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Mechanical and Physical Characteristics of Aerated Concrete with Fly Ash Variations

Intan Syadita Fatriliani[1], Rosidawani[1,*], Hanafiah[1], Maulid M. Iqbal[1], Yakni Idris[1]

[1] Civil Engineering, Faculty of Engineering, Universitas Sriwijaya, 30862 Inderalaya, South Sumatera, Indonesia

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ABSTRACT

Aerated concrete is a lightweight concrete consisting of sand, cement, water, and air-entraining agent such as aluminum powder. This research uses fly ash as a substitute for cement with a percentage of 0%, 10%, and 15%, and quartz sand as fine aggregates. This study aimed to determine the effect of fly ash percentage on the mechanical and physical properties of aerated concrete. The tests carried out in this research were testing for fresh concrete, namely slump flow and setting time, and testing the characteristics of foam concrete, namely specific gravity, compressive strength, flexural strength, and microstructure. The highest slump flow is found in a mixture of 15% fly ash with a value of 14.5 cm. The higher the percentage of fly ash used, the longer the setting time required. The optimum mixture is found in a mixture with a percentage of 15% fly ash substitution, which had a specific gravity of 1728.46 kg/m^3, a compressive strength of 20.24 MPa at the age of 28 days, a flexural strength of 3.819 MPa, and an amorphous percentage of 78.30%.

1. Introduction

Concrete is a material that is most widely used in infrastructure construction purposes. One of the current concrete innovations is lightweight concrete. Lightweight concrete is concrete with a lighter density compared to normal concrete. Usually, lightweight concrete has a specific gravity ranging from 1400-1800 kg/m^3 and has a compressive strength between 7-14 MPa [1]. The use of lightweight materials with low thermal conductivities in the building is continuously increasing because they can reduce the dead load of building structure and energy consumption [2-4].

Karakurt *et al.,* [5] states that aerated concrete is a lightweight mixture of sand, cement, water, and air-entraining agent. The air is artificially trapped by adding a metal powder such as aluminum. The chemical reaction caused by adding aluminum powder expands the mixture to about twice its volume, resulting in a structure with many air cavities. The results of Shabbar *et al.,* [6], Reddy and Kumar [7], and Van *et al.,* [8] research showed that the use of aluminum powder has the potential to produce lightweight concrete with better compressive strength.

* *Corresponding author.*
E-mail address: rosidawani@ft.unsri.ac.id

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Due to its good mechanical properties, high durability, and raw material availability, Portland cement concrete is used in various constructional applications [9]. It was reported that 1 ton of Portland cement, not only about 1 ton of CO_2 will be emitted, but also 2.5 tons of resources will be used [10]. Hence, looking for alternative, more environmentally friendly cement replacement materials is necessary. The use of fly ash, as a waste material of coal power plants has been widely used as a cement replacement material [11].

Based on the description above, a study was conducted on the effect of fly ash percentage on the mechanical and physical properties of aerated concrete. The results of this study are expected to produce aerated concrete with mechanical properties that meet structural requirements, light specific gravity, and are environmentally friendly.

According to Moon *et al.,* [12], materials suitable for aerated concrete are materials with fine gradations. Quartz sand is one of the primary materials in manufacturing aerated concrete. The percentage of quartz sand is higher than other aggregates in the aerated concrete mixture. Quartz sand is a mineral-based aggregate obtained from crushed rock or granite.

Aluminum can be used as an air-entraining agent to manufacture aerated concrete. When aluminum is added (usually about 0.2% to 0.5% by weight of cement) to the mixture, it reacts with calcium hydroxide or alkali, producing hydrogen gas and forming air cavities. Aluminum is available in various forms, usually in powder or paste. Each of them has its advantages and disadvantages. The aluminum used must be finer than 100 or 50 µm to obtain the required mechanical properties of aerated concrete [13].

Fly ash is a refined residue from burning coal and is transported into the air through a chimney. Fly ash is waste from burning coal that is pozzolanic. Fly ash can be used as a partial or complete substitution for cement or fine aggregate to manufacture aerated concrete [14].

