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Effect of Steel Reinforcement Ratios on the Flexural Behavior of Reinforced Lightweight Concrete Beams Made with Treated Attapulgite

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Summary: Using of lightweight concrete as a construction material is increasing due to its desirable properties of reduction of dead loads and cost. Flexural behavior tests were conducted on simply supported singly rectangular reinforcedconcrete (RC) beams of lightweight coarse aggregate concrete subjected to four points bending test up to failure. Lightweight coarse aggregate was produced from natural material locally available (Attapulgite) by burning it at 1100ºC for 30 minutes and treating it with sodium hypochlorite of 6% concentration for 24 hour. The effect of tensile reinforcement ratios (0.8, 1.17 and 1.76%) was investigated. The flexural performance of the beams is discussed in terms of cracking and ultimate load capacity, load-deflection relationships, failure mode, crack pattern and ductility, as well as the mechanical properties of the concrete were studied. The test results show that using of Attapulgite as coarse aggregate and treating it by sodium hypochlorite solution of 6% concentration greatly contributed to enhance the mechanical properties of concrete. Also, as the tensile reinforcement ratio increases, the ultimate load of the tested beams increases. Cracking load to the ultimate load proportion was less than 20% for all beams. Beam of 1.76% steel reinforcement ratio had largest experimental ultimate load capacity in this study. All beams exhibited a typical flexural failure mode. All Attapulgite beams produced sufficient predicted ductility (more than 3).

Keywords: Attapulgite, flexural behavior, steel reinforcement ratios,treated lightweight aggregate.

1. Introduction

The structural lightweight aggregate (coarse aggregate) is the aggregate with abulk density less than 880 kg/m^3[1]. Lower density as well as superior thermal insulation has gained the lightweight concrete its popularity. Lightweight concrete is a desirable material especially in multi-story buildings [2, 3]. Three ways can be used to produce LWC. First technique by producing concrete without fine aggregate completely, which is called “No Fines Concrete”. The second technique by including bubble voids into the mixture of concrete to form a cellular structure, which includes about from 30% to 50% voids, called “Aerated Concrete”, and also it is referred as gas, foamed or cellular concrete. The third technique to produce LWC was by replacing the normal weight aggregate by lightweight aggregate, with specific gravity lower than 2.6, which is called “Lightweight Aggregate Concrete”, (LWAC) [4]. The type of aggregate is one of the factors affecting the strength of lightweight concrete [5]. Attapulgite is a kind of crystalloid hydrous Magnesium–Aluminum silicate mineral [6]. It can be classified as a kind of natural resource from which lightweight aggregates can be made locally. AL Aridhee [7] found that by burring Attapulgite clay at 1100°C, as an optimum firing temperature, for 30 minute leads to produce LWA with bulk density 808 kg/m^3, specific gravity of 1.45, compressive strength of concrete of 27.7 MPa at age 28 day and a dry density of 1824 kg/m^3. It was observed that, there was an improvement in the mechanical properties when using Attapulgite as coarse aggregate in the concrete comparing with results in another study that used porcelanite aggregate concrete.

Reinforced lightweight concrete structures may suffer from a lack in strength and sudden failure in a brittle manner under compression loading after occurrence of first crack. In general, many factors can enhance the flexural behavior of reinforced beams of lightweight concrete. Teo el al. [8] observed that reinforced LWAC beams with low tensile reinforcement ratios met all the serviceability and durability requirements, the tension reinforcement yields before concrete cover crushing in the compression zone. Besides, there wasa considerable deflection provides ample warning before failure occurred. Akmaluddin [9]found that the tensile reinforcement ratio has a significant effect on the effective moment of inertia of reinforced beams made with pumice lightweight concrete because as the tensile reinforcement ratio increases, the cracking moment of inertia increases.

