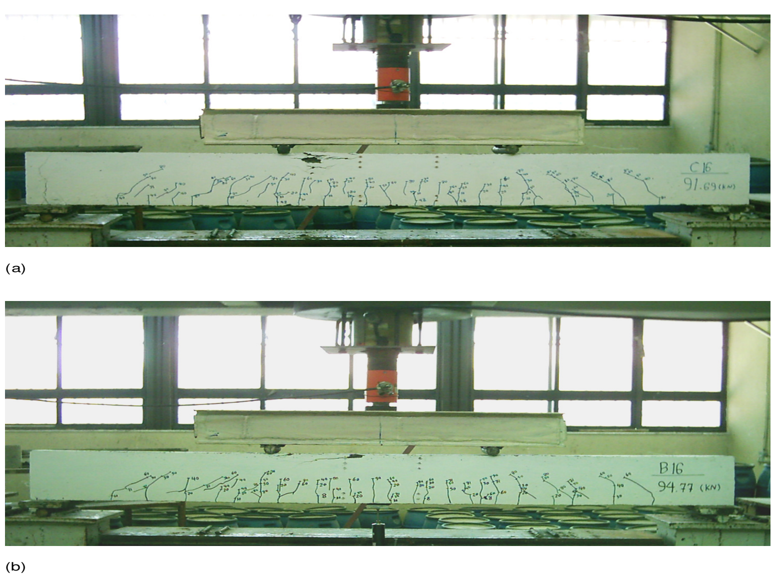

Figure 2. Compressive failure of (a) CL16 and (b) B16 beam.

Table 5. Comparison between experimental and theoretical ultimate moments.

Type of beam	Experimental ultimate moment { $M_{u(exp)}$ (kNm)}	ACI theoretical design moment {M_{ACI} (kNm)}	$\frac{M_{u(\exp)}}{M_{ACI}}$
A16	30.144	24.819	1.21
B16	28.432	24.318	1.17
CL16	27.507	11.041	2.49
A12	19.409	14.229	1.36
B12	18.621	13.276	1.40
C12	20.396	12.861	1.59
A8	10.656	4.918	2.17
B8	10.130	4.868	2.08
C8	10.854	4.983	2.18

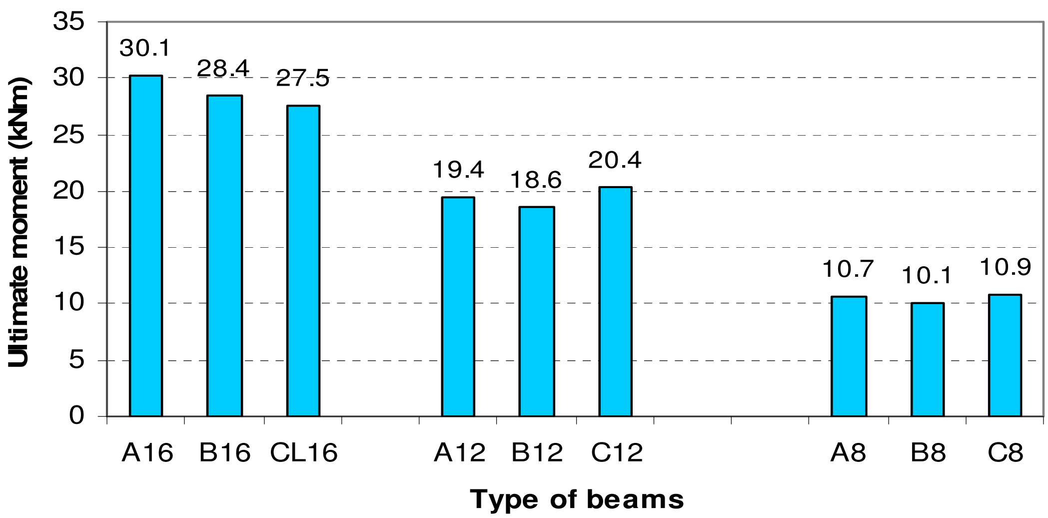

Figure 3. Ultimate strength of beams.