Using fly ash as a cement substitution in concrete saves cement and energy consumption and is more economical. Fly ash can also improve the characteristics of concrete, reduce hydration temperature so that it can be used on mass concrete, reduce water requirements, and improve workability. The main benefit of using fly ash is that it can increase the durability of concrete, such as resistance to sulfates, freezing, and thawing, and reducing the permeability of chlorides [15].

2. Methodology

The research method used is the experimental method. The experimental research method is a scientific activity aimed at obtaining specific data. This research was conducted by making the composition of aerated concrete with variations in the fly ash percentage as a cement substitution. The tests carried out in this study are testing fresh concrete in the form of slump flow and setting time, as well as testing the mechanical properties of aerated concrete in the form of testing compressive strength and flexural strength, testing physical properties in the form of specific gravity and microstructures.

The composition used is the cement water factor of 0.4, the ratio of fine aggregate and cement of 2, and the percentage of aluminum powder of 20%. The composition of the aerated concrete mixture used in this study can be seen in Table 1.

Table 1
The composition of the mixtures

Mixtures Codes	Cement (kg/m^3)	Fly ash (kg/m^3)	Al powder (kg/m^3)	Quartz sand (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
Normal	350	0	0.7	700	140	2.794
AC-0	349.3	0	0.7	700	140	2.794
AC-10	314.3	35	0.7	700	140	2.514
AC-15	296.8	52.5	0.7	700	140	2.374

The code-naming of the specimens in Table 1 is aerated concrete with the symbol AC; the numbers 0, 10, and 15 indicate the percentage of fly ash by 0%, 10%, and 15%.

The specimens used in this study are cylindrical specimens with a diameter of 15 cm, a height of 30 cm, and a beam of size 7.5 cm x 7.5 cm x 30 cm. The mixing method used is non-autoclaved aerated concrete. First, the fine aggregate and cement are mixed using a mixer, then, the aluminum powder is stirred for 30 seconds. Finally, put water in the mixture. The mixture is stirred for approximately 2 minutes until evenly distributed. After stirring, fresh concrete testing is carried out, namely the slump flow test and setting time.

2.1 Setting Time

The setting time of the concrete was determined by conducting tests using penetration resistance apparatus. The test refers to the ASTM C-191 standard [16]. The mortar part of the concrete mix was separated from the concrete and filled in the mold. The penetration resistance of the needle to penetrate 2.5 cm in the mortar was measured. Measurement was taken at different time intervals and the graph was plotted between penetration and elapsed time [17]. Initial setting time is the initial time required for the concrete mixture to bind each other, and the final setting time is the total time required for concrete to harden in a perfect state [18].

2.2 Specific Gravity

Specific gravity test uses ASTM C-138 [19]. Specific gravity is the weight per volume performed by weighing the weight of the specimen in dry conditions before the compressive strength test and calculating the volume of the specimen.

$$\rho = \frac{\mathrm{m}}{\mathrm{v}} \tag{1}$$

where:
ρ = specific gravity (kg/m^3)
m = mass (kg)
v = volume (m^3)

2.3 Compressive Strength

The compressive strength test of concrete uses ASTM C-39 standard [20]. The concrete specimen in this study used a cylindrical specimen with a diameter of 15 cm and a height of 30 cm.

$$\mathrm{fc}' = \frac{\mathrm{P}}{\mathrm{A}} \tag{2}$$

where:
fc' = compressive strength (N/mm^2)
P = force (N)
A = surface area (mm^2)

2.4 Flexural Strength

Flexural strength testing uses ASTM C-78 [21]. The concrete test object in this study used a beam specimen with dimensions of 7.5x7.5x30 cm.

$$R = \frac{3\,P\,L}{b\,d^2} \tag{3}$$

where:
R = modulus of rupture (N/mm^2)
P = maximum applied load (N)
L = span length (mm)
b = average width of the specimen (mm)
d = average depth of the specimen (mm).

3. Results
3.1 Slump Flow

Based on Table 2, the lowest slump flow test results are found in normal concrete mixtures with a value of 12.8 cm and the highest slump flow in AC-15 concrete mixes with a value of 14.5 cm.

