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Effect of the Use of Metakaolin Artificial Lightweight Aggregate on the Properties of Structural Lightweight Concrete

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Abstract: This paper investigates the effect of using metakaolin Artificial Lightweight Aggregates (ALWA) as a substitute for coarse aggregates to produce structural lightweight concrete. A combination of 10M NaOH solution and sodium silicate solution was used as alkali activator. The ratio between the metakaolin binder and the alkali activator used in producing metakaolin ALWA is 48%:52%, by mass. It is shown that metakaolin ALWA has higher abrasion and water absorption, and lower bulk density values compared to normal aggregates. To determine the effect of using metakaolin ALWA as coarse aggregates in concrete, three variations of ALWA dosages were used, i.e. 0%, 50%, and 100% of the total coarse aggregates, by volume. The results show that the compressive strength of concrete decreased along with the increase of ALWA content in the mixture. However, concrete using 100% ALWA as coarse aggregates meets the requirements of compressive strength and density of structural light weight concrete.

Keywords: ALWA; compressive strength; concrete density; geopolymer; lightweight concrete.

Introduction

Indonesia is a country in Asia that is prone to earthquake [1]. Based on data from Team for Revision of Seismic Hazard Maps of Indonesia in 2010, the financial loss incurred by the nation due to this natural disaster has reached trillions of Rupiahs for rehabilitation and reconstruction [2]. In order to minimize the amount of loss, the earthquake's load should be reduced. One promising method on minimizing earthquake hazards to buildings is by reducing the weight of the building, since the magnitude of the seismic force is directly proportional to the weight of the building [3]. Applying lightweight concrete with a density of 1100 kg/m^3 as a replacement of conventional concrete is one way to reduce the weight of structural and non-structural components of buildings.

Based on the classification of lightweight concrete according to the level of compressive strength and aggregate type by Mindess and Young [4], lightweight aggregate concrete using artificial lightweight aggregate (ALWA) or lightweight coarse sintered fly ash and foamed slag aggregates can produce compressive strength values of 17-41 MPa with a density range of 1500-2000 kg/m^3 [4].

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Thus, it is included in the category of lightweight structural concrete because the compressive strength is not less than 17 MPa. One of the alternative materials that serves potentially as the basic ingredient of ALWA is metakaolin. Metakaolin is a material resulting from the calcination of kaolin at a certain temperature. The Ministry of Energy and Mineral Resources (KESDM) in 2015 stated that the availability of kaolin in Indonesia was approximately more than one billion tons with a low utilization rate [5].

Triani et al. and Risdanareni et al.'s study on the use of metakaolin as a raw material for manufacturing geopolymer paste found that the compressive strength of metakaolin-based geopolymer paste reached more than 42 MPa [6,7]. Based on the chemical composition of metakolin, the total amount of SiO_2 + Al_2O_3 + Fe_2O_3 in metakaolin is very high, i.e. 93.99%, thus it can be categorized as natural pozzolan of class N [6]. Subsequent research conducted by Aineto et al. on the manufacture of metakolin ALWA found that sintering at a certain temperature was effective to reduce the unit weight of ALWA [8].

Further, Lauw and Buen showed that the transition from normal to lightweight concrete occurred after 50% of the total volume of the coarse aggregates in concrete was replaced by styrofoam ALWA [9]. Referring to this research finding, the present research investigated three coarse aggregate replacement percentages by metakaolin ALWA, i.e. 0%, 50%, and 100% from the total volume of coarse aggregate, to determine the optimum dosage of ALWA as a substitute of coarse aggregates in manufacturing lightweight structural concrete.

Materials and Method

The research was conducted in the Materials Testing Laboratory and Structure Laboratory at the Faculty of Engineering, Universitas Negeri Malang, and at a ceramic factory in Malang. Metakaolin was obtained by combusting kaolin at temperature of 800°C. Next, the consistency and setting time were evaluated to ensure that the metakaolin was reactive. The ALWA grains were processed using a pan granulator with a composition ratio of metakaolin to alkaline activator of 52%:48%, by mass. This composition was determined from twelve trials that have been performed.

In this study, the alkaline activator solution was a mixture of Na_2SiO_3 (sodium silicate) and 10 M NaOH (sodium hydroxide) solution. The ratio of Na_2SiO_3 to NaOH solution was 2:1, by mass. The mass ratio between metakaolin and alkali activator solution in producing lightweight aggregate was determined during the manufacturing process. The experimental data on obtaining the proportion between metakaolin and alkali activator solution is presented at Table 1, while aggregate manufacture process is presented at Figure 1.