Production of lightweight concrete, from natural resources, and using it in reinforced flexural members with adequate resistance to bending loads and sufficient ductility is consider one of the challenges in structural buildings.Accordingly, the present experimental study focuses on producing a lightweight coarse aggregate from a natural local material, Attapulgiteand investigating the flexural behavior of RC beams which made from treated Attapulgite lightweight aggregate concrete. The reinforcement ratios were considered in the parametric study. The flexural behavior of the beams is discussed in terms of ultimate load capacity, load-deflection relationships, failure mode, crack pattern and ductility.

2. Experimental program

2.1 Manufacture of treated lightweight Attapulgite

The raw material of coarse aggregate which used in this study was Attapulgite clay. The clay hunks were crushed to obtain the required size about 9.5mm as a maximum size aggregate. Then it was burned in a kiln at a temperature of 1100ºC for 30 minutes to crystallize it and to increase the bonding between its particles by removing the absorbed wateraccording to the specifications of the method which was used by Al- Aridhee [7], Fig. 1.The physical and chemical properties of Attapulgite are listed in Table 1, which conforming to ASTM C330/C330M-17a and ACI 213R-14 [10, 11].Attapulgite was treated in a sodium hypochlorite of 6% concentration for 24 hour in order to enhance its mechanical properties, and then it was washed by water and dried at a temperature of 110 ºC for an hour.

Fig. 1 Attapulgite lightweight aggregate

Table 1 Physical and chemical properties of Attapulgite

Property	Test results
Dry loos bulk density (kg/m^3)	787.35
Specific gravity	0.9
Absorption (%)	15.64
Sulfate content (SO_3) (%)	0.037

2.2Materials and mix proportions

Ordinary Portland cement with a specific surface area of 317m^2/kg and compressive strength at 7 days of 29.8 MPa was used.River sand was used as a fine aggregate with a maximum size of 5 mm, fineness modulus of 2.82 and sulfate content (SO_3) of 0.42%. Attapulgite was used as a lightweight coarse aggregate. A water to cement ratio (w/c) of 0.28 was adopted.High rang water reducer admixture (HRWRA) of Glenium51 were used to enhance the strength and workability of LWAC mixture.Table 2 summarizes the mix proportions of the mixture.

Table 2 Mix proportions

Material	Quantity
Cement	580 (kg/m^3)
Sand	555 (kg/m^3)
Attapulgite	520 (kg/m^3)
Water	167 (kg/m^3)
HRWRA	6 (L/m^3)

[Note]HRWRA= high rang water reducer admixture

2.3 Casting preparation of specimens

To evaluate the experimental value of compressive strength(f'_c) and splitting strength (f_t)of treated Attapulgite lightweight aggregate concrete (ALWAC), cylindrical specimens of 100x200 mm diameter and height were casted and tested. Average of two specimens for treated ALWAC mixture was taken to evaluate the compressive and splitting strength according to ASTM C39-01[12] and ASTM C496-11[13], respectively.Prism of 100x100 mm cross section and 500 mm span length was prepared and tested to determine the experimental value of the flexural strength (f_r) of ALWAC according to ASTM C78-02 [14] using two points load electrical testing machine. Cylindrical specimen of 150x300 mm diameter and height was casted and tested to evaluate the experimental value of the modulus of elasticity (Ec) according to ASTM C469-02 [15]. All test specimens' molds were equally filled in three layers with treated Attapulgite concrete and each layer was compacted by electric table. The theoretical values of the mechanical properties calculated according to ACI 318 code [16].

