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FLEXURAL BEHAVIOR OF REINFORCED LIGHTWEIGHT CONCRETE BEAMS MADE WITH ATTAPULGITE AND ALUMINUM WASTE

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Abstract: Lightweight concrete reduces the total dead load of structural elements and seismic loads significantly. This paper presents the production Attapulgite Lightweight aggregate concrete (ALWAC) and its effect on the flexural behavior of reinforced concrete beams. Attapulgite was treated with sodium hypochlorite of 6% concentration for 24 hours. The variable considered was the aluminum waste (AW), used as a fiber, of fraction (0, 0.5 and 1%) by concrete volume. Behavior was investigated in terms of cracking and ultimate load, load-deflection relationship, failure mode, crack patterns and flexural ductility. The mechanical properties of the ALWAC were studied. It was observed that, Attapulgite improves the mechanical properties of concrete when comparing the experimental value with theoretical ones for the reference mixture. AW has a disparate effect on the mechanical properties of ALWAC. The increase in the proportions of AW showed an increase in the cracking load and decrease in the ultimate load by 37.14% and 22.45 %, respectively, at AW of 1%. Experimental value of ultimate load in all beams was higher than the theoretical value (ACI simplified method). AW increases the deflection at the same magnitude of applied load, and reduces the number and propagation of the flexural cracks in beams. All beams exhibited a typical tension failure mode and failed in ductile manner.

Keywords: *Flexural behavior, treated lightweight aggregate, lightweight concrete, Attapulgite, Aluminum waste, ductility.*

1. Introduction

The American Concrete Institute ACI 318-19 code [1] defines the lightweight concrete as concrete which contain a lightweight aggregate and have an equilibrium density from 1440 to 2160 kg/m^3, as specified by ASTM C567 [2]. Lightweight concrete (LWC) is desirable especially in multi-story buildings. More economical benefits as well as environmental benefits can achieve if waste materials are used in manufacture of LWC [3, 4]. There are two types of lightweight aggregate concrete (LWAC), natural and artificial. According to the ACI 213R-14 code [5] the structural lightweight coarse aggregate must have bulk density less than 880 kg/m^3 which complying the requirements of ASTM C330/C330M [6]. Attapulgite clay is a kind of crystalloid hydrous Magnesium–Aluminum silicate mineral [7], and it is a local natural resource for manufacturing the lightweight aggregates through it because it is found in AL-Najaf, Karbala and AL-Anbar regions in Iraq. AL Amide [8] showed experimentally the possibility of using Attapulgite as a super pozzolan with using

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chemical additives to enhance some properties of concrete.

Using of industrial waste material in concrete considered a sustainable development for construction, as it helps to improve the concrete, cement and other building materials with satisfying performance, in terms of serviceability and safety. This can be obtained at a lower cost. Aluminum waste (AW) comes typically in the form of small strips, flexible and thin of variable sizes. It is obtained primarily from using aluminum alloys in residential building elements in engineering applications, such as: windows, sidings and doors. A beam is a structural ingredient that resists the loads, it tends to bend and deflect under loading.

The main objective of this study is to manufacture a lightweight aggregates from Attapulgite clay and use it as coarse aggregate, in the reinforced structural parts carries flexural loads, after treating it with sodium hypochlorite of 6% concentration for 24 hours based on Abdulla et al. [9] study, which used sodium hypochlorite to improve the mechanical properties of lightweight Porcelinite stone. Also, to investigate the effect of aluminum waste on the flexural behavior of this reinforced structural parts (beams), as well as the mechanical properties of concrete. The flexural behavior of beams is studied in terms of ultimate load capacity, load-deflection relationships, failure mode, crack pattern and ductility.

