Advanced Engineering Letters **Vol.5, No.2, 88-100 (2026)** **e-ISSN: 2812-9709**

Mechanical Performance of Mortars with Biomass Ash

UDC:691.53:620.95
Original scientific paper https://doi.org/10.46793/adeletters.2026.5.2.3

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Abstract:
The use of alternative materials in cement-based composites is encouraged to reduce cement consumption and environmental waste. In this context, biomass ash can be considered a sustainable advanced material for partial or full replacement of cement; however, further research is needed to determine its effect on the mortar's mechanical performance. This study examines the effects of replacing cement, both completely (as a precursor in geopolymers) and partially, with biomass ash on the mechanical properties. Along with geopolymer mortars using biomass ash as the main binder, activated by alkaline solutions, a reference mortar containing 100% cement and a combination with 50% volumetric cement replacement were prepared. Tests for flexural and compressive strength of such mortars were performed. Even though the ash's pozzolanic activity index was only 27%, which is below the required 80%, and its flexural strength declined as its ash content increased, mortars containing up to 25% biomass ash as a binder were strong enough to be used in seismically active areas for masonry construction. Additionally, the ash showed outstanding alkaline activation capability, confirming its potential as an advanced binder material. The material's feasibility as a sustainable alternative binder was confirmed when alkali-activated mortars cured at room temperature attained compressive strengths sufficient for masonry applications in seismic regions.

ARTICLE HISTORY
Received: 17 March 2026
Revised: 30 April 2026
Accepted: 11 May 2026
Published: 22 June 2026

KEYWORDS
Biomass ash, Sustainability, Advanced materials, Cement, Mortar, Geopolymer, Seismicity

1. INTRODUCTION

The growing demand for sustainable construction materials has intensified research into alternative binders and supplementary cementitious materials, considered as advanced materials, capable of reducing both cement consumption and environmental impact. The cement industry is a major contributor to global carbon dioxide emissions, while large quantities of biomass ash are generated annually from energy production and industrial processes. The scale of this industry has grown to the point where it has become environmentally intensive, posing a serious threat to climate stability and global sustainability [1,2]. The extensive release of greenhouse gases, the depletion of limited natural resources, and the deterioration of local soil and air quality are only a few of the many ecological disturbances caused by this massive industrial output. The use of industrial by-products and energy-generation by-products in cement-based materials has received significant attention as a solution to these issues. By partially replacing Portland cement, these materials have the potential to lower CO_2 emissions and increase resource efficiency. In addition, the use of crushed brick as a supplementary cementitious material is already well established in practice due to its pozzolanic properties and availability as construction and demolition waste [3]. Because of

