Borneo Engineering: Jurnal Teknik Sipil
Vol. 10 No. 1. April 2026, pp. 65-74

ISSN 2685-7553
e-ISSN 2581-1134

Research Article

Feasibility Study of Biomass Fly Ash as a Partial Cement Replacement in Mortar Cured in Seawater

Amry Dasar[1,2], Dahlia Patah[1,2]*, Nur Okviyani[1], and Apriansyah[1], Nurazuwa Md Noor[5]

[1]Department of Civil Engineering, Faculty of Engineering, Universitas Sulawesi Barat, Majene, Indonesia
[2]Faculty of Vocational Studies, Hasanuddin University, Makassar, Indonesia
[5]Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Johor 86400, Malaysia

*Corresponding author: **dahlia.patah@gmail.com**
DOI. 10.35334/be.v10i1.717

Article history:
Received: Apr 07, 2026
Revised: Apr 11, 2026
Accepted: Apr 13, 2026

Keywords:
biomass fly ash,
mortar,
seawater,
compressive strength,
water absorption.

Abstract

The high consumption of cement and the limited utilization of biomass combustion residues have highlighted the need for the development of more sustainable cement materials, particularly for construction in coastal areas. While biomass fly ash (BFA) has potential as a cement replacement material, information regarding the use of raw BFA, without pretreatment, in mortar cured in seawater remains limited. This study aims to evaluate the technical feasibility of BFA as a partial cement replacement in mortar, based on compressive strength, ultrasonic pulse velocity (UPV), water absorption, and strength activity index (SAI). BFA was used to replace cement at levels of 10%, 20%, and 30% by weight. Mortar mixtures were prepared with a water-to-cement ratio of 0.40, using tap water for mixing and seawater as the curing medium. Compressive strength was tested at 7, 28, and 91 days, while UPV and water absorption were tested at 28 and 91 days. The SAI values were calculated from the compressive strength results to assess the effectiveness of BFA as a cement replacement material. The results indicated that mortar performance was significantly influenced by the BFA substitution level. The mixture with 10% BFA exhibited the best performance, achieving a compressive strength of 32.62 MPa at 91 days, a UPV value of 3434 m/s, and water absorption of 4.80%. The mixture with 20% BFA still showed reasonably good performance, whereas the 30% BFA mixture led to a noticeable deterioration in mortar quality. The SAI results confirmed that 10% replacement was the most effective level. These findings indicate that raw BFA can be directly utilized as a partial cement replacement in mortar cured in seawater.

©The author(s). Published by BEJTS
This is an open-access article distributed under the terms and conditions of the Creative Commons Attribution-ShareAlike 4.0 International License (CC BY-SA 4.0).

Introduction

The cement industry is a key sector in modern infrastructure development but also contributes significantly to global energy consumption and carbon emissions due to clinker production. Therefore, the development of low-carbon cement materials has become a primary focus in sustainable construction research. One of the widely explored approaches is the utilization of supplementary cementitious materials (SCMs) derived from industrial by-products or biomass residues. Several studies have shown that biomass ash has the potential to reduce Portland cement consumption, decrease waste generation, and support the development of more sustainable construction materials, although its performance is highly influenced by the biomass source, chemical composition, particle size, and reactivity (Bonfim & de Paula, 2021; Danish et al., 2023; Thomas et al., 2021; Tosti et al., 2020).

Among various biomass residues, biomass fly ash (BFA) has gained increasing attention as a cement replacement material. In general, BFA contains silica and other mineral components that can act as fillers and, under certain conditions, contribute to secondary reactions in the cement system. However, the behavior of BFA is not uniform. Several studies have shown that the success of utilizing BFA is greatly influenced by the ash source, unburned carbon content, alkali levels, particle fineness, and pre-treatment methods such as grinding, calcination, or flotation (Narani & Siddiqua, 2026; Wang & Baxter, 2007; Wang et al., 2008a, 2008b; Xu et al., 2025). Consequently, the performance of processed BFA cannot be directly equated with that of untreated BFA. The need for more sustainable cement materials is particularly critical in coastal areas, which typically face limited fresh water availability but are exposed to high marine environmental conditions. In this context, the use of seawater in concrete and mortar systems presents an interesting alternative. Some studies have shown that seawater can accelerate early hydration and enhance early strength due to dissolved ions; however, this effect does not always persist over the long term because aggressive ions, especially chloride and sulfate, can affect the microstructure development and durability of the binding system (Li et al., 2021; Saxena & Baghban, 2023; Zhao et al., 2021). Therefore, the evaluation of cement replacement materials in seawater-cured systems is necessary to ensure that testing conditions are more representative of applications in coastal areas.

