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The Effects of Fly Ash and Bottom Ash on the Properties of Aerated Concrete under Density-Based Mix Design

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ABSTRACT

Lightweight concrete has the main characteristic of a lower density value than normal concrete, which ranges from 1400 to 1850 kg/m^3 (ACI 213R) [1]. While density values generally show a decreasing trend along with decreasing mechanical properties. This type of lightweight concrete still needs to be improved in its application to elements that function but do not withstand loads (non-structural) due to its low mechanical properties. The main objective of producing lightweight concrete is its density. In contrast, another objective is the mechanical properties related to the use of lightweight concrete as a non-structural or structural material. Thus, physical properties in the form of density and mechanical properties in the form of compressive strength are important parameters in producing lightweight concrete. The mix method used in lightweight concrete is different from conventional concrete. The foaming agent used in manufacturing lightweight concrete will result in compressive strength and density results that are different from conventional concrete. In this study, lightweight concrete was made using the aerated technique: a foaming agent in aluminum powder and comprises cement, sand, fly ash, bottom ash, water, and superplasticizer. Fly ash as a substitute for cement and bottom ash as a substitute for sand with percentages of 0%, 15%, and 30%, and of 0%, 25%, and 50%, respectively. Those materials were aimed to optimize the composition of aerated concrete. The mix design was conducted with a density-based mix design of density targets of 1000 kg/m^3, 1200 kg/m^3, 1600 kg/m^3, and 1800 kg/m^3. The parameters used to assess the research results were slump value, setting time, density, compressive strength, and water absorption. While the consistency and stability values were found to be an indicator of the achievement of this density-based mix design. The performance indexes which demonstrate the attainment of compressive strength and predicted density in the aerated concrete, show that the mix designs meet the requirements of non-structural lightweight concrete. The mix of ingredients, particularly fly ash and bottom ash, has a considerable influence on the relationship between compressive strength and density in aerated concrete.

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1. Introduction

Aerated concrete is one type of lightweight concrete that, in its manufacture, uses the essential ingredients of cement, sand, water, and additives as a source of silica, a foaming agent [2]. One of the foaming agents for aerated concrete is the addition of aluminum powder or paste, which can form air bubbles when reacting with the leading concrete mix ingredients. This process increases the volume of fresh concrete and produces lighter concrete due to the formation of pores.

Aerated lightweight concrete has many advantages compared to conventional concrete, such as lower density, a lower coefficient of thermal expansion, and good sound insulation due to the air voids within the aerated concrete [3]. In comparison, one of its disadvantages is its low mechanical properties. However, developing aerated concrete with higher mechanical characteristics for use as structural elements is still in progress. This challenge is because the physical characteristics of this type of concrete are not dense due to the presence of air voids, which decrease its compressive strength [4].

The use of additives to replace cement or sand is one of the efforts made to improve the performance and quality of concrete. In addition, fly ash also benefits the environment because it utilizes waste from burning coal. The chemical composition and fineness of fly ash have been widely proven to be used as a substitute for cement. In addition, fly ash has a high silica content that can increase the compressive strength of concrete. The results showed that using fly ash percentages of 30% and 70% of cement can increase the compressive strength of lightweight concrete [5]. Another study was also conducted by adding a percentage of fly ash of 15% and a percentage of aluminum powder of 0.25%, resulting in a compressive strength of 23.75 MPa at 28 days [6].

In addition, to fly ash, bottom ash is also a by-product of burning coal powder. The advantage of using bottom ash in concrete applications is preventing environmental pollution due to factory waste. Previous research used bottom ash to manufacture concrete blocks and road construction as lightweight aggregates [7,8]. Bottom ash particles are also highly porous, so they can reduce the shrinkage that occurs in lightweight concrete [9]. Bottom ash as a partial replacement for sand in lightweight concrete mixes, namely 25% and using a foaming agent of 50%, can contribute to a concrete density of 984 kg/m^3 [10].

The use of binders and fillers in producing lightweight concrete greatly influences its mechanical and physical characteristics. The main objective in producing lightweight concrete is its density, while another objective is the mechanical properties related to the use of lightweight concrete as a non-structural or structural material. Thus, physical properties in the form of density and mechanical properties in the form of compressive strength are important parameters in producing lightweight concrete. For applications involving non-structural elements, density is the primary consideration. However, if this lightweight concrete material is intended for structural elements, other factors must also be considered, including density, compressive strength, and workability.

The difference between lightweight and normal concrete is in the constituent materials, mixture design methods, manufacturing methods, and physical and mechanical properties characteristics. There are no standard rules or guidelines for the design of lightweight concrete mixtures. Therefore, the procedure for designing the proportion of the mixture that applies to normal concrete cannot be applied to lightweight concrete.

As stated by the previous study [11], in the mix design stage of normal-weight concrete, the water/cement ratio (w/c) is the primary key in determining the mix proportion design. The water/cement ratio indicates the compressive strength at 28 days. Based on the results of studies by Rooyen *et al.,* [12], it is concluded that the proposed formula can be used to calculate the proportion of lightweight concrete based on the planned target density. The formula uses a calculation basis based on filler/cement ratio, sand/cement ratio, ash/sand ratio, and cement content with the density target used. The research variables used are the type of sand, variations in the percentage of water-entraining agents, and the treatment method.

This research was conducted by using the proposed formula used in that research [12]. This study used variations in the percentage of fly ash as filler and variations in the percentage of bottom ash as a substitute for sand. The mixed composition used the density target as a reference, with a wider variety of target densities. This study aims to apply the proposed mix design formulation to different types of mixtures, different compositions, and density targets. In addition, mechanical properties in the form of compressive strength and its relationship to the density value are also obtained

To validate the design of aerated lightweight concrete mixes, the research must assess the consistency and stability of aerated concrete by measuring the fresh density against the density target and hardened density at each variable. The mixture is considered consistent and stable when the density ratio is maintained without segregation or bleeding occurring during testing [13]. In addition, the performance indexes show the achievement of compressive strength and the expected density in lightweight concrete.

2. Methodology

This research was conducted by making an aerated concrete composition using cement and fly ash as binders and fine aggregates and bottom ash as fillers, aluminum powder and superplasticizer additives. The fly ash and bottom ash used in this study were obtained from PT. Pupuk Sriwidjaja Palembang. Before making test specimens, the prepared material must be tested for physical and mechanical properties. The materials tested were fine aggregate and bottom ash, and to determine the chemical composition of fly ash and bottom ash, x-ray fluorescence (XRF) testing was conducted. To determine the microstructure of fly ash and bottom ash materials, scanning electron microscopy (SEM) testing was conducted.

2.1 Material Properties Testing

The results of testing the physical characteristics of river sand from Tanjung Raja and bottom ash from PT Pupuk Sriwidjaja is shown in Table 1.