using the ultimate strength of the reinforcement with partial safety factor materials. For beams with reinforcement ratios of approximately 2.08, 1.18 and 0.53% the ultimate moment obtained from the experiment were approximately 17 to 24%, 36 to 59% and 108 to 118%, respectively, for the ACI code, which is higher than the predicted values. Therefore, from the tests performed, it appears that for LECA lightweight concrete beams, ACI 318 can be used to obtain a very good conservative estimate of the ultimate moment capacity. Similar findings by Lim et al. (2006) also been reported. They reported that for LECA lightweight concrete beams, the American code of practice (ACI 318-2005 and ACI 213-2003) can predict the cracking and ultimate strength with quite accurately.

Ultimate moment capacity

The ultimate strength of the beams is shown in Figure 3. Concerning these figures, although the compressive strength and specific weight of the concrete in group C is lower than groups A and B, the ultimate moment of these beams is not significantly different from the other beams. Also, the specific gravity of the concrete in the CL16 and A16 beam is around 30 and 20% lower than normal concrete, respectively. The 10% difference in specific gravity is a considerable difference. However, the ultimate moment of the CL16 beam is only around 8.5% lower than A16. Therefore, it can be concluded that for making a flexural element of a structure with LECA lightweight concrete, it is better to use lighter concrete, which has a lower compressive strength. The reason is that obtaining LECA lightweight concrete with a lower compressive strength and specific gravity is easier than LECA lightweight concrete with a higher compressive strength and specific gravity. In addition, it should be noted that by reducing the weight of concrete considerable advantages can be achieved, while increasing the compressive strength in flexural elements

