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CORROSION RESISTANCE ASSESSMENT OF STEEL BARS EMBEDDED IN THE CIRCULATING FLUIDIZED BED OF FLY ASH AND BOTTOM ASH CONCRETE

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ABSTRACT: This study investigates the integration of industrial waste, specifically fly ash (FA) and bottom ash (BA), as sustainable substitutes for cement and sand in concrete production. The utilization of these materials addresses environmental concerns related to natural resource depletion and waste accumulation from coal-fired power plants. FA and BA were used at varying proportions (15% FA:50% BA and 30% FA:50% BA) in concrete mixtures. The mechanical properties, including compressive and flexural strengths, were evaluated at 7, 28, and 90 days, alongside an accelerated corrosion test to assess chloride-induced corrosion resistance. Microstructural analysis using Scanning Electron Microscopy (SEM) further complemented the study. The results revealed that the 15% FA:50% BA mixture achieved the highest compressive strength and demonstrated superior resistance to chloride-induced corrosion, attributed to enhanced microstructure densification through pozzolanic reactions. However, both FA-BA mixtures exhibited lower flexural strength compared to control concrete, highlighting the brittleness introduced by the substitutions. SEM analysis confirmed reduced porosity and improved particle bonding in the modified mixtures. These findings suggest that a mix of 15% FA and 50% BA provides an eco-friendly and durable alternative for concrete applications in chloride-exposed environments, with future potential for optimizing flexural properties through fiber reinforcement.

Keywords: Fly ash, Bottom ash, Durability, Corrosion resistance, Sustainable construction materials.

1. INTRODUCTION

Concrete is among the most commonly used building materials globally. However, the rising demand for concrete has led to increased usage of cement and natural aggregates, raising significant worries about resource depletion and adverse environmental impacts [1]–[5]. Coarse and fine aggregates, which make up the majority of concrete's volume, primarily rely on natural sources. Unfortunately, these sources, particularly river sand, are becoming scarcer due to over-extraction and regulatory measures [3]. This highlights the pressing need for sustainable practices in the construction industry. Therefore, there is a demand for the creation of alternative, sustainable materials that can partially substitute traditional components.

For many years, coal-fired thermal power plants have produced coal fly ash (FA) and bottom ash (BA), which are by-products generated from the combustion of pulverized coal in steam power plant facilities. FA comprises about 80-90%, while BA accounts for 10-20% from the coal sector and coal-fired power plants. According to the 2021 data from Indonesia's Ministry of Energy and Mineral Resources, coal-fired power plants generated between 6 and 11 million tons of FA and BA annually [6]. The amount of solid waste is expected to keep increasing, necessitating improved waste management strategies to prevent risks to the community. As a result, notable advancements have been made in circulating fluidized bed combustion technology to address this issue [7]. Circulating fluidized bed coal-fired technology is a contemporary and efficient approach to coal-based power generation, providing numerous benefits such as enhanced efficiency, reduced emissions, and improved economic viability [8]. Government Regulation (PP) Number 22 of 2021, which pertains to the Implementation of Environmental Protection and Management, has redefined the classification of fly ash and bottom ash.

The durability of concrete can be improved by adding circulating fluidized bed combustion fly ash (CFBFA), as shown by various studies [9], [10]. The use of CFBFA as a supplementary cementitious material greatly improves its resistance to ion penetration and the alkali-silica reaction, as well as its resistivity and formation factor [11]. Several research studies have explored how coal bottom ash (CBA) affects the fresh, mechanical, and durability properties of concrete, as documented in various sources. The chemical and physical attributes of CBA vary depending on different sources and years of analysis, influenced by the coal combustion system. With a high silica content, CBA exhibits pozzolanic characteristics. Numerous experiments have demonstrated that CBA can be used in specific proportions to improve workability and enhance concrete strength and durability [12]. The compressive strength of concrete was found to increase when utilizing up to 20% bottom ash [13]. Incorporating 5–20% bottom ash as a replacement for sand can result in the production of fly ash blended cement concrete with a strength exceeding 30 MPa at 28 days [14]. It is feasible to create concrete with 20% CBA that exhibits strength comparable to plain concrete at 47 MPa [15].