Table 1
Material properties testing

Material	Code	Sand	Bottom ash	Range
Bulk specific gravity (dry condition)	ASTM C-128 [14]	2.213	2.369	2.5 –2.7
Apparent specific gravity	ASTM C- 128 [14]	2.354	2.637	2.5 – 2.7
Bulk specific gravity (SSD condition)	ASTM C-128 [14]	2.273	2.471	2.5 – 2.7
Water absorption (%)	ASTM C-128 [14]	2.710	4.302	2 – 7
Water content	ASTM C-566[15]	3.465	3.285	3 – 5
Fine modulus	ASTM C-33 [16]	2.381	2.231	1.5 – 3.8
Compact bulk density	ASTM C-29 [17]	1.584	1.352	>1.2
Loose bulk density	ASTM C-29 [17]	1.509	1.254	>1.2
Clay content	ASTM C-142 [18]	2.927	2.547	<5
Organic content	ASTM C – 40 [19]	No. 3	No. 3	

In comparing the results of testing the characteristics of sand and bottom ash, sand has a greater volume weight than bottom ash and a coarser gradation. In contrast, bottom ash testing has the advantage of a more significant percentage of water absorption. It can absorb water well to get a lightweight density target to meet light concrete density standards.

Based on the test from Table 2, for fly ash material, the percentage of SiO_2 is 32.3768%, Al_2O_3 is 16.897%, and Fe_2O_3 is 6.1111%, while for bottom ash material, the percentage of SiO_2 is 35.686%, Al_2O_3 is 8.8445%, and Fe_2O_3 is 6.6032%. In comparison, other phase substances have a percentage intensity below 5%. According to ASTM C-618 [20], fly ash, which has a chemical compound content of CaO ≤ 10%, is included in the class F fly ash category. The XRF test analysis of fly ash obtained a CaO content of 4.6795%, so the fly ash used can be categorized as Class F.

Table 2
Chemical composition of fly ash and bottom ash

No	Components of fly ash	% in mass	Components of bottom ash	% in mass
1	MgO	0.6504	MgO	0.2202
2	Al_2O_3	16.897	Al_2O_3	8.8445
3	SiO_2	32.380	SiO_2	35.686
4	P_2O_5	0.2591	P_2O_5	0.1454
5	SO_3	0.5705	SO_3	0.1515
6	K_2O	0.7907	K_2O	0.5995
7	CaO	4.6795	CaO	2.5107
8	TiO_2	0.9811	TiO_2	0.9042
9	MnO	0.0848	MnO	0.1015
10	Fe_2O_3	6.1111	Fe_2O_3	6.6032
11	ZnO	0.0155	CuO	0.0112
12	SrO	0.1431	ZnO	0.0176
13	Y_2O_3	0.0071	SrO	0.0926
14	ZrO_2	0.0513	ZrO_2	0.0472
15	Ag_2O	0.0598	Balance	44.0646
16	Balance	36.3194		

2.2 Material Microstructure Testing

Figure 1 shows fly ash particles have a spherical shape with different diameters and an irregular and denser shape pattern. Meanwhile, Figure 2 shows that the bottom ash particles are asymmetrical, porous, and darker than fly ash's light grey color. Bottom ash in Figure 2 illustrates the bottom ash's porous internal structure, making it lighter and more brittle than natural sand [19].

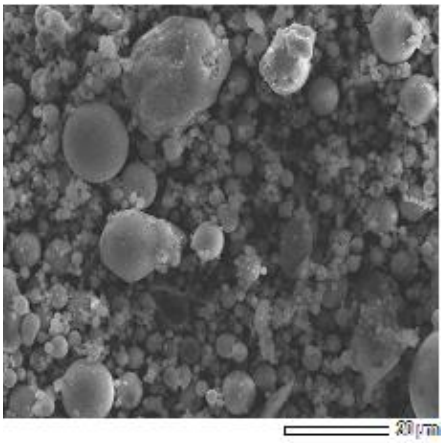


Fig. 1. Microstructure of fly ash

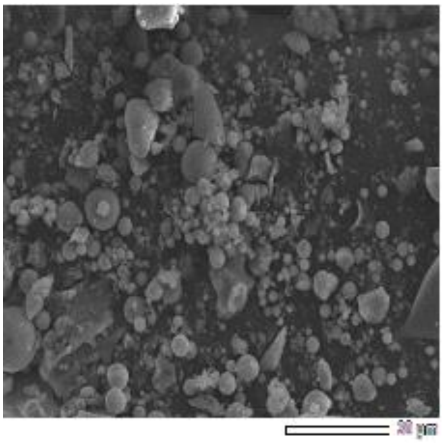


Fig. 2. Microstructure of bottom ash

2.3 Mix Design

The compositions used in this study as shown in Table 3 refer to previously conducted research [12]. The ratio of W/B that gave optimum compressive strength and met the criteria for lightweight concrete was determined. This study used fly ash as a cement substitute at 0%, 15%, and 30%, and bottom ash as a fine aggregate substitute at 0%, 25%, and 50%. The foaming agent used is an aluminum powder with a percentage of 0.2% to 0.3% and a density target design of 1000 kg/m^3 (D1000), 1200 kg/m^3 (D1200), 1600 kg/m^3 (D1600), and 1800 kg/m^3 (D1800). In the design of aerated concrete, the mass of all constituents should be equal to the density target of the mix [12], which leads to Eq. (1)

$$\rho_m = xc + xc({}^{W}/_{c}) + xc({}^{W}/_{S})({}^{S}/_{c}) + xc({}^{W}/_{a})({}^{a}/_{c}) + xc({}^{S}/_{c}) + xc({}^{a}/_{c}) + (RD_{AEA})(V_{AEA}) \quad (1)$$

where

ρ_m : Density target(kg/m^3)
xc : Cement content (kg/m^3)
w/s : Water/ sand ratio
w/c : Water/cement ratio
w/a : Water/ash ratio
s/c : Sand/ cement ratio
a/c : Fly ash/ cement ratio
RD_{aea} : Relative density of air entraining agent
V_{aea} : Volume of the air entraining agent

Table 3
Composition of constituents

No	Specimen	Target density	Cement (C) (kg/m^3)	Fly ash (FA) (kg/m^3)	Sand (S) (kg/m^3)	Bottom ash (BA) (kg/m^3)	Water (W) (kg/m^3)	AP (kg/m^3)	W/ (C+FA)	(C+FA)/ (S+BA)
1	N-F0-B0-AL0	-	350	0	700	0	140	0	0.4	0.5
2	F0-B0-AL0.2	D1000	349.3	0	385	0	140	0.7	0.4	0.9
3	F15-B0-AL0.2	D1000	296.8	52.5	385	0	140	0.7	0.4	0.9
4	F30-B0-AL0.2	D1000	244.3	105	385	0	140	0.7	0.4	0.9
5	F0-B0-AL0.3	D1000	348.95	0	385	0	140	1.05	0.4	0.9
6	F15-B25-AL0.2	D1200	296.10	52,5	360	120	140	0.7	0.4	0.7
7	F30-B25-AL0.2	D1200	243.60	105	360	120	140	0.7	0.4	0.7
8	F0-B50-AL0,2	D1200	349.30	0,0	240	240	140	0.7	0.4	0.7
9	F15-B50-AL0.2	D1200	296.80	52.5	240	240	140	0.7	0.4	0.7
10	N-F0-B0-AL0	-	350	0	700	0	140	0	0.5	0.5
11	F15-B25-AL0.2	D1600	350	0	700	0	175	0	0.5	0.5
12	F30-B25-AL0.2	D1600	296.1	52.5	652.5	217.5	175	0.7	0.5	0.4
13	F0-B50-AL0.2	D1600	243.6	105	652.5	217.5	175	0.7	0.5	0.4
14	F15-B50-AL0.2	D1600	349.3	0	435	435	175	0.7	0.5	0.4
15	F15-B25-AL0.3	D1600	296.8	52.5	435	435	175	0.7	0.5	0.4
16	F15-B0-AL0.2	D1800	295.4	52.5	652.5	217.5	175	1.05	0.5	0.4
17	F30-B0-AL0.2	D1800	296.80	52.5	1150	0	175	0.7	0.5	0.3
18	F0-B0-AL0.3	D1800	244.30	105	1150	0	175	0.7	0.5	0.3
19	F15-B0-AL0.3	D1800	348.95	0.0	1150	0	175	1.1	0.5	0.3
20	F30-B0-AL0.3	D1800	296.45	52.5	1150	0	175	1.1	0.5	0.3