2. Literature review

The possibility of using Attapulgite clay as coarse aggregate to produce lightweight concrete according to ASTM C330-05 was studied experimentally by AL-Aridhee [10]. It was found that by burring Attapulgite clay at 1100°C for 30 minutes leads to produce lightweight aggregate (LWA) with bulk density 808 kg/m^3. A compressive strength of concrete at age 28 day and a dry density obtained of 27.7 MPa and 1824 kg/m^3, respectively, it was observed that there was an enhancement in the mechanical properties of concrete when using Attapulgite as coarse aggregate comparing with porcelanite aggregate concrete. Attapulgite, after firing it at temperature of 700°C for 1 hour, was replaced partially or completely with ordinary aggregates in the Hammad et al. [11] experimental study. It was observed that the mixture which contains 100% Attapulgite fine and coarse aggregate had density less than mixture which contains 50% ordinary fine aggregate, 50% Attapulgite fine aggregate and 100% Attapulgite coarse aggregate. There is a variation in previous studies about the effect of aluminum waste on the mechanical properties of concrete. Vijayalakshmi and Rajeswari [12] proved experimentally that using aluminum dross and aluminum powder as partial replacement of cement weight led to decrease the density and compressive strength of concrete due to gas producing from aluminum within the mixture and 10% was the optimum percent of aluminum dross to obtain a required strength of concrete. While Muwashee et al. [13] found experimentally that using aluminum straight strips from Coco-Cola waste cans as percentages by volume improved the mechanical properties of mortar and concrete especially at percent of 2.5% for concrete, and gave more toughness and ductility to concrete matrix.

Many authors have addressed the study of flexural behavior of reinforced LWAC beams. AL Nasser et al. [14] observed that the flexural behavior of LWC beams made with natural scoria was similar to that of normal weight concrete (NWC) beams with relatively larger curvatures and deflections. Also, the crack pattern was typical of flexural beam and identical to the one informed for NWC beam. Bernardo et al. [15] observed experimentally that reinforced concrete (RC) beam of expanded clay lightweight aggregate undergo a reduction in ductility with increment of tensile reinforcement ratio until $\rho \approx 1.5–2.0\%$, for approximately constant magnitude of compressive strength of concrete. After these limits, failure tends to be brittle. Also, increase in the compressive strength caused a slight increase in ductility for similar longitudinal steel reinforcement ratios.

3. Experimental program

3.1. Manufacture of treated LWA (Attapulgite)

In this study, the specification of method which was used by Al-Aridhee [10] was adopted to manufacture the Attapulgite lightweight coarse aggregate. Table 1 lists the physical and chemical properties of Attapulgite. Moreover, in this study Attapulgite lightweight coarse aggregate was treated with sodium hypochlorite of 6% concentration for 24 hours in order to increase its stiffness. Attapulgite clay was obtained from Tar AL-Najaf in the form of dried large hunks. In the construction materials laboratory at Engineering Faculty of Al-Mustansiriyah University, the Attapulgite was crushed manually by a hammer to smaller sizes and then crushed it by Jow crusher machine to obtain required size about 9.5mm as a maximum size aggregate. Then it was burned, in the same laboratory, in Wenger Kiln at temperature of 1100ºC for 30 minutes in the same laboratory in order to crystallize the Attapulgite, increase the bonding between its particles by removing the absorbed water. After the kiln was turned off, the Attapulgite was left inside it for the next day. After that, Attapulgite was soaked in a sodium hypochlorite solution (NaOCL) of 6% concentration for 24 hours in order to enhance its mechanical properties, and then it was washed with water. The Attapulgite was put in an oven to get dry at temperature of 110 ºC for an hour.

Table 1. Physical and chemical properties of Attapulgite

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

3.2. Materials

Ordinary Portland cement with a specific surface area of 317m^2/kg and compressive strength at 7 days of 29.8 MPa was used in this study. Major chemical properties of the cement were silicon dioxide (SiO_2) of 22.15% and calcium oxide (CaO) of 63.21%. 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%. The properties of cement and sand met the Iraqi specification limits (IQ.S) No.5/1984 [16] and No.45/1984 [17]. Attapulgite was used as a lightweight coarse aggregate as shown in Fig. 1, with bulk density of 787.35 kg/m^3 and maximum size aggregate of 9.5mm. Aluminum waste with length of 3 mm as a maximum size and with bulk density of 514.72kg/m^3 was used as fiber in the concrete mixtures as shown in Fig.2. High range water reducer admixture (HRWRA) of Glenium51 was used.

Figure 1. Attapulgite LWA

Figure 2. Aluminum waste

3.3. Trial mix and mix proportions

Three trial mixes were designed according to ACI 211.2-98 [18]. The Attapulgite concrete compressive strength target was 30 MPa after 28 days of curing. Trial mixes were prepared using rotary mixer of 0.15m^3 capacity. For every trial mixture, three standard cubes of 100 mm were cast and taken the average compressive strength of it's at age of 7 and 28 days. Table 2 lists the density and compressive strength of Attapulgite (without treatment) concrete specimens for all trial mixes.

