International Journal of Advanced Technology and Engineering Exploration, Vol 10(99)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2022.10100080

Research Article

Analysis of chloride resistance in light weight concrete made from fly ash and bottom Ash

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Received: 31-August-2022; Revised: 10-February-2023; Accepted: 13-February-2023

Abstract
The combustion process of coal in a steam power plant produces about 5% of fly ash and bottom ash (FA-BA) waste, which is a solid waste material that cannot be burned and can cause environmental pollution. This research aimed to modify lightweight concrete by using fly ash waste as a substitute for Portland cement and bottom ash waste as a substitute for fine aggregate. The lightweight concrete was tested for resistance to hydrochloric acid (HCl) with a potential of hydrogen (pH) range of 6-8 under three test conditions. The percentage of fly ash waste used as a substitute for cement ranged from 10% to 40% of the total weight of cement, while the percentage of bottom ash waste used as a substitute for fine aggregate ranged from 30% to 50% of the total weight of fine aggregate. The test results showed that the lightweight concrete composition with the lightest specific gravity was found in the FL40BO50 mixture with a density of 1.70 gr/cm^3 and a minimum compressive strength of 15.92 MPa. However, the most optimal specific gravity was found in the FL20BO30 mixture. The lightweight concrete with a specific gravity of 1.84 gr/cm^3 and the most optimal compressive strength of 25.17 MPa was obtained. In the test results for HCl resistance, the lightweight concrete with the FL20BO30 mixture experienced the minimum mass loss, while the FL40BO50 mixture experienced the maximum decrease in mass. Under testing conditions 1, the lightweight concrete experienced a mass decrease ranging from 0.36% to 1.61% of the initial mass. Under testing conditions 2, the lightweight concrete decreased in mass by 0.65% to 3.50% of the initial mass. Under testing condition 3, the lightweight concrete experienced a mass decrease ranging from 1.03% to 4.81% of the initial mass. The decrease in mass was due to the formation of microcracks in the lightweight concrete caused by the chloride content in the HCl solution, which attacked the bonding mechanism in the lightweight concrete.

Keywords
Lightweight concrete, Fly Ash, Bottom Ash, HCl resistance.

1.Introduction
In recent years, lightweight concrete has gained popularity over conventional concrete due to its lower specific gravity, which reduces the building's mass, simplifies the construction process, and lowers production costs [1]. Fly ash and bottom ash (FA-BA) waste materials are often used as lightweight aggregates in lightweight concrete. Fly ash, which is a fine particle produced during combustion, can be collected using electrostatic precipitation (ESP), bag houses, or mechanical cyclones. The particles in fly ash are mostly microscopic and round in shape, varying in diameter, giving them the appearance of spherical bubbles of different sizes. Several studies have investigated the use of fly ash as a cementitious material [2–6].

Partial replacement of cement with coal fly ash in concrete can improve its compressive strength by enhancing particle dispersion and pozzolanic reaction. Scanning electron microscope (SEM) results have shown that fly ash particles fill the pores in mortar concrete. Replacing cement with fly ash has improved the mechanical properties of concrete, reduced production costs, and addressed environmental concerns [3]. Fly ash can also be used as a cement replacement in concrete [7–11]. However, caution must be exercised while replacing cement with fly ash, as the replacement ratio must be adjusted according to the characteristics of the fly ash. Additionally, fly ash has been combined with other materials such as gypsum [12], microorganisms [13], silica fume [14], slag [15–17], and bottom ash [18–21] in other studies.

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The study of bottom ash as the one of the concrete mixtures has been conducted for concrete constituent material [22‒25]. Bottom ash, which is identical to sand, can be utilized as a replacement for fine aggregate [26‒29]. Bottom ash could be a cost-effective alternative to sand for making concrete [29]. The substitution of 100% fine aggregate by bottom ash could offers a maximum compressive strength of 36.6 MPa utilizing fly ash as much as 54% of the total cementitious material. This result is not significantly different from the compressive strength of mortar using sand as fine aggregate, which is 42.8 MPa [18]. By considering the existing potential, FA-BA is not only identified as a hazardous coal-burning solid waste but also as a useful material resource with economic value. Various countries with the largest portion have widely studied the use of FA-BA and focused on applying FA-BA as a concrete material [13]. Previous research shows that the weight of concrete does not decrease significantly after 28 days in a sodium sulphate solution. The largest weight loss occurred was 0.41% of the initial weight in concrete that used 40% fly ash and 100% bottom ash. It shows a better resistance of concrete to sulphate attack [14].

Bukit Asam, Tbk, a Perseroan Terbatas (PT), has a high potential for FA-BA, as it operates a power plant that consumes approximately 1.25 million tons of coal per year. The consumption is increasing each year until it reaches ± 6,65 million/year. The FA-BA from PT Bukit Asam, Tbk needs to be considered as a useful waste. This study proposed lightweight concrete utilizing fly ash for Portland cement replacement and bottom ash for fine aggregate replacement. Then, the concrete is tested for mechanical properties and resistance to hydrochloric acid (HCl) solution with a PH range of 6-8. HCl in this study is representing the swamp environment, which is identical to South Sumatera area. The proposed study has an impact to PT Bukit Asam, Tbk. as a sustainable waste and financial impact.

The objective of this study was to investigate the performance of lightweight concrete containing FA-BA when subjected to chloride attacks. The study proposes the use of FA-BA sourced from Bukit Asam Company in South Sumatra, Indonesia as a constituent material for the concrete. This could support the development of a sustainable environment in Indonesia.

This paper is divided into six sections. Section 1 provides an introduction that explains the background and objectives of the study. Section 2 presents a literature review of past research, limited to the last few years. The materials and methods used in the study are presented in section 3. Section 4 presents the results of the study, including mechanical and microstructural results as well as durability findings. In section 5, the discussion and limitations of the results are addressed. Finally, section 6 describes the conclusion and potential future work of the study.

2.Literature review

To make use of waste materials, this study proposes using FA-BA as a substitute material for both cement and fine aggregate. This substitution could decrease the weight of the concrete, resulting in lightweight concrete. Cement has a higher specific gravity than both coarse and fine aggregates in a concrete mixture. By substituting cement with fly ash, the specific gravity of the resulting concrete could be reduced, thereby achieving lightweight concrete.