2.4 Preparation of Test Specimens

The composition of the mixture has determined the mixing stage of all aerated concrete materials, testing fresh concrete, placing the mixture into a 5 cm x 5 cm x 5 cm cube mold, and continuing with curing. This stage begins with weighing the material, and after all the materials are considered and ready to use, the material mixing process is carried out. The mixing method used is non-autoclaved aerated concrete. The materials used in this method are cement, fly ash sand, bottom ash, and aluminum powder. First, fine aggregate is mixed with cement, fly ash, and bottom ash using a mixer; then, add aluminum powder and mix for 30 seconds.

After all, was mixed, water was added to the mixture. The mixture was stirred for about 3 minutes until it was evenly distributed. After the stirring, the fresh concrete was tested, namely the slump flow test. After that, the mixture was poured into a cube mold measuring 5 cm x 5 cm x 5 cm. In this phase, aluminum powder begins to react with cement and water. The mixture will continue to expand for approximately one hour. Therefore, the filling of the material into the mold needs to be completed. Only about 80 percent are filled. When the mixture expands, it must be leveled again. Then the mold is opened after 24 hours. Aerated concrete removed from the mold is treated with the water curing method.

2.5 Testing of Specimens

The tests carried out in this study include fresh concrete testing, hardened concrete testing, setting time testing, and slump flow testing. Setting time testing is carried out based on standards to know the time required for the concrete to harden.

This study's hardened concrete testing parameters are concrete density testing, compressive strength testing, and water absorption.

2.6 Setting Time

The setting time of concrete is determined by conducting tests using Vicat's apparatus. The test refers to the ASTM C-191 standard [21]. The mortar portion of the concrete mix is separated from the concrete and filled into a mold. The penetration resistance of the needle to penetrate 2.5 cm in the mortar is measured. Measurements were taken at different intervals, and graphs were plotted between penetration and elapsed times [22].

2.7 Specific Gravity Testing

Specific gravity test using ASTM C-138 [23]. Specific gravity is the weight per volume calculated by weighing the weight of the test specimen in a dry state before the compressive strength test is carried out and calculating the volume of the test specimen.

$$\rho = \frac{\mathrm{m}}{\mathrm{v}} \tag{2}$$

where

ρ : Density (kg/m^3)
m : Mass (kg)
v : Volume (m^3)

2.8 Compressive Strength Testing

Concrete compressive strength testing uses a Compressive Strength Machine with a 5 cm x 5 cm x 5 cm cube test specimen, which is tested by ASTM C-39 standards [24].

$$fc' = \frac{P}{A} \tag{3}$$

where

fc' : Compressive strength (N/mm^2)
P : Force (N)
A : Area (mm^2)

2.9 Water Absorption Testing

Water absorption is the ratio of the weight of water that can be absorbed by the pore to the dry weight of concrete. Water absorption testing is carried out according to the ASTM C-642 standard [25]. The percentage of water absorption is formulated as follows

$$\text{Water absorption} = \frac{W2-W1}{W1} \times 100\ \% \tag{4}$$

where

W_1 : Weight of the oven-dried sample (gram)
W_2 : Weight of the saturated surface-dried sample (gram)

2.10 Consistency, Stability, and Performance Index Analysis

The consistency of the concrete mix is a measure of fluidity. This consistency is highly dependent on the proportions and properties of the concrete mix. According to Ref. [13] and [26], the consistency and stability of foamed concrete with a fresh mix can be calculated by measuring the fresh density against the density target and hardened density.

$$\text{Consistency} = \frac{\text{Fresh density}}{\text{Target density}} \tag{5}$$

$$\text{Stability} = \frac{\text{Fresh density}}{\text{Hardened density}} \tag{6}$$

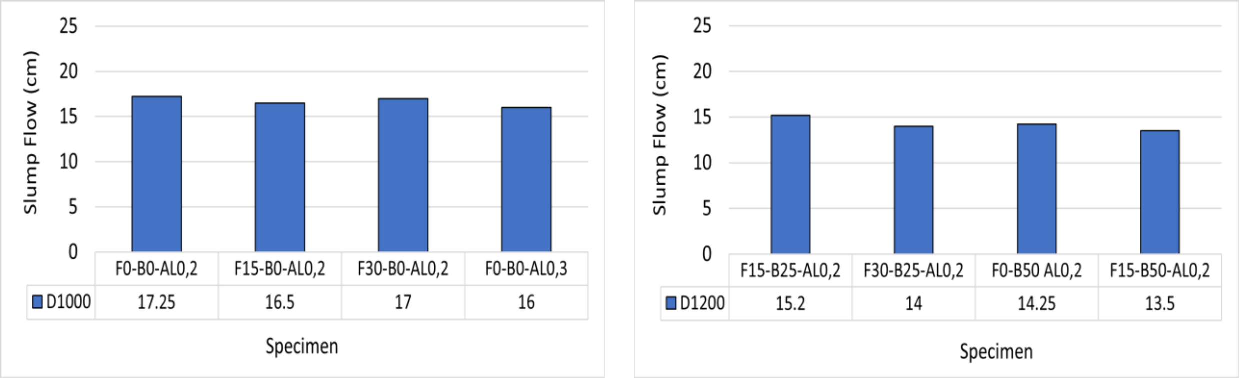
$$\text{Performance index} = \frac{\text{Compressive strength x 1000kg/m3}}{\text{Hardened density}} \tag{7}$$