Previous research has also shown that the substitution level is a critical parameter that determines the performance of cement-based materials. For various substitution materials, lower levels typically maintain mechanical performance, while higher levels tend to reduce strength due to a decreased proportion of active cement, low reactivity of some particles, and increased matrix porosity (Bonfim & de Paula, 2021; Narani & Siddiqua, 2026; Wang et al., 2008a). In the context of biomass-based materials and seawater systems, Patah et al. (2025) demonstrated that the use of ultrafine palm oil fuel ash at an optimal level could improve the mechanical properties and durability of concrete using seawater and sea sand. Dasar et al. (2025) also reported that the addition of nano-palm oil fuel ash in seawater and sea sand-based paving blocks could enhance both mechanical properties and material resistance. These findings suggest that combining biomass waste materials with marine environments is a relevant research direction, but its performance is highly influenced by ash type, processing levels, and substitution ratios. The substitution levels of 10%, 20%, and 30% BFA in this study were chosen incrementally to represent low, medium, and relatively high substitution ranges commonly used in studies of biomass-based cementitious materials. The 10% level was selected to evaluate whether untreated BFA could still provide particle filling effects and maintain mortar performance when the active cement fraction is still dominant. The 20% level was chosen as an intermediate level to assess the transition point, where the benefits of waste utilization and cement reduction begin to increase, but the risk of performance decline also becomes more apparent. Meanwhile, the 30% level was selected to examine how well the mortar system can maintain its quality at higher substitution levels, particularly considering that the BFA used was as-received and had not undergone pretreatment to enhance reactivity. Therefore, these three substitution levels were not chosen arbitrarily but were intended to capture gradual changes in mortar behavior and identify technically viable substitution ratios in seawater curing environments, consistent with findings that higher substitution levels often become a limiting factor in biomass ash-based materials (Bonfim & de Paula, 2021; Narani & Siddiqua, 2026; Wang et al., 2008a). However, studies on the use of untreated BFA in seawater-cured mortar systems are still limited. This gap is significant both scientifically and practically. Scientifically, it is unclear at

which substitution level BFA can still maintain mortar matrix quality in a seawater curing environment. Practically, using untreated BFA is much more realistic for areas with limited waste processing facilities. Additionally, evaluating the feasibility of BFA should not only be based on compressive strength but also needs to consider internal material quality and fluid transport characteristics through UPV and water absorption tests.

Based on the above considerations, this study aims to evaluate the technical feasibility of BFA as a partial cement replacement in seawater-cured mortar. BFA was used at 10%, 20%, and 30% by weight of cement, and the mortar performance was assessed through compressive strength, UPV, water absorption, and SAI. The novelty of this research lies in the evaluation of untreated BFA in a seawater-curing mortar system, providing experimental groundwork for the development of simpler, more resource-efficient cement materials, with better biomass waste utilization, and more relevant to coastal environments.

Methodology

Materials

Cement and Biomass Fly Ash (BFA)

The binding material used in this study was Portland Composite Cement (PCC) conforming to SNI 15-7064-2004, with a specific gravity of 3.08. Biomass fly ash (BFA) was obtained from the biomass boiler of PT Tirta Fresindo Jaya, Gowa, South Sulawesi, Indonesia. This ash was produced from a fuel mixture consisting of 70% palm kernel shell and 30% tea leaf waste, combusted at a temperature of approximately 800°C. Unlike many previous studies, BFA in this research was used in its as-received condition, without any pre-treatment such as drying, grinding, or sieving. BFA has a specific gravity of 2.94 and a maximum particle size of approximately 300 µm. The main oxide composition of BFA includes SiO_2 (40.43%), CaO (34.30%), P_2O_5 (7.84%), MgO (4.62%), K_2O (4.06%), SO_3 (4.055%), Al_2O_3 (0.69%), and Fe_2O_3 (0.33%). The physical appearance of PCC and BFA, as well as their surface morphology, are shown in Figure 1.

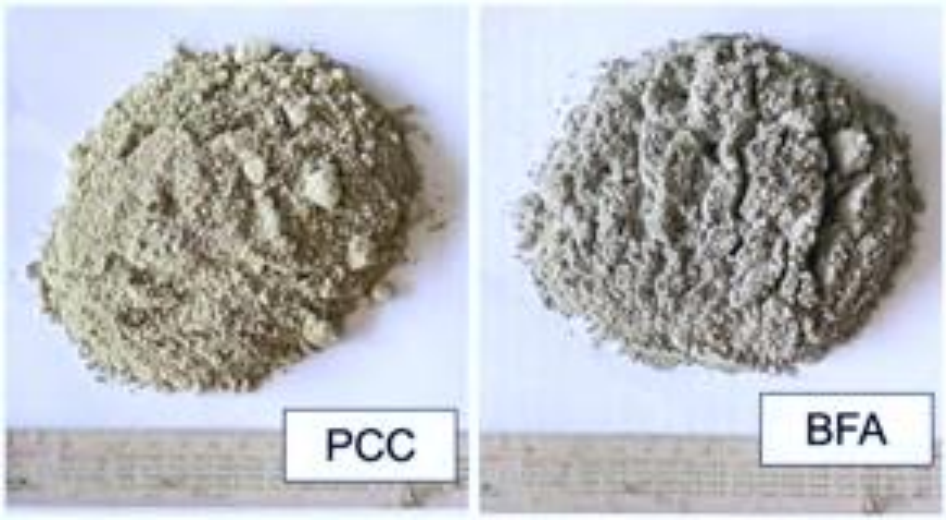


Figure 1. Morphology of PCC and BFA

Fine Aggregate and Water

The fine aggregate used was natural river sand conforming to ASTM C33/C33M-18, prepared in a saturated surface-dry (SSD) condition. The physical characteristics of the sand are presented in Table 1. Tap water was used for mixing, while seawater taken from Pangali-ali Beach, Majene, Indonesia, was used as the curing medium. The seawater had a salinity of 30.2‰, a specific gravity of 1.03, and a pH of 7.3 (Patah et al., 2025).