Manufacturing metakaolin ALWA was performed using a granulator pan. The slope angle of the granulator pan used in this research was 45°. After setting-up the granulator pan, metakaolin was poured into the granulator pan, while the alkali activator solution was added gradually. The process of adding alkali activator solution into the mixture was stopped when the paste has formed aggregate granules of 1 to 2 cm in diameter, and the surface of metakaolin granules aggregates appeared slightly wet.

ALWA granules were dried in an oven for 24 hours to remove the water content. Then, they were burned at a temperature of 600 °C for 6 hours to create pores in metakaolin ALWA, in order to obtain a bulk density of less than 1100 kg/m^3.

The specimens in this research were 54 concrete cylinders of 7.5 cm diameter and 15 cm height, produced using two different types of coarse aggregates, i.e. metakaolin ALWA (AM) and normal coarse aggregates (AN). The amount of metakaolin ALWA was varied from 0%, 50%, and 100% of the total volume of coarse aggregates required to produce concrete. Concrete specimens using only normal coarse aggregates was assigned as the control group, to be compared with concrete specimens made using 50% and 100% metakaolin ALWA. The specimens are described in detail in Table 2, while the mix design of concrete specimens is presented in Table 3.

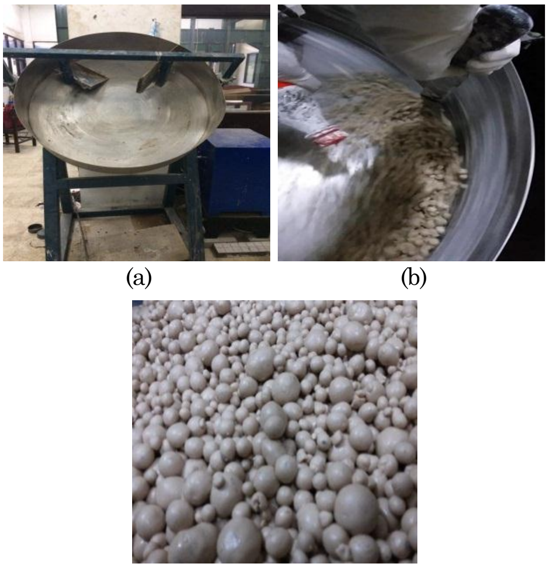


Figure 1. Manufacturing ALWA (a) Pan Granulator machine (b) Pelletizing Process (c) Metakaolin ALWA

Several physical properties tests were performed on ALWA to find out the material properties of ALWA, i.e. to determine setting time, bulk density, water

Table 1. Composition between Metakaolin and Alkali Activator

Manufacturing number	Weight (gram)				Precentage (%)	
	Metakaolin	Alkali Aktivator			Metakaolin	Alkali Alkali Activator
		Initial	Rest	Use		
1	317	660	321	339	48	52
2	361	643	332	311	54	46
3	374	666	263	403	48	52
4	432	660	240	420	51	49
5	426	645	260	385	53	47
6	475	660	215	445	52	48
7	431	627	240	387	53	47
8	410	653	260	393	51	49
9	459	570	244	326	58	42
10	514	664	213	451	53	47
11	452	662	254	408	53	47
12	487	668	236	432	53	47
Average	428			392	52	48

Table 2. Details of the Specimens

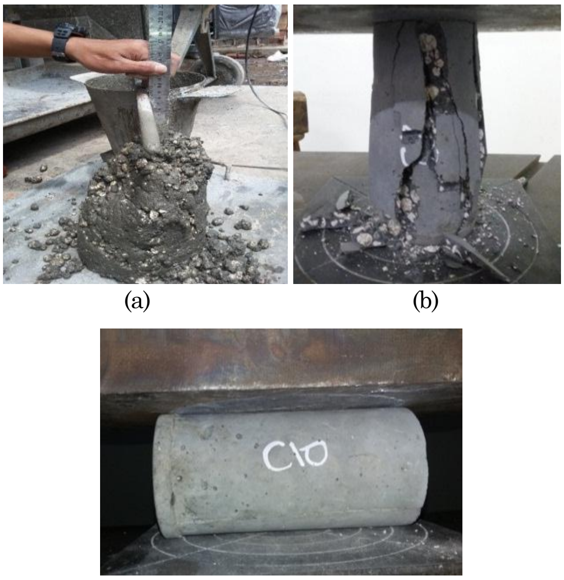
Sample Code	Composition of Aggregate		Number of Specimens						Total
	AM (%)	AN (%)	Tensile Strength & Density (day/piece)			Compressive Strength & Density (day/piece)			
			7	14	28	7	14	28	
A	0	100	3	3	3	3	3	3	18
B	50	50	3	3	3	3	3	3	18
C	100	0	3	3	3	3	3	3	18
								Total	54