3. Results

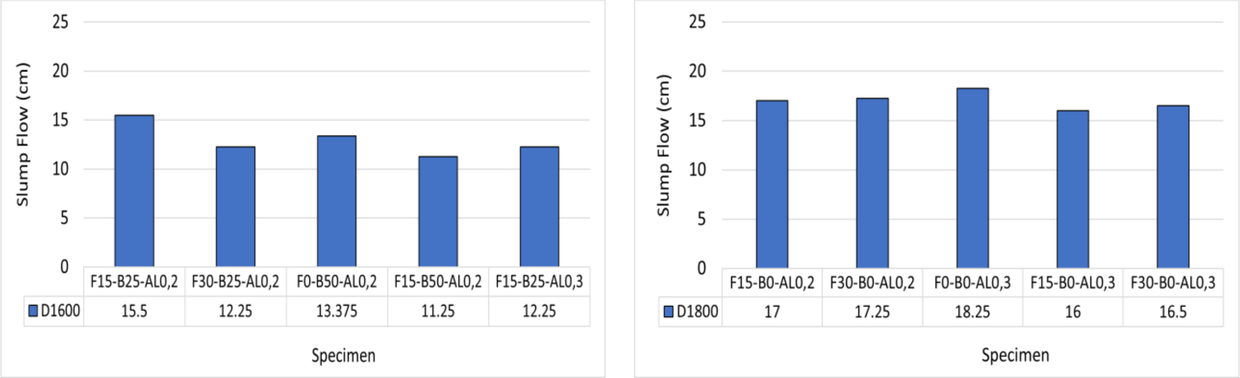
3.1 Slump Flow

From the test results for each target density (refer to Figure 3), it can be seen that the slump flow value with the highest diameter is found at the slump flow value at a density target of 1000 kg/m^3

and 1800 kg/m^3, wherein the mixture used is a mixture of cement, fly ash, and aluminum powder. The mixture tends to be thinner than the other mixtures at a 30% fly ash percentage with a low target density. Fly ash has properties that can lubricate the mixture and increase workability. With the addition of fly ash, the workability of concrete is improved [27]. While the effect of adding bottom ash to the composition of the mixture tends to be lower, this is because bottom ash can absorb water, thereby reducing workability [28].



(a) Density target of 1000 kg/m^3 (D1000) (b) Density target of 1200 kg/m^3 (D1200)

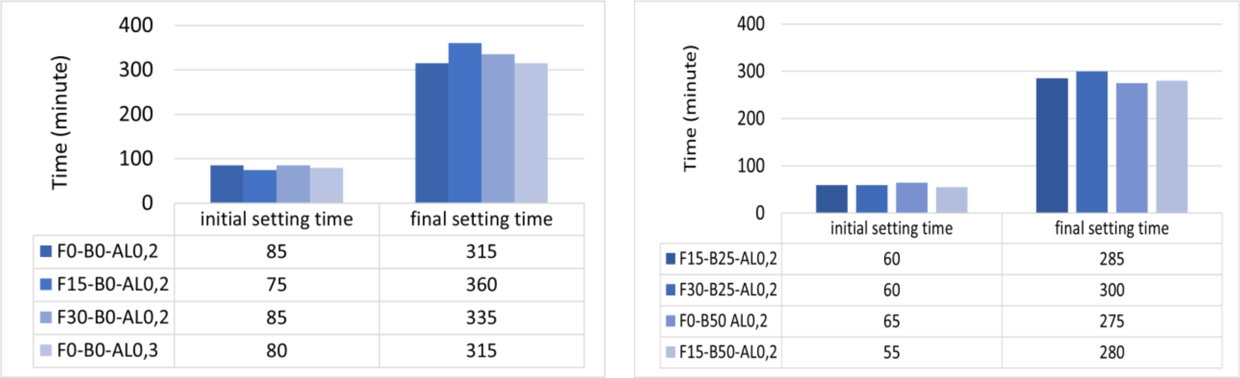


(c) Density target of 1600 kg/m^3 (D1600) (d) Density target of 1800 kg/m^3 (D1800)

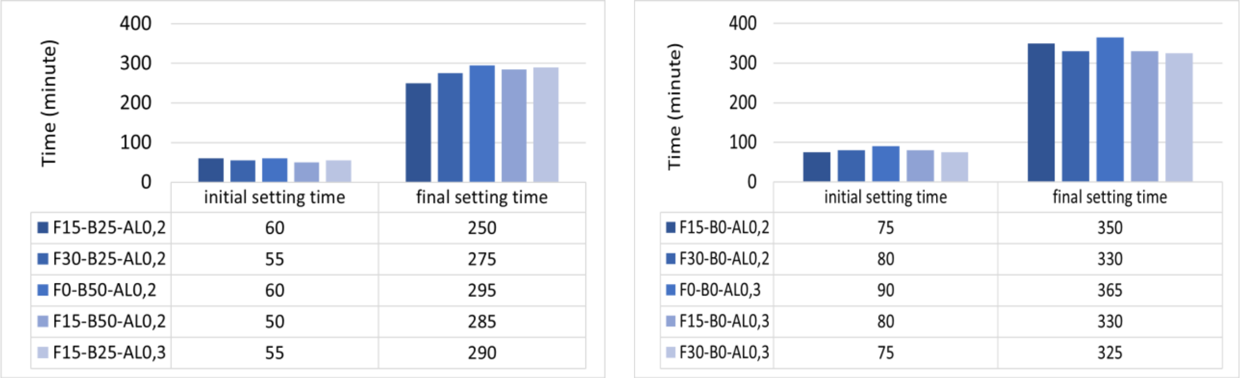
Fig. 3. Slump flow of fresh aerated concrete for each density target mix design

3.2 Setting Time

The results of the setting time test consist of the initial and final setting times, which can be seen in Figure 4. The results of the setting time test show that the initial setting time of the control mixture and the mixture that only uses an additional percentage of fly ash, namely for the initial mix, ranges from 75–90 minutes longer than in the cement mixture with fly ash and bottom ash, which is 50–65 minutes. The small particle size of fly ash causes the need for insufficient water but does not reach workable and flowable conditions. However, the addition of water causes dispersion and segregation, so the use of fly ash must be controlled. From the results of all variables using bottom ash, the percentage of bottom ash showed an effect on the value of the initial and final setting time, which was faster. The results showed the same phenomenon using a higher percentage of fly ash. Bottom ash contains alumina, silica, and calcium compounds that are pozzolanic and accelerate the hydration process [29].



(a) Density target of 1000 kg/m^3 (D1000)
(b) Density target of 1200 kg/m^3 (D1200)



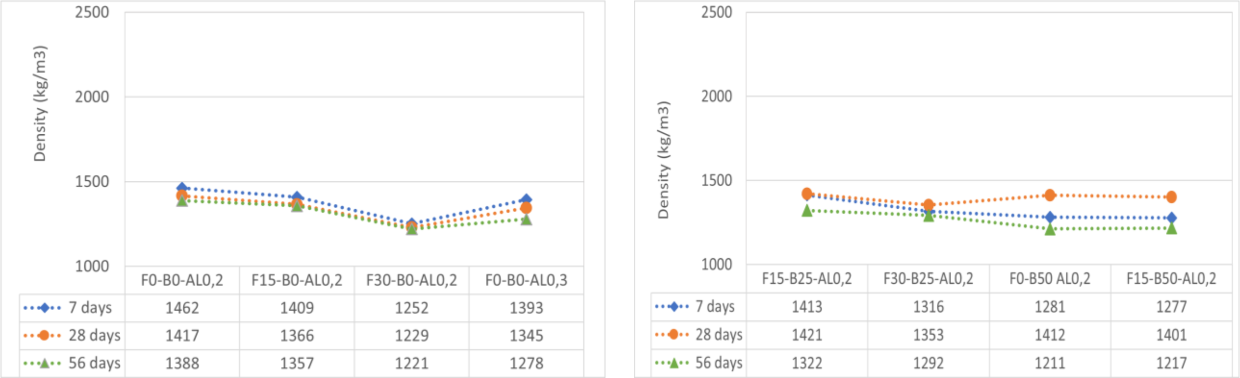
(c) Density target of 1600 kg/m^3 (D1600)
(d) Density target of 1800 kg/m^3 (D1800)