Table 2. Density and compressive strength of trail mix

Mix no.	Cement-kg/m^3	Sand -kglm^3	Attapulgite-kg/m^3	Water -kg/m^3	HRWRA-l/m^3	Density-kg/m^3	f_{cu} at 7 days-MPa	f_{cu} at 28 days-MPa
1	500	600	390	140	6	1753	27	33.6
2	550	550	381	154	6.5	1824	30.1	37.2
3	570	525	373	167	6	1860	29.6	38.7

Slump test between (18-23) cm

Mix no. 3 was more suitable mix and was selected as a reference mix in the experiments. The ratios of mixtures listed in Table 3. The letter "M" indicates the mixture, the number "0" indicates that no AW used in the mixture (reference mixture). The letter "A" indicates that aluminum waste was used in the mixture and the number indicates the percentage of AW by volume of concrete. The letter "B" indicates the beam.

Table 3. Mix proportions

Beam no.	Mix type	Aluminum waste (%)
B1	M0	0
B2	MA,0.5	0.5
B3	MA,1	1

3.4. Test setup for mechanical properties of treated Attapulgite lightweight aggregate concrete

Cylindrical specimens of 100x200 mm diameter and height were casted for each concrete mixture and tested to evaluate the compressive and splitting strength of Attapulgite lightweight aggregate concrete (ALWAC) according to ASTM C39-01[19] and ASTM C496-11[20], respectively. A uniaxial load was applied monotonically and increased at a rate of 15 MPa/min by using digitally compressive testing machine of 2000 kN as a maximum capacity. Average of two specimens for each ALWAC mixture was taken to evaluate the compressive and splitting strength.

To evaluate the modulus of rupture of ALWAC, prism of 100x100 mm cross section and 500 mm span length was prepared and tested according to ASTM C78-02 [21] for each concrete mixture. Clear span length of prism was 450mm. Two points load electrical testing machine of 3000 kN as a maximum capacity was used.

To evaluate the modulus of elasticity of ALWAC, cylindrical specimen of 150x300 mm diameter and height was casted and tested for each concrete mixture according to ASTM C469-02 [22] using compressometer of accuracy of 0.002 and electrical compressive testing machine which has a maximum capacity of 3000 kN. All test specimens' molds were equally filled in three layers with Attapulgite concrete and each layer was compacted by electric table.

3.5. Details and test setup of reinforced beams

All beams had rectangular section of 120 mm wide and 200 mm overall height. The beam length was 1200 mm with clear span 1100 mm. Two longitudinal tensile reinforcement deformed bars of 12 mm nominal diameter of grade 400 and yield strength of 476 MPa were used. Steel bar of 6mm nominal diameter and yield strength of 612 MPa, was used as a shear stirrups (90° hook) and 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 compression zone of cross section to support the stirrups. Hook was placed at each ends of cage. Longitudinal tensile reinforcement ratio of 1.17 % was adopted in this study to avoid shear failure of beams.

To examine the flexural behavior of treated Attapulgite reinforced beams, beams loaded monotonically with two symmetrical point loads up to failure by using hydraulic universal testing machine (MFL) of 3000 kN capacity. First cracking and ultimate load recorded for each beam. ELE dial gauge of 0.01mm accuracy was installed in contact underneath the center of reinforced treated ALWAC beams to measure the mid span deflections of beams. Fig. 3 shows the details and test setup of reinforced treated ALWAC beams.