Table 1. Physical Properties of Fine Aggregate

Material	Apparent Specific Gravity	Bulk Specific Gravity (Oven-Dry)	Bulk Specific Gravity (SSD)	Water Absorption (%)
Sand	2.43	2.32	2.36	1.92

Mixing Proportions and Test Specimen Preparation

The mortar mixture was designed with a fixed water-to-cement (w/c) ratio of 0.40. BFA was used as a partial substitute for PCC at 10%, 20%, and 30% by weight of cement, while the mixture without BFA was used as the control. All mixtures were assigned the following codes: N-R-TS, BA-R-TS, BB-R-TS, and BC-R-TS, representing BFA content of 0%, 10%, 20%, and 30%, respectively. Fine aggregates were prepared in the SSD condition to maintain consistent effective moisture content in each mixture.

Mixing was carried out using a 50 L pan mixer, following SNI 03-3976-1995 standards. The dry ingredients, including cement, BFA, and sand, were initially mixed for 1 minute. Water was then added gradually while mixing for 1 more minute. The mixer was paused briefly to manually dislodge any material adhered to the walls and base of the mixing container, then mixing resumed for another 2 minutes to obtain a homogeneous fresh mortar. The fresh mortar was then poured into 50 × 50 × 50 mm cube molds and compacted using a vibrating machine to minimize air entrapment. After molding, the specimens were stored at a temperature of 23 ± 2°C and covered with plastic sheets to prevent moisture loss. After 24 hours, the specimens were removed from the molds and submerged in seawater at 23 ± 2°C until the designated testing age. The mixture proportions are shown in Table 2.

Table 2. Mortar Mix Proportions

Mix ID	Unit weight (kg/m^3)			
	PCC	BFA	Water	Sand
N-R-TS	580		232	1223
BA-R-TS	551	29	232	1221
BB-R-TS	493	87	232	1217
BC-R-TS	435	145	232	1213

Testing Method

Compressive Strength

The compressive strength of the mortar was tested according to ASTM C109/C109M using cube specimens measuring 50 × 50 × 50 mm. Testing was conducted at 7, 28, and 91 days. For each testing age, the compressive strength was determined as the average of three specimens for each mixture. Variations in the results between specimens were evaluated descriptively using standard deviation to assess the consistency of the test data. The test was performed using a 2000 kN capacity compression machine, with a loading rate of 0.25 MPa/s until specimen failure occurred. The compressive strength value (f'c) was calculated using Equation (1).

$$f'c = \frac{P}{\Delta t} \quad (1)$$

Where, f'c is the compressive strength (MPa), P is the maximum load applied to the specimen (N), and A is the loaded area (mm²).

Strength Activity Index and Strength Contribution

To evaluate the feasibility of BFA as a partial cement replacement material, the strength activity index (SAI) was calculated based on the compressive strength of the mortar. SAI is expressed as the ratio of the compressive strength of the BFA-containing mortar to the compressive strength of the control mortar at the same testing age, expressed as a percentage. The interpretation of SAI follows ASTM C311, where an SAI value ≥ 75% indicates that the substitute material still provides adequate strength contribution to the cement system. SAI was calculated using Equation (2).

$$SAI\ (\%) = \frac{f_{c,BFA}}{f_{c,control}} x\ 100 \quad (2)$$

where, $f_{c,\mathrm{BFA}}$is the compressive strength of mortar containing BFA (MPa), $f_{c,\mathrm{control}}$ is the compressive strength of control mortar without BFA substitution (MPa)

Additionally, to evaluate the relative contribution of BFA to the strength development of the mortar, the specific strength index approach was used. The specific strength ratio is calculated using Equation (3).

$$R = \frac{fc}{q} \quad (3)$$

where fc is the compressive strength of the mortar (MPa), q is the proportion of cement or BFA in the total cementitious material, and R is the relative strength contribution per unit of binder material

In this approach, R_c represents the strength efficiency of the control mixture without BFA, while R_m represents the strength efficiency of the mixture containing BFA. The additional strength contribution of BFA to the mortar, R_p, is calculated using Equation (4).

$$R_p = R_m - R_c \quad (4)$$

Subsequently, the percentage of the additional strength contribution of BFA, P is calculated using Equation (5)

$$P = \frac{R_p}{R_m} \times 100\% \quad (5)$$

A positive P value indicates that the presence of BFA contributes positively to the strength development of the mortar.

Ultrasonic Pulse Velocity (UPV)

The ultrasonic pulse velocity (UPV) test was performed using a Pundit device according to ASTM C597. The testing was conducted at 28 and 91 days. The travel time of ultrasonic waves with a frequency of 54 kHz passing through the specimen was recorded, and the wave velocity was then calculated. For each mixture and testing age, the UPV value was obtained from three specimens and expressed as the average value. Data variations between specimens were analyzed descriptively using standard deviation. The classification of mortar quality based on UPV values is presented in Table 3.

Table 3. Classification of Mortar Quality Based on UPV Value

UPV Value (m/s)	Mortar Quality
> 4500	Very Good
3500 – 4500	Good
3000 – 3500	Questionable
2000 – 3000	Poor
< 2000	Very Poor

Water Absorption

The water absorption test was conducted at 28 and 91 days on three 50 × 50 × 50 mm mortar cube specimens for each mixture variation, and data variations were evaluated descriptively using standard deviation. This test follows ASTM C642-13.

