EPI International Journal of Engineering
Volume 9, Number 1, February 2026, pp. 29-37
DOI: 10.25042/epi-ije.022026.05

*p*ISSN 2615-5109
*e*ISSN 2621-0541

Performance Optimization of Biomass Fly Ash as a Partial Cement Replacement in Concrete Based on Compressive Strength, Sorptivity, and Half-Cell Potential

Yusman[a], Nur Okviyani[b,*], Irma Ridhayani[c], Muh. Isra[d], Akbar Indrawan Saudi[e], Ainun Jariah Hilal Anshary[f], Amalia Nurdin[g]

[a]Department of Civil Engineering, Faculty of Engineering, Universitas Sulawesi Barat. Email: yusman.its@gmail.com
[b]Department of Civil Engineering, Faculty of Engineering, Universitas Sulawesi Barat. Email: nur.okviyani@unsulbar.ac.id
[c]Department of Civil Engineering, Faculty of Engineering, Universitas Sulawesi Barat. Email: irma.ridhayani@unsulbar.ac.id
[d]Department of Civil Engineering, Faculty of Engineering, Universitas Sulawesi Barat. Email: aisra1820@gmail.com
[e]Department of Civil Engineering, Faculty of Engineering, Universitas Sulawesi Barat. Email: akbarindrawan@unsulbar.ac.id
[f]Department of Civil Engineering, Faculty of Engineering, Universitas Sulawesi Barat. Email: ainunjariahhilalanshary@unsulbar.ac.id
[g]Department of Civil Engineering, Faculty of Engineering, Universitas Sulawesi Barat. Email: amalianurdin@unsulbar.ac.id

Abstract

The use of biomass fly ash (BFA) as a supplementary cementitious material offers a practical approach to reducing cement consumption while enhancing concrete durability. This study evaluates the effect of BFA as a partial cement replacement on the mechanical and durability performance of concrete produced with river sand and freshwater. BFA was added at substitution levels of 0%, 5%, 15%, and 25% of cement mass, with a constant water-to-binder ratio of 0.40. Compressive strength was checked at 7, 28 and 91 days, sorptivity was checked at 28 and 91 days, and embedded reinforcing steel corrosion probability was measured (Half-Cell Potential method) at 7 and 91 days. The results show that BFA reduced early-age strength, particularly at 15% and 25% replacement, because pozzolanic reaction is slower. However, later-age performance was much better. The mixture with 25% BFA achieved the highest compressive strength at 91 days (36.46 MPa), representing a 27.48% increase compared with the control mixture. This mixture also produced the lowest sorptivity of 0.91 mm, indicating the reduced capillary water absorption. Half-Cell Potential results showed that all mixtures reached the low corrosion probability range at 91 days with the 25% BFA mixture at -59.13 mV. Overall, 25% BFA was the best balance between compressive strength, water absorption resistance, and corrosion-related durability.

Keywords: Biomass fly ash, compressive strength, concrete durability, half-cell potential, sorptivity

1. Introduction

Concrete, as a key material in infrastructure development, must have good compressive strength, high formability, low cost and ability to be applied in a variety of environmental conditions. However, the extensive use of concrete continues to raise environmental concerns because Portland cement production requires high energy consumption and generates substantial carbon dioxide emissions. This condition has encouraged the development of sustainable concrete through the use of supplementary cementitious materials (SCMs) as partial cement replacements. SCMs can reduce clinker consumption, lower environmental impacts, and improve concrete performance when incorporated at appropriate proportions [1, 2]. Studies published by Elsevier also indicate that the development of new SCM sources, including biomass ash, has become an important direction in the decarbonization of the cement and concrete industries.

One alternative material with potential application as an SCM is biomass fly ash (BFA). BFA is a residue produced from biomass combustion and may contain silica, alumina, calcium oxide, and other mineral compounds that contribute to pozzolanic reactions and pore-filling effects. Rajamma et al. (2015) [3] reported that BFA has potential as a mineral additive in cement-based materials because its physical, chemical, and morphological characteristics can influence both fresh and hardened properties. Other studies have also shown that the use of BFA in cement-based materials can serve as a strategy for biomass waste management while supporting the reduction of cement consumption [4, 5].

From a mechanical perspective, the use of BFA as a partial cement replacement can affect the development of concrete compressive strength. At early ages, replacing part of the cement with BFA may reduce compressive strength because the effective cement content decreases

*Corresponding author. Tel.: +62-852-155-505-22
Department of Civil Engineering, Faculty of Engineering,
Universitas Sulawesi Barat, Majene, Indonesia, 91411

and the pozzolanic reaction has not yet developed optimally. However, at later ages, BFA has the potential to enhance the formation of additional hydration products, particularly calcium silicate hydrate or C-S-H, resulting in a denser cementitious matrix. Wang and Baxter (2007) [6] demonstrated that BFA can affect the strength, microstructure, and durability of concrete through reactions between ash components and calcium hydroxide. Similar findings have been reported in studies on BFA concrete, which demonstrated improved performance at later ages, particularly after hydration and pozzolanic resistance had developed more stable.

Concrete durability is a main aspect because concrete deterioration often begins with the ingress of water, chloride ions, carbon dioxide, and other aggressive agents through the pore system. Studies on fly ash concrete have shown that the use of pozzolanic materials can reduce sorptivity and chloride permeability due to microstructural refinement at later ages [7-9]. Therefore, sorptivity testing is important for assessing the contribution of BFA to the resistance of concrete against water penetration.