Bingöl and Balaneji [14] conducted a study on the combination of silica fume and fly ash in relation to sulphate attack in concrete. They found that the use of 10% fly ash could improve the concrete's compressive strength, while the use of 20% fly ash resulted in a slight decrease in strength beyond 28 days. However, a lower compressive strength occurred when the fly ash content was increased to 30%.

Patel et al. [4] investigated the use of fly ash cenospheres and sintered fly ash as replacements for fine and coarse aggregate, respectively, and evaluated the concrete's durability against sulphate and chloride attack. They observed that the formation of magnesium silicate hydrate in sulphate attack conditions reduced the cohesion between fly ash cenospheres and sintered fly ash, resulting in a decrease in compressive strength.

Liu et al. [7] studied the effects of chloride attack on fly ash concrete in a water-soaking environment. They found that substituting 15% or 30% of cement with fly ash reduced chloride ion diffusion in the concrete, and increasing the fly ash content further decreased chloride diffusion. They also proposed an equation to calculate the chloride binding capacity based on their test results.

The durability of concrete containing a combination of fly ash and microorganisms was investigated by another study [13], which found that this combination enhanced the concrete's mechanical performance and robustness while reducing hydration heat and water loss. Additionally, the early compressive strength was increased by 30%.

Ortiz-Salcedo et al. [8] investigated the effect of chlorides on fly ash concrete and found that the fly ash content in the concrete had the ability to bind chlorides, which could reduce the possibility of rebar corrosion. A dense pore structure in the concrete also helped to reduce chloride penetration.

According to American Standard Testing and Material (ASTM) C 618 standard, fly ash is classified into Class C and Class F. Previous research has shown that Class F fly ash has greater compressive strength than Class C fly ash [2]. Furthermore, Class F fly ash exhibits better compressive strength and stress-strain behavior than ordinary Portland cement (OPC) [9].

Ibrahim et al. [22] conducted a study on the use of bottom ash as a cementitious material in concrete with regards to compressive strength and chloride resistance. They found that the presence of bottom ash could affect the workability of the concrete mix, but it also resulted in a significant increase in compressive strength after 56 days. The study also showed that bottom ash had low chloride penetration, making it more durable against chloride attack.

In another study, Ramana et al. [28] investigated the use of bottom ash as a replacement for natural fine aggregate in concrete. They found that a 10%-15% replacement was suitable and did not adversely affect the concrete's properties.

Ali et al. [26] studied the use of a combination of silica fume and bottom ash in concrete. They found that replacing 12.5% of cement with silica fume and 30% of fine aggregate with bottom ash resulted in a compressive strength of 38.45 MPa and a flexural strength of 4.74 MPa. Additionally, increasing the bottom ash content enhanced the concrete's durability against sulphate attack.

Reviews suggest that substituting fine natural aggregate or cementitious material with bottom ash can be beneficial, both economically and ecologically, in concrete mixes.

Studies on the combination of FA-BA in concrete mixtures have been conducted [18–21, 30–32]. Kumar and Singh [20] investigated the effect of using recycled aggregates and bottom ash in concrete. Their study showed that including bottom ash decreased the tensile strength by 26%, and the combination of both aggregates resulted in high water absorption properties. Nanda and Rout [21] studied the replacement of fine aggregate with FA-BA and found that the combination increased the splitting tensile strength by 10% more than conventional concrete. However, the proposed mixtures had higher absorption and large pore volume, making them unsuitable for snowy environments. Nonetheless, the proposed mixtures performed better against sulphate and magnesium sulphate attacks.

Studies on the utilization of FA-BA in geopolymer concrete have also been conducted [33-37]. Çevik et al. [33] investigated the durability of geopolymer concrete by immersing specimens in sulfuric acid for 180 and 365 days, which showed an increase in strength loss from 180 to 365 days. On day 180, the strength loss was 81.3% in concrete using cement alone, 69.8% in concrete using cement and fly ash, and 67.6% in concrete using cement, fly ash, and microorganism solution. On the 365th day, the strength decreased to 93.7%, 84.2%, and 83.1%, respectively. These results indicate that fly ash significantly reduces the strength loss in concrete. Jiao et al. [34] conducted experiments on the influence of Class C and Class F fly ash on geopolymer mortars and found that a high content of Class C fly ash with a small water-to-binder ratio and sand-to-fly ash ratio made the geopolymer mortar less fluid and resulted in higher compressive strength. Morla et al. [37] studied the durability of geopolymer concrete with respect to chloride penetration by incorporating FA-BA. The study showed that the FA-BA could decrease the chloride diffusion from 23×10-12 m^2/s in conventional concrete to 4.5×10-12 m^2/s, and the corrosion initiation was delayed from 102 hours to 500 hours.

There have been several review studies on the use of FA-BA as a concrete constituent [38–42]. It is important to consider the use of bottom ash as a replacement for fine aggregate because it can have a negative effect on the mechanical properties of concrete, such as compressive and tensile strength [38, 40]. Utilizing bottom ash as a cementitious material is also challenging due to its lower pozzolanic activity. The replacement of cement with bottom ash should not exceed 10-20%, as a replacement above 30% could lead to a decrease in the compressive and tensile strength of the concrete [39]. Hay and Ostertag [41] reviewed the effect of fly ash on alkali-silica reaction, which showed that fly ash can effectively react with alkali in the long term, resulting in reacted fly ash particles in the dense matrix. This makes it difficult for fly ash to release unbound aluminium into the pores.

Overall, the literature shows that the use of FA-BA can significantly enhance the performance of concrete, making it lighter and more durable than conventional concrete. However, the development of FA-BA studies from South Sumatera is still limited.

3.Material and method

This research is based on an experimental method. The study uses Type 1 Portland cement, fine aggregate, FA-BA, and water as the main materials.