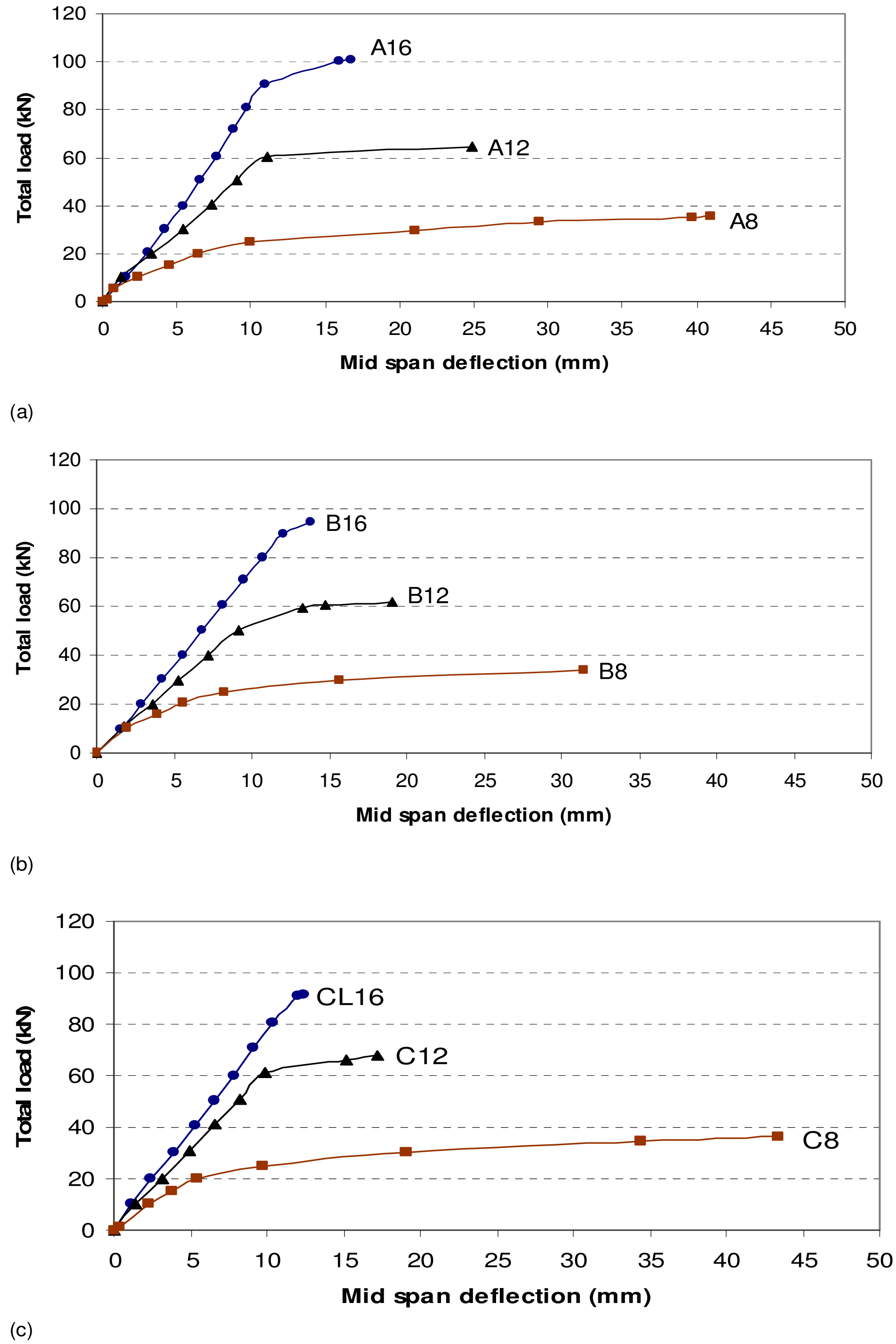

Figure 4. Mid span deflection of different beams (a) group A, (b) group B, (c) group C and CL16.

does not appear to produce any significant results.

Deflection

The mid span deflections due to short-term loading of the beams, A, B, C and CL, are presented in Figures 4(a), (b) and (c), respectively. It was found that the steel reinforcement ratios were more dominant than the concrete compressive strength except for the B16 and CL16 beam for which the mode of failure was in compressive area. The results also showed that the