Beside water absorption, reinforcement corrosion is a major factor that reduces the service life of reinforced concrete. Corrosion can occur when aggressive substances, particularly chloride ions, reach the steel reinforcement surface and damage the passive layer. One non-destructive evaluation method widely used to detect corrosion potential is Half-Cell Potential (HCP). This method measures the electrochemical potential of the steel reinforcement with respect to a reference electrode, thus indicating the tendency for corrosion to occur. Studies published by Elsevier show that HCP is relevant for evaluating the corrosion condition of reinforcing steel in concrete, especially in concrete exposed to aggressive environments or incorporating various cementitious materials [10, 11].

Several recent studies in Indonesia have investigated the use of biomass ash, palm oil fuel ash (POFA), rice husk ash, seawater, sea sand, and local materials in concrete and paving blocks [12-16]. The results showed potential improvements in mechanical properties and durability thus suggesting that biomass ash-based materials and local materials can support the development of sustainable concrete. Although their performance should be evaluated based on the type of ash, replacement rate, concrete age and durability parameters.

Research by Dasar et al. also reinforces the importance of biomass ash and local materials in sustainable concrete where the use of POFA and seawater affects the corrosion resistance of reinforcing steel in concrete [17]. This is also seen in the mechanical properties and durability of biomass ash concrete with a mixture of fresh water and river sand [18], in another study Dasar et al. (2025) [19] found that nano-POFA in paving blocks made with seawater and sea sand can improve mechanical performance and durability. These findings indicate that biomass-derived ash has the potential as a partial replacement for cement. However, it is highly dependent on particle size, chemical composition, replacement rate, type of aggregate and curing media.

Although several studies have examined biomass ash, fly ash, POFA, seawater, sea sand, and concrete durability, there has been no research specifically analyzing the use of BFA as a partial replacement of cement in concrete made from river sand and fresh water is still limited. This is seen in the simultaneous evaluation of compressive strength, sorptivity, and HCP at various levels of BFA replacement where these three parameters are important because compressive strength represents mechanical capacity, sorptivity reflects resistance to capillary water absorption, and HCP indicates the tendency of reinforcing steel corrosion. Therefore, this study aims to analyze the effect of partial replacement of cement with BFA at 0%, 5%, 15%, and 25% on concrete durability, with a particular focus on compressive strength, sorptivity, and corrosion potential based on HCP testing.

2. Method

2.1. Materials

The research used Portland composite cement (PCC) as the main binder, biomass fly ash (BFA) as a partial replacement for cement derived from the combustion of biomass with 70 % palm kernel shells and 30% tea waste from packaged tea factories which were burned at a temperature 600^0C-800^0C, river sand, fresh water and reinforcing steel.

The specific gravity values of PCC 3.08 and BFA 2.98. River sand from Mapilli served as fine aggregate with classification as zone 3 fine aggregate (fineness modulus 3.04). Fresh water used as mixing water and curing medium. BFA was likely dominated by SiO_2 (41.60%) and CaO (27.90%). Other oxides detected included Al_2O_3 4.23%, Fe_2O_3 3.30%, MgO 3.59%, SO_3 3.22%, K_2O 4.87%, Na_2O 0.597%, P_2O_5 2.95%, TiO_2 0.353%, and Cl_2 0.386%. The presence of oxides indicates that BFA contains mineral components that can contribute to pozzolanic reactions and microstructural compaction in the cement system. However, due to the presence of alkali, sulfate, and chloride, this situation needs to be considered in the durability assessment. Fig. 1 shows the visual appearance of BFA and PCC used in this study.

2.2. Mix proportions

The concrete mix proportions were designed according to SNI 03-2834-2000. Four mixtures were prepared, consisting of one control mixture without BFA and three mixtures incorporating BFA as a partial cement replacement at 5%, 15%, and 25% by binder mass. The control mixture was coded as N-R-TT. The mixtures containing 5%, 15%, and 25% BFA were coded as BA-R-TT, BB-R-TT, and BC-R-TT, respectively. The physical appearance of the materials used in this study is shown in Fig. 1.

The total binder content was kept constant at 580 kg/m³ for all mixtures. The freshwater content was maintained at 232 kg/m³, resulting in a constant water-to-binder ratio of 0.40. The mix proportions are presented in Table 1.

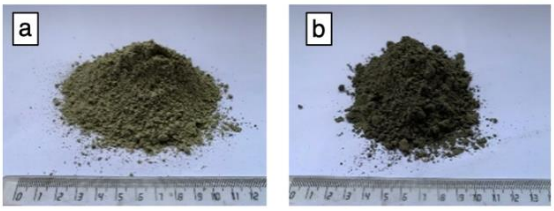

Figure 1. Visual appearance of (a) PCC; (b) BFA

Table 1. Mix proportions of concrete per m³

Mix ID	Freshwater (kg/m³)	Cement (kg/m³)	BFA (kg/m³)	River sand (kg/m³)
N-R-TT	232	580	0	1223
BA-R-TT	232	551	29	1221
BB-R-TT	232	493	87	1217
BC-R-TT	232	435	147	1217

2.3. Specimen preparation and curing

The specimen preparation started with weighing PCC, BFA, river sand, and freshwater according to the designed mix proportions. PCC, BFA, and river sand were first dry-mixed until a uniform mixture was obtained. Freshwater was then added gradually during mixing, and the mixing process was continued until the fresh concrete reached a homogeneous condition. Fresh concrete was placed into molds according to the testing requirements. Cube specimens measuring 50 mm × 50 mm × 50 mm were prepared for compressive strength and sorptivity tests. Cylindrical specimens with a diameter of 50 mm and a height of 100 mm were prepared for the Half-Cell Potential (HCP) test. A reinforcing steel bar was embedded at the center of each cylindrical specimen to evaluate the electrochemical response associated with corrosion tendency. After casting, the specimens were compacted to reduce entrapped air in the mixture. The specimens were kept in the molds for 24 h. After demolding, all specimens were cured by immersion in freshwater until the designated testing ages. The curing procedure followed SNI 2493-2011. Fig. 2 shows the specimen design used in this study.