Fig. 4. Setting time of fresh aerated concrete for each density target mix design

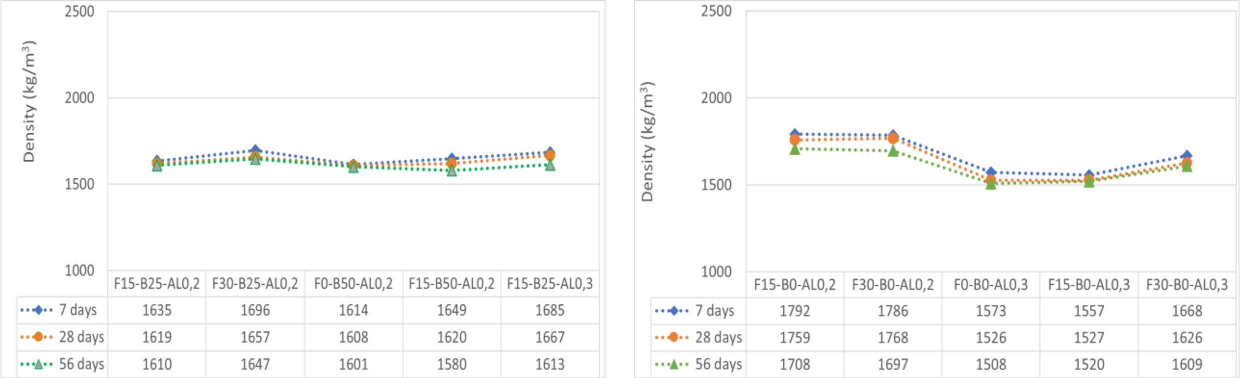
3.3 Density Testing

The results of concrete density testing with a density target range of 1000 kg/m^3 to 1800 kg/m^3 show quite fulfilling results, with achievements close to the desired density target. In Figure 5, the density test results graph falls within the density target's standard deviation. At a low-density target of 1000 kg/m^3, the density results obtained have yet to reach the target. Using fly ash in the concrete mix tends to make the concrete denser and can reduce voids in the concrete. In addition, fly ash makes the concrete surface look flatter and smoother.

The results closest to the density target are in the 1600 kg/m^3 density target variable, where all variables meet the density target criteria. Mixtures with fly ash and bottom ash variations are mixtures with the maximum FAS value. Using fly ash and bottom ash in concrete mixtures increases the water demand in the concrete mixture. It is considered consistent because the hardened definite density value falls into the density target range.



(a) Density target of 1000 kg/m^3 (D1000) (b) Density target of 1200 kg/m^3 (D1200)



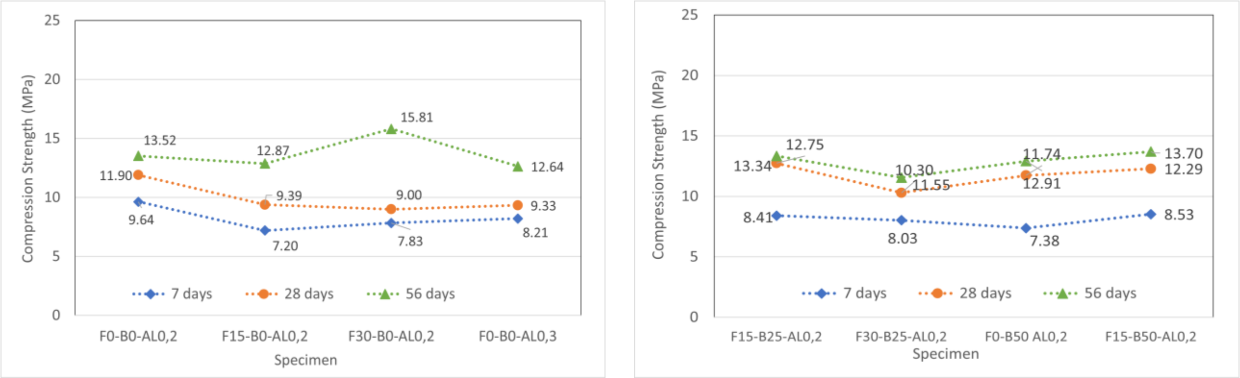
(c) Density target of 1600 kg/m^3 (D1600) (d) Density target of 1800 kg/m^3 (D1800)

Fig. 5. Density of aerated concrete for each density target mix design

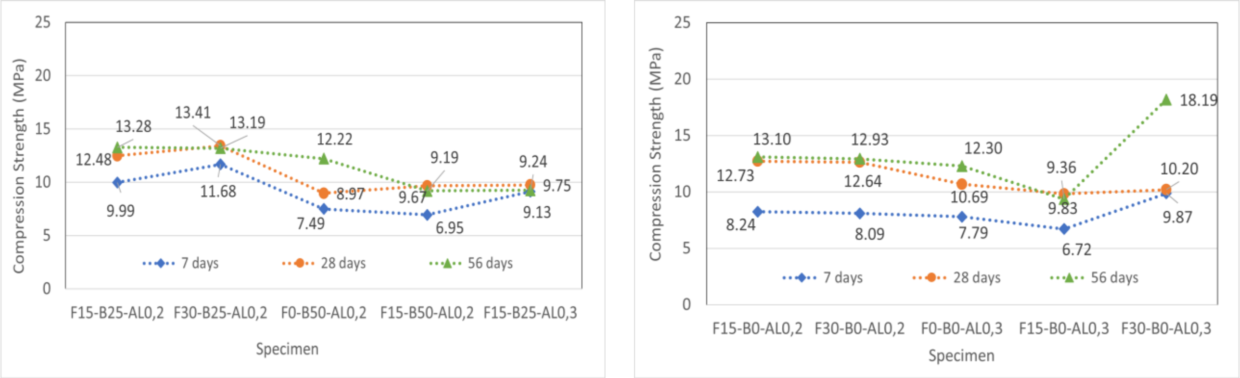
3.4 Compressive Strength Testing

The highest compressive strength test results with a density target of 1800 kg/m^3 showed the highest compressive strength in variable F30-B0-AL0.3 with an optimum compressive strength of 18.19 MPa, which meets the requirements of structural concrete and is more than 17 MPa based on ASTM C39. The results of this study (refer to Figure 6) correspond to the effects of Ref. [4], which produced the optimum compressive strength at a percentage of 30% fly ash. Fly ash has a high silica content to increase the compressive strength of concrete. In the composition that uses fly ash and bottom ash, the compressive strength value increases at 28 days and decreases at 56 days.

The bottom ash has prominent enough pores to result in more water absorption and reduce the strength of concrete. In all variables, the compressive strength value based on the percentage of bottom ash usage decreased. It can be concluded that the greater the rate of bottom ash, the smaller the compressive strength produced [8].