3.1Ordinary Portland cement

The cement used type 1 cement. This cement is ordinary cement without special advantages such as rapid hardening and chemical resistance. The cement chemical composition is shown in *Table 1*. It shows that the SO_3 value was below 4%. It conforms to Standar Nasional Indonesia (Indonesian National Standard) (SNI) 7064 2014 standard about Portland composite cement in Indonesia. The Blaine test is ranged from 3768-4060 cm^2/gr, which above the minimum value 2800 cm^2/gr.

Table 1 Portland composite cement chemical composition

S. No.	Chemical composition	Content (%)
1	SiO_2	17.2
2	Al_2O_3	4.8
3	Fe_2O_3	2.4
4	CaO	58.8
5	MgO	0.8
6	SO_3	1.9

3.2Fine aggregate

The fine aggregate comes from the Martapura River, South Sumatra. The fine aggregate properties are shown in *Figure 1* and *Table 2*. It shows that the fine aggregate sieve analysis result has met for ASTM C 33 (*Table 2*). The results show that the fine texture of aggregate is determined from the sieve analysis. The clay content is below 3.4% which conform to ASTM C33.

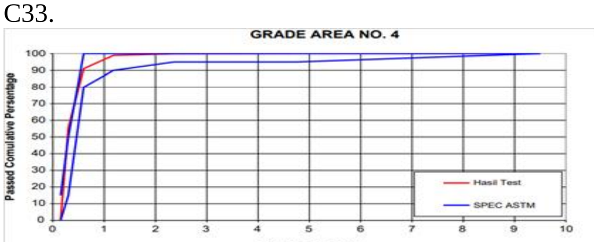


Figure 1 Fine aggregate gradation graph

Table 2 Test results of fine aggregate

S. No.	Description	Test result
1	Saturated Surface Dry	2.24
2	Absorption	2.89%
3	Moisture Content	3.71%
4	Fineness Modulus	1.54
5	Clay content	3.4%

3.3Fly ash

The results of the SEM test with a particle magnification of 2000x show that fly ash particles have a plate-like structure with irregular shapes and angles of different sizes and have many pores (*Figure 2*). So, workability is low and absorbs water highly. While the total chemical composition of SiO_2, Al_2O_3 and Fe_2O_3 in fly ash is 74.95%. Following ASTM C 618 standard the results shows that, the fly ash belongs to class F as shown in *Table 3*.

Figure 3 show the X-ray diffraction (XRD) test result. It shows the fly ash material is consist of Quartz mineral (SiO_2), Gismondine ($CaAl_2Si_2O_8.4H_2O$), Monetite syn ($CaHPO_4$) and Wadsleyite syn ($Mg_{1.5}Fe_{0.5}$ SiO_4) with area crystalline index as 37,078 %, where the crystal phase shows a position at 2θ = 20,8556; 26,6420; 36,5465; 39,4723; 40,3138; 42,3964; 45,8279; 50,1305; 53,5895; 59,9006; 68,1123.

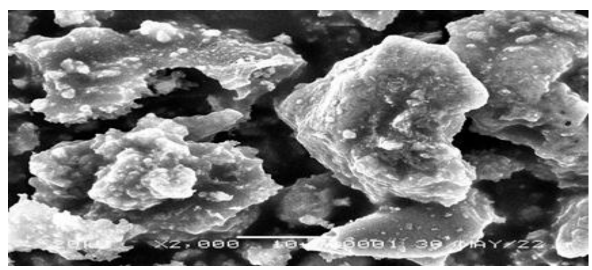


Figure 2 SEM results of Fly Ash

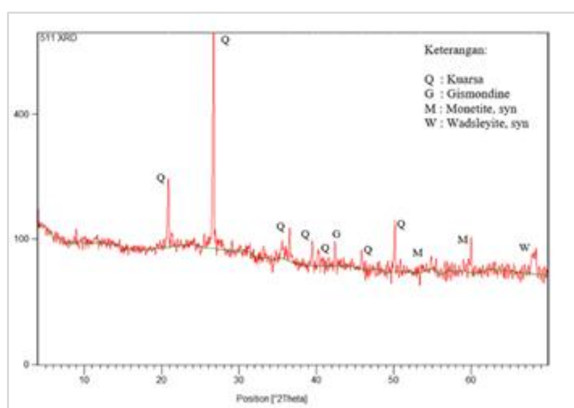


Figure 3 XRD test results in fly ash

Table 3 X-ray fluorescence (XRF) results of fly ash

S. No.	Chemical composition	Content (%)	ASTM C 618 class F (%)	
1	SiO_2	46,53	min (1+2+3)	70
2	Al_2O_3	22,53		
3	Fe_2O_3	5,89		
4	CaO	3,66	Max.	10
5	Na_2O	3,48	-	-
6	MgO	1,36	-	-
7	SO_3	1,13	Max.	5
8	K_2O	0,882	-	-
9	TiO_2	0,700	-	-
10	P_2O_5	0,285	-	-
11	MnO	0,054	-	-

3.4 Bottom Ash

Figure 4 shows the SEM results of bottom ash particle. It has an irregular shape with large pores; thus, it affects the workability of the concrete. High water absorption due to the large pores could resulted in a bad workability in concrete [26, 27].

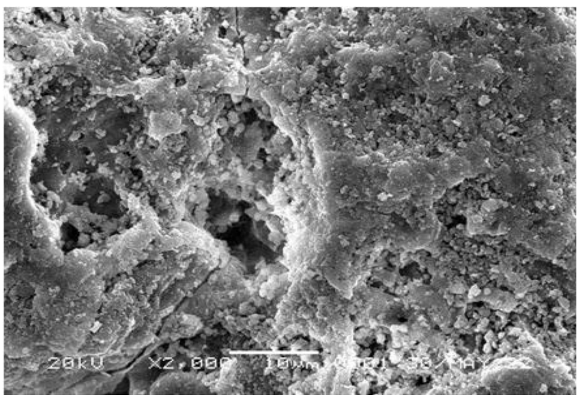


Figure 4 SEM results on bottom Ash

The XRF of bottom ash results show a higher content of SiO_2 with 65.73% and Al_2O_3 with 24.19%. The high content of SiO_2 makes a possibility for bottom ash to have a binding ability with the cement in the late hydration process. The chemical composition of bottom ash is shown in *Table 4.*