Results and Discussion

Compressive Strength

Figure 2 shows the development of the compressive strength of the mortar at 7, 28, and 91 days. All mixtures exhibited an increase in compressive strength over time, indicating that hydration and the

development of the binding structure continued during the curing period. This trend is consistent with the findings of Thomas et al. (2021) and Cho et al. (2019), who reported that mortar or concrete systems containing biomass ash continue to experience strength development at later ages, although the rate of increase is significantly influenced by the chemical and physical characteristics of the ash.

Based on the test results, the mixture with 10% BFA substitution showed the most favorable response, particularly at 91 days. At this level, the amount of active cement was still sufficient to maintain primary hydration, while the presence of BFA particles likely helped improve particle packing and reduce voids between particles. This interpretation aligns with Velardo et al. (2023), who found that biomass ash substitution at low to medium levels can still produce competitive compressive strength if the balance between the active cement fraction and the contribution of the substituting material is maintained. The mixture with 20% BFA still showed significant compressive strength development until 91 days, but its value was still lower compared to the 10% BFA mixture. These results indicate that at 20%, BFA still contributes to the mortar system, but the benefits start to be limited by the reduced amount of effective cement. This finding is consistent with Velardo et al. (2023) and Vanhove et al. (2024), who demonstrated that at higher substitution levels, system efficiency begins to decline due to an increased binder dilution effect, and not all substituting particles contribute effectively to matrix formation. In contrast, the clear reduction in compressive strength at 30% BFA indicates that at this level, the amount of active cement has been reduced too much, while the BFA used is not sufficiently reactive to effectively replace the function of cement. Narani and Siddiqua (2026) emphasize that BFA without pretreatment generally has limited reactivity, making its use at high substitution levels often detrimental to mechanical performance unless pre-treatment is applied to enhance the fineness and reactivity of the material.

Regarding the effect of the curing medium, seawater can support the development of early hydration due to its dissolved ion content. However, this effect is not always sufficient to compensate for the limitations of the substituting material at high levels. Li et al. (2021) and Saxena and Baghban (2023) show that cement-based systems cured in seawater still highly depend on the binder composition to maintain microstructure development and mechanical performance at later ages. Overall, the compressive strength results indicate that 10% BFA substitution is the most effective level in the mortar system studied. At this level, the balance between the amount of active cement, particle filling effect, and the potential contribution of long-term reactions is still in the most favorable condition.

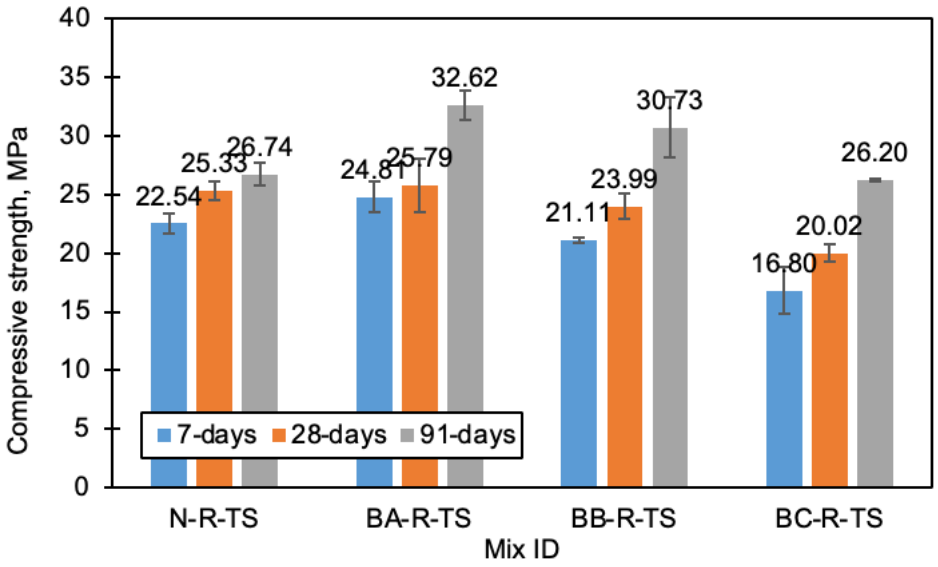


Figure 2. Compressive Strength of Mortar at 7, 28, and 91 Days

Strength Activity Index and Strength Contribution

The SAI values in Table 4 show that the mixture with 10% BFA provided the best performance across all testing ages, with 110.07% at 7 days, 103.16% at 28 days, and 121.99% at 91 days. The mixture with 20% BFA also maintained an SAI value above the 75% threshold, while the mixture with 30% BFA showed the lowest values, especially at early ages. These results indicate that at low

substitution levels, BFA can still maintain the effectiveness of the binder system, while increasing the substitution level begins to reduce the efficiency of active cement utilization. Thomas et al. (2021) explain that the success of biomass ash as a cement replacement material is highly influenced by the substitution level, particle fineness, and its chemical composition. Narani and Siddiqua (2026) also emphasize that untreated BFA generally has limited effectiveness at low substitution levels, while higher substitution levels require pre-treatment to maintain satisfactory mechanical performance. In this context, the high SAI values in the 10% BFA mixture indicate that at this level, the balance between the amount of active cement and the physical and chemical contributions of the ash is still in the most favorable condition.

