2025 Scienceline Publication

*Journal of Civil Engineering and Urbanism*

Volume 15, Issue 4: 173-181; December 25, 2025

ISSN-2252-0430

DOI: https://dx.doi.org/10.54203/jceu.2025.10

# Evaluation of Pozzolanic Activity, Mechanical Strength, and Alkali-Silica Reaction in Cement Mortars Containing Biomass Ash

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RESEARCH ARTICLE
PII: S225204302500010-15
Received: October 02, 2025
Revised: December 15, 2025
Accepted: December 16, 2025

**ABSTRACT**

Sustainable construction practices are of great importance in mitigating the impacts of climate change and conserving natural resources. In this context, the present study investigates the feasibility of utilizing biomass ash (BA), derived from cotton and corn agricultural residues, as a pozzolanic additive in cement and concrete products. The experimental program evaluated the pozzolanic activity of BA, its influence on compressive strength, and its potential to mitigate alkali–silica reaction (ASR). In the pozzolanic activity test, the reference mortars achieved compressive strengths of 45.14 MPa and 51.13 MPa at 7 and 28 days, respectively, while BA-incorporated samples reached 35.12 MPa and 35.82 MPa, corresponding to a pozzolanic activity index of approximately 0.70. In concrete mixtures, compressive strength was maintained at acceptable levels for 15–20% BA replacement, whereas a significant reduction occurred at 25%, although strengths remained above 30 MPa. Furthermore, BA incorporation at 15%, 20%, and 25% reduced ASR-induced expansion by approximately 90% at 28 days, with all values remaining below ASTM limits. Overall, biomass ash demonstrated pozzolanic behavior and provided satisfactory mechanical and durability performance, highlighting its potential as a sustainable cement replacement and an effective material for mitigating ASR-related deterioration.

**Keywords:** Agricultural waste, Alkali–silica reaction mitigation, Biomass ash, Concrete durability Pozzolanic material, Mechanical performance.

## INTRODUCTION

Structural concrete, with an estimated annual global consumption of nearly 10 billion tons, represents the fundamental construction material of the modern building sector. Its extensive use is primarily due to its ease of placement and molding, relatively low cost, wide availability of raw materials, and high compressive strength. Portland cement, the principal binder in concrete, is currently the most widely used material. However, its production accounts for approximately 5% of global carbon dioxide ($CO_2$) emissions. The manufacture of one ton of cement releases about 222 kg of $CO_2$, contributing to severe environmental concerns (Kolip & Savaş, 2010; Worrell et al., 2001). Consequently, efforts to reduce environmental impacts, lower raw material and fuel consumption, and improve product quality have intensified. Numerous studies have therefore recommended the partial substitution of Portland cement with low-cost industrial by-products. In line with these approaches, composite cements incorporating supplementary materials such as fly ash (Class C and F), blast furnace slag, and silica fume have been identified as sustainable alternatives (Dwivedi et al., 2006).

With the rapid depletion of underground fuel resources, alternative solutions in energy production have gained increasing importance. In particular, the timber products industry has become prominent in developed countries. The utilization of industrial waste materials as supplementary pozzolans in concrete and cement production not only reduces Portland cement consumption but also contributes to improved waste management and environmental sustainability. Pozzolans, which contain siliceous or siliceous–aluminous compounds but lack intrinsic binding ability, are defined as mineral additives that react with cement and water to develop binding capability. Accordingly, they are generally categorized as natural (e.g., calcined diatomaceous earth, volcanic ash, shale) or artificial (e.g., silica fume, wood ash, fly ash, blast furnace slag) (Raheem et al., 2025).

The development of affordable, sustainable, and high-quality construction materials remains a challenge for the research community. Extensive studies have been conducted to evaluate the properties of concrete incorporating agricultural by-product ashes as pozzolanic additives (Thomas et al., 2021). Moreover, artificial pozzolans derived from industrial and agricultural by-products are now widely applied as partial cement replacements, primarily to reduce energy consumption during clinker production and to mitigate environmental impacts. Although initially regarded as low-value wastes, these materials have increasingly been recognized as indispensable additives that lower costs and environmental burdens in concrete and cement production. Nevertheless, the efficiency of pozzolans varies considerably, and further studies are needed to better understand their properties and the specific behaviors they impart to concrete (Becerra-Duitama & Rojas-Avellaneda, 2022).