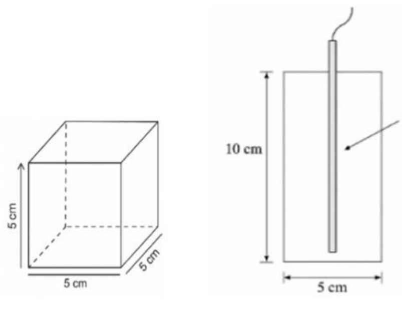

Figure 2. Specimen design for compressive strength, sorptivity, and Half-Cell Potential tests

2.4. Experimental program

The experimental program was designed to evaluate the effect of BFA replacement level on compressive strength, sorptivity, and corrosion potential. Compressive strength was tested at 7, 28, and 91 days. Sorptivity was tested at 28 and 91 days. HCP was monitored from 7 to 91 days. The number of specimens for each mixture is presented in Table 2.

Table 2. Number of specimens used in the experimental program.

Mix ID	Compressive strength and sorptivity			HCP, 7-91 d	Total
	7 d	28 d	91 d		
N-R-TT	3	3	3	2	11
BA-R-TT	3	3	3	2	11
BB-R-TT	3	3	3	2	11
BC-R-TT	3	3	3	2	11
				Total	44

2.5. Testing method

The compressive strength testing procedure follows ASTM C109/C109M to evaluate the strength development of concrete mixtures incorporating biomass fly ash (BFA) as a partial replacement of cement conducted at the ages of 7, 28, and 91 days with cube specimens with dimensions of 50 mm x 50 mm x 50 mm. before testing, the specimens were removed from the curing medium and excess surface water was wiped off. Each specimen was then placed in the center of the compression testing machine to ensure uniform load distribution. The load was applied continuously until failure occurred. The compressive strength of its cross-section (Fig. 3). Carried out with three tests to obtain an average value so that a standard deviation was obtained where if the error bar graph shows greater variability.

The Half-Cell Potential (HCP) test was conducted to evaluate the corrosion probability of reinforcing steel embedded in concrete. The test was performed at 7, 10, 14, 21, 28, 35, 42, 49, 56, 63, 70, 77, 84, and 91 days. The testing procedure followed ASTM C876 [33], which provides a standard method for measuring the corrosion potential of uncoated reinforcing steel in concrete. A copper/copper sulfate electrode ($Cu/CuSO_4$) was used as the reference electrode. Before measurement, the concrete surface was cleaned and moistened to improve electrical contact between the reference electrode and the concrete surface. One terminal of the measuring device was connected to the embedded steel bar, while the reference electrode was placed on the concrete surface (Fig. 4). The potential values were recorded in millivolts (mV). The interpretation of HCP values followed the threshold limits specified in ASTM C876 [33]. A potential value more positive than -200 mV indicates a low probability of corrosion. A value between -200 mV and -350 mV indicates an uncertain corrosion condition. A value more negative than -350 mV indicates a high probability of corrosion. The changes in HCP values were analyzed to evaluate the influence of BFA replacement level on the corrosion tendency of reinforcing steel in concrete.

Figure 3. Compressive strength test setup

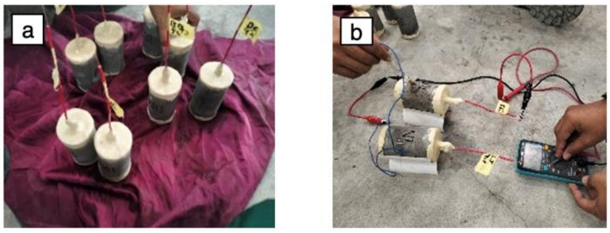

Figure 4. (a) HCP specimen; (b) Half-Cell Potential measurement setup

The sorptivity test was conducted to evaluate the rate of capillary water absorption in concrete. The test was performed at 28 and 91 days. The testing procedure followed ASTM C1585 [34], which measures the rate of water absorption in hydraulic cement concrete when only one surface is exposed to water. Before testing, the specimens were oven-dried until they reached a constant mass. After drying, the side surfaces of each specimen were coated with epoxy to restrict water flow and ensure one-dimensional absorption. The specimens were then placed in contact with water at a depth of approximately 3 mm, allowing only the bottom surface to absorb water (Fig. 5).

The mass increase of each specimen was recorded at selected time intervals. The cumulative absorption is calculated from the increase in mass divided by the exposed surface area and the density of water. This relationship used to determine sorptivity where a lower sorptivity value indicates a denser pore structure and greater resistance to capillary water absorption. cumulative absorption was calculated using Eq. (1).

$$I = \frac{\Delta m}{A \times \rho} \quad (1)$$

where I is the cumulative absorption (mm), Δm is the mass change of the specimen (g), A is the exposed surface area in contact with water (mm²), and ρ is the density of water (g/mm³).