Table 2
Slump flow test results

Mixture Codes	Fly Ash (%)	Slump Flow (cm)
Normal	0	12.80
AC-0	0	13.00
AC-10	10	13.80
AC-15	15	14.50

Based on Figure 1, the higher percentage of fly ash can increase workability because fly ash has a round-shaped microstructure which means that fly ash can lubricate the concrete mixture.

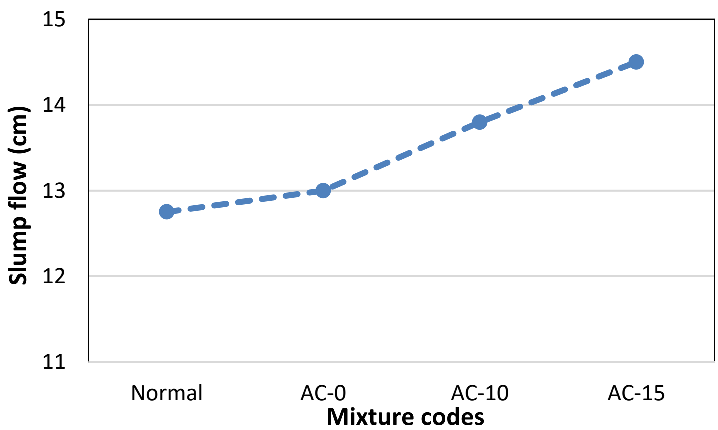

Fig. 1. Slump flow test

3.2 Setting Time

Based on Figure 2, the test results of setting time show that normal concrete has a faster setting time than aerated concrete. Then the higher the percentage of fly ash used, the longer the setting time required. The initial setting time was obtained in 45 minutes, while the final setting time was obtained in 90 minutes for normal concrete and 150 minutes for aerated concrete.

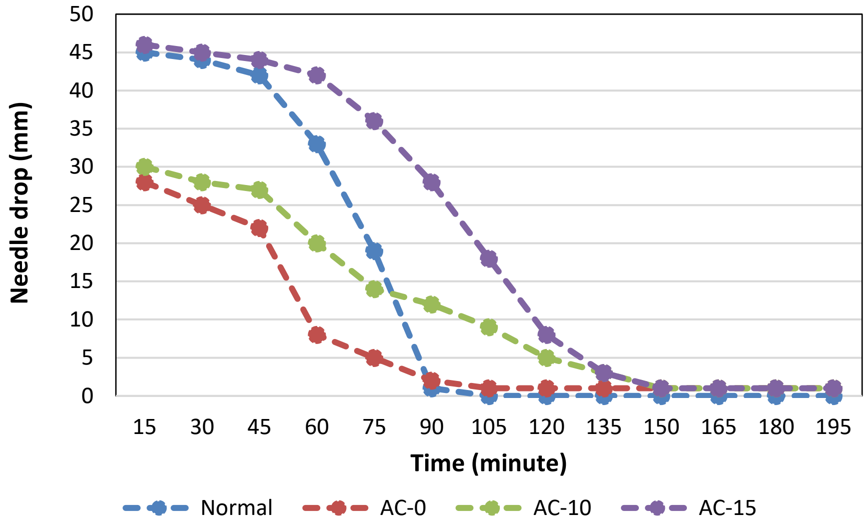

Fig. 2. Setting time test

3.3 Specific Gravity

Based on ASTM C 330 [22], the density and compressive strength values obtained are classified as lightweight structural concrete with a density range of 1350 – 1900 kg/m^3 and more than 17 MPa compressive strength.

It can be seen in Table 3 that the highest specific gravity is found in a normal concrete mixture with a specific gravity value of 2011.86 kg/m^3. In comparison, the highest percentage of specific gravity change is found in AC-15 concrete mixes with a specific gravity value of 1728.46 kg/m^3.

Based on Figure 3, it can be concluded that using aluminum powder causes a decrease in specific gravity because many air cavities are formed due to the reaction of aluminum powder with cement hydration. Aerated concrete also experienced a reduction in specific gravity along with an increase in the percentage of fly ash use. This is because the specific gravity of fly ash is lighter than the specific gravity of cement.