Utilizing these two materials together can enhance the utilization of disposal wastes and reduce environmental impacts [16], [17]. Rafieizonooz, M. et al. [18] examined the effect of substituting sand with bottom ash (BA) at 25 – 100% in concrete that used fly ash (FA) as a cement substitute at 20%. The results showed that the compressive strength of 100% BA and 30% FA concrete at an initial age of 28 days was lower than normal concrete. However, the difference in concrete compressive strength values decreases as the curing time increases at 90 and 120 days. The binding reaction facilitated by cement is supported by the pozzolanic properties of FA and BA, resulting in this effect. Other research increasingly shows that adding BA as a substitute for sand causes the pore size and water absorption level to increase [19]. However, the use of surface-dry BA can reduce pores and mortar water absorption due to the pozzolanic reaction between BA and sand, thereby increasing particle bonding in the mortar core.

Fly ash (FA) possesses a smaller particle size compared to cement and is rich in silica and aluminum, which can improve cement hydration. This similarity makes it possible for FA to partially replace raw materials in concrete. Furthermore, FABA can function as a low-content filler. In soil stabilization, where cement is typically utilized, the properties of FABA indicate its potential as a binding agent for geotechnical layers. The traits of FABA are influenced by the quality of coal, combustion methods, and cooling techniques, necessitating direct testing from coal-fired plants to determine its suitability for civil construction. While existing research predominantly examines FA or BA individually, there is a scarcity of studies investigating their combined effects in concrete formulations. Most research on BA concentrates on its pozzolanic characteristics, whereas FA has received extensive attention as a cement replacement; however, the joint effects of using both FA and BA together remain largely unexamined. [20].

This study intends to investigate the mechanical and durability characteristics of concrete that includes a blend of fly ash and bottom ash. The research particularly assesses the compressive and flexural strengths, as well as the corrosion resistance of reinforced concrete specimens. By carefully examining the microstructural alterations caused by these materials, this study offers new insights into their practical uses and the potential for enhancing performance. The findings contribute to a broader understanding of SCM usage and provide practical recommendations for sustainable construction approaches. The research method includes a comparative study of concrete blends that utilize varying proportions of fly ash and bottom ash. The findings will be assessed through mechanical evaluations, corrosion tests, and scanning electron microscopy (SEM) to examine alterations in pore structure. These results will aid in verifying the efficacy of these materials in improving concrete performance while simultaneously promoting environmental sustainability.

2. RESEARCH SIGNIFICANCE

Some industrial waste can be used partially or fully as a substitute for cement and sand in concrete with performance equivalent to cement and sand. In order to assess the suitability of FABA for civil construction purposes, it is essential to conduct direct testing on the quality of FABA derived from coal-fired power plants. The findings of this research provide grounds for the potential use of FABA as a substitute material in concrete production to create cost-effective and eco-friendly concrete. The research will specifically concentrate on the utilization of FABA that remains largely untapped. This research will concentrate on examining the ability of FABA concrete to withstand corrosion caused by chloride exposure in construction applications. Also, the study used microstructural analysis using SEM to illustrate how FA and BA diminish porosity and improve the density of the concrete matrix, providing insights into the synergistic behavior of the materials.

3. MATERIAL AND METHODS

The research utilized natural sand, coarse aggregate, fly ash, bottom ash (FABA) and Portland cement composite. The components, including cement, fine and coarse aggregate, water, and FABA concrete materials, were initially weighed under saturated surface dry (SSD) conditions in accordance with the mixture composition. This study combines FA and BA as replacements, with FA serving as a substitute for cement and BA as a substitute for fine aggregate. FA is used as a substitute for cement at levels of 15% and 30%, which are the minimum and maximum limits specified by SNI 7064:2014 for its use in cement mixtures. While BA is used at a level of 50%, based on previous research by [18], [19], [21], that identifies this as the optimal limit for its use in concrete mixtures.