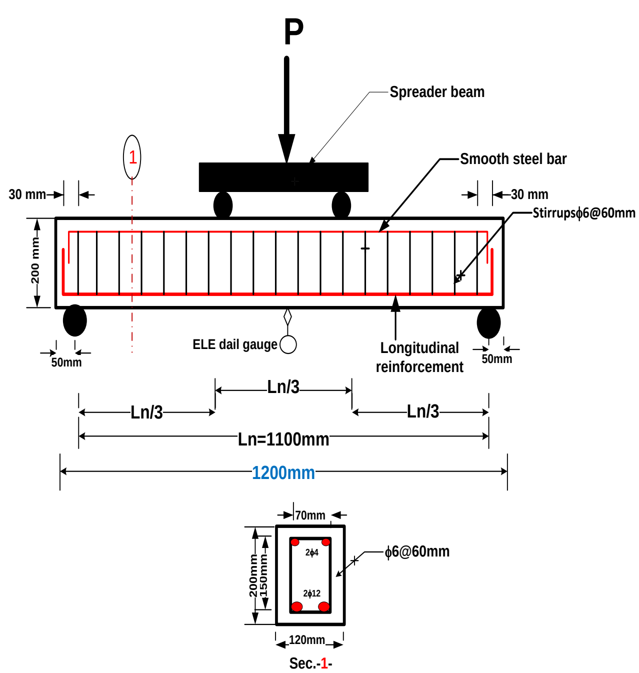


Figure. 3 Details and test setup of reinforced beams

4. Experimental results and discussion

4.1. Mechanical properties

Table 3 summarizes the experimental results for the mechanical properties of treated ALWAC. Compressive strength of the trial mix no.3 was 38.7 MPa at age of 28 days for cubic specimen and without treatment with NaOCL. While the compressive strength of the treated reference mixture (M0) was 38.5 MPa at age of 28 days for cylindrical specimen. Therefore, it can be concluded that treatment with NaOCL of 6% concentration enhances the compressive strength of ALWAC because compressive strength of cylindrical specimen usually equal to approximately 0.80 compressive strength of cubic specimen.

The procedure of calculating the theoretical values of splitting strength (f_t), modulus of rupture (f_r) and modulus of elasticity (Ec) of M0 according to ACI 318 code for LWC is given by the following equations:

$$f_t = 0.56\, \lambda \sqrt{f'_c} \quad (1)$$

$$f_r = 0.62\, \lambda \sqrt{f'_c} \quad (2)$$

$$Ec = w_c^{1.5}\, 0.043\, \lambda \sqrt{f'_c} \quad (3)$$

Theoretical value of f_t, f_r and Ec of M0 according to ACI 318 code for LWC was 2.60, 2.88 and 16703.6 MPa, respectively. Accordingly, the experimental value of splitting strength, modulus of rupture and modulus of elasticity of M0 increased by 36.15, 32.64 and 37.15%, respectively as compared to the theoretical values, that can be attributed to the influence of the coarse aggregate (Attapulgite) which improved the mechanical properties of concrete significantly.

Table 4. Mechanical properties of treated ALWAC

Mix type	Density (kg/m^3)	f'_c (MPa)	f_t (MPa)	f_r (MPa)	*Ec* (MPa)
M0	1910	38.5	3.54	3.82	22908.2
MA,0.5	1890	38.1	4.52	2.70	12346.3
MA,1	1910	36.3	4.86	2.25	10425.46

The main objective of using aluminum waste in this study is to reduce the cost and eliminate the environment problems by recycling it, using it for construction purposes and producing lightweight concrete at the same time. There is a decrease in the compressive strength when using aluminum waste in the concrete mixture at rates of 1.04% and 5.71% for 0.5% and 1% aluminum waste fraction, respectively, as compared to M0, Fig. 4. For splitting tensile strength, increases were obtained as 27.70% and 37.30% for 0.5% and 1% aluminum waste, respectively, because AW was used as a fiber in this study, and achieved 4.86 MPa as a maximum value, Fig. 5. The aluminum metal reacts with water (in the alkaline solution of cement past), and then producing aluminum hydroxide and hydrogen gas, however, not all of this hydrogen gas is entrapped inside the mixture; but some of the gas leaves at early age and escapes the system [23]. This gas creates air voids inside the concrete mixture and thus weakens it, which leads to reduce the compressive strength, modulus of rupture and modulus of elasticity of AW lightweight concrete. Fig. 6 and Fig. 7 show the effect of AW on f_r and *Ec* of ALWAC, respectively. Doubling the ratio of AW led to an increase in the density, because AW was added to the concrete as a fiber (an addition ratio not a replacement ratio).