The incorporation of solid fuel ashes as supplementary hydraulic binders in blended cements is considered an effective strategy to reduce global cement production. Several researchers (Elinwa & Ejeh, 2004; Elinwa et al., 2008; Elinwa & Mahmood, 2002; Udoeyo & Dashibil, 2002) have reported that wood waste ash can be effectively used as a partial cement replacement at levels ranging from 5% to 30% in concrete products. Wood ash, rich in silica and alumina, demonstrates limited binding ability on its own. However, when finely ground and exposed to moist conditions, it reacts with calcium hydroxide to form cementitious compounds, thereby qualifying as a pozzolan. Produced mainly by burning wood (e.g., sawdust, bark, branches) for energy generation, this by-product results from calcination at 400–1100 °C, yielding 6–10% ash recovery depending on the type of wood (e.g., pine, eucalyptus, hardwoods) (Siddique, 2012). Furthermore, the use of wood biomass as a renewable energy source has been widely studied. High-calcium wood ash (HCWA), in particular, has attracted attention as a by-product of industrial-scale, fully automated boiler systems (e.g., Bio-Turbomax). For instance, Cheah et al. (2011) investigated the pozzolanic properties of HCWA derived from the rubber tree species *Hevea brasiliensis* and demonstrated its potential for cement replacement.

Within this study, the potential utilization of biomass ash, obtained from a power plant in Söke district producing electricity, as a pozzolanic additive in cement and concrete products was investigated. An experimental program was conducted in which four groups of concrete mixtures were prepared with biomass ash replacement levels of 15%, 20%, and 25%. Compressive strength tests were performed at 7 and 28 days, and the pozzolanic activity of the biomass ash was evaluated based on compressive strength development. In addition, the effect of biomass ash on alkali–silica reaction (ASR) in mortars containing reactive siliceous aggregates was assessed. The findings obtained in this context provide significant insights into the potential application of biomass ash in the production of sustainable and renewable construction materials.

## MATERIALS AND METHODS

### Materials

#### *Aggregate*

For the preparation of mortar specimens used in the pozzolanic activity and compressive strength tests, Rilem-Cembureau standard sand conforming to TS EN 196-1 was employed. The granulometric properties of the sand are presented in Table 1, and its bulk density was determined as 2.01 g/cm³ (TS EN 196-1).

For the investigation of ASR behavior in biomass ash–blended mortars, aggregates in the 0–7 mm size range were obtained from a sand quarry located in the Geyve district along the Sakarya River. The ASR report of the aggregate, determined in accordance with ASTM C289 and TS 2517, is presented in Table 2 (ASTM C289-94; TS 2517). The reactive silica content of the Geyve sand (0–7 mm) was identified using the chemical analysis method specified in ASTM C289 and TS 2517.

**Table 1.** Granulometric properties of RILEM-Cembureau standard sand

| Sieve aperture (mm) | Retained (%) |
|---|---|
| 0.08 | 98 ± 2 |
| 0.16 | 87 ± 2 |
| 0.50 | 67 ± 2 |
| 1.00 | 33 ± 2 |
| 1.60 | 9 ± 2 |
| 2.00 | 0 |

**Table 2.** Chemical ASR report of aggregate determined in accordance with TS 2517

| Test parameter | Result | |
|---|---|---|
| NaOH (Consumed) | 350 (mmol/L) | III. Zone (Hazardousaggregate) |
| $SiO_2$ (Solved) | 700 (mmol/L) | III. Zone (Hazardousaggregate) |

#### *Cement and biomass ash*

Biomass ash was obtained by burning the roots and stems of cotton and corn plants harvested at the end of the season, together with branches and twigs collected from tree pruning, at temperatures ranging from 850 to 1100 °C for electricity generation. The ash was produced in a grate-fired boiler equipped with four grate stages.