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the increased dependence on biomass as a renewable energy source, biomass ash has become one of these residues of growing interest. Owing to its mineral composition, biomass ash can be used in agricultural activities, especially as a soil amendment, and may also be applied in cementitious systems. However, biomass ash may contain hazardous heavy metals, such as Cd, Pb, Cr, Ni, and Zn, which restrict its safe reuse when present at elevated concentrations or in leachable forms. Consequently, these applications necessitate thorough chemical characterisation and environmental assessment [4-7]. Therefore, strict compliance with regulatory limits and thorough chemical characterisation are essential before considering its utilisation in agro-environmental contexts. Maj et al. [8] reviewed recent biomass ash streams and emphasized that their suitability for construction applications is highly dependent on the variable contents of calcium, silicon, phosphorus, chlorine, and potentially hazardous trace elements. This finding underscores the necessity for comprehensive psysicochemical characterisation prior to reuse. Valorising these residues in cement-based composites represents a promising strategy within the framework of circular economy principles [9,10]. However, the performance of biomass ash in mortar and concrete depends strongly on its origin, chemical composition, particle size distribution, and interaction with the cementitious matrix [11,12]. The advantages and disadvantages of using biomass ash in cement systems have been reported in earlier research [13,14]. Despite the environmental benefits of cement replacement, modifying the binder system may significantly alter mortar's mechanical behaviour, necessitating a thorough assessment of strength development and structural suitability [15-17]. The development of compressive and flexural strength may be directly affected by changes in binder composition. The dilution effect can reduce compressive strength, especially if the substituted material has little or no pozzolanic reactivity. Similarly, variations in crack-propagation mechanisms, interfacial transition zone properties, and microstructural cohesion may affect flexural strength. Recent research has increasingly focused on the valorisation of biomass-derived ashes as supplemental cementitious materials and aggregate substitutes in mortar and concrete, seeking to promote sustainability while retaining mechanical and durability performance. A thorough review of the literature on using wood waste ash (WWA) as a partial substitute for cement in structural-grade concrete and mortar was given by Ban and Ramli [18]. They methodically addressed the physical and chemical properties of WWA as well as the rheological behaviour, mechanical performance, and durability-related properties of blended systems. Building on this materials-oriented viewpoint, Ramos et al. [19] conducted an experimental evaluation of wood waste ash as a cement alternative in mortar, focusing on durability indicators, including alkali-silica reaction and carbonation resistance, as well as mechanical strength. They showed that up to 20% cement replacement can maintain structural integrity while greatly reducing expansion brought on by harmful chemical reactions. Simultaneously, Modolo et al. [20] focused on aggregate substitution, investigating the use of bottom ash from the combustion of forest biomass to render mortars as an alternative to natural sand. Replacements ranging from 50% to 100% produced mixtures that met standards and were similar to reference mortars, while consuming less natural aggregate and having a lower environmental impact. Regarding the mechanical ramifications, Beltrán et al. [21] found that replacing cement and natural sand with biomass bottom ash resulted in a general decrease in strength and an increase in porosity, even though bedding mortars that met technical criteria could still be produced. Long-term durability was further examined by Modolo et al. [22], who assessed fly ash from forest-biomass combustion as a calcite replacement in Portland cement mortars. While 20% substitution levels were acceptable for mechanical performance, sulfate resistance deteriorated significantly, underscoring durability constraints associated with certain ash chemistries. From a sustainability-oriented standpoint, Pavlíková et al. [23] demonstrated that mechanically activated wood chip ash used as a 20% cement replacement could reduce CO_2 emissions by approximately 15% and energy consumption by 16%, without compromising strength, activity, or pozzolanic performance. Fava et al. [24] investigated using mixed biomass ash derived from wood and agricultural waste as a cement substitute in mortars, broadening the range of materials. They verified the technical viability of adding such blended ashes to cement-based products through regression-based analyses of workability, compressive strength, and leaching behaviour. The use of wood and peat fly ash from fluidised-bed combustion as additional cementitious materials was subsequently investigated by Rissanen et al. [25]. Compressive strengths were better than those with limestone filler and equivalent to mortars using coal fly ash, despite greater porosity and capillary absorption. More recently, Hubert et al. [26] demonstrated that wood biomass fly ash can also be incorporated into masonry and rendering mortars. Although mechanical strength declined as the replacement level increased, mortars containing 10% substitution still remained appropriate for practical application, while the water absorption and porosity were not significantly affected. In the context of materials activated by alkalis, Archer de Carvalho et al. [27] reported that the incorporation of biomass fly ash into geopolymer mortars based on metakaolin led to a reduction in consistency diameter and compressive strength, together with an increase in efflorescence. Nevertheless, after optimisation, mixtures containing 39% biomass fly ash were still projected to reach approximately 30 MPa in compressive strength after seven days of curing, specifically under ambient conditions. Similarly, Ardhira et al. [28] showed that sugarcane bagasse ash (SCBA) and rice husk ash (RHA) can be successfully incorporated into geopolymer mortars cured at ambient temperature, with optimum additions of 10% and 5%, resulting in enhanced mechanical performance and favourable chemical resistance. A related strategy was reported by Marinho et al. [29], who produced ecological mortars using sustainable hydrated lime derived from biomass ash and found that 50% replacement of industrial hydrated lime was optimal, while even complete replacement was feasible without considerable strength loss. In another study focused on geopolymers, Prochon et al. [30] observed that phosphate-containing additions in fly ash mortars containing wood biomass fly ash improved both flexural and compressive strength over time, although porosity also increased, thereby underlining the strong influence of ash chemistry on geopolymer microstructure and mechanical behaviour. Collectively, these studies have significantly advanced understanding of biomass-derived ashes as potential cementitious and aggregate-replacement materials in the broader field of advanced materials. However, further systematic research is needed to clarify long-term durability, variability due to ash origin and combustion methods, and to standardise their use in structural applications.