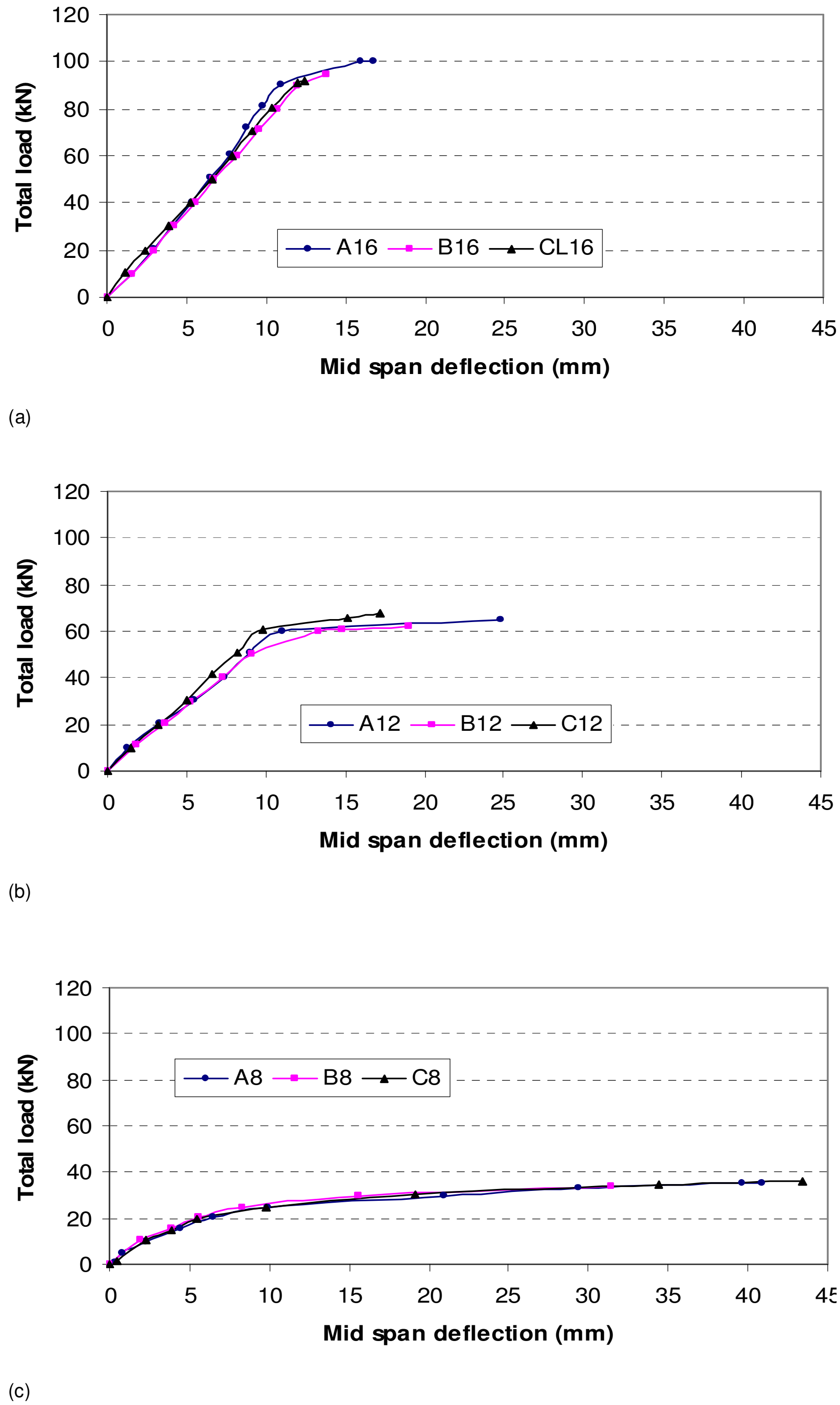

Figure 5. Mid span deflection of different beams in groups (a) high, (b) medium and (c) low tensile reinforcement ratio.

beams with low tensile reinforcement ratio underwent larger deflections compared to beams with a higher ratio. This indicates that increasing the reinforcement ratio decreases the deflection and ductility. In other words, greater deflection and ductility can only be achieved with a lower reinforcement ratio. Lim et al. (2006) reported that in reinforced LECA lightweight concrete beams an increase in amount of tension reinforcement drastically reduces ductility. Figures 5(a), (b) and (c) show the typical experimental total load-deflection curves in groups with high, medium and low tensile reinforcement ratio. Almost good overlapping in more points of these groups of beams shows that the bond between the steel and the concrete in the beams with different densities, until the yielding of the steel, are almost the same.

This discussion also supports the similar discussion and result provided earlier, in section ultimate moment capacity, which says for making a flexural structural member using LECA, it is preferred to use lighter LECA lightweight concrete.

Conclusion

The experimental results of nine beams, with high, medium and low tensile reinforcement ratio were presented in this paper. The aim of this research was to investigate the application of high strength lightweight concrete made with lightweight expanded clay aggregate (LECA) in reinforced concrete beams. The LECA lightweight concrete in this study had a compressive strength in rang of 37 to 62 MPa and an air dry density of 1600 to 1850 kg/m^3. Based on the results, the ultimate moment of beams made with LECA lightweight concrete could be predicted satisfactorily via the equations provided by the ACI 318 building Code. For preventing the brittle failure of LECA beams, it suggests that the maximum section bars of the ACI code should be changed from $\rho_{\max} = 0.75\rho_b$ to $\rho_{\max} = 0.6\rho_b$. Furthermore, the investigation of the ultimate moment and deflection of the beams revealed that for making a flexural element by using LECA lightweight concrete, it is preferred to use a lighter concrete that may has lower compressive strength.

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