Table 3
Specific gravity test results

Mixture Codes	Fly Ash (%)	Specific Gravity (kg/m^3)
Normal	0	2011.86
AC-0	0	1802.94
AC-10	10	1755.07
AC-15	15	1728.46

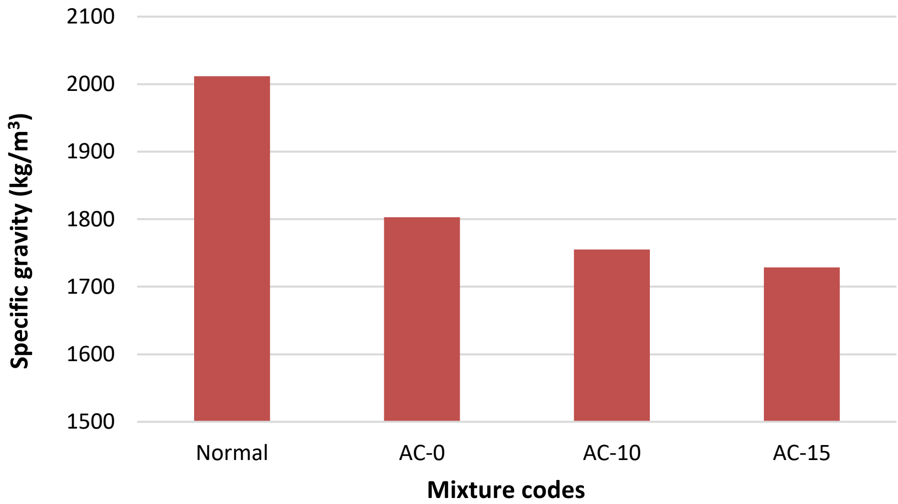

Fig. 3. Specific gravity test

3.4 Compressive Strength

Because of its porous nature, the pore structure of aerated concrete plays a dominant role in controlling its mechanical strength [23]. Concrete compressive strength testing is carried out at the age of 7, 28, and 56 days. Based on Table 4, the highest concrete strength development in each age is found in normal concrete mixtures, while the lowest is found in each age in AC-0 concrete mixtures with a fly ash percentage of 0%.

Based on Figure 4, it can be seen that the pattern of development of compressive strength in concrete with a variation in the percentage of fly ash at a test age of 7 days and 28 days has a significant increase. At a test age of 56 days, concrete remains an increase in compressive strength. Concrete without fly ash has a lower compressive strength than concrete with fly ash. It shows that adding fly ash to the cement partially can increase the compressive strength. This study obtained the optimum content value of fly ash substitution at 15%.

Table 4
Compressive strength test results by age

Mixture Codes	Fly Ash (%)	Compressive Strength (MPa)		
		7 days	28 days	56 days
Normal	0	27.80	32.08	33.43
AC-0	0	11.05	14.61	15.71
AC-10	10	13.85	17.70	20.15
AC-15	15	17.11	20.24	22.61