Figure 5. Sorptivity test setup

3. Results and discussion

3.1. Compressive strength test

Fig. 6 shows the development of concrete compressive strength at 7, 28, and 91 days for each mixture. At 7 days, the control mixture N-R-TT produced the highest compressive strength of 23.41 MPa. The BA-R-TT mixture reached 22.70 MPa, while BB-R-TT and BC-R-TT produced the same compressive strength of 18.67 MPa. These results indicate that increasing the BFA content tended to reduce the early-age compressive strength of concrete. This reduction was associated with the lower effective cement content caused by partial cement replacement and the limited development of the pozzolanic reaction of BFA at early ages. This pattern is consistent with the general behavior of SCMs, whose contribution to strength becomes more dominant at later ages after the pozzolanic reaction develops more steadily [2, 3].

At 28 days, the BC-R-TT mixture showed the highest compressive strength of 27.63 MPa, which was 8.91% higher than that of the control mixture at 25.37 MPa. The BA-R-TT mixture also showed a slight improvement compared with the control mixture, reaching 25.93 MPa or 2.21% higher. In contrast, BB-R-TT produced a compressive strength of 22.64 MPa, which was 10.76% lower than the control mixture. These differences indicate that the effect of BFA was not determined only by the replacement level, but also by the balance between cement dilution, pore-filling effect, and pozzolanic reaction development. Biomass fly ash can act as a mineral addition in cementitious systems, but its effectiveness is strongly influenced by its physical and chemical characteristics, particularly particle size, silica content, calcium content, unburned carbon, and pozzolanic reactivity [4, 6].

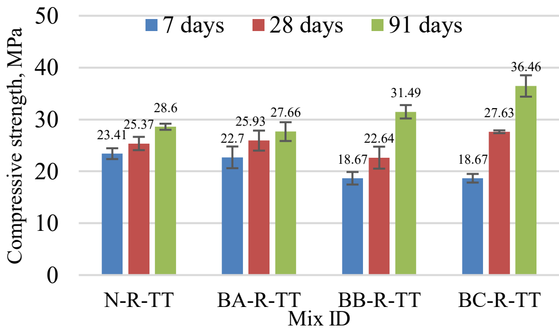

Figure 6. Compressive strength test results

At 91 days, all mixtures showed strength development compared with their 7-day values. The greatest increase occurred in the BC-R-TT mixture, from 18.67 MPa at 7 days to 36.46 MPa at 91 days. This increase corresponded to 95.29%. At the same age, the control mixture reached only 28.60 MPa, indicating that BC-R-TT provided a 27.48% increase in compressive strength compared with the control mixture. The BB-R-TT mixture also exceeded the control mixture with a compressive strength of 31.49 MPa, while BA-R-TT reached 27.66 MPa. These results confirm that the contribution of BFA to compressive strength became more significant at later ages. The compressive strength results represent average values from three specimens, with variability shown as standard deviation error bars in Fig. 6 larger bars reflecting greater spread in the measured data.

The gains in compressive strength seen at higher BFA replacement levels can be traced back to secondary hydration products forming through the pozzolanic reaction. When silica and alumina compounds in BFA react with calcium hydroxide released during cement hydration, additional calcium silicate hydrate gel is produced. This gel fills capillary pores, strengthens the interfacial transition zone, and makes the cementitious matrix denser overall. This mechanism helps explain the improvement in later-age compressive strength, a pattern also documented in prior studies on BFA and biomass ash in cement-based systems [3, 6].

These results align with Patah et al. [14], who observed notable compressive strength gains in fly ash concrete extending out to 91 days. They also match findings from Dasar et al. [18], who reported that biomass ash concrete made with freshwater and river sand showed potential gains in both mechanical and durability properties. Similarly, Patah et al. [16] demonstrated that using ultrafine palm oil fuel ash as a partial cement replacement can enhance both the mechanical and durability performance of sustainable concrete.

Looking at the compressive strength data overall, the BC-R-TT mixture with 25% BFA delivered the strongest performance at 91 days, achieving both the highest compressive strength and the most substantial strength gain among all mixtures tested. This makes 25% BFA the most effective replacement level for boosting later-age compressive strength in concrete systems made with river sand and freshwater.

The drop in early-age compressive strength seen in higher-BFA mixtures carries real implications for construction practice. Reduced early strength can affect scheduling decision, particularly around formwork removal, load application, and early structural performance and may call for longer curing times or delayed formwork stripping to make sure adequate strength has developed. So while BFA clearly benefits long-term performance, its effect on early-age strength needs careful attention during construction planning and quality control.

3.2. Half-Cell Potential (HCP)

Fig. 7 shows the variation in Half-Cell Potential (HCP) values of reinforced concrete from 7 to 91 days. The interpretation of the results followed ASTM C876 [33], in which potential values more positive than -200 mV indicate a low probability of corrosion, values between -200 mV and -350 mV indicate an uncertain corrosion condition, and values more negative than -350 mV indicate a high probability of corrosion. The HCP method is used as a non-destructive test to assess the probability of reinforcement corrosion, not to directly measure the corrosion rate [20, 21].

At early ages, the HCP values of all mixtures generally ranged from the uncertain corrosion zone to the high corrosion probability zone. The control mixture N-R-TT showed a value of -164.55 mV at 7 days, then decreased to -461.85 mV at 35 days. The BA-R-TT, BB-R-TT, and BC-R-TT mixtures also showed highly negative values between 10 and 42 days. The most negative value was recorded in the BC-R-TT mixture, reaching -553.85 mV at 14 days. This pattern indicates that, at early ages, the concrete pore system remained relatively open, the pore moisture content was still high, and the passive film on the steel surface had not yet stabilized. These conditions can produce more negative potential readings, particularly when concrete is in a moist condition. Yodsudjai and Pattarakittam [22] explained that HCP values are influenced by chloride content, moisture content, compressive strength, and concrete condition. Therefore, HCP results should be interpreted together with the development of the concrete matrix properties.