The proportions of FA and BA as substitutes for cement and sand are 15%FA:50%BA and 15%FA:50%BA, respectively. Tests to assess the mechanical properties, specifically compressive strength, were conducted using cylinders measuring 150 mm x 300 mm at 7, 28, and 90 days, while flexural strength tests were performed on concrete specimens measuring 400 mm x 100 x 100 mm at 28 and 90 days. Furthermore, a test for chloride-induced corrosion was carried out to evaluate the corrosion resistance of FABA concrete when exposed to chloride. Additionally, microstructure testing using scanning electron microscopic (SEM) was conducted on FA and BA materials. The test results have been thoroughly analyzed and discussed, with their performance being compared to the relevant regulations that govern the use of concrete as a building material. The objective is to utilize the findings of this study in order to create innovative products, such as environmentally friendly, cost-effective, and sustainable concrete materials.

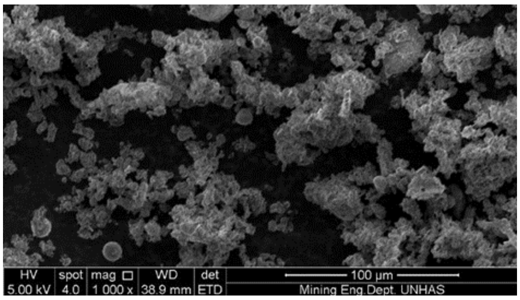


Fig. 1 SEM image of FA

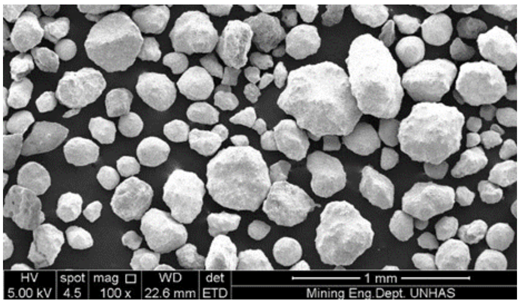


Fig. 2 SEM image of BA

The composition of FA (fly ash) and BA (bottom ash) from the X-ray fluorescence (XRF) test is presented in Table 1. The primary components of FA are SiO_2 (59.16%), Fe_2O_3 (6.25%), Al_2O_3 (25.31%), and CaO (3.21%). On the other hand, the main components of BA are SiO_2 (35.22%), Fe_2O_3 (5.82%), Al_2O_3 (8.13%), and CaO (7.96%). The microstructure of FA consists of irregular and spherical-shaped particles, predominantly with porous surfaces (Fig. 1), whereas the microstructure of BA is characterized by uniformly sized spherical particles with smooth surfaces (Fig. 2).

The concrete mix design was carried out using a trial mix process to obtain a proportional mix composition for concrete with a quality target of f'c is 21 MPa with a water-cement factor of 0.49. Three variations of the concrete mix were made using FABA as a cement and fine aggregate substitute using the weight ratio method. This research used control concrete (C) without FABA to compare the performance of FABA concrete. Fly ash (FA) was used at 15% and 30% as a cement substitute, while bottom ash (BA) was used at 50% as a sand substitute (15%FA:50%BA and 15%FA:50%BA). Table 2 shows the concrete mix design with the replacement of FABA. To achieve the slump target of 12 ± 2 cm, a superplasticizer of ranging from 0.5% to 2% of the total weight of cement and fly ash is used.

3.1 Compressive Strength Test

Compressive strength test is a key indicator of concrete quality. In this study, SNI 1974:2011 was adopted for compressive strength test. This was conducted on cylindrical concrete specimens with a diameter of 100 mm and a height of 200 mm at ages 7, 28, and 90 days. The load was applied at a rate of 0.15 MPa/s until the specimens failed. Compressive strength was calculated using the Eq.1:

$$f'c = P/A \tag{1}$$

where f'c is the compressive strength (MPa), P is the maximum load (N), and A is the cross-sectional area (mm^2).