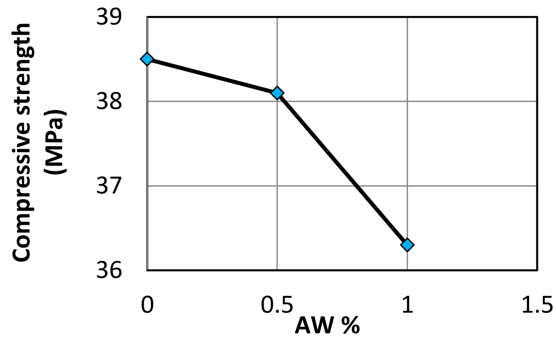


Figure 4. Effect of Aluminum waste on compressive strength

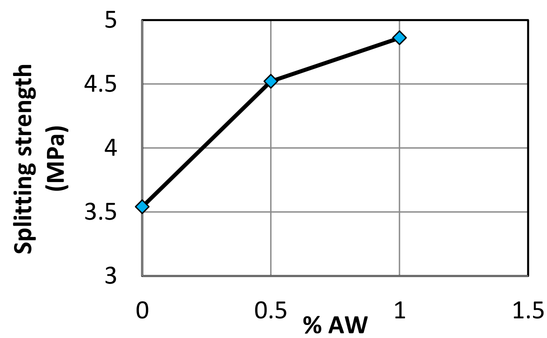


Figure 5. Effect of Aluminum waste on splitting strength

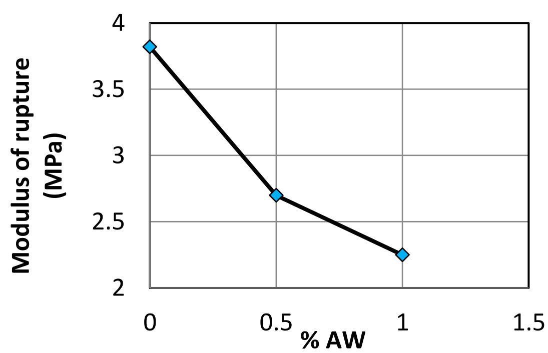


Figure 6. Effect of Aluminum waste on modulus of rupture

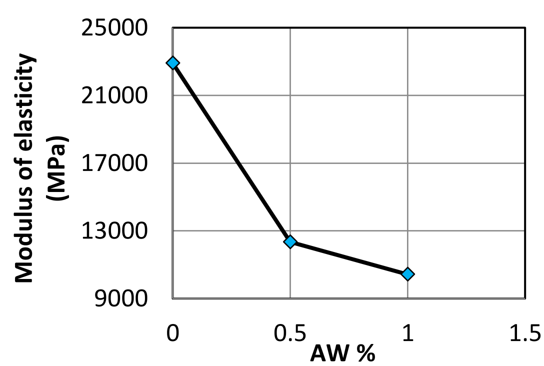


Figure 7. Effect of Aluminum waste on the modulus of elasticity

4.2. Flexural behavior of reinforced beams

4.2.1 Cracking and ultimate load

Cracking and ultimate load are given in Table 5. First cracking occurred in B1, B2 and B3 at about 14.3%, 20% and 25.3% of ultimate load, respectively. First cracking load increased with the addition of aluminum waste. It is noticed that there is a similar trend for the curves of first cracking load and splitting strength of the specimens containing aluminum waste as can be seen in Fig. 8. The improvement of tensile strength of the specimens, because AW used in this study as fiber, is reflected on increasing the first cracking load. The maximum increment was found when aluminum waste was added at 1% by concrete volume. At this adding rate, the first cracking load increased to 24 MPa, which corresponds to 37.14% increment in the first cracking load. However, reaction of aluminum with water and creating of air voids accelerated the occurrence of macro cracks and total failure in beams. The results show that experimental ultimate load of beams is reduced with the addition of aluminum waste to 112.5 MPa and 95 MPa at 0.5% and 1% of aluminum waste, respectively, Fig. 9.

According to ACI simplified method by using equations 4 and 5, a comparison between the experimental ultimate flexural load ($P_{u(exp.)}$) and the theoretical ultimate flexural load ($P_{u(theo.)}$) is made, Fig. 10.

$$M = A_s f_y [d-(a/2)] \quad (4)$$

$$M = P_u \, Ln/6 \quad (5)$$

It should be noticed that in spite of the reduction in the experimental ultimate load with the addition of aluminum waste, the remaining ultimate load, even with maximum reduction at 1% of aluminum waste, is still significantly acceptable and sufficient for construction applications, especially with increasing that achieved in experimental values compared to the theoretical values of ultimate load. Furthermore, take into account other advantages of aluminum concrete such as lightweight and effective contribution to recycling the industrial waste, as mentioned earlier.