Table 4 Bottom Ash chemical composition

S. No.	Chemical composition	Content (%)
1	SiO_2	65,73
2	Al_2O_3	24,19
3	Fe_2O_3	4,63
4	CaO	1,02
5	Na_2O	0,665
6	MgO	0,486
7	SO_3	0,0646
8	K_2O	0,803
9	TiO_2	0,656
10	P_2O_5	0,0559
11	MnO	0,0399

3.5 Lightweight concrete mix composition

This study begins with the preparation of materials and equipment. The materials prepared are type 1 cement, fly ash, bottom ash, water, and fine aggregate. Meanwhile, the equipment prepared is the scales, measuring cylinders, mixers, cube molds, and compressive strength instruments. The next step is to determine the composition of the mixture from the sample plan. The composition of fly ash used was 10%, 20%, 30%, and 40% of cement's total weight. The bottom ash percentage was considered with 30%, 40% and 50% as fine aggregate substitution. Details of the composition of the mixture can be seen in *Table 5.*

Next is the stage of casting the sample. The sample is cast in a cube specimen with 5 cm × 5 cm × 5 cm size, where each specimen of each mix design consists of 12 specimens. After mixing and casting, the molds were released after 24 hours. The specimen was wrapped with plastic wrap for 28 days to cure the concrete once it has been removed from the mold. Then, the testing stage of the test object was performed. The tests looked at the concrete's physical properties, specific gravity, and mechanical properties, such as its compressive strength after 28 days. Testing the resistance of the HCl solution with a potential of hydrogen (pH) range of 6-8 concrete is conducted by dividing the test object into 3 conditions, namely conditions 1, 2, and 3. In the event of condition 1, the test object was left in the room until the day of testing. In this condition, the moisture and the temperature of the room was kept to 25^{o} C. The sample on the first condition is shown in *Figure 5*. In the event of condition 2, the specimens were immersed in a solution for a long-term period until the testing day. HCl as the immersion media is controlled by its pH. The preparation is shown in *Figure 6.*

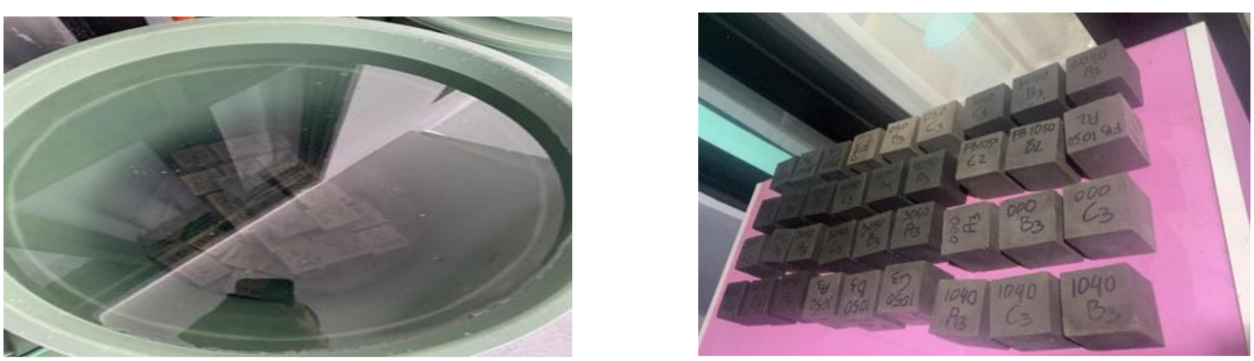
Table 5 Lightweight concrete mixture composition

S. No.	Specimen	OPC (gr)	Fly ash (gr)	Bottom ash (gr)	Fine aggregate (gr)	Water (ml)
1	FL00BO50	500	0	687.50	687.50	484
2	FL10BO40	450	50	550,00	825.00	484
3	FL10BO50	450	50	687.50	687.50	484
4	FL20BO30	400	100	412.50	962.50	484
5	FL20BO40	400	100	550,00	825.00	484
6	FL20BO50	400	100	687.50	687.50	484
7	FL30BO40	350	150	550,00	825.00	484
8	FL30BO50	350	150	687.50	687.50	484
9	FL40BO30	300	200	412.50	962.50	484
10	FL40BO40	300	200	550,00	825.00	484
11	FL40BO50	300	200	687.50	687.50	484

Figure 5 Specimen preparation on condition 1

Figure 6 Specimen preparation on condition 2

In the third condition, the specimens were subjected to a wet-dry cycle. They were immersed in an HCl solution for 24 hours and then removed and kept in an open room for a similar duration as their immersion period. This cycle was repeated continuously until the day of testing, which was 56 days. Each time testing for each condition, pH testing of the solution was carried out, along with weighing and visual testing on all test objects. *Figure 7(a)* shows the specimens being immersed, and *Figure 7(b)* shows them being removed from the solution and exposed to air.



(a) (b)

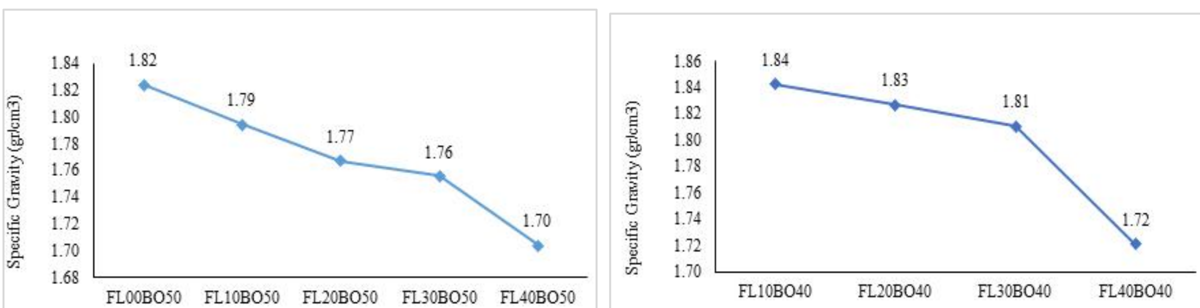
Figure 7 (a) The wet environment and (b) the dry environment

4. Results

In the case of specific gravity tests, FL40BO50 has the highest specific gravity with 1.84 gr/cm^3, while FL20BO30 has the lowest specific gravity with 1.70 gr/cm^3. The specific gravity for the entire mixture was suitable for the requirements specified in ACI 318-14. FL40BO50 has the highest compressive strength, with 25.17 MPa. While the lowest compressive strength with 15.92 MPa was the FL20BO30 specimen. *Table 6* shows the results of concrete specific gravity and compressive strength. The utilization of an additional 10% fly ash may lead to a decline in specific gravity ranging from 0.54% to 4.97%, whereas the incorporation of an extra 10% bottom ash will result in a decrease in specific gravity that ranges from 0.54% to 3.28%, as shown in *Figure 8* for the variation of fly ash and in *Figure 9* for the variation of bottom ash.