Mechanistically, the higher SAI value at 10% BFA can be attributed to the dominant filler effect at low substitution levels, where the ash particles help improve particle packing, reduce interparticle voids, and support the formation of a denser matrix without excessively reducing the active cement fraction. At early ages, the strength contribution to the ash-based system is generally more controlled by these physical mechanisms than by the pozzolanic reaction, which is still limited. Tangpagasit et al. (2005) show that in mortars with fly ash, the contribution to the strength activity index at early ages is primarily influenced by the packing effect, while the pozzolanic reaction becomes more significant at later ages. This interpretation aligns with the findings of this study, where the 10% BFA mixture exhibited high SAI values from 7 days and continued to increase until 91 days.

The increase in SAI values at later ages, especially in the 10% and 20% BFA mixtures, suggests that, in addition to the physical effects, there may be a gradual chemical contribution during the curing process. In cement systems, ash particles containing reactive silica can react with calcium hydroxide from cement hydration to form secondary products, especially additional C-S-H gel, which contributes to microstructure densification and strength enhancement. This mechanism is generally not dominant at very early ages, but becomes more prominent at later ages when secondary reactions continue. This pattern is consistent with the development of compressive strength, UPV, and water absorption in this study, which together indicate improvements in the internal quality of the mortar in the low to medium BFA mixtures. Thomas et al. (2021) and Liang et al. (2024) stress that the contribution of biomass ash to mortar performance is highly determined by the combination of physical characteristics, mineral composition, and material reactivity, so strength enhancement at later ages is more likely to occur when the filling effect and secondary reactions can balance the reduction in active cement. In contrast, the lower SAI value in the 30% BFA mixture suggests that at high substitution levels, the binder dilution effect becomes more dominant compared to the physical and chemical benefits provided by BFA. In this case, the amount of active cement has decreased significantly, limiting the formation of primary hydration products. This situation is particularly important in this study because BFA was used in its as-received condition, without grinding or any other pre-treatment to improve its fineness and reactivity. Narani and Siddiqua (2026) report that the main limitation of untreated BFA lies in its low reactivity and workability, so the substitution level that can be maintained without reducing strength is generally relatively low. Liang et al. (2024) also show that variations in the chemical composition and physical characteristics of biomass ash lead to highly inconsistent performance of this material, so at high substitution levels, its benefits are not always sufficient to compensate for the reduced cement fraction. Therefore, the reduction in SAI in the 30% BFA mixture can be understood as the result of a combination of reduced active cement, limited secondary reactions, and suboptimal microstructure densification.

Table 4. Strength Activity Index of Mortar

Mixture	7-Day SAI (%)	28-Day SAI (%)	91-Day SAI (%)
N-R-TS	100,00	100,00	100,00
BA-R-TS	110,07	103,16	121,99
BB-R-TS	93,74	95,96	114,92
BC-R-TS	74,53	80,04	97,98

Description: SAI = Strength Activity Index

The specific strength ratio values, additional strength contribution, and percentage of additional contribution in Table 5 show that all mixtures containing BFA still provide a positive additional contribution to the development of mortar strength. However, the efficiency of this contribution

decreases as the substitution level increases. Xu et al. (2025) show that the performance of mortar containing biomass ash is greatly influenced by the quality of the ash and its pre-treatment; ashes with more stable and reactive properties tend to provide better strength contributions, especially at later ages. In this study, the consistently positive additional strength contributions in all mixtures indicate that BFA does not only act as an inert material but still contributes to the binding system. However, the magnitude of this contribution varies across substitution levels. At 10%, this additional contribution is more effective because it occurs in a system still dominated by active cement and supported by internal structure densification. At 20%, the contribution continues, but its efficiency begins to be limited by the reduced cement amount and the increased likelihood of non-optimal ash particle reactivity. At 30%, although the additional contribution is still mathematically identified, its influence is no longer strong enough to result in better overall performance compared to mixtures with lower substitution levels.

Table 5. Specific Power Ratio and Power Contribution

Mixture	Rm 7 days	Rm 28 days	Rm 91 days	Rp 7 days	Rp 28 days	Rp 91 days	P 7 days (%)	P 28 days (%)	P 91 days (%)
N-R-TS	0,2254	0,2500	0,2674	–	–	–	–	–	–
BA-R-TS	0,2757	0,2866	0,3624	0,0503	0,0366	0,0950	18,23	12,76	26,22
BB-R-TS	0,2641	0,2999	0,3841	0,0387	0,0499	0,1167	14,66	16,63	30,39
BC-R-TS	0,2400	0,2859	0,3743	0,0146	0,0359	0,1069	6,08	12,54	28,56

Description: Rm is the specific strength ratio of the mortar mixture containing BFA, Rp is the additional strength contribution resulting from the presence of BFA, and P is the percentage of the additional strength contribution of BFA.

Overall, the results in Tables 4 and 5 reinforce that 10% BFA substitution is the most effective level in maintaining and enhancing the mechanical performance of the mortar. This interpretation is supported by the trend that at low substitution levels, BFA still provides synergy between the particle filling effect, the potential contribution of secondary reactions at later ages, and the preservation of the active cement fraction, while at higher levels, the binder dilution effect and the limitations of untreated BFA reactivity become more dominant.