2.4 Details and test setup for structural treated ALWAC beams

The experimental program consists of three reinforced treated ALWAC beams, Table 3. The beams had rectangular section with longitudinal tensile and web reinforcement. The cross section of all beams specimens had dimensions of 120 mm wide and 200 mm overall height. The beam length is 1200 mm with clear span 1100 mm.Two diameter of longitudinal reinforcement deformed bar of 10 and 12mm grade 400 were used. The yield strength of steel is 495 MPa and 476 MPa, respectively. Shear stirrups (90° hook) with nominal diameter of 6mm deformed bar, and yield strength of 612 MPa, placed at 60 mm center to center spacing over all the length of cage. Two smooth steel bars of 4mm diameter were used in the cross section at the compression zone to provide support for stirrups. The details and test setup of reinforced treated ALWAC beams are shown in Fig. 2.The steel cages were placed in oiled wooden molds. The concrete mixture was poured into the molds in three layers and each layer was compacted by electrical vibration table. The beams and specimens were left to be dried for 24 hr. and then cured for 28 days. All beams were investigated for flexural behavior using hydraulic universal testing machine (MFL) of 3000 kN capacity. Beams loaded monotonically with two symmetrical point loads up to failure. When the first crack occurred, the load was recorded as a first cracking load. The ultimate load of each beam specimen was recorded. The deflections of beams were measured using ELE dial gauge of 0.01mm accuracy, which was installed in contact underneath the center of reinforced ALWAC beams.

Table 3 Details of reinforced beams

Beam no.	Steel reinforcement ratio (ρ %)
B1	1.17
B2	0.8
B3	1.76

[Note] B= beam.