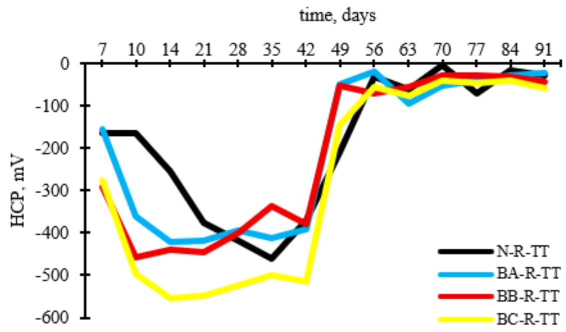

Figure 7. HCP values

A major shift occurred beyond the 49-day point, with all mixtures moving toward more positive potentials and reaching the low corrosion probability zone. At 91 days, N-R-TT, BA-R-TT, BB-R-TT, and BC-R-TT recorded HCP values of -27.31 mV, -20.98 mV, -42.90 mV, and -59.13 mV, respectively each one more positive than the -200 mV benchmark, indicating low corrosion probability as defined by ASTM C876 [33]. This trend suggests that cement hydration combined with the pozzolanic reaction of BFA contributed to reduced pore connectivity and improved resistance to aggressive ion penetration. This matches what Boğa and Topçu [23] reported, namely that fly ash can improve corrosion resistance and reduce chloride ion permeability in concrete.

The BC-R-TT mixture containing 25% BFA showed the most negative HCP values at early ages, particularly from 10 to 42 days. However, after 49 days, its potential value increased sharply from -146.90 mV to -59.13 mV at 91 days. This change indicates that mixtures with high BFA content require a longer period to develop a denser matrix. Once the pozzolanic reaction develops, the additional hydration products improve the pore structure and restrict the access of water and aggressive ions to the steel reinforcement surface. This finding is consistent with Chalee et al. [24], who found that replacing cement with ground palm oil fuel ash at levels between 15% and 35% enhanced concrete's resistance to both chloride penetration and steel corrosion in marine exposure conditions.

The upward trend in HCP values found in this study also finds support in earlier work by Patah and Dasar. Specifically, Patah and Dasar [13] demonstrated that incorporating rice husk ash along with seawater and sea sand had an impact on the corrosion potential of reinforcing bars within concrete. Patah et al. [25] further highlighted that electrochemical conditions and initial chloride contamination play a major role in shaping the corrosion behavior of steel bars embedded in SCM-based mortar. Additionally, Dasar et al. [17] found that both POFA and seawater affected the corrosion resistance of reinforcing steel, as measured through HCP testing. These studies confirm that biomass-based pozzolanic materials can improve corrosion resistance when pozzolanic reactions and microstructural densification develop adequately.

Overall, the HCP results show that all mixtures experienced a high corrosion probability phase at early ages, then shifted to the low corrosion probability zone at later ages. The BC-R-TT mixture showed the greatest fluctuation at early ages, but still reached a safe condition from 49 to 91 days. Considering the HCP results and the low sorptivity value at 91 days, the 25% BFA replacement can be considered effective in improving the durability resistance of concrete against reinforcement corrosion risk. However, this conclusion is limited to the conditions of this study, namely concrete made with river sand, freshwater, and freshwater curing.

3.3. Sorptivity test

Fig. 8 and Fig. 9 show the development of capillary absorption in concrete at 28 and 91 days. The values presented represent cumulative absorption, I, in mm as a function of testing time. This parameter was used to evaluate the ability of concrete to absorb water through its capillary pore network. A lower I value indicates lower water ingress into concrete, reflecting a denser pore structure and more limited capillary pore connectivity. Sorptivity is an important indicator in durability assessment because water transport is the initial pathway for aggressive ion ingress into concrete [26, 27].

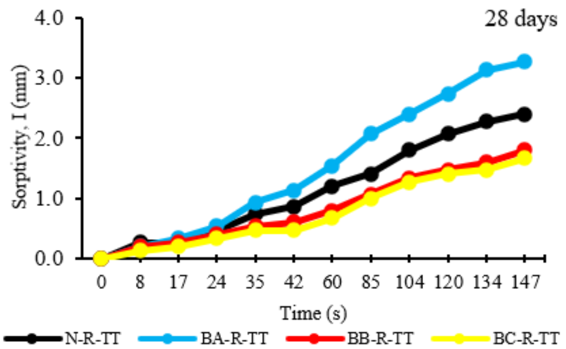

Figure 8. Sorptivity at 28 days

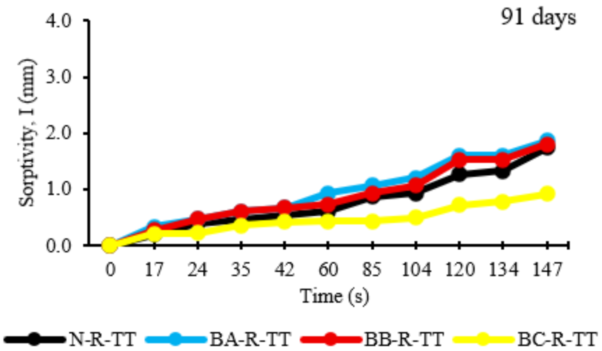

Figure 9. Sorptivity at 91 days

At 28 days, the BA-R-TT mixture showed the highest final absorption value of 3.27 mm. This value was higher than that of the control mixture N-R-TT, which reached 2.40 mm. In contrast, the BB-R-TT and BC-R-TT mixtures showed lower absorption values of 1.80 mm and 1.67 mm, respectively. Compared with the control concrete, the use of 15% BFA reduced absorption by 25.00%, while 25% BFA reduced absorption by 30.56%. These results indicate that higher BFA contents began to improve the resistance of concrete to capillary water absorption at 28 days.