Depending on its type, the ash can be collected from four different sources: (i) bottom ash beneath the grate, (ii) bunker ash under the heater tubes, (iii) bunker ash under the economizer tubes, and (iv) bunker ash beneath the cyclone–multicyclone system.

The ash used in this study was collected from the bunker beneath the multicyclone system, and its chemical analyses were carried out in the laboratory of Batı Söke Cement Factory. Prior to testing, the biomass ash sample was dried at 105 °C for 24 hours and sieved through a No. 100 sieve with a 0.150 mm aperture to prepare it for experimental use.

According to the chemical analysis, the potassium oxide ($K_2O$) content of the biomass ash was determined as 12.26%, while the calcium oxide (CaO) content was 19.27%.

As stated in ACI 221, the equivalent alkali content of cement ($Na_2O + 0.658 \cdot K_2O$) should not exceed 0.6%, with a recommended value of 0.4%. The alkali content of the cement used in this study was calculated as ($Na_2O + 0.658 \times K_2O$) = 0.38 + 0.658 × 0.67 = 0.82, which exceeds the specified limit (Yıldırım et al., 2014).

The chemical compositions of the biomass ash and cement (TS EN 197-1) are presented in Table 3, while the images of the materials are shown in Figure 1.

**Table 3.** Chemical composition of cement and biomass ash

| Test parameter | CEM I 42,5 R | Biomass Ash |
|---|---|---|
| $H_2O$ (%) | 0.22 | 0.46 |
| Free Lime (%) | 2.21 | 2.16 |
| Loss on Ignition (%) | 3.60 | 7.43 |
| CaO (%) | 62.22 | 19. 27 |
| $SiO_2$ (%) | 19.09 | 30.28 |
| $Al_2O_3$ (%) | 4.74 | 6.26 |
| $Fe_2O_3$ (%) | 3.20 | 2.39 |
| MgO (%) | 2.93 | 8.19 |
| $SO_3$ (%) | 3.03 | 0.07 |
| $Na_2O$ (%) | 0.38 | 2.53 |
| $K_2O$ (%) | 0.67 | 12.26 |
| $Na_2O$ Equivalent (Calculated) | 0.82 | 10.60 |
| Cl- (%) | 0.0219 | 1.4703 |
| 32 µm (%) | 10.00 | ------ |
| 45 µm (%) | ------ | 68.00 |
| 90 µm (%) | 0.60 | 47.10 |
| Specific Gravity | 3.12 | 2. 58 |
| Blaine | 3667 | 6789 |

**Figure 1.** Photographs of biomass feedstock and resulting ash.

**Method**

The strength and performance of concrete depend on various mechanical and durability properties. In this study, the mechanical and durability behavior of mortars and concretes incorporating biomass ash was evaluated through pozzolanic activity testing, compressive strength measurements, and assessment of ASR performance in mortars containing reactive silica aggregates. All mechanical test results represent the mean values of three specimens (n = 3), and the corresponding standard deviations and coefficients of variation (CoV) were calculated and reported to ensure statistical reliability of the measurements.

***Pozzolanic activity test***

The activity of pozzolans is determined by mechanical and chemical tests (ASTM C618-12a). In the experiment, biomass ash was used as a 20% replacement for cement. According to these mix proportions, six specimens with dimensions of 40 × 40 × 160 mm were cast for each group. The mix proportions of the mortar specimens used in the pozzolanic activity test are presented in Table 4.

**Table 4.** Mix proportions of mortars used in the pozzolanic activity test

| Mixture ID | Pozzolan addition (20%) (g) | Cement (g) | Standard sand (g) | W/C = 0.5 Water (g) | Average weight (g) |
|---|---|---|---|---|---|
| Control Sample | --- | 500 | 1320 | 250 | 615 |
| Biomass Ash Sample | 100 | 400 | 1320 | 250 | 604 |

***Compressive strength test***

In the compressive strength tests, RILEM-Cembureau standard sand, cement, and biomass ash were used together in the preparation of mortar specimens. Concrete mix groups were cast in molds with dimensions of 40 × 40 × 160 mm. The water-to-cement ratio (W/C) was fixed at 0.50, and four groups of concrete were prepared with biomass ash replacement levels of 15%, 20%, and 25%. Compressive strength tests were performed on the specimens at 7 and 28 days in accordance with TS EN 12390-3. The mix proportions of the biomass ash–blended concrete prepared for the compressive strength tests are presented in Table 5.