Table 1 The composition of FA and BA from X-ray fluorescence (XRF) test

Material	Weight (wt.%)								
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	LOI
FA	3.21	59.16	25.31	6.25	0.48	0.31	1.06	0.38	3.31
BA	7.96	35.22	8.13	5.82	0.97	3.33	0.91	0.75	2.12

Table 2 Concrete mix design

Mix ID	Water (kg/m^3)	Cement (kg/m^3)	FA (kg/m^3)	Sand (kg/m^3)	BA (kg/m^3)	Coarse Aggregate (kg/m^3)	Superplasticizer (kg/m^3)
C	236	486	0	741	0	1115	0
15%FA50%BA	236	413.1	72.9	370.5	370.5	1115	3.89
30%FA50%BA	236	340.2	145.8	370.5	370.5	1115	6.41

3.2 Flexural Strength Test

Flexural strength testing refers to SNI 4431:2011 using the two-point loading method. In this method, a concrete beam sample measuring 10 cm x 10 cm x 40 cm is installed on two supports with a 30 cm clear span. The loading point is placed at a distance of 10 cm from each support, as in Figure 3. The loading speed is 0.1kN/s until the test object fails. Flexural strength was determined using Eq. 2:

$$f_r = (P.L)/(B.H^2) \quad (2)$$

where, fr: flexural strength (MPa), P: load at failure (N), L: distance between specimen support (mm), B: width of specimen (mm) and H: height of specimen (mm). The test results are based on the average of three samples for each variation.

Fig. 3 Flexural strength test setup using the two-point loading method

3.3 Acceleration Corrosion Test

Testing will employ cylindrical concrete specimens (100x200 mm) with 16 mm deformed steel bars (100 mm length). Accelerated corrosion testing will be performed after curing specimens for 0, 24, 48, 72, 96, 120, and 144 hours to investigate stage effects. The specimens will be submerged in a 3% NaCl solution, and a continuous voltage (10V) will be applied to expedite the corrosion process. The top 20 cm of the test specimen was left in contact with air, allowing oxygen to seep into the concrete. Figure 4 shows a schematic of the accelerated corrosion test setup. Every 24 hours, the test object's current is turned off for an hour, and a half-cell potential (HCP) test is performed on the reinforcement using an Ag/AgCl type reference electrode. For one test item, HCP testing was conducted at four spots on each side. The HCP values were utilized to assess the amount of reinforcement corrosion according to ASTM C876-15. HCP values > -200 mV are classified as "90% no corrosion," -200 mV > HCP > -350 mV are classified as "uncertainty condition," and HCP < -350 mV are classified as "90% corrosion".

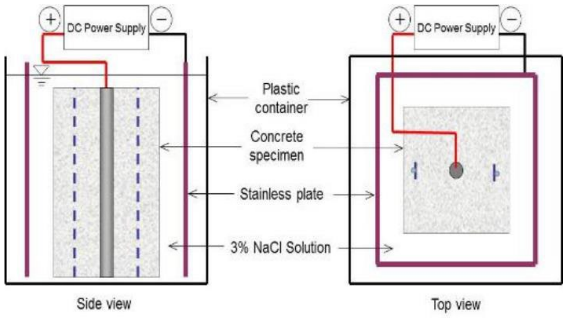


Fig. 4 Schematic of the accelerated corrosion test

3.4 Scanning Electron Microscopy (SEM)

SEM is a strong imaging method that uses a focussed electron beam to study material surfaces. It generates signals from electrons interacting with sample atoms to reveal topography and composition. SEM shows microstructural elements that affect concrete performance, making it useful in concrete investigation. Current SEM methods have significant drawbacks, including a semi-automated, unadaptable procedure. This makes analyses time-consuming and limits concrete sample kinds and magnifications.

4. RESULTS AND DISCUSSION

4.1 Workability

The slump test results are presented in Table 3. When adding FABA to concrete, it is necessary to use a superplasticizer (SP) to achieve the desired slump of 10 - 14 cm. The higher the amount of FA in the mix, the more SP is needed. However, adding BA to the mix does not significantly affect the SP requirement. This is because the spherical shape of the BA particles creates a ball-bearing effect in the fresh concrete mix. The SP value needed to reach the slump target still falls within the specified range of 0.3% - 2% by weight of cement, ensuring that the concrete remains free from segregation.