Table 5. Cracking and experimental ultimate load of tested beams

Beam no.	Aluminum waste (%)	Cracking load (kN)	Ultimate load (kN)
B1	0	17.5	122.5
B2	0.5	22.5	112.5
B3	1	24	95

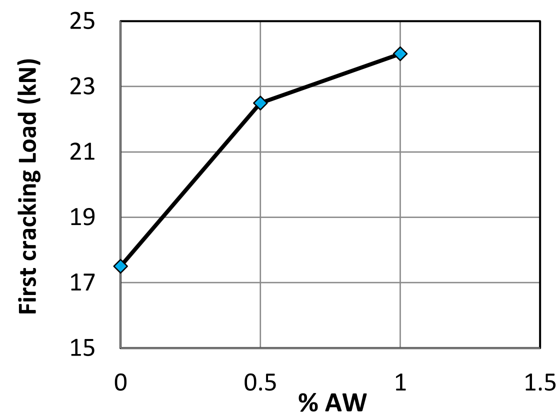


Figure 8. Aluminum waste fraction versus first cracking load

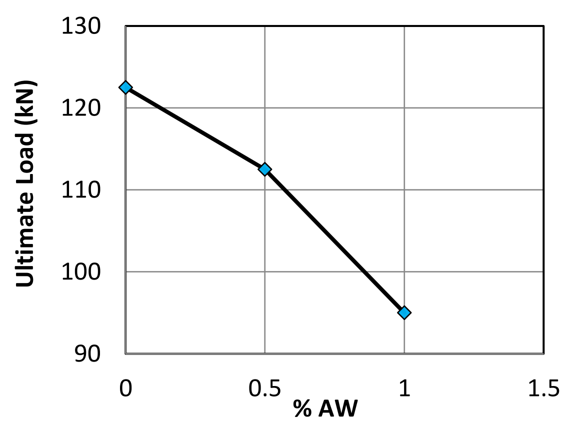


Figure 9. Aluminum waste fraction versus ultimate load

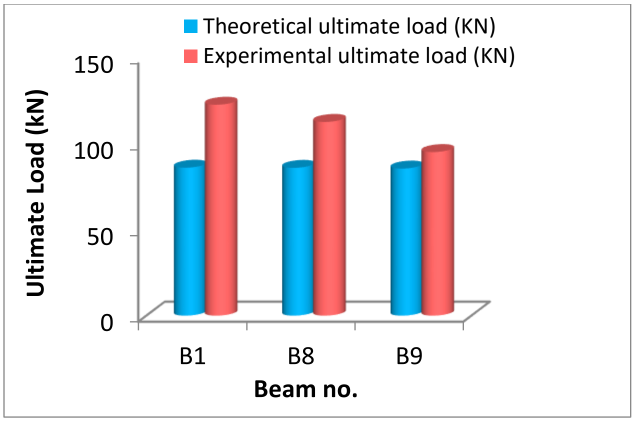


Figure 10. Percent of increasing in experimental ultimate load compared to the theoretical value of tested beams

4.2.2 Load-mid span deflection

The results are discussed based on a comparison of B2 and B3 with B1. The load-mid span deflection relationship for all beams is shown in Fig. 11. In the pre-cracking stage for all lightweight beams, the deflection increases linearly with increasing loading. This is expected because the strains in the concrete and steel are relatively small and materials are in the elastic part of their responses (elastic stage). In the post-cracking stage (elastic-plastic stage), there is a change in the slope of load-deflection curve because of cracking. After cracking, deflection increases again with load up to point just before ultimate magnitude of load in beam. After this point, deflection significantly increases without noticeable increase in applied load until reach the ultimate loading stage (fully plastic stage).

As compared to B1, aluminum waste had no evident effect on the load-mid span deflection behavior at pre-cracking stage. After the first cracking occurs, aluminum waste had negative effect in terms of stiffness and deflection behavior of ALWAC beams due to the formation of air voids inside the concrete mixture. Where, the higher percentage of aluminum wastes led to lower stiffness and larger mid span deflection at same applied load. However, aluminum waste does not have a noticeable negative effect on the flat platue stage in load-deflection curves compared to B1, which means sufficient time for warning before the total collapse of member.