**Table 5.** Mix proportions of biomass ash–blended concrete prepared for compressive strength tests

| Mixture ID | Standard sand (g) | Cement (g) | Mineral additive (Biomass ash) (g) | Water (g) | W/C |
|---|---|---|---|---|---|
| Reference Mix | 1320 | 500 | - | 250 | 0.50 |
| BK-1 % 15 | 1320 | 425 | 75 | 250 | 0.50 |
| BK-2 % 20 | 1320 | 400 | 100 | 250 | 0.50 |
| BK-3 % 25 | 1320 | 375 | 125 | 250 | 0.50 |

***Alkali–silica reaction (ASR) test***

For the ASR tests, mixtures were prepared in accordance with the proportions specified in ASTM C227. The reactive silica-containing aggregate was partially replaced with biomass ash at levels of 15%, 20%, and 25%. In the mortar mixtures, the flow values were maintained within the range of 120–150 mm, while the water-to-cement (W/C) ratio was fixed at 0.50. The prepared mixtures were cast into prismatic molds with dimensions of 25 × 25 × 285 mm, and at least four specimens were produced for each mixture. The mix proportions of the mortars used in the ASR tests are presented in Table 6 (ASTM C227-97).

The accelerated mortar bar test described in ASTM C1260 was applied to determine the alkali reactivity of the aggregates (ASTM C1260-94). The expansion percentages obtained at the end of the 16-day test period were evaluated according to specified criteria. Accordingly, if the expansion at 16 days is below 0.10%, the aggregates are considered innocuous; if it exceeds 0.20%, they are classified as potentially deleterious. When the expansion values fall within the range of 0.10–0.20%, the aggregates may exhibit either deleterious or non-deleterious behavior under field conditions. In such cases, it is recommended that the test duration be extended to 28 days for a more reliable assessment.

**Table 6.** Mix proportions of materials used in ASR test specimens

| Mixture ID | Standard sand (g) | Cement (g) | Biomass ash (g) | Water (g) | W/C |
|---|---|---|---|---|---|
| Reference Mix | 1320 | 450.00 | - | 225 | 0.50 |
| BK-1 | 1320 | 382.50 | 67.50 | 225 | 0.50 |
| BK-2 | 1320 | 360.00 | 90.00 | 225 | 0.50 |
| BK-3 | 1320 | 337.50 | 112.50 | 225 | 0.50 |

## RESULTS AND DISCUSSION

**Unit weight**

The unit weight of the concrete mixtures decreased gradually with increasing biomass ash content. The reference mixture exhibited the highest value (1924 kg/m³), while the BK-1, BK-2, and BK-3 mixtures showed slight reductions of 0.52%, 0.68%, and 0.83%, respectively. This systematic decline is attributed to the lower specific gravity and more porous microstructure of biomass ash compared with Portland cement, which collectively reduce the overall density of the concrete matrix.