(a) Density target of 1000 kg/m^3 (D1000)
(b) Density target of 1200 kg/m^3 (D1200)

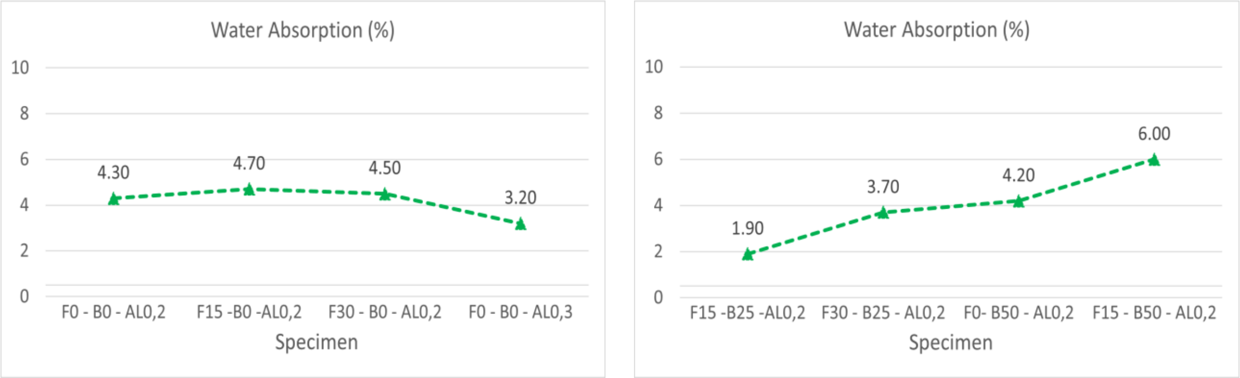


(c) Density target of 1600 kg/m^3 (D1600)
(d) Density target of 1800 kg/m^3 (D1800)

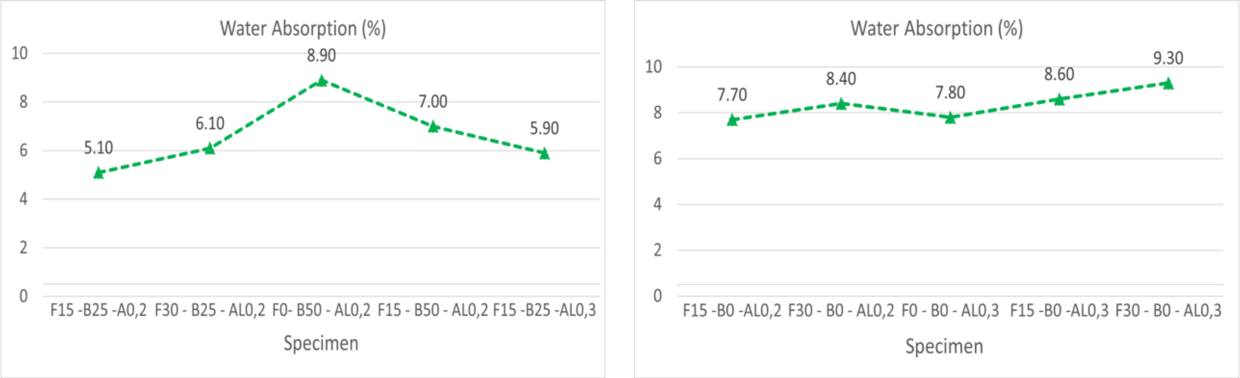
Fig. 6. Compression strength of aerated concrete for each density target mix design

3.5 Water Absorption Testing

The reliability of concrete against an impermeable environment is determined by the level of water absorption on the surface of the concrete, called absorption as shown in Figure 7. The results of the water absorption test showed that the highest water absorption value was found in the mixture variable F30-B0-AL0.3 for the density target of 1800 kg/m^3, which was 9.3%. The research [30] shows that the higher the percentage of fly ash, the more water absorption will increase, and is supported by research conducted by Ref. [31], which shows that a more significant portion of aluminum powder has a considerable influence on the concrete mixture due to the number of air bubbles in the test specimen spreading and increasing the water absorption capacity.



(a) Density target of 1000 kg/m^3 (D1000) (b) Density target of 1200 kg/m^3 (D1200)

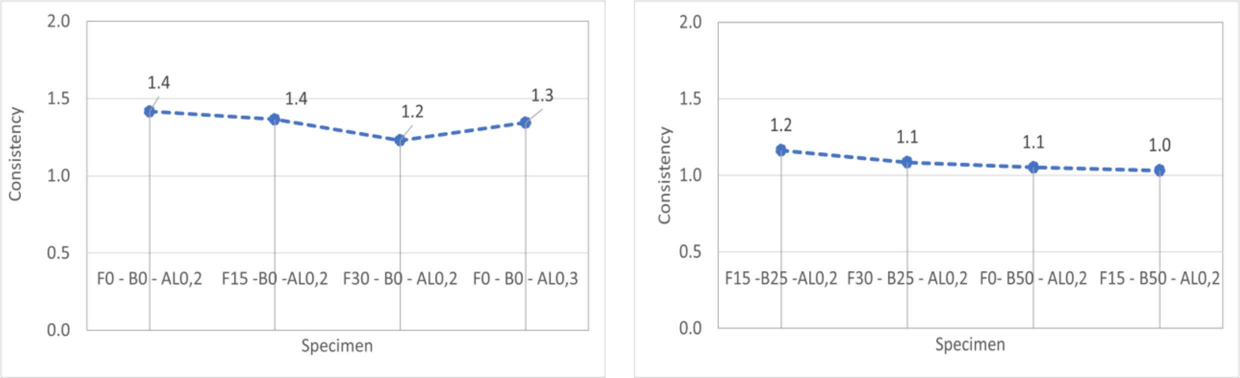


(c) Density target of 1600 kg/m^3 (D1600) (d) Density target of 1800 kg/m^3 (D1800)

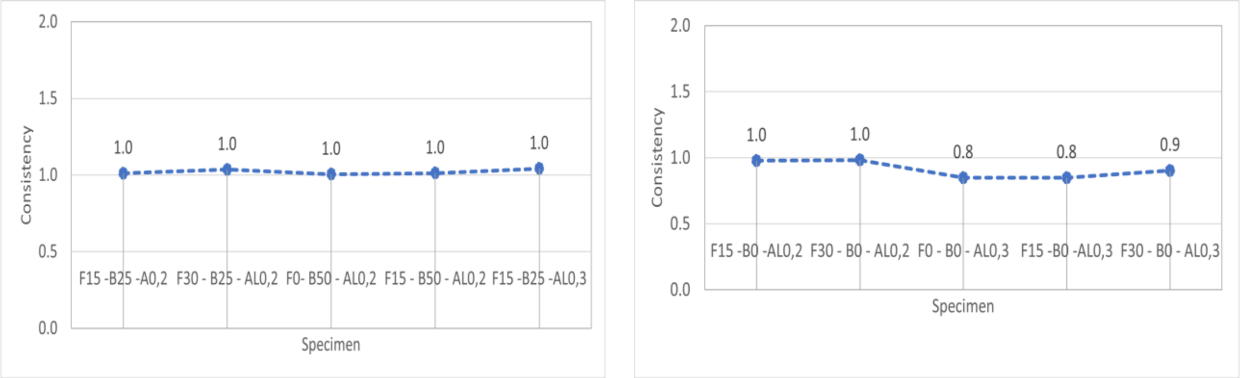
Fig. 7. Water absorption testing result for each density target mix design

3.6 Consistency Analysis

From the results of the research on the consistency of aerated concrete mixes for several target densities, namely 1000 kg/m^3, 1200 kg/m^3, 1600 kg/m^3, and 1800 kg/m^3, the optimum consistency value is obtained, which is close to 1 in the concrete mix variable with a density target of 1600 kg/m^3, which on average in each variable has a good value of 1.0 (refer to Figure 8). In this case, the phenomenon that occurs due to comparing hardened density and density target values can be kept close to 1. This consistency is highly dependent on the proportions and properties of the concrete mixture. The consistency and stability of fresh-mix foamed concrete are calculated by measuring the fresh density against the density target and hardened density. The mix is considered consistent and stable if the density ratio is kept close to one without regression or bleeding occurring during the test [13].