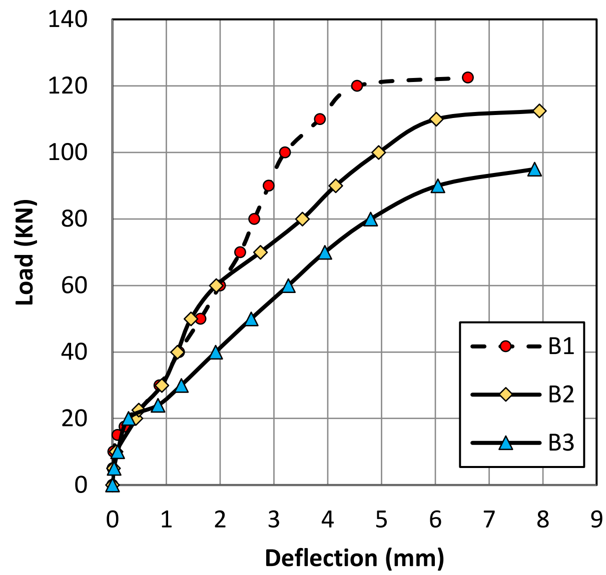
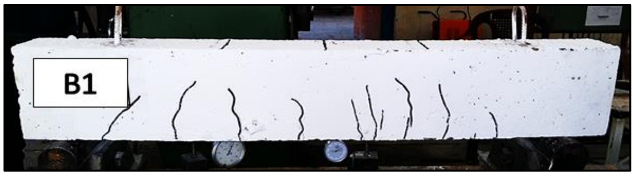


Figure 11. Load-mid span deflection of tested beams

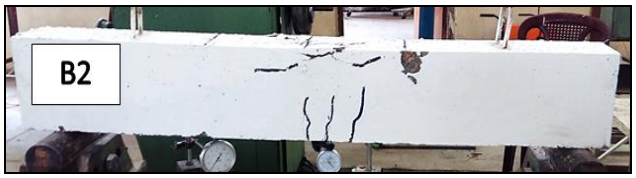
4.2.3 Failure mode and crack patterns

Failure can be defined as an increase in deflection despite a decrease in applied load, as well as to reinforcement yielding and/or concrete failure. The mode failure of all reinforced treated ALWAC beams is tension failure. Yielding of tensile steel reinforcement observed first, and then crushing without spalling of concrete cover occurred in compression zone of B2 and B3. Thus, the use of aluminum waste to produce typical tension failure in flexural zone of concrete beams has been experimentally proven. As it is clear from the cracking patterns of the ALWAC beams in Fig. 12, adding of 0.5% of aluminum waste led to retreat the cracking appearance only in the pure bending zone and in a small number compared to B1. This means that the combined flexural-tensile and shear stress does not exceed the tensile strength of the concrete. In B3

(AW=1%) more flexural cracks appeared, but with less extension and almost limited.



(a) AW = 0 %



(b) AW = 0.5 %

(c) AW = 1 %

Figure 12. Crack patterns of tested beams

4.2.4 Flexural ductility

Ductility of beam may be defined as the ability of beam to sustain deformation nearby or at the ultimate load without a considerable lack in the load bearing capacity until complete failure [24]. The ductility of beams in this study measured mathematically according to Pam et al. [25] model as follows:

$$\mu = 9.5\,(f_{cu})^{-0.3}\,(\rho/\rho_{bal})^{-0.75} \qquad (6)$$

In this study, the cube compressive strength (f_{cu}) is equal to (f'_c/0.80). It was observed that from Fig. 13 the ductility decreased slightly as the aluminum waste increased at the same longitudinal reinforcement ratio. This is expected because the ductility decreases as the compressive strength decreases according to equation (6), because the compressive strength is one of the parametric that used to calculate the value of ρ_{bal} and decreasing it (f_{cu}) leads to decrease ρ_{bal}, then consequently decrease the ductility index. The ρ_{bal} has a larger effect on the ductility index according to equation (6). The lower limit to ensure the ductile behavior in the flexural members is 3 [26]. In this study all reinforced treated ALWAC beams satisfy this lower limit. Experimentally, it was observed that all ALWAC beams failed in a ductile manner. Therefore, the ductility results are perfectly compatible with the obtained failure modes.