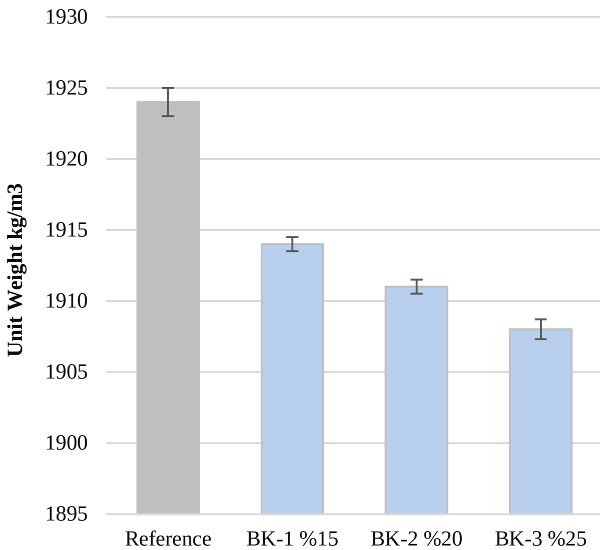


**Figure 2.** Unit weight of biomass ash- blended conrete

Similar observations have been reported in the literature for concretes incorporating biomass-derived ashes. Chen et al. (2025) noted that the reduction in density is primarily associated with the lower apparent density and more porous microstructure of biomass ash compared with conventional aggregates. In the present study, the unit weight decreased slightly (0.52–0.83%) with increasing BA content, which is consistent with the lighter and more irregular morphology of BA particles that occupy a larger volume per unit mass. Likewise, Rosales et al. (2025) observed that biomass bottom ash reduces the density of concrete due to its porous texture and lower specific gravity, which in turn may influence parameters such as water absorption and open porosity. The modest but systematic reduction in unit weight in the current study therefore reflects the intrinsic physical characteristics of BA and suggests a potential impact on the subsequent mechanical and durability behavior of the mixtures.

**Compressive strength results of the Pozzolanic activity test**

Compressive strength tests were conducted on the prepared specimens at 7 and 28 days, and the obtained results are presented in Table 7 and Figure 3.

The findings from the pozzolanic activity tests demonstrated that biomass ash achieved strength ratios of 0.78 at 7 days and 0.70 at 28 days, thereby meeting the minimum requirement for its use as a pozzolanic material. According to ASTM C618, the pozzolanic activity index must be at least 0.75 at 7 days, while EN 450-1 requires a minimum of 0.85 at 28 days. Although the 7-day value (0.78) satisfies the ASTM criterion, the 28-day value (0.70) falls below the EN 450-1 limit, suggesting that the material demonstrates partial pozzolanic performance depending on the standard applied. These results indicate that biomass ash possesses the potential to be used as a cement replacement material.

**Table 7.** Compressive strength results of biomass ash obtained from the pozzolanic activity test

| | 7 Gün | | 28 Gün | |
|---|---|---|---|---|
| **Specimen** | **7-Day strength (MPa)** | **Strength ratio** | **28-Day strength (MPa)** | **Strength ratio** |
| Reference Mix | 45.14 | 1.00 | 51.1 | 1.00 |
| Biomass Ash–Blended Mortar | 35.12 | 0.778 | 35.8 | 0.70 |

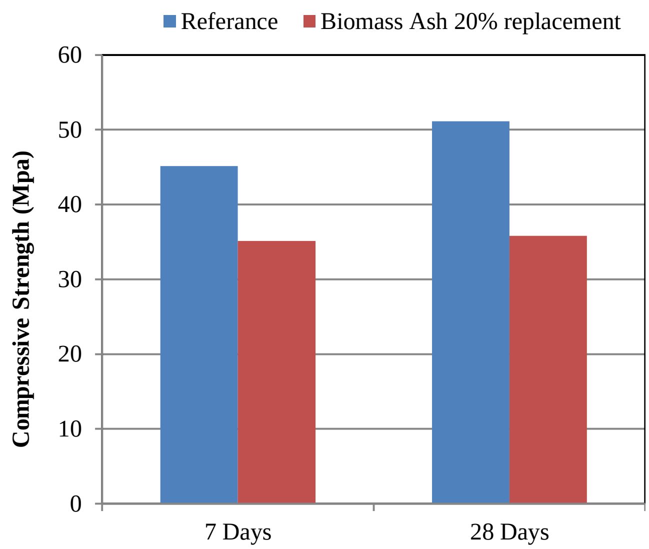


**Figure 3.** Compressive strength results at 7 and 28 days from the pozzolanic activity test of biomass ash–blended concrete.

This finding aligns with previous studies. For instance, Xu et al. (2025) reported that reactive $SiO_2$ and $Al_2O_3$ present in biomass ash react with $Ca(OH)_2$ released during cement hydration, forming additional C–S–H phases that enhance mechanical performance. Consequently, biomass ash can act not only as a filler material but also as an active pozzolan.