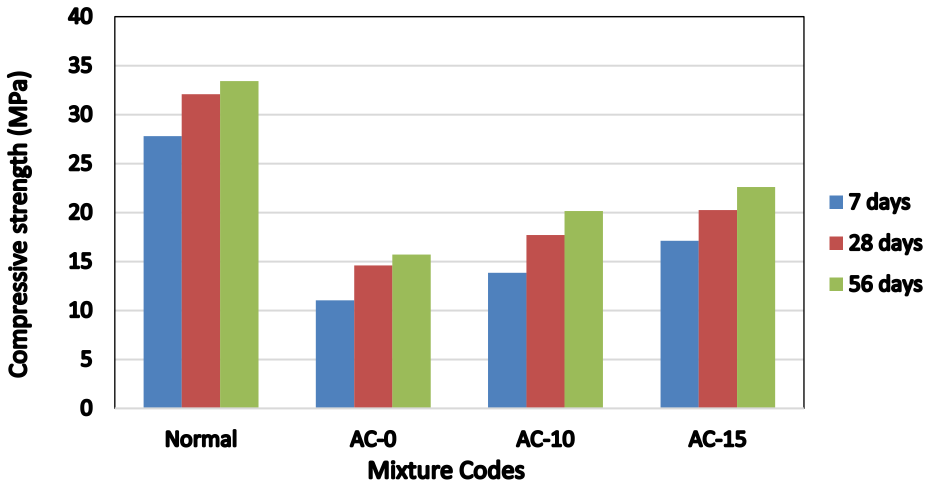

Fig. 4. Relationship between compressive strength and concrete age

3.5 Flexural Strength

Testing of the flexural strength of concrete is carried out at the age of 28 days. Based on Table 5, the highest flexural strength is found in normal concrete mixtures, while the lowest flexural strength is found in AC-0 concrete mixtures with a fly ash percentage of 0%.

Based on Figure 5, it can be seen that aerated concrete that does not use fly ash has a lower flexural strength result than concrete with the use of fly ash. It shows that substituting fly ash for partial cement can increase flexural strength.

Table 5
Flexural strength test results

Mixture Codes	Fly Ash (%)	Flexural Strength (MPa)
Normal	0	4.99
AC-0	0	2.76
AC-10	10	3.38
AC-15	15	3.82

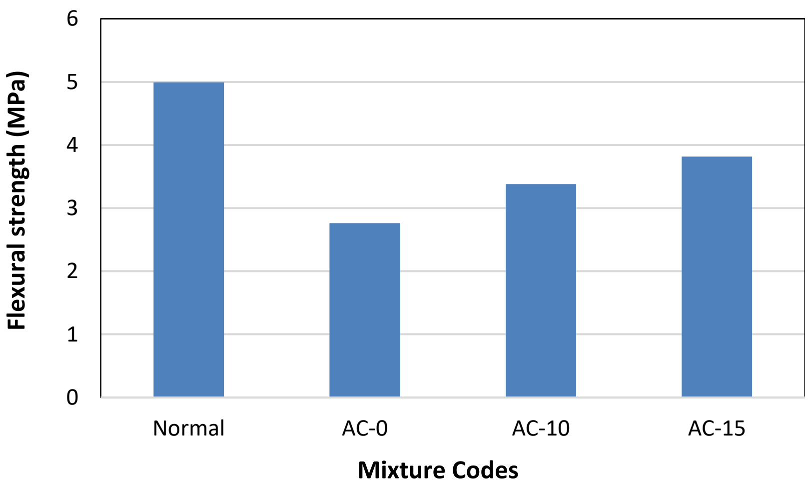

Fig. 5. Flexural strength test

3.6 X-Ray Diffraction (XRD)

X-Ray Diffraction (XRD) is a non-destructive rapid analysis technique mainly used for phase identification of crystalline materials and can provide information about the dimensions of cell units.

The XRD test results shown in Figure 6 indicate that all test objects consist of a composition dominated by the minerals Quartz (SiO_2) and Portlandite ($Ca(OH)_2$). It corresponds to the predominant piece of cement, silica sand, and fly ash with the mineral SiO_2, while $Ca(OH)_2$ is a by-product of the concrete hydration reaction. The percentage of amorphous that occurs can be seen in Table 6.