(a) Density target of 1000 kg/m^3 (D1000) (b) Density target of 1200 kg/m^3 (D1200)

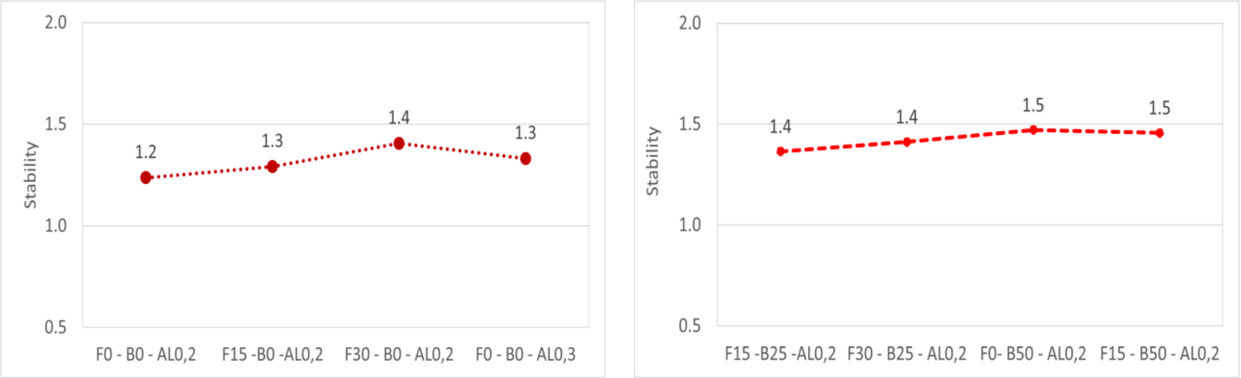


(c) Density target of 1600 kg/m^3 (D1600) (d) Density target of 1800 kg/m^3 (D1800)

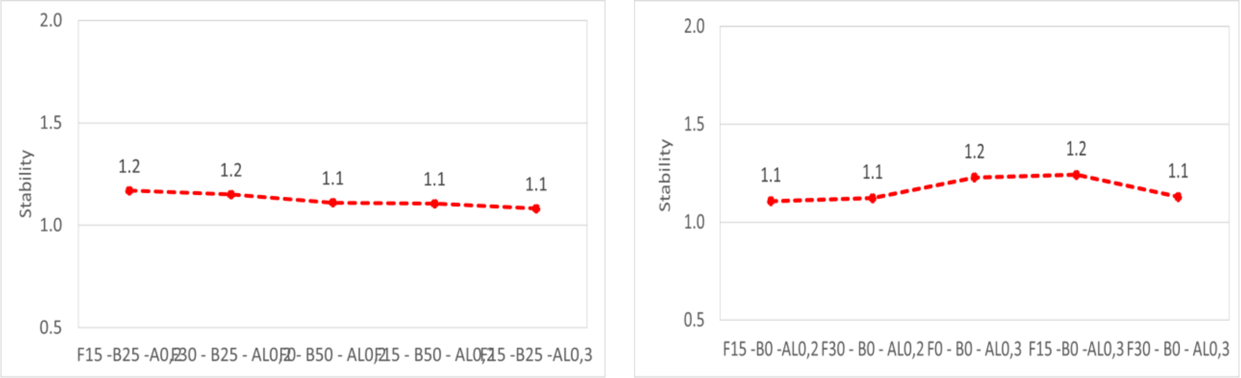
Fig. 8. Consistency of aerated concrete for each density target mix design

3.7 Stability Analysis

The stability of a foam concrete mix can be calculated by measuring the fresh density against the density target and the hardened density as shown in Figure 9. The mix is considered stable if the density stability is kept close to one without segregation [32]. Optimization of the design mix depends on several parameters, namely the water-cement ratio, the cement-sand ratio, and the particle size distribution [14]. The study of stability values at each density target obtained results on the variation of cement, fly ash, bottom ash, and aluminum powder mix. The most stable stability values are found at target densities of 1600 kg/m^3 and 1800 kg/m^3 with a water-cement ratio of 0.5 and water-sand ratios of 0.3 and 0.4.



(a) Density target of 1000 kg/m^3 (D1000)　　(b) Density target of 1200 kg/m^3 (D1200)

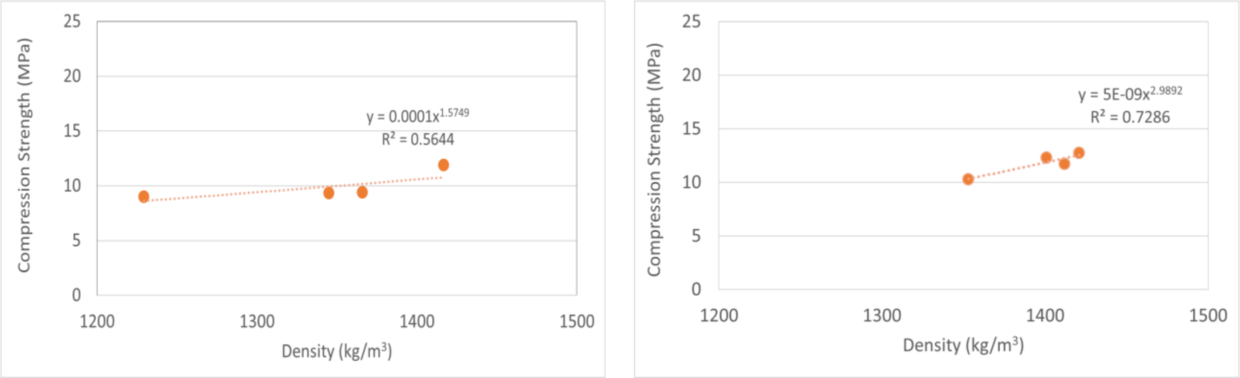


(c) Density target of 1600 kg/m^3 (D1600)　　(d) Density target of 1800 kg/m^3 (D1800)

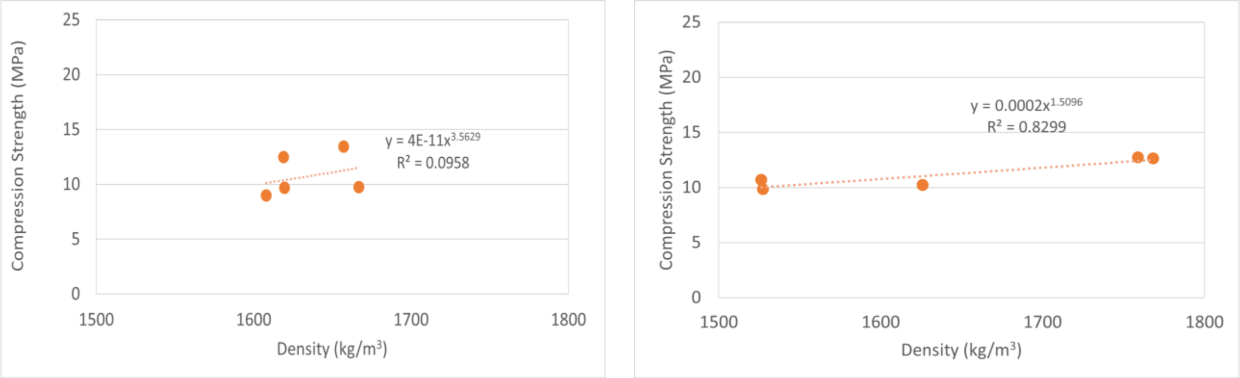
Fig. 9. Stability of aerated concrete for each density target mix design