At 91 days, the differences among the mixtures became more evident. The final absorption values of N-R-TT, BA-R-TT, BB-R-TT, and BC-R-TT were 1.73 mm, 1.87 mm, 1.80 mm, and 0.91 mm, respectively. The BC-R-TT mixture produced the lowest value and reduced absorption by 47.31% compared with the control concrete. This reduction indicates that 25% BFA provided the most effective improvement in the ability of concrete to resist capillary water absorption at later ages. This trend agrees with the findings of Nath and Sarker and Islam et al. [28, 29], who reported that fly ash can reduce sorptivity and improve concrete durability after longer curing periods.

The decrease in absorption from 28 to 91 days also indicates the role of curing time in microstructural densification. In the BC-R-TT mixture, absorption decreased from 1.67 mm to 0.91 mm, corresponding to a reduction of 45.20%. This decline was larger compared to the control mixture, which fell from 2.40 mm to 1.73 mm. This gap points to a more pronounced pozzolanic reaction of BFA as curing age progresses. The additional hydration products produced during this stage work to fill capillary pores, enhance the interfacial transition zone, and reduce routes for water transport. Rajamma et al. [3] noted that BFA shows potential as a mineral additive within cement-based materials, since its physical and chemical traits can shape the hardened performance of cementitious systems.

Compared with the control concrete, the BA-R-TT mixture showed no gain in sorptivity performance. Absorption values for this mixture remained higher than N-R-TT's at both 28 and 91 days. This points to 5% BFA being an insufficient replacement level to meaningfully improve the concrete's pore system. Several factors replacement level, particle fineness, oxide composition, and reactivity strongly shape how well BFA performs. If the BFA has low reactivity or is not well dispersed, its ability to fill pores may be quite restricted. Result in no significant reduction in absorption. Consistent with recent findings on BFA, this result suggests that the suitability of biomass ash as a cement replacement is closely tied to the characteristics of its source and the pretreatment process it undergoes.

Consistent with prior work by Patah and Dasar, the present results confirm that biomass ash along with pozzolanic materials contributes to improved concrete performance as curing age increases. Additionally, Dasar et al. [18] reported that biomass ash concrete produced with freshwater and river sand revealed a notable connection between its mechanical behavior and durability performance. Patah et al. [15] showed that the use of fly ash and sea sand affected the strength and durability of concrete. Patah et al. [30] also reported that POFA influenced the mechanical and durability properties of sustainable foamed concrete. In addition, Patah et al. [16] demonstrated that the use of ultrafine palm oil fuel ash in sustainable concrete improved durability performance through matrix refinement.

Overall, the sorptivity results indicate that 25% BFA was the most effective variation in reducing capillary absorption, especially at 91 days. The BC-R-TT mixture not only produced the lowest absorption value, but also showed the greatest reduction from 28 to 91 days. These results confirm that the contribution of BFA to durability became more dominant at later ages, when pozzolanic reactions and microstructural densification have developed more steadily.

3.4. Integrated performance evaluation and optimum BFA replacement level

To show the optimal performance of BFA used as a cement substitute, an evaluation was carried out on 3 main combined parameters, namely compressive strength, sorptivity and HCP, where compressive strength is used to assess the mechanical performance of concrete. Sorptivity is used to evaluate the ability of concrete to absorb water and HCP is used to determine the probability of corrosion of reinforcing steel based on ASTM C876.

Table 3. Performance evaluation of concrete at 91 days

Mix ID	Compressive strength at 91 days (MPa)	Sorptivity at 91 days (mm)	HCP at 91 days (mV)
N-R-TT	28.60	1.73	-27.31
BA-R-TT	27.66	1.87	-20.98
BB-R-TT	31.49	1.80	-42.90
BC-R-TT	36.46	0.91	-59.13

On the 91st day, the BC-R-TT mixture containing 25% BFA reached the highest compressive strength of 36.46 Mpa. This value is 27.48% higher than the N-R-TT control mixture which reached 28.60 MPa. For the sorptivity of the BC-R_TT mixture also produced the lowest value of 0.91 mm, which is a decrease of 47.31% compared to the control mixture of 1.73 mm. It can also be seen that the HCP value of -59.13 mV is still in the low corrosion probability zone because it is more positive than -200 mV. This shows that 25% BFA provides the best combination of compressive strength, capillary water absorption and resistance to the risk of reinforcement corrosion.

The increase in compressive strength of the BC-R-TT mixture indicates that the contribution of BFA became more dominant at later ages. At early ages, cement hydration remained the main mechanism controlling strength development, while the pozzolanic reaction of BFA had not fully developed. At 91 days, the silica and alumina compounds in BFA reacted with calcium hydroxide produced during cement hydration and formed additional hydration products, particularly calcium silicate hydrate. These hydration products filled capillary pores, improved the interfacial transition zone, and increased the density of the cementitious matrix. This mechanism is consistent with the general behavior of SCMs, which tend to provide a significant contribution at later ages through pozzolanic reactions and pore-filling effects [2, 3, 6].