Ultrasonic Pulse Velocity

Figure 3 shows the UPV values of the mortar at 28 and 91 days. All mixtures exhibited an increase in UPV over time, indicating the development of the internal quality of the mortar during curing. At 91 days, the BA-R-TS mixture showed the highest UPV value, followed closely by BB-R-TS, while BC-R-TS maintained the lowest value.

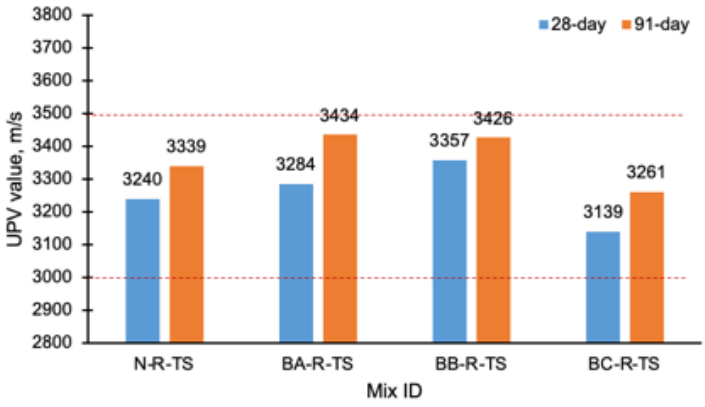


Figure 3. UPV Values of Mortar at 28 and 91 Days

The increase in UPV values in the 10–20% BFA mixtures indicates that at these levels, BFA still supports the formation of a relatively homogeneous internal structure in the mortar. Thomas et al. (2021) explain that biomass ash can provide benefits through the particle filling effect and, depending on the material characteristics, potentially limited reactive contributions that help improve the paste

structure. Bonfim and de Paula (2021) also reported that mortars containing biomass ash at certain levels can still exhibit good physical and mechanical performance when the chemical and physical characteristics of the ash support the formation of a denser matrix. In contrast, the lower UPV values in the 30% BFA mixture suggest that the increased substitution level leads to a decline in the internal quality of the mortar. Narani and Siddiqua (2026) indicate that untreated BFA has limitations in reactivity and efficiency at high substitution levels, so excessive substitution tends to reduce the homogeneity and compactness of the matrix.

The UPV results are also consistent with the compressive strength data. The BA-R-TS mixture exhibited the highest compressive strength and UPV, while BC-R-TS showed the lowest values in both parameters. This indicates that changes in UPV values reflect changes in the internal quality of the mortar. Velardo et al. (2023) and Zhao et al. (2021) demonstrated that UPV is closely related to matrix homogeneity, porosity, and the mechanical quality of cement-based materials.

Overall, the UPV results show that 10–20% BFA substitution can still support the formation of a relatively good internal structure in the mortar, while 30% substitution leads to a more noticeable decline in internal quality.

Water absorption

Figure 4 shows that all mixtures experienced a decrease in water absorption from 28 days to 91 days. At 91 days, the BA-R-TS mixture exhibited the lowest water absorption, while the BC-R-TS mixture had the highest value. This trend indicates that the increased curing age promotes microstructure densification in the mortar, reducing the number and connectivity of open pores. The lowest water absorption value in BA-R-TS indicates that 10% BFA substitution produces mortar with the most effective internal structure in limiting water penetration. Bonfim and de Paula (2021) show that changes in water absorption in mortars containing biomass ash are closely related to the physical-chemical characteristics of the ash and the development of pore structure. Velardo et al. (2023) also report that mortars with biomass ash at low to medium levels can exhibit lower porosity at later ages, along with improved compressive strength and microstructure enhancement. The BB-R-TS mixture still showed a considerable reduction in water absorption, but its value remained higher than that of BA-R-TS. This indicates that at the 20% substitution level, BFA still contributes to the densification of the structure, but not as effectively as at 10%. Thomas et al. (2021) explain that the success of biomass ash as a cement substitute is highly influenced by the substitution level, particle fineness, and its chemical composition. The highest water absorption value in BC-R-TS suggests that at 30% BFA substitution, the mortar becomes more permeable to water due to an increase in the number or connectivity of open pores. Tosti et al. (2018) show that using high levels of BFA does not always result in better durability performance, while Narani and Siddiqua (2026) emphasize that untreated BFA requires pre-treatment to be used at high substitution levels without degrading material quality.

The relationship between water absorption and porosity in this study can be further explained through the characteristics of the BFA particles used, which were in the as-received condition with a maximum particle size of about 300 μm. At low substitution levels, the presence of BFA particles still allows for the occurrence of the filler effect, where fine particles fill some of the interparticle voids, thereby making the paste structure denser and limiting water transport paths. However, the effectiveness of this mechanism is highly influenced by the particle size distribution, morphology, and surface area of the ash particles. Liang et al. (2024) explain that biomass fly ash generally has very varied characteristics, with particle morphology that tends to be irregular, a more non-uniform shape compared to coal fly ash, and a wide particle size distribution. These characteristics lead to the particle packing ability and contribution to microstructure densification being highly dependent on the substitution level and the physical quality of the ash itself. In the BA-R-TS mixture, the lowest water absorption result suggests that at 10% substitution, the BFA particle characteristics still adequately support improved particle packing. With a relatively limited substitution amount, BFA particles are believed to play a role in filling some of the empty spaces between cement grains and fine aggregates, thus reducing the open pores or making them less connected. This condition is consistent with the best performance in compressive strength and UPV observed in this mixture. Conversely, when the substitution level is increased to 20% and especially 30%, the influence of BFA particle characteristics on pore formation becomes more pronounced. If the ash is used without sieving or separating coarse fractions, the larger particles and irregular morphology tend to reduce packing efficiency, increase local water demand, and result in a more heterogeneous microstructure. Narani and Siddiqua (2026) report that the inherent