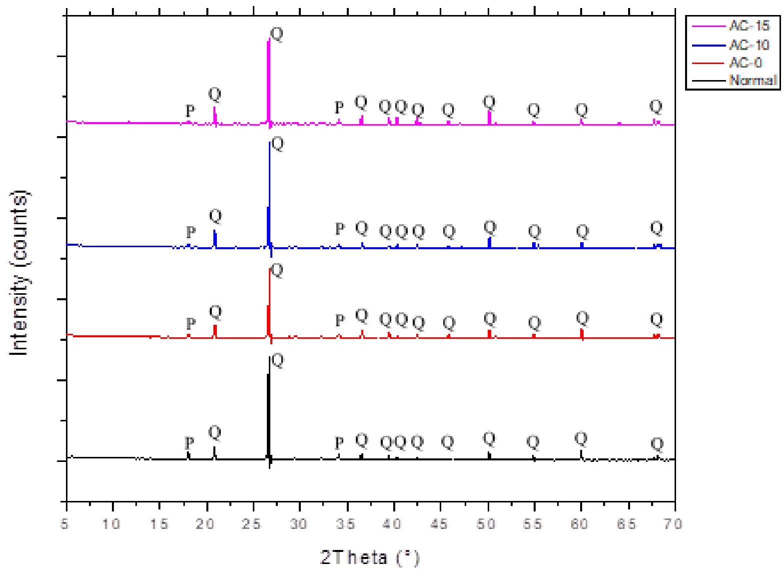

Fig. 6. XRD test results

Table 6
Amorphous percentage

Mixture Codes	Crystalline (%)	Amorphous (%)
Normal	21.40	78.60
AC-0	36.98	63.02
AC-10	22.37	77.63
AC-15	21.70	78.30

From the results of the amorphous percentage, it can be concluded that the highest amorphous percentage is found in normal concrete, with a value of 78.60%, and the lowest is found in the AC-0 mixture, with a value of 63.02%.

3.7 Scanning Electron Microscope (SEM)

A scanning electron microscope (SEM) is a type of electron microscope that produces sample images by scanning the surface with focused electron rays with magnification to a particular scale. The microstructure and mechanical properties of the entire mixture are correlated based on hydration products formed after 28 days of age. The reasons behind the strength of concrete are analyzed and explained based on the development of hydration products in the microstructure of concrete mixtures. Here are the results of the SEM testing of each mix. Here are the results of the SEM testing of each combination.

From Figure 7, it can be seen that there is C-S-H scattered in the mixture of normal concrete, which affects the increasing mechanical properties of concrete. The formation of Portlandite (CH) and Calcite is also sprayed on the mix. The appearance and distribution of such minerals are one of the causes of the increased mechanical properties of concrete. There is also ettringite that fills the voids of concrete.

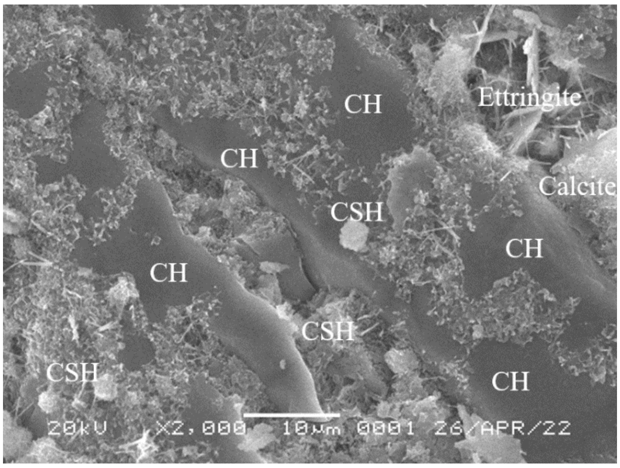

Fig. 7. SEM Normal

From Figure 8, it can be seen that the formation of C-S-H is reduced due to the addition of aluminum powder which forms many cavities, thereby reducing the strength of concrete. In addition, the reduced C-S-H is caused by particles that do not react to the mixture. The formation of Portlandite (CH) and Calcite is also reduced, causing a decrease in the strength of concrete. From Figure 8, it can be seen that the formation of C-S-H is diminished due to the addition of aluminum powder which forms many cavities, thereby reducing the strength of concrete. In addition, the reduced C-S-H is caused by particles that do not react to the mixture. The formation of Portlandite (CH) and Calcite is also reduced, causing a decrease in the strength of concrete.