However, pozzolanic effectiveness is strongly influenced by the chemical composition and preparation conditions of the ash. Variations in the proportions of $SiO_2$, $Al_2O_3$, and CaO—particularly the presence of reactive amorphous oxides—significantly affect pozzolanic reactivity. This observation is consistent with the findings of Acordi et al. (2021), who noted that the chemical composition of wood ash varies with combustion temperature and biomass type. They reported that ashes rich in $SiO_2$ and $Al_2O_3$ exhibit desirable pozzolanic characteristics, whereas ashes with low reactive oxide content and high loss on ignition often fail to meet performance requirements. In addition, high loss on ignition may increase the water demand of cement paste, while sulfur-based compounds can prolong setting time and hinder hydration.

Therefore, the pozzolanic activity value of approximately 0.70 obtained in this study is in agreement with previous literature, indicating that biomass ash can be considered a sustainable supplementary cementitious material when appropriate preparation and curing conditions are ensured. At the same time, the variability associated with ash source and production conditions highlights the necessity for comprehensive chemical and mineralogical characterization prior to its use in different field applications.

**Compressive strength results**

The 7- and 28-day compressive strength results of concrete specimens produced by replacing cement with 15%, 20%, and 25% biomass ash, along with the reference specimen, are presented in Figure 4.

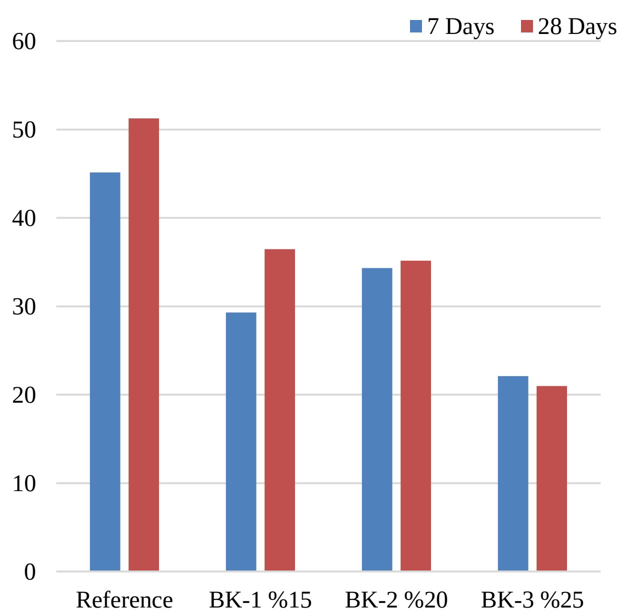


**Figure 4.** Compressive strength of biomass ash–blended concrete at 7 and 28 days.

According to the experimental results, the 7- and 28-day compressive strengths of the reference specimen were 45.14 MPa and 51.13 MPa, respectively, which comply with the CEM I 42.5 standard. The BK-1 (15%) and BK-2 (20%) replacement groups achieved 65–78% and 70–72% of the reference strength at 7 and 28 days, respectively. In contrast, the BK-3 (25%) group showed a more pronounced reduction, reaching only about 50% at 7 days and 40% at 28 days. These findings indicate that low to moderate replacement levels remain feasible, whereas higher replacement ratios have a detrimental effect on mechanical performance.

Similar observations have been reported in the literature. Chowdhury et al. (2015), in their study on wood ash, reported that compressive strength decreased with increasing replacement ratios, attributing this trend to the increased surface area of filler material to be bonded with cement. Similarly, Nagrockienė and Daugėla (2018) found that replacing cement with 5–10% biomass ash improved compressive strength, reporting an 11.9% increase at 28 days for the 5% replacement level. They associated this enhancement with the high reactive $SiO_2$ content of the ash in fly ash form. However, in the present study, biomass ash replacement at 15–25% resulted in reduced compressive strength compared with the reference, and the decline became substantially more pronounced at 25%.