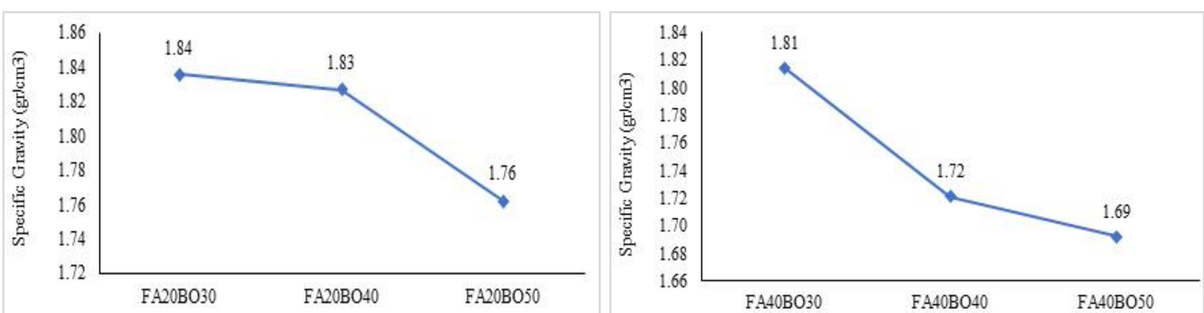
Table 6 Result of specific gravity and compressive strength

S. No.	Specimen	Average specific gravity (gr/cm^3)	Average compressive strength (MPa)
1	FL00BO50	1.82	24.77
2	FL10BO40	1.84	24.51
3	FL10BO50	1.79	21.70
4	FL20BO30	1.84	25.17
5	FL20BO40	1.83	22.51
6	FL20BO50	1.77	21.29
7	FL30BO40	1.81	20.21
8	FL30BO50	1.76	19.75
9	FL40BO30	1.77	18.37
10	FL40BO40	1.72	16.16
11	FL40BO50	1.70	15.92



(a) (b)

Figure 8 Effect of fly ash content on specific gravity (a) the 50% of bottom ash and (b) the 40% of bottom ash



(a) (b)

Figure 9 Effect of bottom ash content on specific gravity (a) the 20% of fly ash and (b) the 40% fly ash

Figure 10 demonstrates that the enhancement in compressive strength is directly proportional to the rise in specific gravity. It also exhibits that the coefficient of determination (R_2) attained is almost equal to one, indicating a strong correlation between the specific gravity and compressive strength of lightweight concrete. The value demonstrates that the results of linear regression analysis were in accordance with the proportionality of specific gravity and compressive strength.

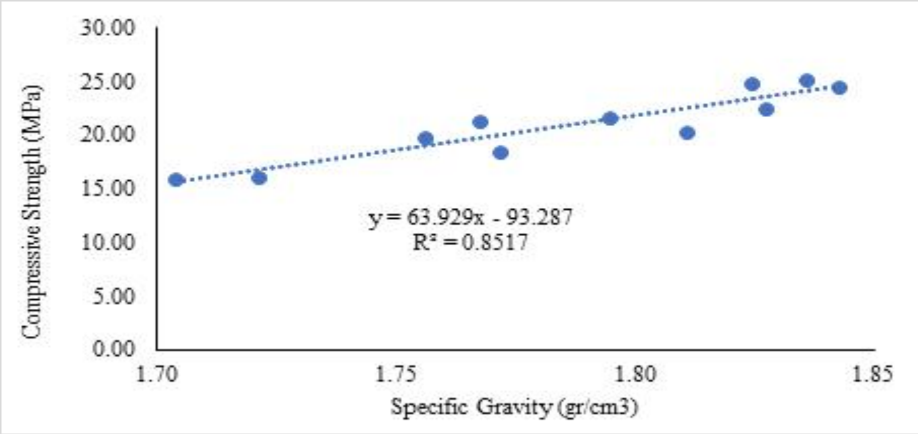


Figure 10 Relationship between compressive strength and specific gravity of lightweight concrete

4.1 HCl resistance test

Table 7 presents the results of the resistance test of HCl in concrete with a substitution of 30% bottom ash. The table indicates that as the fly ash content increases, the mass reduction increases as well, especially when condition 3 is applied. In the case of a 30% bottom ash substitution, the reduction in mass ranges from 0.36% to 2.87%. It can be seen that FL40BO30 experienced a mass reduction of 2.87% from its initial mass in condition 3, while FL20BO30 showed a decrease of 1.03% under the same conditions. *Table 8* illustrates the variation in fly ash with a 40% substitution of bottom ash. The data demonstrates that an increase in bottom ash substitution from 30% to 40% results in a higher mass reduction. The sample FL40BO40 exhibits a significant mass reduction, as shown in *Table 8*, under all conditions. The mass reduction ranges from 0.46% to 3.79% for a 40% bottom ash substitution. *Table 9* presents the results of the mass reduction for a 50% substitution of bottom ash. The mass reduction ranges from 0.61% to 4.81%. The FL40BO50 sample shows the highest mass reduction among all the samples, with a reduction of 10.30 gr. The *Tables* from *7* to *9* indicate that an increase in FA-BA substitution results in a higher mass reduction. The specimens under condition 3 exhibit a higher mass reduction than the others. *Figure 8* provides a graphical representation of the overall mass reduction for each sample.