Description: AM = Metakaolin ALWA; AN = Normal Aggregate

content, water absorption, and abrasion. On the other hand, several test on concrete produced with ALWA, such as slump test, compressive test and tensile splitting strength test were conducted in order to determine mechanical properties of concrete. All tests were conducted according to relevant ASTM standards. The research documentation is presented in Figure 2

Table 3. Mix Design of Concrete

Materials (%)	Specimen's Code		
	A	B	C
Water	8	8	8
Cement	23	23	23
Coarse Aggregate	39	20	0
ALWA	0	20	39
Fine Aggregate	30	30	30
Total Volume	100	100	100



(a) (b)

(c)

Figure 2. Research Documentation: (a) Slump Test, (b) Compressive Strength Test; (c) Tensile Splitting Strength Test

Result and Discussion

Properties of Metakaolin

The properties of metakaolin ALWA are presented in Table 4.

Table 4. Properties of Metakaolin ALWA

No	Testing	Result
1	Setting Time:	
	a. initial setting time	99 minutes
	b. final setting time	130 minutes
2	Water content	1.20%
3	Water Absorption	3.03%
4	Bulk Density	939 kg/m^3
5	Abrasion	43%

The setting time test was carried out to determine the initial and final setting time of metakaolin paste. The data were required to estimate the hardening time of ALWA during molding process. The test of setting time was carried out in accordance with the guidelines of ASTM C127 [10]. The test result showed that the initial and final setting time of metakaolin paste was 99 minutes and 130 minutes, respectively. These results are in good agreement with Triani et al., who stated that setting time of metakaolin paste was between 60 to 120 minutes [6].

Water content and water absorption tests were performed to determine the water content and the absorption capacity of ALWA in Saturated Surface Dry (SSD) condition. Both tests were performed in accordance with ASTM C127-01 [10]. Based on the test results, the water content and water absorption of metakolin ALWA were found to be 1.25% and 3.03%, respectively. The water absorption value of metakaolin ALWA produced in this study is lower compared to those reported by Sivakumar, i.e. within a range of 8.9-25.5% [11]. This different result occurred most probably due to different sintering temperature performed in producing ALWA, where the higher the sintering temperature performed, the higher the number of voids occured, that leads to higher water absorption of ALWA.

The abrasion test was performed to determine the resistance of metakaolin ALWA to abrasion using the Los Angeles abrasion machine in accordance with SNI 2417:200 [12]. The result showed that the abrasion level of metakaolin ALWA was 43%. Thus, it can be predicted that the concrete produced might have low strength. According to ASTM C 535, concrete produced with aggregate which has aggregate abrasion level of 40%-50% is a low quality concrete (≤ 20 MPa) [13].

Metakaolin ALWA has a relatively low bulk density of 939 kg/m^3, lower than gravel which generally has a bulk density of 1450 kg/m^3. With a bulk density below 1000 kg/m^3, metakaolin ALWA is eligible for use as lightweight artificial aggregate in the manufacture of structural lightweight concrete.

Slump Test of Fresh Concrete

Slump test was performed to measure the workability of fresh concrete and to obtain the uniformity of water use. Slump test was conducted with guidelines from ASTM C143-78 [14]. Slump test results are presented in Table 5. Based on slump test results, it can be seen that sample-C has lower slump value compared to others. This condition is mostly caused by a higher water absorption value of ALWA compared to gravel. With the high water absorption of ALWA, the existing water in the concrete mixture will be absorbed by ALWA and causes the fresh concrete to be thicker and has low slump value. Similarly, Nadesan and Dinakar stated that increasing ALWA levels in concrete mixtures would decrease the workability of fresh concrete due to its high water absorbtion [15]. They advised that using ALWA as coarse aggreagtes should be in SSD condition to reduce the possibility of absorbing water from concrete.

Table 5. Slump Value of Fresh Concrete

Sample Code	Coarse Aggregate Ratio		Slump Value
	AM	AN	(mm)
A	0%	100%	95
A	0%	100%	95
B	50%	50%	95
C	100%	0%	75

Physical Properties of Concrete

The test of physical properties carried out in this study was the one to determine the density of the cylindrical concrete specimens. The density of concrete was determined from the average values of three specimens. The mean value of the density test result of each the cylindrical concrete, and is presented in Table 6.