A comprehensive review by Al-Kharabsheh et al. (2022) further supports this trend. They reported low replacement levels (5–10%) of wood or biomass ash generally improve or maintain strength, whereas higher levels (20–30%) lead to significant reductions. The findings of this study are largely consistent with that trend. Specifically, the mixes with 15% and 20% biomass ash replacement exhibited acceptable compressive strengths, whereas a notable strength loss occurred at 25% replacement. Nevertheless, some studies have reported strength enhancement even at 20% replacement. The comparatively lower values obtained in this study may be attributed to the chemical composition of the biomass ash (e.g., high $K_2O$ and low $SiO_2$ contents), combustion conditions (850–1100 °C), particle size distribution, and differences in curing conditions.

Therefore, the influence of biomass ash on concrete performance depends not only on the replacement ratio but also directly on the preparation conditions and mineralogical characteristics of the material.

**Alkali–silica reaction (ASR)**

The expansion results of the control mixture and biomass ash–blended specimens are presented in Table 8, while the graphical representation of ASR development is shown in Figure 5.

**Table 8.** Expansion values from the ASR test in biomass ash–blended mortar groups.

| Age (days) | Reference Mix | BK-1 (15%) | BK-2 (20%) | BK-3 (25%) |
|---|---|---|---|---|
| Day 7 | 0.191 | 0.251 | 0.196 | 0.19 |
| Day 14 | 0.37 | 0.0898 | 0.0694 | 0.0596 |
| Day 28 | 0.437 | 0.0407 | 0.0288 | 0.0351 |

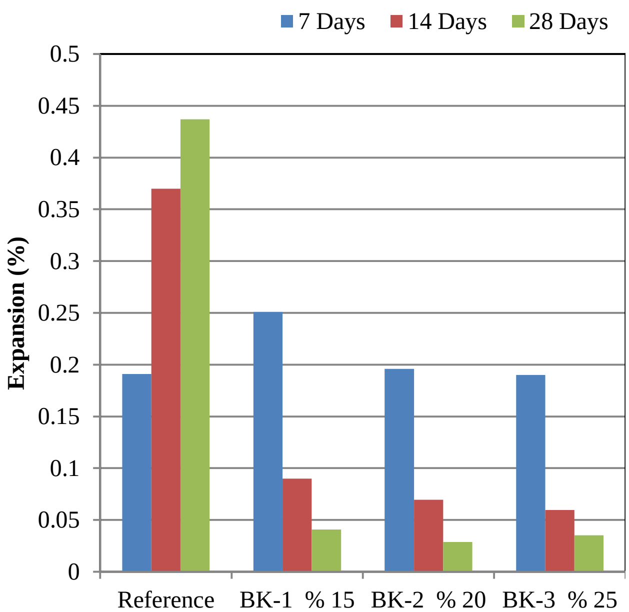


**Figure 5.** ASR formation graph in mortar groups with Biomass Ash additive

The results of the ASTM C1260 accelerated mortar bar test were evaluated based on the maximum standard limit of 0.20%. It was observed that the 16- and 28-day expansion values of the biomass ash–blended mortar groups remained below this threshold. Although the BK-1 group (15% replacement) exhibited an expansion of 0.25% at 7 days, the BK-2 (20%) and BK-3 (25%) groups showed lower values of 0.19%. More importantly, all blended specimens fell below the standard limit thereafter. By the end of 28 days, expansions were reduced by approximately 90% for the 15% replacement, 93% for the 20% replacement, and 92% for the 25% replacement when compared with the reference mixture. This pronounced reduction in expansion is attributed to the simultaneous effects of alkali dilution, consumption of $Ca(OH)_2$ through pozzolanic reactions, and the development of a denser microstructure, all of which limit the availability of reactive species and restrict the formation and swelling of ASR gel.

Similar trends have been reported in the literature. Rajamma et al. (2011) noted that mortars produced with highly reactive aggregates exhibited expansions of 0.31% at 14 days and 0.51% at 28 days in the reference mix. Although biomass ash replacements reduced expansions (0.21–0.25% at 14 days; 0.31–0.39% at 28 days for 20–30% replacement), the values remained above ASTM C1260 limits. In contrast, mixtures incorporating both biomass ash and metakaolin (20% BFA + 10% MK) achieved expansions as low as 0.03–0.11%, demonstrating effective ASR control. These findings indicate that while biomass ash alone provides a degree of mitigation, its performance may be constrained by mineralogical composition and particle size.