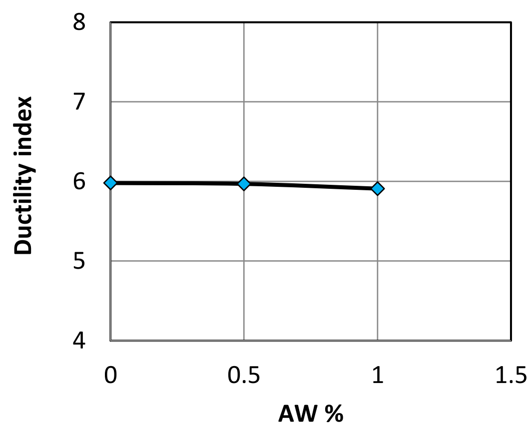


Figure 13. Effect of aluminum waste on ductility index

5. Conclusions

The conclusions of the experimental work can be drawn as follows:

1. Lightweight coarse aggregate concrete of treated Attapulgite was produced by burning Attapulgite clay at 1100ºC for 30 minutes and then treated it within sodium hypochlorite of 6% concentration for 24 hours.
2. The obtained dry loos bulk density of Attapulgite coarse aggregate was 787.35 kg/m^3 and complies with the specifications of ASTM C330/C330M-17a. Also, the obtained density and compressive strength of treated ALWAC at age of 28 days were 1910 kg/m^3 and 38.5 MPa, respectively.

3. The experimental value of splitting strength, modulus of rupture and modulus of elasticity of ALWAC increased by 36.15, 32.64 and 37.15%, respectively as compared to the theoretical values due to the positive effect of Attapulgite on the mechanical properties of concrete.
4. Addition of aluminum waste as fiber by 0.5 and 1% of concrete volume had a disparate effect on the ALWAC mechanical properties. There is a decrease in the compressive strength, modulus of rupture and modulus of elasticity of ALWAC of 5.71%, 41.10% and 54.5%, respectively, as compared to the reference specimen, when the AW fraction is 1% by volume. For the same AW content, an increment by 37.30% was obtained for the splitting tensile strength.
5. Increasing the aluminum waste ratio increases the cracking load due to the increase in the splitting tensile strength, while the reduction in the ultimate load for beams can be attributed to the random orientation and proportion of AW within the tested area. But even with this decreasing in ultimate load, the aluminum beams showed sufficient results for construction applications in terms of flexural load capacity.
6. All beams achieved increasing in the experimental values of ultimate load compared to the theoretical values by 42.58, 31.10 and 11.22% for B1, B2 and B3, respectively, due to good characteristics of producing coarse aggregate (Attapulgite).
7. In the pre-cracking stage deflection of all beams increased linearly with increased loading. After that, increasing of aluminum waste percentage led to increase the mid span deflection at the same applied load. However, aluminum waste did not have a noticeable negative effect on the flat platue stage.
8. The use of aluminum waste to produce typical tension failure in flexural zone of concrete beams has been experimentally proven. Aluminum waste reduced the number and extent of the flexural cracks in beams.
9. All beams failed in ductile manner and gave sufficient time for warning before the total collapse. The ductility decreased as the aluminum waste increased.
10. For future research: investigating the structural behavior of reinforced Attapulgite lightweight concrete beams under impact load. Also, studying the effect of steel fiber in combination with silica fume on the flexural behavior of reinforced Attapulgite lightweight concrete beams.

6. Notations

a: Depth of the concrete rectangular block.
d: Effective depth.
Ec: Chord modulus of elasticity of concrete.
f'_c: Cylinder compressive strength of concrete.
f_{cu}: Cube compressive strength of concrete.
f_r: Modulus of rupture of concrete.
f_t: Splitting tensile strength of concrete.
f_y: Yield strength of steel bar.
Ln: Clear span length.
M: Flexural strength.
P: Applied load.
P_u: Ultimate load.
w_c: Density of concrete.
ρ: Tensile reinforcement ratio.
ρ_{bal}: Balance Tensile reinforcement ratio
λ: Modification factor for mechanical properties of lightweight concrete, equal to 0.75.
μ: Ductility index.
Ø: Nominal diameter of steel bar.

Conflict of interest

The publication of this article causes no conflict of interest.

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