properties of BFA, including low reactivity, unburned particle content, and high water demand, are key factors limiting its use at high replacement levels without pre-treatment. This interpretation is also consistent with findings that simple physical treatments like sieving or grinding can improve the performance of biomass fly ash-based mortars by reducing coarse particle fractions and improving the homogeneity of the binding system. Rajczyk et al. (2023) show that sieving activation can increase the utilization rate of biomass fly ash up to 15% without significantly reducing the mechanical properties of the mortar, demonstrating that particle size characteristics play a direct role in the quality of the microstructure and water absorption behavior. Therefore, the higher water absorption values in the BB-R-TS and especially BC-R-TS mixtures in this study can be understood as a consequence of the increased proportion of BFA particles that have not been physically optimized, resulting in larger open pores and increased pore connectivity compared to mixtures with lower substitution levels.

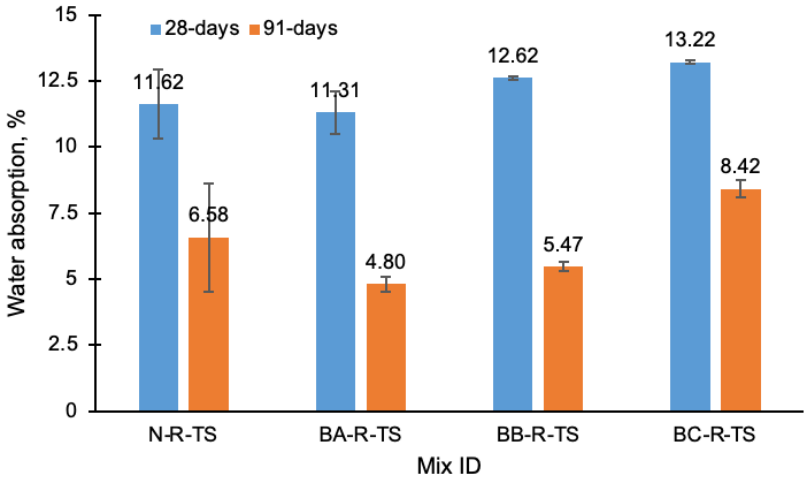


Figure 4 Water Absorption of Mortar at 28 and 91 Days

The trend in water absorption changes is also consistent with the previous two parameters, compressive strength and UPV. The mixture with the lowest water absorption, BA-R-TS, is the same mixture with the highest compressive strength and UPV. Conversely, BC-R-TS shows the highest water absorption, along with the lowest compressive strength and UPV values. Li et al. (2021) and Saxena and Baghban (2023) emphasize that microstructure quality and pore distribution are key determinants of mechanical properties and fluid transport in cement materials, including systems involving seawater. In the context of this study, this relationship indicates that changes in water absorption not only reflect differences in substitution levels but also demonstrate that the characteristics of BFA particles play a crucial role in determining the effective porosity of the mortar.

Overall, the water absorption results again indicate that 10% BFA substitution is the most effective level in producing mortar with the densest structure and greatest resistance to water penetration..

Conclusion

This study evaluates the technical feasibility of biomass fly ash (BFA) as a partial cement replacement in mortar cured in seawater. The results show that all mixtures exhibited property development as curing age increased; however, this response was significantly influenced by the BFA substitution level. Among all the mixture variations, the 10% BFA substitution provided the best overall performance, as demonstrated by the highest compressive strength at 91 days, the highest UPV value, and the lowest water absorption. These results indicate that at this level, the optimal balance between the remaining active cement content, particle filling effect, and the development of the mortar structure at later ages was achieved.

Increasing the substitution level to 20% still showed reasonably good performance, but all parameters remained below those of the 10% BFA mixture. In contrast, the 30% BFA substitution led to a noticeable deterioration in mortar quality, indicating that at this level, the binder dilution effect became more dominant, while the BFA was not reactive enough to effectively replace the function of cement. The SAI results further corroborated these findings, where the mixtures with 10% and 20%

BFA still demonstrated adequate strength effectiveness, while the 30% BFA mixture began to lose its efficiency at early ages.

Overall, this study demonstrates that BFA can be directly utilized as a partial cement replacement in mortar cured in seawater, with an optimal substitution level of 10%. These findings support the potential use of untreated biomass combustion residues as a more resource-efficient construction material, particularly for applications in coastal environments...

Conflicts of Interest

The authors declare no conflict of interest.

References

ASTM International. (2018). Standard specification for concrete aggregates (ASTM C33/C33M-18). West Conshohocken, PA: ASTM International.

ASTM International. (2021). Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens) (ASTM C109/C109M-21). West Conshohocken, PA: ASTM International.

ASTM International. (2022). Standard test method for pulse velocity through concrete (ASTM C597-22). West Conshohocken, PA: ASTM International.