A comparable observation was reported by Esteves et al. (2012). They found that biomass ash additions significantly reduced ASR expansion compared to the reference, though values still exceeded ASTM limits. However, the inclusion of metakaolin (20% BFA + 10% MK) resulted in substantial reductions, again confirming effective mitigation.

Furthermore, Ramos et al. (2013) investigated the effects of wood waste ash (WWA) on ASR and found that 10% and 20% replacements reduced expansion by approximately 18% and 60%, respectively. According to ASTM C1567, the harmful expansion threshold of 0.1% at 14 days was lowered below this limit with 20% WWA, resulting in a low-risk binder–aggregate combination. Furthermore, SEM/EDX analyses confirmed the presence of typical alkali–silica gel on the surface of reactive aggregates, with Na, Si, and O identified as the dominant elements in the gel.

Taken together, these findings demonstrate that biomass ash replacement significantly limits expansion in mortars containing reactive aggregates. Notably, in the present study, even biomass ash used alone reduced expansions below ASTM limits by 28 days—an achievement more advanced than many results reported in the literature. Therefore, biomass ash not only contributes to waste valorization from an environmental perspective but also offers a technically valuable alternative for sustainable concrete production by mitigating ASR-related risks.

The chemical composition of the biomass ash used in this study (Table 3) provides important insight into its mechanical and durability-related behavior. The relatively low $SiO_2$ content (19.99%) and moderate $Al_2O_3$ content (6.26%) are consistent with the pozzolanic activity index of approximately 0.70, indicating limited yet measurable pozzolanic reactivity. The high $K_2O$ level (12.26%)

explains the slightly elevated early-age ASR expansion observed in the BK-1 mixture, while the high LOI value (7.43%) likely contributed to increased water demand and the reduction in compressive strength at higher replacement levels. Moreover, the moderate CaO content (19.27%) indicates minimal contribution to hydraulic reactions, supporting the conclusion that performance is governed primarily by pozzolanic and filler effects.

## CONCLUSIONS

This study addresses an important knowledge gap by examining the mechanical and durability performance of biomass ash derived from cotton in cementitious systems. The findings demonstrated that biomass ash exhibits a pozzolanic activity index of approximately 0.70, confirming its potential as a supplementary cementitious material. In compressive strength tests, performance was maintained at acceptable levels for 15–20% replacement, whereas a significant reduction was observed at 25% replacement, although strengths remained above 30 MPa. These results indicate that biomass ash can be effectively utilized in sustainable concrete production at low to moderate replacement levels, while higher replacement ratios have limited applicability.

In the ASR tests, approximately 90% reduction in expansion was achieved at 28 days for the 15%, 20%, and 25% replacement groups compared to the reference mixture, with all values falling below the ASTM limit. This demonstrates that biomass ash has strong potential to mitigate deleterious ASR-induced expansions, particularly in mixes containing reactive aggregates.

Overall, when proper preparation and curing conditions are ensured, biomass ash can improve both the mechanical and durability performance of concrete. This study, focusing on agricultural-waste-derived biomass ash in Türkiye, represents a significant step toward transforming local residues into sustainable construction materials, offering not only environmental benefits but also valuable economic contributions.

Future studies may focus on evaluating lower biomass ash replacement levels (5–10%), which may offer a more balanced performance in terms of both strength development and ASR mitigation. In addition, enhancing the reactivity of biomass ash through finer grinding or mechanical activation, or incorporating it into hybrid binder systems with materials such as metakaolin or silica fume, may further improve its pozzolanic behavior and overall efficiency in cementitious mixtures.

## DECLARATIONS

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### Acknowledgments

The authors gratefully acknowledge Mavi Bayrak – Biomass Energy Plant, Batı Söke Cement Factory, and Oyak Ready-Mixed Concrete Aydın Facility for their valuable contributions in providing materials and laboratory support for this study.

### Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

### Supplementary Information

The online version contains supplementary material available at link or upon request from the corresponding author.

### Competing interests

The authors declare no competing interests in this research and publication.

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