As expected, the results shown in Table 6 indicate that the higher amount of metakaolin ALWA used in making concrete is inversely proportional to the density of the concrete. This is in accordance with previous research by Gonzalez-Corrochano et al. They stated that higher sintering temperature reduces the bulk density of ALWA, and resulting in lower density of concrete produced [16].

Mechanical Properties of Concrete

The tests of mechanical properties in this study were performed to examine the compressive strength and tensile splitting strength of cylindrical concrete. Compressive and tensile splitting tests were carried out on concrete aged 7, 14, and 28 days. The value of compressive strength and tensile splitting strength of concrete was obtained by averaging the results of three specimens. The insides of the specimens A, B, and C after the tensile splitting strength testing can be seen in Figure 3, while the compressive strength and tensile splitting strength values are presented in Table 7.

Based on the image of spesimens after tensile splitting test displayed at Figure 3, it can be seen that the amount of ALWA crushed on specimen C is higher compared to specimen B. The rupture of ALWA in specimen C was caused by its low strength, which made them crushed even during the concrete making process. The crushed of ALWA during the concrete making process resulting in the decrease of mechanical properties of concrete. This is consistent with the expectation that ALWA which has abrasion value more than 40% will produce low strength concrete (less than 20 MPa). Previous research also revealed that the strength of ALWA measured by Aggregate Impact value (AIV) greatly affects the mechanical properties of the resulting concrete [15]. The recommended AIV value for ALWA is less than 30%. With AIV value less than 30%, the chance that ALWA will be crushed during concrete manufacturing process can be minimized [17]. Further research on how to increase the strength of ALWA needs to be performed in order to produce high quality concrete.

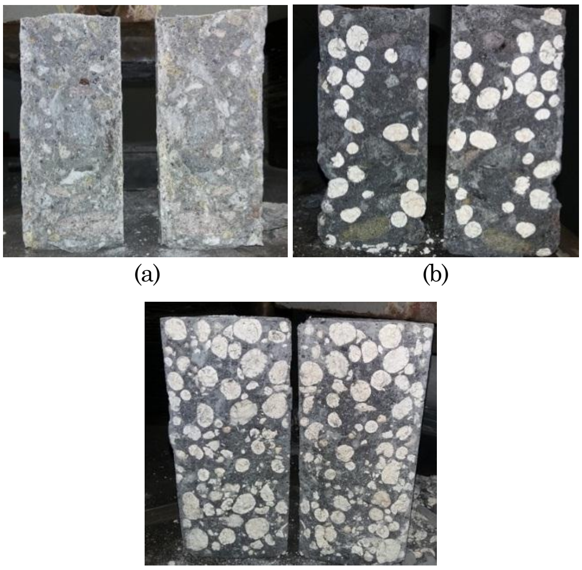
Table 6. Test Results of the Density of Cylindrical Concrete Specimens

Sample Code	Composition of Coarse Aggregate		Average Value				
			Diameter	Height	Volume	Weight	Volume Weight
	AM	AN	(cm)	(cm)	(cm^3)	(gram)	(kg/m^3)
A	0%	100%	7.45	15.33	667.58	1480	2216
B	50%	50%	7.43	15.28	662.20	1377	2080
C	100%	0%	7.45	15.68	684.19	1260	1841

Description: AM = Metakaolin ALWA; AN = Normal Aggregate

Table 7. Testing Results of the Compressive Strength and Split Tensile Strength of Specimens

Sample Code	Composition of Coarse Aggregate		Average Mechanical Strength of Specimen					
			Day/ Compressive Strength (MPa)			Day/ Split Tensile Strength (MPa)		
	AM	AN	7	14	28	7	14	28
A	0%	100%	20.98	23.03	31.16	3.44	3.36	3.47
B	50%	50%	17.26	21.07	22.52	2.29	1.67	3.18
C	100%	0%	8.94	12.24	18.55	3.13	2.52	3.23



(a) (b) (c)

Figure 3. Photos of Specimens after the Tensile Splitting Tests (a) Specimen A (0% ALWA), (b) Specimen B (50% ALWA), (c) Specimen C (100% ALWA).