ASTM International. (2024). Standard test methods for sampling and testing fly ash or natural pozzolans for use in portland-cement concrete (ASTM C311/C311M-24a). West Conshohocken, PA: ASTM International.

Badan Standardisasi Nasional. (1995). Tata cara pengadukan dan pengecoran beton (SNI 03-3976-1995). Jakarta, Indonesia: Badan Standardisasi Nasional.

Badan Standardisasi Nasional. (2004). Semen Portland komposit (SNI 15-7064-2004). Jakarta, Indonesia: Badan Standardisasi Nasional.

Bonfim, W. B., & de Paula, H. M. (2021). Characterization of different biomass ashes as supplementary cementitious material to produce coating mortar. Journal of Cleaner Production, 291, 125869.

Cho, Y. K., Jung, S. H., & Choi, Y. C. (2019). Effects of chemical composition of fly ash on compressive strength of fly ash cement mortar. Construction and Building Materials, 204, 255–264. https://doi.org/10.1016/j.conbuildmat.2019.01.208

Danish, A., Karadag, O., Bilir, T., & Ozbakkaloglu, T. (2023). Valorization of biomass ashes in the production of cementitious composites: A comprehensive review of properties and performance: Construction and Building Materials, 405, 133244.

Dasar, A., & Patah, D. (2024). Kekuatan dan durabilitas beton menggunakan palm oil fuel ash (POFA) dan pasir pantai. Borneo Engineering: Jurnal Teknik Sipil, 8(1), 83-94.

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.

Li, P., Li, W., Sun, Z., Shen, L., & Sheng, D. (2021). Development of sustainable concrete incorporating seawater: A critical review on cement hydration, microstructure, and mechanical strength. Cement and Concrete Composites, 121, 104100. https://doi.org/10.1016/j.cemconcomp.2021.104100

Nagrockienė, D., & Daugėla, A. (2018). Investigation into the properties of concrete modified with biomass combustion fly ash. Construction and Building Materials, 174, 369-375.

Narani, S., & Siddiqua, S. (2026). Biomass electrostatic precipitator fly ash treatment methodologies to maximize cement replacement in mortar and concrete. Construction and Building Materials, 506, 144879. https://doi.org/10.1016/j.conbuildmat.2025.144879

Patah, D., Dasar, A., & Apriansyah, A. (2024). Pengaruh air laut pada kualitas paving block untuk aplikasi nonstruktural. Borneo Engineering: Jurnal Teknik Sipil, 8(3), 253–266.

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.

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. In Materials Science Forum (Vol. 1091, pp. 111-118). Trans Tech Publications.

Saxena, S., & Baghban, M. H. (2023). Seawater concrete: A critical review and future prospects. Developments in the Built Environment, 16, 100257.

Thomas, B. S., Yang, J., Mo, K. H., Abdalla, J. A., Hawileh, R. A., & Ariyachandra, E. (2021). Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review. Journal of Building Engineering, 40, 102332. https://doi.org/10.1016/j.jobe.2021.102332

Tosti, L., van Zomeren, A., Pels, J. R., Damgaard, A., & Comans, R. N. J. (2020). Life cycle assessment of the reuse of fly ash from biomass combustion as secondary cementitious material in cement products. Journal of Cleaner Production, 245, 118937.

Tosti, L., van Zomeren, A., Pels, J. R., & Comans, R. N. J. (2018). Technical and environmental performance of low-carbon-footprint cement mortars containing biomass fly ash as a secondary cementitious material. Resources, Conservation and Recycling, 134, 25–33.

Vanhove, Y., Dossa, J. G., Page, J., & Djelal, C. (2024). Rheological benefits of biomass fly ash as filler replacement in cement-based materials. Case Studies in Construction Materials, 22, e04133. https://doi.org/10.1016/j.cscm.2024.e04133

Velardo, P., Sáez del Bosque, I. F., Sánchez de Rojas, M. I., De Belie, N., & Medina, C. (2023). Design and evaluation of physical, mechanical, and micro-structural properties of eco-friendly binary-blended mortars using biomass bottom ash or construction and demolition waste powder. Cement and Concrete Composites, 143, 105252. https://doi.org/10.1016/j.cemconcomp.2023.105252

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.

Wang, S., Miller, A., Llamazos, E., Fonseca, F., & Baxter, L. (2008a). Biomass fly ash in concrete: Mixture proportioning and mechanical properties. Fuel, 87(3), 365-371.

Wang, S., Baxter, L., & Fonseca, F. (2008b). Biomass fly ash in concrete: SEM, EDX, and ESEM analysis. Fuel, 87(3), 372–379.

Xu, M., Takasu, K., Liu, Z., & Suyama, H. (2025). Study on the modification effect by the flotation method of wood biomass fly ash and the applicability to cement-based composites. Case Studies in Construction Materials, 22, e04478.

Younis, A., Ebead, U., Suraneni, P., & Nanni, A. (2018). Fresh and hardened properties of seawater-mixed concrete. Construction and Building Materials, 190, 276–286.

Zhao, Y., Hu, X., Shi, C., Zhang, Z., & Zhu, D. (2021). A review on seawater sea-sand concrete: Mixture proportion, hydration, microstructure, and properties. Construction and Building Materials, 295, 123602.