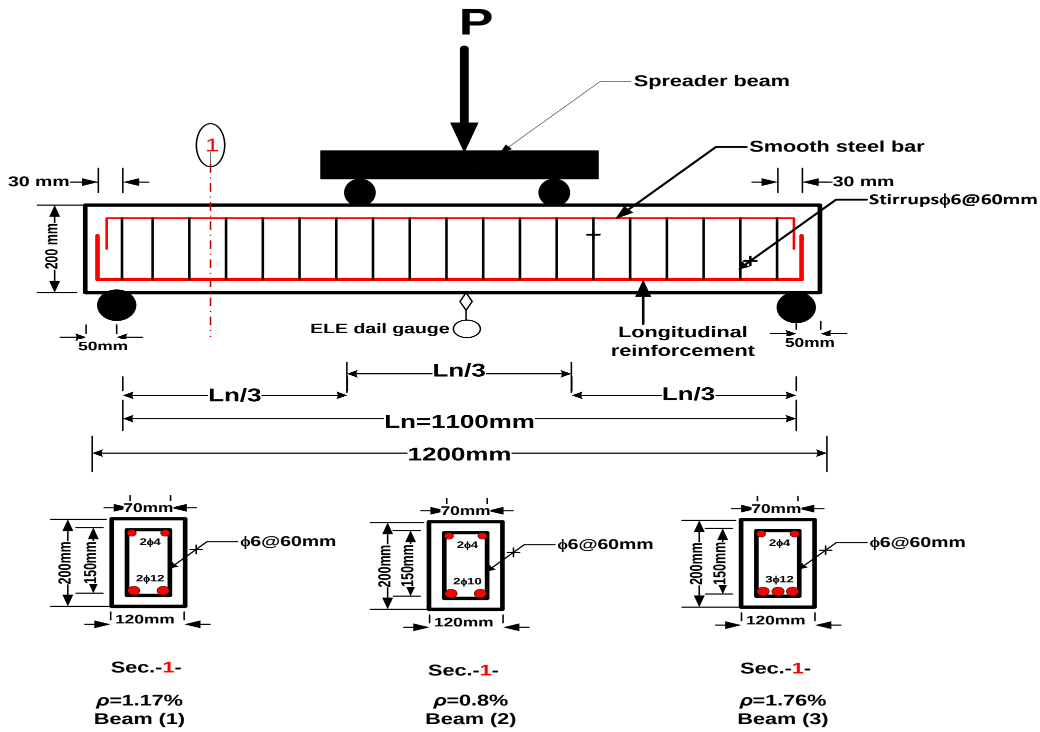

Fig.2 Details of reinforced treated ALWAC beams

3. Experimental results and discussion

3.1 Mechanical properties of treated ALWAC

Table 4 summarizes the experimental results, as well as the theoretical value, for mechanical properties of treated ALWAC. The density of treated ALWAC is within the required limits of ACI 318-19 [16] code for lightweight concrete. The compressive strength of treated ALWAC was 38.5 MPa at age of 28 days. The experimental values of the mechanical properties were higher than the theoretical values. The increasing rate in the experimental results of f_t, f_r and Ec of treated ALWAC is 36.15%, 32.64% and 37.14%, respectively, as compared to the theoretical value. The ACI code provisions gave more precautions. The mechanical properties of the concrete mixture are significantly influenced by the strength of the materials that composed of it, especially the coarse aggregate. Treating coarse aggregate (Attapulgite) by sodium hypochlorite solution of 6% concentration greatly contributed to enhance the coarse aggregate strength and thus improving its mechanical properties.

Table 4 Mechanical properties of treated ALWAC

Property	Result	
	Experimental	Theoretical
Density (kg/m^3)	1910	-
Compressive strength, f'_c (Mpa)	38.5	-
Splitting strength, f_t (Mpa)	3.54	2.60
Flexural strength, f_r (Mpa)	3.82	2.88
Modulus of elasticity, Ec (Mpa)	22908.2	16703.6

3.2 Flexural behavior of reinforced treated ALWAC beams

3.2.1 Behavior in general

All lightweight beams showed typical flexural failure. Vertical flexural cracks were noticed at the bottom of beams (flexural zone). All lightweight beams failed with experimental value of ultimate load higher than theoretical value. Yielding of tensile reinforcement had been occurred without crushing in the concrete cover.

3.2.2 Cracking and ultimate load

The values of first cracking load and ultimate load (experimental and theoretical value) for the tested lightweight beams, relative to the longitudinal reinforcement are recorded in Table 5. The first vertical crack in B1 initiated at 17.5 kN in flexural zone. First cracking occurred in B1, B2 and B3 at about 14.3%, 18.4% and 17.3% of ultimate load, respectively. First cracking load in B3 was invisible (did not progress to the surface of concrete).The low longitudinal reinforcement ratio (0.8%) has limited effect on the first cracking load. The effect of longitudinal reinforcement was more obvious in the lightweight beam with higher longitudinal reinforcement ratio (1.76%), with an increment in first cracking load about 28.57% compared to B1. This indicates that the increasing in longitudinal reinforcement contributed to enhance the load resistance in beam and delay the occurrence of first crack. Also, this gives an indication of strong bonding between treated lightweight concrete and reinforcing steel bars. Tensile reinforcement ratio of 1.76% achieved the highest value of ultimate load by 130 kN in this study.

A comparison between the experimental ultimate flexural load ($P_{u\ (exp.)}$) and the theoretical ultimate flexural load ($P_{u(theo.)}$) is made according to ACI simplified method by using equations 1, 2 and 3. The ACI simplified method equations are given as:

$M_n=M_u$ …………… (1)

$M_n=A_s f_y\,[d-(a/2)]$ …………… (2)

$M_u=P_u l_n/6$ …………… (3)

Where M_n is the nominal flexural strength, M_u is the ultimate flexural strength, A_s is the area of steel reinforcement, f_y is the yield strength of steel bar, d is the effective depth of the beam, a is the depth of the concrete rectangular block , P_u is the ultimate load and l_n is the clear span length of beam.Fig. 3 shows the percent of increasing in experimental ultimate load compared to the theoretical value, which indicate a significant increment in flexural load capacity in treated ALWAC beams. The ACI-318 building code equations werefound to be extremely conservative in obtaining the ultimate load for ALWAC beams.