The decrease of the compressive strength of concrete specimens with 50% and 100% metakaolin ALWA, compared to the one with 0%, are 8.6 MPa (28%) and 12.6 MPa (40%), respectively. It can be concluded that the amount of metakaolin ALWA used is inversely proportional to the concrete compressive strength. The higher the amount of metakaolin ALWA used in the mixture, the lower the resulting compressive strength.

As predicted, increasing the amount of ALWA in concrete mixture decreases the density of the concrete, which results in decrease of mechanical properties of concrete. However, based on concrete compressive strength and density test results, the specimen C meets the qualification as a lightweight structural concrete, because it has a density of less than 2000 kg/m^3 and has a compressive strength above 17 MPa [4]**.** Based on this result, it can be concluded that metakaolin ALWA is a promising alternative lightweight aggregates to produce lightweight structural concrete. Previous research by Yliniemi et al. also revealed that geopolymer aggregates have better physical properties compared to commercial lightweight expanded clay aggregates [18].

There was no significant difference in the values of the tensile splitting strength among the concrete specimens utilizing different aggregates. In other words, the use of metakaolin ALWA as coarse aggregates does not affect the value of tensile splitting strength of concrete. This result has a good agreement with previous research conducted by Beushausen and Dittmer, which investigated the influence of the aggregate type on strength of the concrete [19]. Beushausen and Dittmer stated that the coarse aggregate type did not significantly affect the tensile strength of the concrete. Another report by Gomathi and Sivakumar also stated that tensile splitting strength is more dependant on mortar rather than aggregate type, due to the development of maximum diametral tension on concrete [20].

Correlation Between Split Tensile and Compressive Strength

The relationship between compressive strength and tensile splitting strength of concrete is presented in Table 6. It can be seen that the pattern formed by the tensile splitting strength is stable. The compressive strength of sample B compared to C increased by 3.96 MPa (21%) and that of sample B compared to A decreased by 8.65 MPa (38%). The tensile strength of sample B compared to C increased by only 0.05 MPa and that of sample B compared to A decreased by 0.29 MPa. These results indicate that the value of tensile splitting strength is not directly proportional to the value of compressive strength of concrete.

The empirical formula to determine the tensile splitting strength derived from the relationship between the tensile splitting strength and the compressive strength of concrete produced in this study was $fct = 0.68\sqrt{fc'}$, while the ratio between tensile splitting strength and compressive strength of concrete was in range of 0.1-0.17. A review on the performance of structural concrete utilizing ALWA aggregates conducted by Nadesan and Dinakar summarized that the ratio between tensile splitting strength and compressive strength of concrete with fly ash ALWA is in the range of 0.05-0.12 [15]. The ratio between tensile splitting strength and compressive strength of concrete using metakaolin ALWA aggregates is similar to those of fly ash ALWA aggregates.

Table 8. Correlation between Compressive Strength and Tensile Splitting Strength

Sample Code	Composition of Coarse Aggregates		Compressive Strength (MPa)	Tensile Splitting Strength (MPa)
	AM	AN		
A	0%	100%	31.16	3.47
B	50%	50%	22.52	3.18
C	100%	0%	18.55	3.23

Description:
AM = Metakaolin ALWA; AN = Normal Aggregate

Conclusion

The dosage level of metakaolin ALWA used in concrete mixture composition is inversely proportional to the resulting concrete density. The higher the amount of metakaolin ALWA used in the concrete mixture, the lower the resulting density. The density acceptable for lightweight concrete, i.e. less than 1850 kg/m^3, could only be achieved by using only metakaolin ALWA as the coarse aggregates, without using any normal aggregates.

The amount of metakaolin ALWA used as coarse aggregates is inversely proportional to the value of concrete compressive strength. The higher the amount of metakaolin ALWA used in the mixture, the lower the resulting compressive strength of concrete. The concrete specimens using metakaolin ALWA as coarse aggregates with replacement level of 0%, 50%, and 100% produced concrete with compressive strength of 31.2, 22.5, and 18.6 MPa, respectively. These values are acceptable for structural concrete, i.e. more than 17 MPa. On the other hand, the use of metakaolin ALWA as coarse aggregates does not significantly affect the value of tensile splitting strength of concrete.

Based on the research results, concrete utilizing 100% metakaolin ALWA as coarse aggregates produces concrete with density of 1841 kg/m^3 and compressive strength of 18.55 MPa. It meets the criteria for structural lightweight concrete in accordance to SNI 03-2461-2002, i.e. the concrete density shall not exceed 1850 kg/m^3 with a compressive strength of not less than 17 MPa [21].

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