Table 3. Superplasticizer requirements for slump test

Mix ID	Slump (cm)	SP (%)
C	13	0
15%FA50%BA	12.6	0.8
30%FA50%BA	12	1.32

4.2 Compressive Strength Test

Figure 5 shows the compressive strength values at 7, 28 and 90 days for each concrete variation. Compressive strength increases with increasing concrete age. Increasing compressive strength indicates that FABA can synergize well with the concrete mixture. The 15%FA50%BA concrete mixture produces the highest compressive strength value of all the variations. This increase in strength over time can be attributed to the additional pozzolanic reactions resulting from FA and BA. This aligns with the study by Rafieizonooz et al., which observed increased compressive strength in concrete mixtures using FA and BA up to a certain threshold [18]. On the other hand, the 30%FA50%BA concrete mixture demonstrates lower compressive strength compared to the 15%FA50%BA concrete mixture. This is due to a smaller amount of cement in the mixture, which reduces the availability of $Ca(OH)_2$ needed to react with silica from FA, thereby hindering the pozzolanic reaction process in mixtures containing more than 15% FA. Concerning the reduction of strength, data in research such as Arunachalam et al. indicate that high admixture ratios impair compressive strength due to insufficient $Ca(OH)_2$ for pozzolanic processes [22].

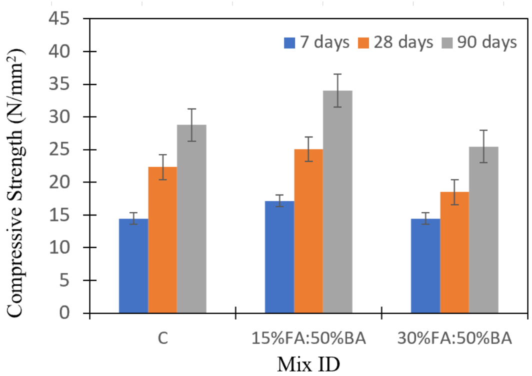


Fig. 5 Compressive strength

4.3 Flexural Strength

The results of the flexural strength are shown in Figure 6. The control concrete specimen has the highest flexural strength at 28 days, while the FA30%BA50% variation has the smallest flexural strength and is related to the added material. Substitution of FABA in the mixture resulted in changes in flexural strength values. The flexural strength of FA15%BA50% and FA30%BA 50% has a lower flexural strength of 10.44% and 15.38% respectively compared to control concrete. The test results show that the addition of FABA to the mixture causes the concrete to become brittle so that it is weak in carrying bending loads. Meanwhile, at 90 days, the trend of flexural strength values showed that the mixture of 15%FA50%BA produced greater flexural strength values than control concrete (C), but FA30%BA50% is still below. This is in line with the 90-days compressive strength results, where additional pozzolanic reactions occurred between $Ca(OH)_2$ from cement and silica from FA. The results of this reaction cause the pores of the concrete to decrease and produce a dense microstructural structure. This results in a greater flexural strength value when compared to control concrete (C). The addition of FABA resulted in a reduction of flexural strength, especially at 30% FA, likely attributable to the brittleness of the combination. This is consistent with Suda et al., who found a negative association between the increase in additional materials and flexural strength [23]. The improvement after 90 days indicates late-stage pozzolanic action, resulting in partial recovery.