The relationship between compressive strength and sorptivity indicates that higher concrete strength was associated with lower capillary water absorption. The BC-R-TT mixture produced both the highest compressive strength and the lowest sorptivity value at 91 days. This condition indicates that concrete with a denser cementitious matrix had lower pore connectivity, thereby limiting the pathway for water ingress into concrete. The reduction in sorptivity in concrete containing pozzolanic materials has also been reported in previous studies, mainly due to the formation of a denser microstructure after longer curing periods [26, 27, 29, 31, 32].

The HCP results further supported the durability evaluation. All mixtures were within the low corrosion probability zone at 91 days. Although the HCP value of BC-R-TT was not the most positive among all mixtures, it remained far above the -200mV. threshold specified in ASTM C876 [33]. This result indicates that the use of 25% BFA did not increase the corrosion risk at later ages. The improvement in HCP values was related to the reduction in pore connectivity and the limited access of water and aggressive ions to the reinforcing steel surface. The use of fly ash has also been reported to enhance corrosion resistance and reduce chloride ion permeability through pore structure densification in concrete [23].

The findings are also consistent with previous studies by Patah and Dasar on concrete incorporating biomass ash and local materials. Patah et al. [16] showed that the use of ultrafine palm oil fuel ash improved the mechanical and durability properties of sustainable concrete. Dasar et al. [19] reported that nano-POFA enhanced the mechanical and durability performance of paving blocks prepared with seawater and sea sand. Dasar et al. [18] also showed that biomass ash concrete produced with freshwater and river sand had potential for improving mechanical and durability performance. Patah et al. [15] reported that the use of fly ash and sea sand affected the strength and durability of concrete. This indicates that cement can be replaced by using biomass ash in amounts that can still ensure the strength and durability of the concrete.

The research conducted identified the mixture with the optimum value as shown in the BC-R-TT variation with 25% BFA. This mixture produced the highest compressive strength of 36.46 MPa, the lowest sorptivity value of 0.91 mm, and an HCP value of -59.13 mV at 91 days. This combination indicates that 25% BFA improved both mechanical performance and durability against capillary water absorption and reinforcement corrosion potential. The 5% BFA mixture did not provide consistent improvement because its 91-day compressive strength was lower than that of the control mixture and its sorptivity was higher. The 15% BFA mixture improved compressive strength but did not effectively reduce sorptivity. Therefore, 25% BFA can be considered the most effective replacement level for concrete produced with river sand and freshwater under the conditions of this study.

4. Conclusion

This study demonstrates that biomass fly ash (BFA) can be used as a partial cement replacement to improve the later-age performance of concrete made with river sand and freshwater. The incorporation of BFA reduced early-age compressive strength, particularly at higher replacement levels, due to the slower development of pozzolanic reactions. However, the 25% BFA mixture showed the best overall performance at 91 days, achieving the highest compressive strength of 36.46 MPa, the lowest sorptivity value of 0.91 mm, and an HCP value of -59.13 mV, which remained within the low corrosion probability range based on ASTM C876. Overall, the data point to 25% BFA as the most suitable replacement ratio, given that it delivers the best combination of mechanical strength, capillary water resistance, and durability with respect to corrosion.

Further studies should also explore higher BFA replacement ratios and examine the environmental advantages using life cycle assessment, which would help support its adoption in sustainable concrete practices. However, attention should be given to early-age strength reduction, which may influence construction scheduling and formwork removal in practical applications.

References

[1] Scrivener, K. L., John, V. M., & Gartner, E. M. (2023). Future and emerging supplementary cementitious materials. Cement and Concrete Research, 169, 107199.

[2] Juenger, M. C. G., Snellings, R., & Bernal, S. A. (2019). Supplementary cementitious materials: New sources, characterization, and performance insights. Cement and Concrete Research, 122, 257-273. https://doi.org/10.1016/j.cemconres.2019.05.008

[3] Rajamma, R., Senff, L., Ribeiro, M. J., Labrincha, J. A., Ball, R. J., Allen, G. C., & Ferreira, V. M. (2015). Biomass fly ash effect on fresh and hardened state properties of cement-based materials. Composites Part B: Engineering, 77, 1-9. https://doi.org/10.1016/j.compositesb.2015.03.019

[4] Cheah, C. B., & Ramli, M. (2011). The implementation of wood waste ash as a partial cement replacement material in the production of structural grade concrete and mortar: An overview. Resources, Conservation and Recycling, 55(7), 669-685.

[5] Berra, M., Mangialardi, T., & Paolini, A. E. (2015). Reuse of woody biomass fly ash in cement-based materials. Construction and Building Materials, 76, 286–296.

[6] Wang, S., & Baxter, L. (2007). Comprehensive study of biomass fly ash in concrete: Strength, microscopy, kinetics and durability. Fuel Processing Technology, 88(11-12), 1165-1170.

[7] Chindaprasirt, P., Chotithanorm, C., Cao, H. T., & Sirivivatnanon, V. (2007). Influence of fly ash fineness on the chloride penetration of concrete. Construction and Building Materials, 21(2), 356–361.

[8] Siddique, R. (2011). Properties of concrete incorporating high volumes of fly ash, Resources, Conservation and Recycling 55, 1107–1116.

[9] Liu, Y., et al. (2025). Advances in durability of fly ash concrete, Journal of Materials in Civil Engineering (2025).

[10] Elsener, B. (2003). Half-Cell Potential mapping to assess repair work on RC structures, Construction and Building Materials 17, 133–139.