The FL40BO50 specimen experienced the highest mass loss, with a reduction of 4.81%. This demonstrates that a higher substitution of FA-BA leads to a greater decrease in mass. The data in *Tables 7* to *9* demonstrates that specimens under condition 3 underwent a significant mass reduction, while those under condition 1 had a lower mass reduction compared to the others. The relationship between specific gravity and mass reduction is illustrated in *Figure 11*.

Table 7 Mass reduction at each condition test for 30% substitution of bottom ash

S.No.	Specimen	Condition 1	Condition 2	Condition 3
		Average mass reduction (gr)	Average mass reduction (gr)	Average mass reduction (gr)
1	FL20BO30	-0.83	-1.49	-2.36
2	FL40BO30	-2.09	-4.14	-6.32

Table 8 Mass reduction at each condition test for 40% substitution of bottom ash

S. No.	Specimen	Condition 1	Condition 2	Condition 3
		Average mass reduction (gr)	Average mass reduction (gr)	Average mass reduction (gr)
1	FL10BO40	-1.07	-1.98	-2.56
2	FL20BO40	-1.96	-3.90	-5.49
3	FL30BO40	-2.06	-4.27	-5.38
4	FL40BO40	-3.14	-5.78	-8.20

Table 9 Mass reduction at each condition test for 50% substitution of bottom ash

S. No.	Specimen	Condition 1	Condition 2	Condition 3
		Average mass reduction (gr)	Average mass reduction (gr)	Average mass reduction (gr)
1	FL00BO50	-1.41	-2.15	-2.99
2	FL10BO50	-1.87	-3.34	-4.11
3	FL20BO50	-2.67	-4.20	-5.95
4	FL30BO50	-2.95	-5.11	-8.50
5	FL40BO50	-3.43	-7.43	-10.30

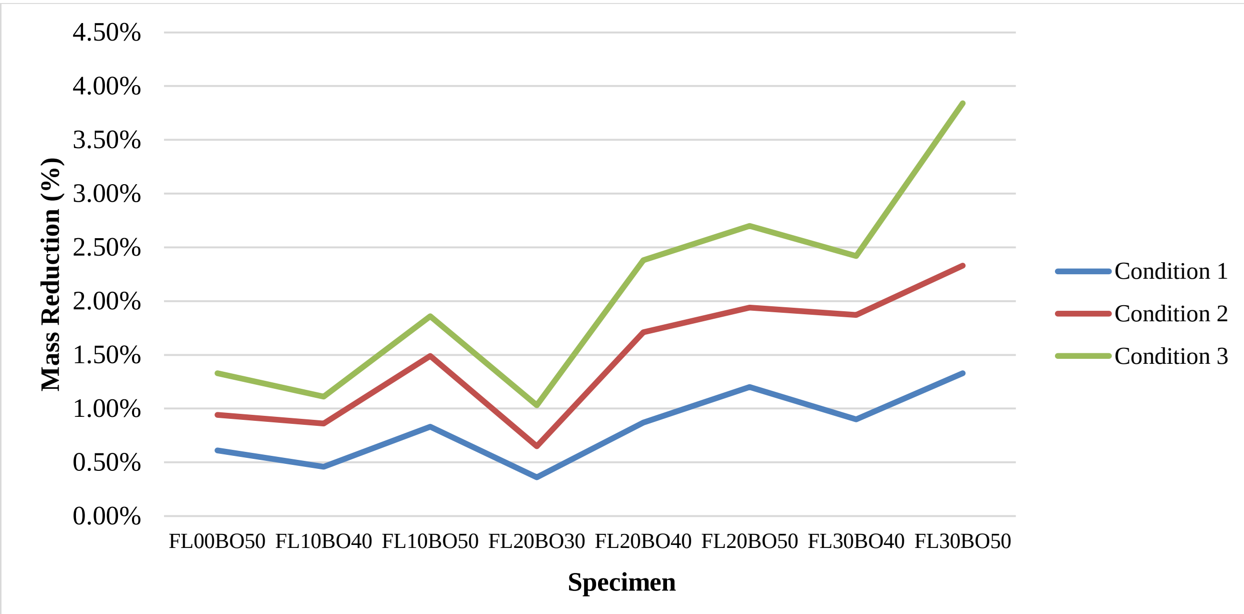


Figure 11 Overall mass reduction in each sample

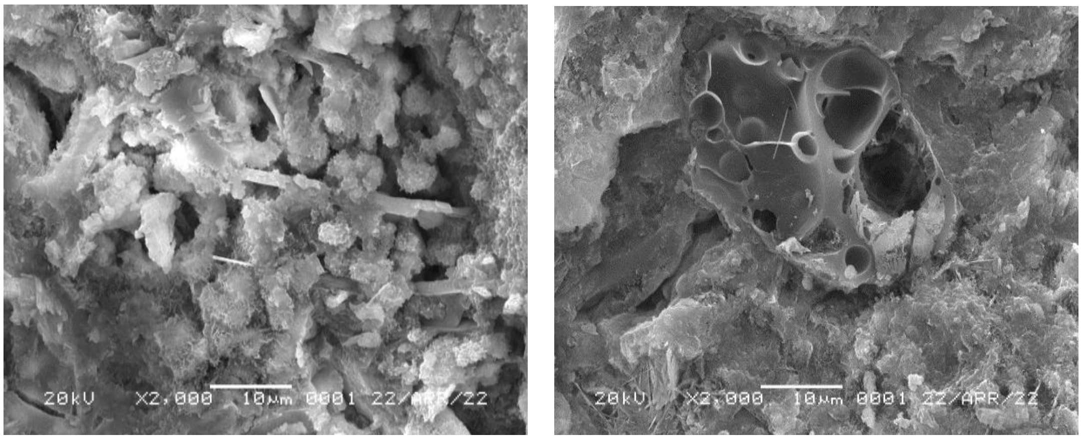
4.2 Effect of HCl in microstructural analysis

Figure 12 presents the results of the condition 1, SEM, which depicts an unbonded mixture of FA-BA. This creates numerous pores in the concrete. Although the presence of pores in the FL20BO30 mixture is visible, it still demonstrates a higher compressive strength than the other types of concrete. *Figure 12 (b)* highlights a larger pore size in the concrete, which is associated with a lower compressive strength achieved by the FL40BO50 mixture.