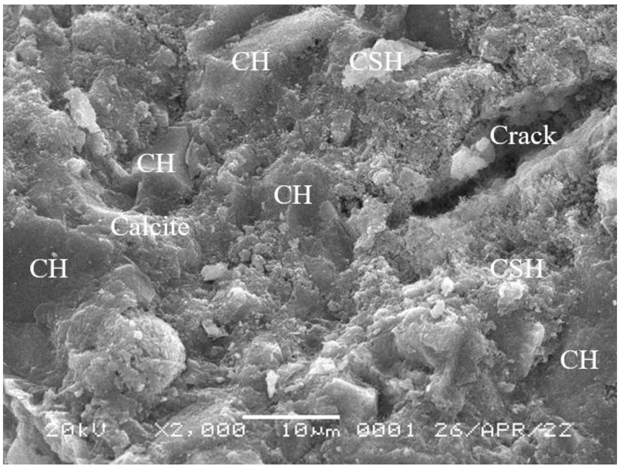

Fig. 8. SEM AC-0

From Figure 9, it can be seen that there is more C-S-H formation compared to AC-0. The shape of the microstructure is also different from normal concrete due to the reaction of adding fly ash and aluminum powder. The number of CH and Calcite formed is also more so that the strength of the concrete is increased compared to the AC-0 concrete. However, there is fly ash that does not react, so it could be more optimal in increasing the strength of concrete.

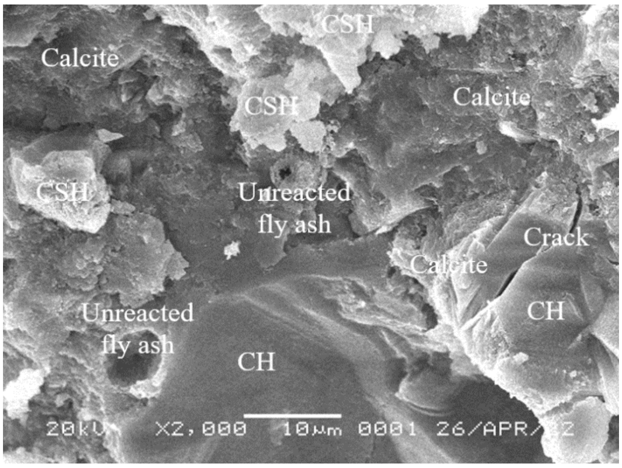

Fig. 9. SEM AC-10

Figure 10 shows that CSH, CH, and Calcite formation is much more widely dispersed than other aerated concrete mixtures. This test piece's mechanical strength is better than the AC-10 test piece.

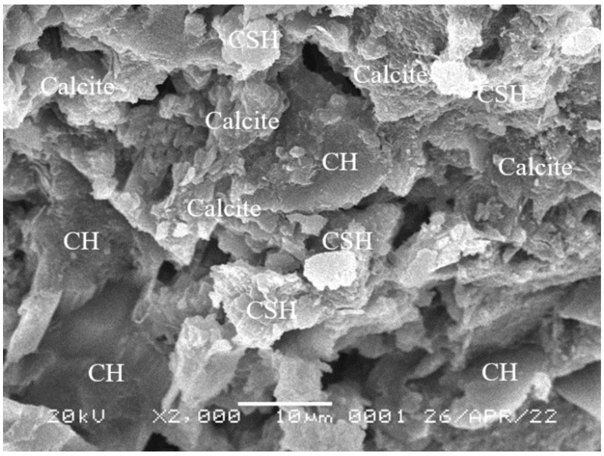

Fig. 10. SEM AC-15

4. Conclusions

The highest slump flow value is found in the mixture with a fly ash percentage of 15%, which is 14.5 cm. The greater the percentage of fly ash substituted for cement, the greater the slump flow value obtained. It is because the microstructure of the fly ash is spherical, so it lubricates the mixture and increases the workability of the mixture.

The setting time on normal concrete is faster than on aerated concrete. Then the higher the percentage of fly ash used, the longer the setting time required.

The lowest specific gravity of concrete is found in concrete mixtures with a fly ash percentage of 15%, which is 1728.46 kg/m^3. It is because the specific gravity of fly ash is lighter than the specific gravity of cement.

Based on the relationship between compressive strength and concrete age, it can be concluded that the development pattern of compressive strength in concrete between 7 days and 28 days of age has increased significantly. At 56 days, concrete remains an increase in compressive strength.

Aerated concrete that does not use fly ash has a lower flexural strength yield than concrete with fly ash. It shows that the accretion of fly ash on partial cement can increase flexural strength.

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