[11] Chen, D., et al. (2022). Corrosion monitoring of reinforcing steel in concrete using Half-Cell Potential measurement. Construction and Building Materials, 302, 124420.

[12] Patah, D., & Dasar, A. (2022). Strength performance of concrete using rice husk ash as supplementary cementitious materials (SCM). Journal of the Civil Engineering Forum, 8(3), 261–276.

[13] Patah, D., & Dasar, A. (2023). The impact of using rice husks ash, seawater and sea sand on corrosion of reinforcing bars in concrete. Journal of the Civil Engineering Forum, 9(3).

[14] Patah, D., Dasar, A., Apriansyah, A., & Caronge, M. A. (2023). Strength development of seawater mixed and cured concrete with various replacement ratios of fly ash. Materials Science Forum, 1091, 111–118.

[15] Patah, D., Dasar, A., Fakhruddin, F., Shintarahayu, B., & Apriansyah, A. (2024). The impact of fly ash and sea sand on strength and durability of concrete. Key Engineering Materials, 1000, 23-33.

[16] Patah, D., Dasar, A., & Nurdin, A. (2025). Sustainable concrete using seawater, sea-sand, and ultrafine palm oil fuel ash: Mechanical properties and durability. Case Studies in Construction Materials, 22, e04129.

[17] Dasar, A., Patah, D., Sainuddin, S., & Caronge, M. A. (2023). Ketahanan korosi baja tulangan dalam beton menggunakan palm oil fuel ash (POFA) dan air laut. Media Komunikasi Teknik Sipil, 29(2), 243–252.

[18] Dasar, A., Patah, D., & Apriansyah, A. (2024). Mechanical properties and durability of biomass ash concrete using freshwater and river sand. Key Engineering Materials, 960, 27–35.

[19] Dasar, A., Patah, D., & Okviyani, N. (2025). Impact of incorporating nano-palm oil fuel ash on the mechanical properties and durability of paving blocks prepared with seawater and sea sand for sustainable construction. Construction and Building Materials, 481, 141539. https://doi.org/10.1016/j.conbuildmat.2025.141539

[20] Leelalerkiet, V., Kyung, J. W., Ohtsu, M., & Yokota, M. (2004). Analysis of Half-Cell Potential measurement for corrosion of reinforced concrete. Construction and Building Materials, 18(3), 155-162.

[21] Koga, G. Y., Albert, B., & Nogueira, R. P. (2018). Revisiting the ASTM C876 standard for corrosion of reinforcing steel: On the correlation between corrosion potential and polarization resistance during the curing of different cement mortars. Electrochemistry Communications, 95, 1-4.

[22] Yodsudjai, W., & Pattarakittam, K. (2017). Influence of concrete properties on Half-Cell Potential measurements, Construction and Building Materials 141, 106–114. https://doi.org/10.1016/j.conbuildmat.2017.03.009

[23] Boğa, A. R., & Topçu, I. B. (2012). Influence of fly ash on corrosion resistance and chloride ion permeability of concrete. Construction and Building Materials, 31, 258-264.

[24] Chalee, W., Cheewaket, T., & Jaturapitakkul, C. (2021). Enhanced durability of concrete with palm oil fuel ash in a marine environment. Case Studies in Construction Materials, 14, e00535.

[25] Patah, D., Dasar, A., & Hamada, H. (2022). Electrochemical consideration on corrosion performance of steel bar embedded in SCMs mortar with initial chloride contaminated. AIP Conference Proceedings, 2543, 030016.

[26] Gopalan, M. K. (1996). Sorptivity of fly ash concretes. Cement and Concrete Research, 26(8), 1189-1197. https://doi.org/10.1016/0008-8846(96)00105-6

[27] Dong, Y., & Wang, K. (2024). A detailed insight into rate of water absorption of concrete using Sorptivity test: A state-of-the-art review. Expert Systems with Applications, 255, 124756.

[28] Islam, M. M., Islam, M. S., Mondal, B. C., & Islam, M. R. (2017). Effect of class F fly ash on the durability properties of concrete. Sustainable Environment Research, 27(1), 25-31. https://doi.org/10.1016/j.serj.2016.10.001

[29] Nath, P., & Sarker, P. K. (2011). Effect of fly ash on the durability properties of high strength concrete. Procedia Engineering, 14, 1149-1156. https://doi.org/10.1016/j.proeng.2011.07.14

[30] Patah, D., Dasar, A., & Noor, N. M. (2025). The effects of palm oil fuel ash on mechanical and durability properties of sustainable foamed concrete. Journal of the Civil Engineering Forum, 75-84.

[31] Patah, D., Dasar, A., Okviyani, N., Apriansyah, A., & Noor, N. M. (2026). Feasibility Study of Biomass Fly Ash as a Partial Cement Replacement in Mortar Cured in Seawater. Borneo Engineering: Jurnal Teknik Sipil, 65-74.

[32] Dasar, A., Patah, D., Suryani, H., Idris, R. N., Djamaluddin, I., & Apriansyah, A. (2025). Perfoma Mekanik dan Laju Penyerapan Air Mortar Ramah Lingkungan dengan Penggunaan Ultrafine Palm Oil Fuel Ash (POFA). JTT (Jurnal Teknologi Terpadu), 13(2), 158-165.

[33] ASTM International. (2025). Standard test method for corrosion potentials of uncoated reinforcing steel in concrete. ASTM C876/C876M. West Conshohocken (PA): ASTM International.

[34] ASTM International. (2020). Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes. ASTM C1585-20. West Conshohocken (PA): ASTM International.