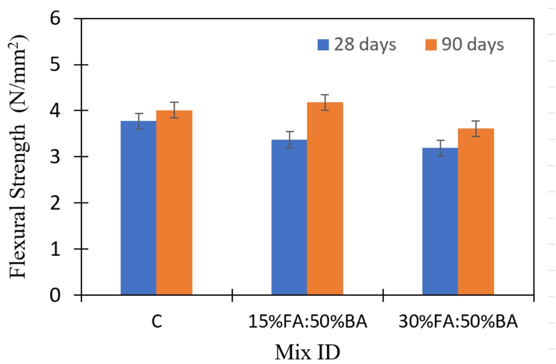


Fig. 6 Flexural strength

4.4 Acceleration Corrosion Test

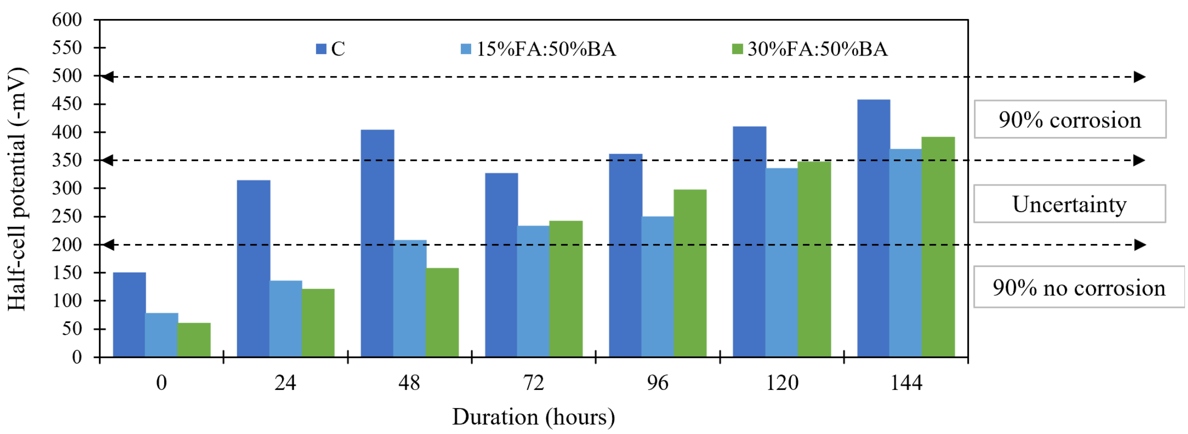


Fig. 7 HCP value of concrete aged 28 days

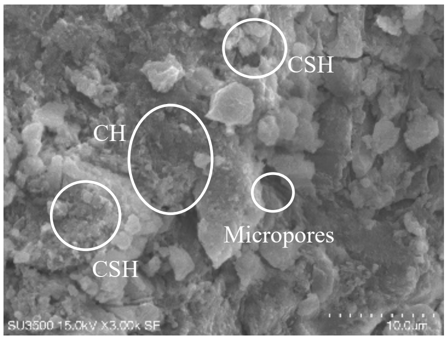
The half-cell potential (HCP) test results of concrete specimens with 15%FA50%BA and 30%FA50%BA as a cement and sand substitute at the age of 28 days are presented in Figure 7. The results show that the HCP value of all specimen before corrosion acceleration is in the "90 no corrosion" condition. As acceleration time progresses, the HCP value increases for all test objects. For the first 24-hour period, the HCP value of the test object ranged from 200 mV to 340 mV, which indicates that the process of passive breaking of the reinforcement film is underway. In the test specimens that used FA as a cement substitute and BA as a sand substitute, the corrosion rate was recorded to be slower when compared to control concrete. In the 96 hours, the control test object without FABA showed corrosion initiation, with the HCP value of the test object was 368 mV. Meanwhile, the HCP value of 15%FA50%BA and 30%FA50%BA concrete ranges from 265 mV to 280 mV and is still in the "uncertainty" category. This condition is caused by the synergy between FA and BA in the concrete mixture, which is able to reduce the pores in the concrete, which has implications for increasing the compressive strength value. High compressive strength values can produce excellent corrosion resistance. So, a concrete mixture with 15%FA as a cement substitute and 50% BA as a sand substitute can be an option for concrete designs exposed to environments containing high chloride ions. Enhanced corrosion resistance due to reduced chloride permeability aligns with Yalley's findings, emphasizing the synergy of FA and BA in mitigating corrosion [24]. The use of SEM to validate microstructural improvements, such as pore reduction, supports broader claims on densification benefits of fly ash-based concrete.

4.5 Visual Observation

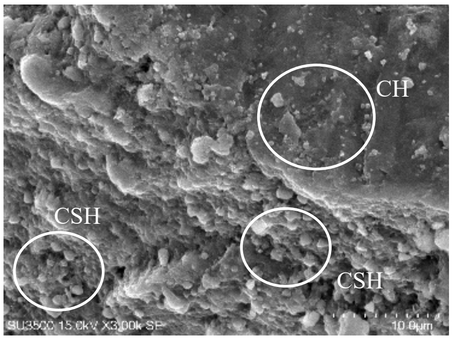
Figure 8 shows the condition of the test specimen after the corrosion acceleration test. It is clearly seen that the control test specimen without FA experienced significant damage due to corrosion, where a large amount of corrosion products covered the surface of the test specimen. Meanwhile, the corrosion products produced in concrete with FA is relatively less than in control concrete without FA. 15% of FA concrete shows very good corrosion resistance due to the contribution of additional pozzolanic reactions from FA, which cover the pores of the concrete and inhibit the rate of chloride penetration into the reinforcement surface. In addition, the crack width produced by 15% FA concrete is relatively small compared to other test specimens. The results of visual observations are in line with the compressive strength and HCP values. The higher the compressive strength value, the higher the corrosion resistance of the test specimen.