Figure 13 displays the SEM results for condition 2, which shows a similar microstructure as condition 1. In the FL20BO30 mixture, small pores are present despite the coverage of bottom ash and fly ash particles by the calcium silicate hydrate (CSH) matrix. Conversely, the FL40BO50 mixture exhibits a large number of unreacted fly ash particles, which serve as fillers in concrete rather than as cementitious materials. The long-term immersion in a chloride solution weakens the bonding between the constituent materials, leading to the creation of a larger number of pores.

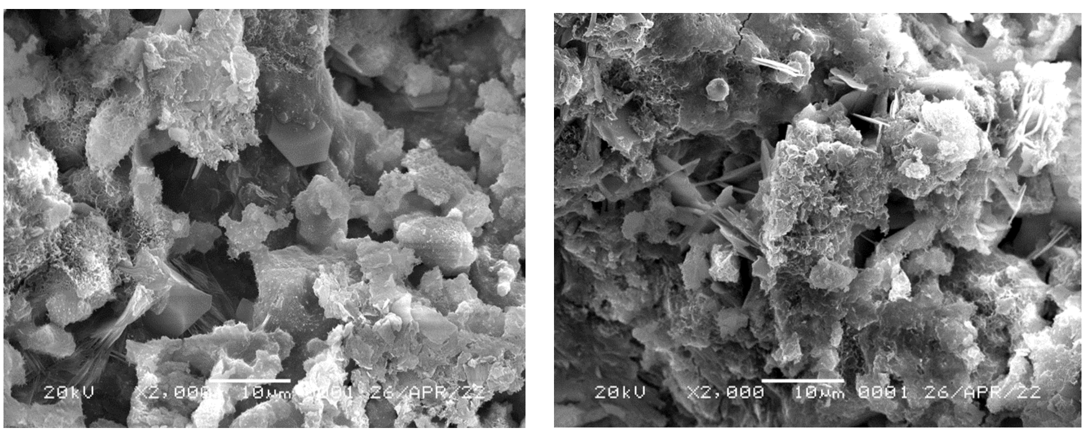
Figures 14 (a) and *14 (b)* illustrate the contrast between FL20BO30 and FL40BO50, respectively. *Figure 14 (a)* shows that FL20BO30 generates a significant amount of CSH with plate-like patterns and a dense microstructure, resulting in a lower mass reduction in condition 3 tests. In contrast, *Figure 14 (b)* reveals a lack of CSH formation due to the high FA-BA substitution in the mixture, which leads to the formation of microcracks and a high mass reduction for the FL40BO50 sample.

Figure 12 shows the relationship between specific gravity and mass reduction, demonstrating that the specimens in condition 3 exhibit a higher mass reduction compared to those in condition 1. Specimens with a lower specific gravity experience a higher mass loss compared to those with a higher specific gravity. *Table 6* shows that FL40BO50, with a specific gravity of 1.70 gr/cm^3, has the lowest specific gravity and the highest mass reduction. From *Figure 12* to *Figure 14*, the microstructure of specimens in condition 3 is severely degraded, as evidenced by the formation of microcracks in concrete of varying compressive strengths. The wet-dry cycles induce the formation of these microcracks, leading to a decrease in compressive strength due to the presence of pores and microcracks in the concrete.



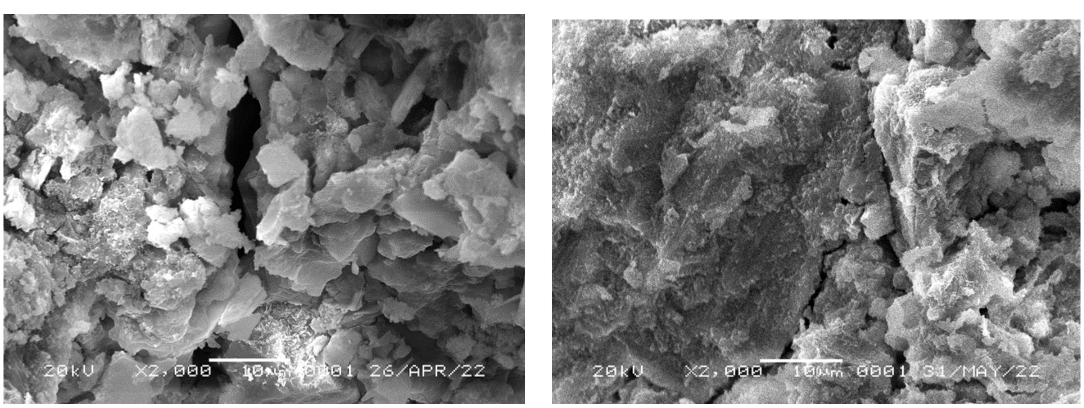
(a) FL20BO30 (b) FL40BO50

Figure 12 A contrast difference is observed between lower (a) and higher (b) mass reductions in condition 1



(a) FL20BO30 (b) FL40BO50

Figure 13 A contrast difference between a lower (a) and higher (b) mass reduction in condition 2



(a) FL20BO30 (b) FL40BO50

Figure 14 A contrast difference between a lower (a) and higher (b) mass reduction in condition 3

4.3Relation of compressive strength and mass losses

Relationship between the compressive strength of lightweight concrete and its resistance to HCl attack under various conditions is depicted in *Table 10*. The table also demonstrates the correlation between mass reduction and the resulting compressive strength.