3.8 Performance Index of Compressive Strength

Figure 10 shows the relationship between compressive strength and density. The compressive strength will increase as the density value increases. The relationship between compressive strength and density in porous concrete, such as aerated concrete, is strongly influenced by the composition of materials that cause differences in the proportion of aerated concrete voids. The voids formed by the aeration process in concrete cause the matrix to be less dense and affect its mechanical properties. The results showed that all density target groups' relationship between compressive strength and density tended to form a power equation—the higher density target results in a power regression equation with a higher COV.



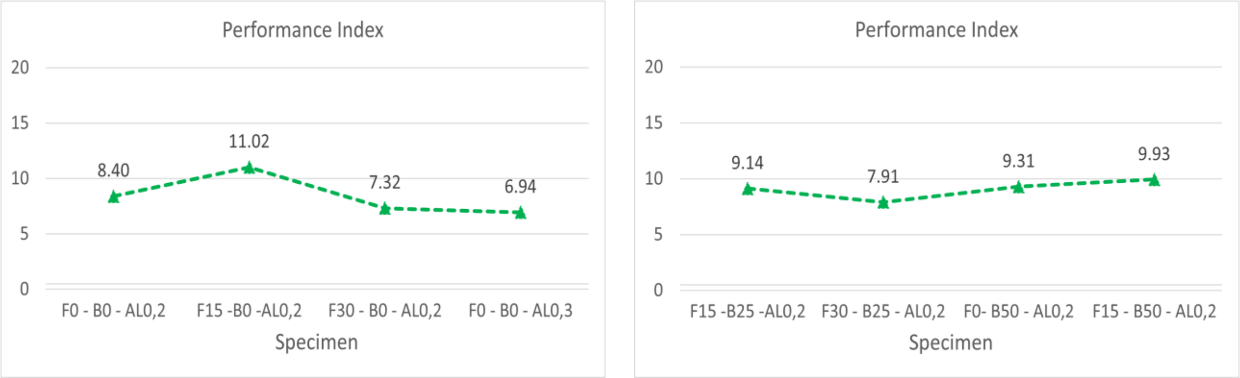
(a) Density target of 1000 kg/m^3 (D1000) (b) Density target of 1200 kg/m^3 (D1200)



(c) Density target of 1600 kg/m^3 (D1600) (d) Density target of 1800 kg/m^3 (D1800)

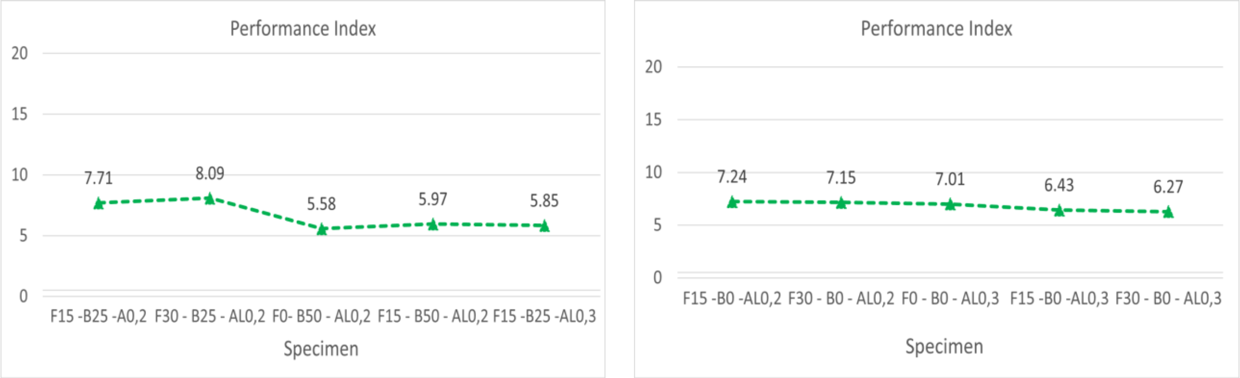
Fig. 10. Compression strength vs density of aerated concrete for each density target mix design

The compressive strength performance index value shows the relationship between the achievement of compressive strength and the expected density in lightweight concrete (refer to Figure 11). The compressive strength performance index value is determined based on the ratio of compressive strength achievement to the 1000 kg/m^3 density value [33]. Based on the results of this study, the performance index ranges from 5.58 to 11.02. The index was determined from the compressive strength at 28 days. The highest performance index was 11.02 in the composition with a mixture of fly ash 15%, bottom ash 0%, and aluminum powder 0.2%, with a compressive strength of 15.05 MPa at the age of 28 days. This highest performance index was achieved by the mix design of a density target of 1000 kg/m^3 (D1000). The obtained compressive strength meets the requirements of non-structural materials. Based on the density value, it meets the needs of lightweight concrete. According to the studies [33,34], the performance indexes of aerated concrete in this research demonstrate the same trend, with all mix designs classified as non-structural lightweight concrete.



(a) Density target of 1000 kg/m^3 (D1000)

(b) Density target of 1200 kg/m^3 (D1200)



(c) Density target of 1600 kg/m^3 (D1600)

(d) Density target of 1800 kg/m^3 (D1800)

Fig. 11. Performance index of aerated concrete for each density target mix design

4. Conclusions

The following conclusions can be drawn based on the tests carried out. All variables using bottom or fly ash in aerated concrete with the higher percentage showed faster initial and final setting times.

The results of concrete density testing with a density target range of 1000 kg/m^3 to 1800 kg/m^3 show quite fulfilling results, with achievements close to the desired density target. The results closest to the density target are in the 1600 kg/m^3, where all variables meet the density target criteria. The consistency and stability values showed as indicator of the achievement of this density-based mix design.

The highest compressive strength test results with a density target of 1800 kg/m^3 showed in variable F30-B0-AL0.3 with an optimum compressive strength of 18.19 MPa at 56 days, which meets the requirements of structural concrete.

The relationship between compressive strength and density in aerated concrete is strongly influenced by the composition of materials, especially fly ash and bottom ash, that cause differences in the proportion of aerated concrete voids. The results showed that all density target groups' relationship between compressive strength and density tended to form power equations.

The performance index shows the achievement of compressive strength and the expected density in lightweight concrete. The highest performance index was 11.02 in the composition of mix design of a density target of 1000 kg/m^3 (D1000) with a mixture of fly ash 15%, bottom ash 0%, and aluminum powder 0.2%. This highest performance index was achieved by the compressive strength of 15.05 MPa at 28 days, which meets the requirements of non-structural materials.

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