Table 5 Cracking and ultimate load of tested beams

Beam no.	Cracking load (kN)	Ultimate load (kN)	
		Experimental	Theoretical (ACI 318)
B1	17.5	122.5	85.92
B2	18	98	63.83
B3	22.5	130	122.84

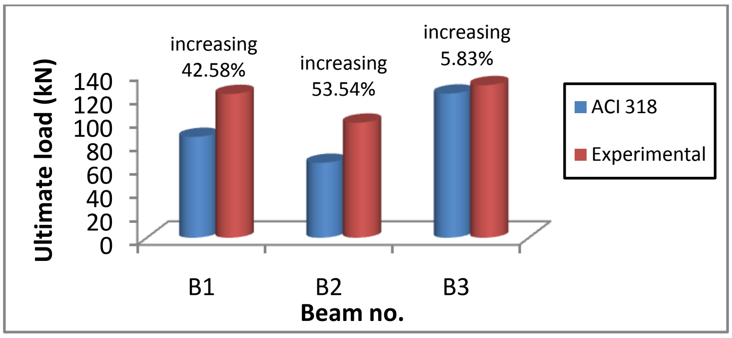

Fig. 3 Percent of increasing in experimental ultimate load compared to the theoretical value for the beams

3.2.3Load- mid span deflection

The results are discussed based on a comparison of all beams with B1.The beam with higher value of tensile reinforcement ratio (B3) has stiffer response to loading in the pre-cracking stage due to higher moment of inertia. In the post-cracking stage, cracking reduced the effective moment of inertia; hence there was a change in the slope of load-deflection curve represented by increasing in the deflection value. At the same value of applied load, a beam with a higher steel reinforcement ratio (B3) exhibits less deformation. The tendency of the load-deflection curve is an indicator of the beam stiffness. Therefore, increasing in steel reinforcement ratio led to increase the stiffness of the ALWAC beam. Fig.4 shows that the tensile reinforcement ratio has a noticeable and significant effect on the behavior of load-deflection of treated ALWAC beams.

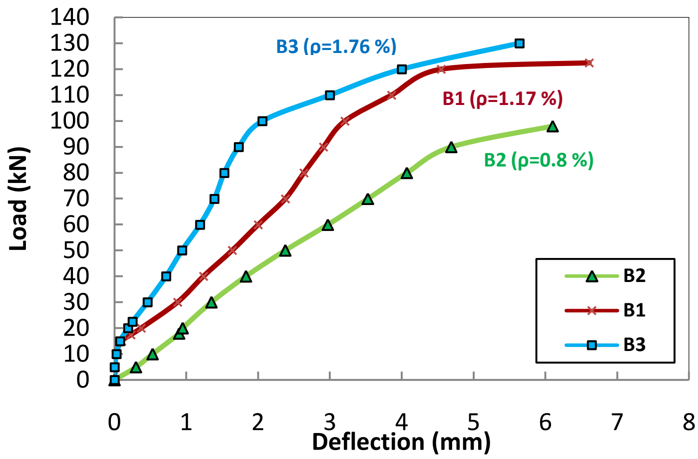

Fig. 4 Effect of longitudinal reinforcement onthe load-mid span deflection relationship

3.2.4 Failure mode and crack patterns

Failure is defined as increasing of deflection with decreasing in load, in addition to reinforcement yielding and/or concrete failure. The observed failure modes and crack patterns for all lightweight RC beams are shown in Fig. 5. All beams failed in flexural zone and showed a typical tension failure. In B1, B2 and B3yielding of tension reinforcement occurred in pure bending zone without any crushing in concrete cover. This is expected because all the beams were under-reinforced section ($\rho<\rho_b$). It was observed that, when the tensile steel ratio more close to the balanced steel ratio (higher ρ/ρ_b) the failure mode was occurred at a higher load.

All lightweight beams in this study, at first crack load, had the first crack in the flexural zone (flexural crack) because the moment applied in this reign is high. When the applied load exceeded the first crack load, the first crack continued to propagate and extended to the neutral axis and some new flexural cracks appeared at discrete intervals along the beam.For B2 (ρ=0.8%), the cracks formed only within the pure bending zone. As the tensile reinforcement ratio increases, cracks begin to propagate outside the pure bending zone. For B3 (ρ= 1.76%), inclined cracking started to form due to the increase in shear stresses as the applied load increased. B3 experienced significant flexural cracks before starting of the flexure-shear crack, indicating flexural dominance.