Table 10 Relation of compressive strength and mass reduction

S. No.	Specimen	Average compressive strength (MPa)	Condition 1 Average mass reduction (gr)	Condition 2 Average mass reduction (gr)	Condition 3 Average mass reduction (gr)
1	FL00BO50	24.77	0,61%	0,94%	1,33%
2	FL10BO40	24.51	0,46%	0,86%	1,11%
3	FL10BO50	21.70	0,83%	1,49%	1,86%
4	FL20BO30	25.17	0,36%	0,65%	1,03%
5	FL20BO40	22.51	0,87%	1,71%	2,38%
6	FL20BO50	21.29	1,20%	1,94%	2,70%
7	FL30BO40	20.21	0,90%	1,87%	2,42%
8	FL30BO50	19.75	1,33%	2,33%	3,84%
9	FL40BO30	18.37	0,98%	1,86%	2,87%
10	FL40BO40	16.16	1,48%	2,69%	3,79%
11	FL40BO50	15.92	1,61%	3,50%	4,81%

In Condition 1, the test showed a maximum mass reduction of 1.61%. The lower mass reduction was attributed to the hydration process and evaporation of excess water in the concrete, resulting in minimal impact on the concrete's mass reduction. In Condition 2, the test revealed the effects of long-term immersion in a chloride solution, resulting in a higher mass reduction compared to Condition 1, but still lower than Condition 3. The long-term immersion caused a mass reduction ranging from 0.94% to 3.50%.

The study found that the compressive strength of lightweight concrete has a direct correlation with its resistance to HCl attack. In particular, concrete with lower compressive strength such as FL40BO50 exhibited greater loss of mass due to higher HCl attack or less resistance to it, whereas concrete with higher compressive strength such as FL20BO30 displayed lower mass reduction. The SEM results in *Figure 7(a)* revealed that FL20BO30 had denser bonding between particles, which was associated with its higher compressive strength.

5. Discussion

The results of the study revealed that the composition of fly ash-blast furnace slag (FA-BA) in concrete has a significant impact on its specific gravity. Increasing the amount of FA-BA in the mix resulted in lighter concrete. The lightest concrete in the study had a specific gravity of 1.70 g/cm^3 in the FL40BO50 mix, which had the highest substitution for cement and fine aggregate. However, this concrete also had the lowest compressive strength at 15.92 MPa.

The study found that the resistance to chloride attack is related to the content of waste materials in the concrete. The concrete with a higher content of waste materials showed the highest mass reduction of 4.81% in the chloride resistance test. A high content of FA-BA generally leads to low specific gravity and compressive strength. The microcracks observed in *Figure 14(b)* provided evidence that condition 3 was a destructive environment for the lightweight concrete.

The study also observed a relationship between the resistance to chloride attack and specific gravity of concrete. In all test conditions, the lowest specific gravity tended to have the highest mass reduction, while a higher specific gravity led to a lower mass reduction, as seen in the FL20BO30 specimen with a 1.03% reduction in condition 3. Furthermore, a higher specific gravity and compressive strength made the concrete more resistant to chloride attacks, as demonstrated by the lower mass reduction observed in FL20BO30 in all conditions. The microscopic analysis in *Figures 12* to *14* also supported this conclusion. Condition 3 showed a higher number of microcracks and larger pores compared to conditions 1 and 2. The higher amount of FA-BA content tended to reduce compressive strength. It is important to note that this study was limited to testing the resistance of FA-BA lightweight concrete to HCl. The FA-BA material used in the study was sourced from South Sumatera, Indonesia. The results were limited to testing compressive strength, density, mass loss due to HCl exposure, and microstructural evaluation. Comparisons with other studies are shown in *Table 11*, which indicates that the current study showed better performance in resisting HCl attack, while other studies showed better performance in resisting sulfate attack. The low compressive strength observed in this study is likely due to differences in material characteristics, composition, mixing methods, and curing procedures compared to other studies. A complete list of abbreviations is shown in *Appendix I.*

Table 11 Comparison with other studies

Study	Highlighted composition	Compressive strength (MPa)	Result on durability test
Current Study	FA-BA	25.17	Better results facing the HCl attacks
Ali et al. [26]	Silica fume and Bottom ash	38.45	Excellent resistance against sulphate
Huseien et al. [13]	Fly ash and microorganism	42.49	Improve sulphate resistance
Hasim et al. [19]	FA-BA	34.26	No durability test
Nanda and Rout [21]	FA-BA	36.9	Better resistance to sulphate attack

6. Conclusion and future work

Based on the test results, the FL40BO50 composition of lightweight concrete demonstrated the lowest specific gravity of 1.70 gr/cm^3 and compressive strength of 15.92 MPa, while the most optimal specific gravity and strength were shown by FL20BO30 with 1.84 gr/cm^3 and a compressive strength of 25.17 MPa. It was observed that lightweight concrete made with a denser and tighter microstructure from FA-BA, which had higher specific gravity and compressive strength, experienced less mass loss or was not susceptible to HCl attack. On the other hand, lower specific gravity and compressive strength made the lightweight concrete highly vulnerable to HCl attack.

The results of this study suggest that the proposed mix design has the potential for structural applications in construction and can be used for beams, columns, or slabs. Depending on the requirements, it can be made with either precast or cast in situ methods. The use of lightweight concrete as structural members could significantly reduce building mass, and incorporating FA-BA could contribute to sustainable construction practices in Indonesia. However, additional research needs to be conducted to ensure the suitability of the proposed mix design for structural use. Utilizing this mix design could also have the potential to increase regional income in South Sumatera.

In conclusion, the study highlights the potential of using lightweight concrete with FA-BA for structural applications, which could benefit the construction industry in Indonesia. However, further research and testing are necessary to confirm the structural suitability of this mix design.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Panca Kola: Draft writing, paper framework concept, revise the paper, conduct the study and result analysis. **Saloma:** Study conceptualization, Supervise the conducted study and checking the study result. **KM Aminuddin:** Study conceptualization, supervise the conducted study and checking the study result. **Fathoni:** Study conceptualization, supervise the conducted study and checking the study result.

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Appendix I

S. No.	Abbreviation	Description
1	ASTM	American Standard Testing and Material
2	CSH	Calcium Silicate Hydrate
3	ESP	Electrostatic Precipitation
4	FA-BA	Fly Ash – Bottom Ash
5	HCl	Hydrochloric Acid
6	OPC	Ordinary Portland Cement
7	pH	Potential Hydrogen
8	SEM	Scanning Electron Microscope
9	XRD	X-Ray Diffraction
10	XRF	X-Ray Fluorescence