Fig. 8 Visual condition of specimens after corrosion acceleration test (left to right: Control specimen (C), 15%FA50%BA, 30%FA50%BA)

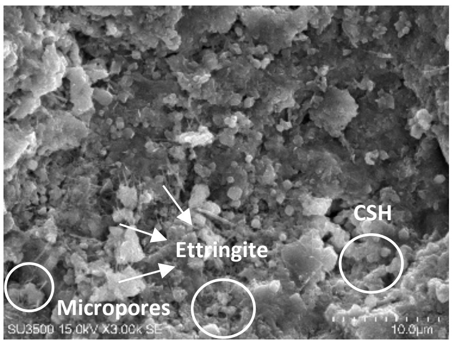
4.6 Scanning Electron Microscopy (SEM)



(a) Control specimen (C)



(b) 15%FA50%BA



(c) 30%FA50%BA

Fig. 9. Microstructure of the concrete as observed from SEM analysis

Microstructure of the concrete as observed from SEM analysis are shown in Figure 9. The micrographs indicate that the 30%FA50%BA sample exhibits a more compact microstructure primarily comprised of dense calcium silicate hydrate (C-S-H) gel along with some ettringite. Typically, ettringite is formed when calcium hydroxide [$Ca(OH)_2$], generated during the hydration of cement, reacts with sulfate compounds. The 15%FA50%BA specimen also contains C-S-H but shows a significant amount of calcium hydroxide (CH) in a flaky form and displays a few visible micro-cracks. Both the 15%FA50%BA and the control samples present less compact gel formations and exhibit the presence of pores, with the control specimen showing the highest level of porosity and cracking in its microstructure overall.

These findings correspond with the corrosion performance results discussed in Section 4.4. The accelerated corrosion rate observed in the control specimen can be linked to its more porous structure, which allows for the easier penetration of chlorides and moisture, thus speeding up steel corrosion

Conversely, the denser and more refined pore structures found in the FABA-modified mixtures lower permeability and offer improved protection to embedded reinforcement. Moreover, the compressive strength of 32.1 MPa achieved by the 15%FA50%BA mixture at 28 days not only indicates excellent pozzolanic reactivity but also suggests durable behavior. A strength exceeding 30 MPa is generally acknowledged as adequate for structural-grade concrete, frequently correlating with low permeability and long-term resistance to aggressive agents. When combined with the SEM evidence of diminished pore connectivity and matrix densification, it can be concluded that the FABA concrete displays favorable durability traits suitable for standard structural applications, even though long-term environmental exposure tests were not performed in this investigation.

5. CONCLUSION

The analysis of FABA concrete test data leads to important insights, notably that while the workability of fresh concrete diminishes with FABA addition, this effect can be mitigated through the use of superplasticizers. Optimal compressive strength is achieved with a mix of 15% fly ash (FA) as a cement substitute and 50% bottom ash (BA) as a sand substitute, though this composition does not correspondingly improve flexural strength. Moreover, specimens with 15% FA and 50% BA, as well as those with 30% FA and 50% BA, display enhanced corrosion resistance compared to the control specimens. Future research recommendations include exploring methods to augment the flexural strength of FABA concrete, potentially through the integration of various fibers, and conducting corrosion testing in actual marine environments to validate laboratory findings and further refine the use of FABA in concrete applications.

Based on the research findings, several recommendations for enhancing the study of FABA as a concrete material can be made. To improve the flexural strength of FABA concrete, further investigation into the incorporation of various fiber types, including steel, polypropylene, carbon, and glass fibers, is advisable. Additionally, conducting corrosion testing in real marine environments would strengthen the validity of the laboratory experimental results. Also, future studies should consider conducting a detailed lifecycle assessment (LCA) to quantitatively evaluate the environmental benefits of FABA concrete compared to conventional concrete. This will help validate its sustainability potential and promote its practical adoption in environmentally sensitive construction practices.

6. ACKNOWLEDGMENTS

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