Fig.5 Failure mode and crack patterns of tested beams

3.2.5 Flexural ductility

Ductility is the ability of a structural member to sustain deformation near or at the failure load without a considerable loss in the load carrying capacity until complete failure [17]. The ductility of treated ALWAC beams is estimated in term of its ductility index (µ). The ductility of beams in this study calculated mathematically according to an equation developed by Pam et al. [18] to predict the ductility of the normal and high strength beams, as follows:

$\mu = 9.5\,(f_{cu})^{-0.3}\,(\rho/\rho_{bal})^{-0.75}$ …………….. (4)

Where µ is the ductility index, f_{cu} is the cube compressive strength and ρ_{bal} is the balance reinforcement ratio. In this study it is considered that, the (f_{cu}) is equal to ($f'c$/0.83). The ductility index of the tested beams is given in Fig. 6.

As compare to B1, the ductility in the tested flexural beams mainly influenced by the tensile reinforcement ratio. The ductility decreased significantly as the tensile reinforcement ratio increased, which is expected and accepted due to the increase in tensile reinforcement ratio.The stiffness of the beam increases and the load-deflection behavior decreases, thus the ductility of the beam decreases. The value of 3 for the ductility is considered the minimum limit to ensure the ductile performance in the flexural members, the beams with the tensile reinforcement ratio exceed 1.5% would not satisfy this limit [19]. In this study all treated ALWAC beams satisfy that lower bound even B3 which have tensile reinforcement ratio equal to 1.76% (exceed than 1.5%). The ductility results are completely consistent with the failure modes obtained because all ALWAC beams failed in ductile manner.

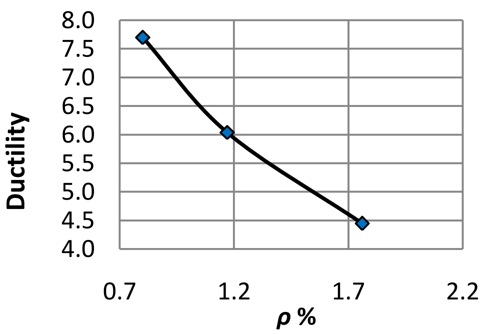

Fig. 6 Effect of steel reinforcement ratio on the ductility index of tested beams

4. Conclusion

The following conclusions of the experimental results can be drawn:

1. A dry loose bulk density of 787.35 kg/m^3 was obtained by producing of lightweight coarse aggregate from natural material (Attapulgite) by burning it at 1100ºC for 30 minutes and it complies with the specifications of ASTM C330/C330M-17a.
2. The obtained compressive strength of ALWAC at 28 days and its unit weight are 38.5 MPa and 1910 kg/m^3, respectively, after treating the Attapulgite aggregate with sodium hypochlorite of 6% concentration.
3. All ALWA reinforced concrete beams exhibited a significant increment in the flexural load capacity as compared with theoretical value prediction. This increasing attributed to the good strength of the producing aggregate (Attapulgite) since the mechanical properties of concrete, thus the structural behavior of beam, are greatly depends on the strength of LWA.
4. Proportion of the cracking load to the ultimate load was found to be less than 20% for all beams, that can be attributed to the influence of the coarse aggregate (Attapulgite) which reduces the propagation of cracks and increases the fracture energy.
5. Increasing of longitudinal reinforcement ratios to 1.76 % improved the load carrying capacity of the beams by 32 % as compared to ρ=0.8 % . The deformation of the beam with largest ρ was less by 41.7%.
6. All lightweight beams showed a typical tension failure. After yielding of steel reinforcement, all beams experienced significant inelastic deformation. Flexural cracks were observed in all beams. Flexure shear crack was formed in beam of higher longitudinal tensile reinforcement ratio (1.76%).
7. All Attapulgite reinforced beams showed sufficient ductility (more than 3). Tensile reinforcement ratio hassignificant effect on the ductility. The ductility decreased as the tensile reinforcement ratio increased.

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