2. MATERIALS AND METHODS

The performance of constituent materials in cementitious systems is strongly governed by their properties, and this chapter summarizes their chemical composition, heavy-metal content, particle-size distribution, and pozzolanic activity as a basis for assessing reactivity, environmental impact, and suitability for construction applications.

2.1 Pozzolanic Activity of Ash

The pozzolanic activity of the biomass ash was determined in accordance with HRN EN 450-1:2013 – Fly Ash for Concrete, Part 1: Definitions, Specifications and Conformity Criteria [31]. Cement prisms were prepared as a reference mixture and as a mixture with 25% of the cement replaced by biomass ash. Both mixtures were cast into three-part moulds, and after 24 hours, the hardened prisms were demolded, labelled, and submerged in water for further curing. At 90 days of age, the prisms were subjected to compressive strength testing in accordance with HRN EN 1015-11:2019 – Methods of Test for Mortar for Masonry, Part 11: Determination of Flexural and Compressive Strength of Hardened Mortar [32], as illustrated in Fig. 1.

Fig. 1. Experimental setup: a) specimens for testing the pozzolanic activity of ash, and b) compressive strength testing [33]

2.2 Granulometric Curves

The reactivity, packing density, and overall performance of the examined materials in cementitious systems are significantly influenced by their particle-size distributions. The range and homogeneity of particle sizes, which directly affect the materials' workability, hydration kinetics, and pozzolanic activity, were described using granulometric curves. The particle size distribution of cement and biomass ash was determined in accordance with HRN ISO 13320:2021 – Particle Size Analysis: Laser Diffraction Methods [34], confirming that cement is significantly finer, with 100% passing 239 µm compared to 55% for the ash (Fig. 2).

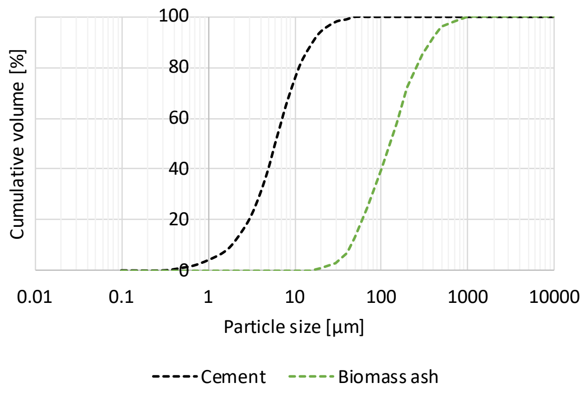


Fig. 2. Granulometric curves of cement and ash

The coarser particle-size distribution of the biomass ash, relative to cement, is an important factor in interpreting its pozzolanic performance. Since pozzolanic reactivity is largely governed by the available specific surface area, the lower fineness of the ash is expected to reduce its reactivity independently of its chemical composition. The river sand used as aggregate was characterized by particle size distribution according to HRN EN 933-1:2012 – Tests for geometrical properties of aggregates – Part 1: Determination of particle size distribution – Sieving method [35], with the resulting curve presented in Fig. 3.

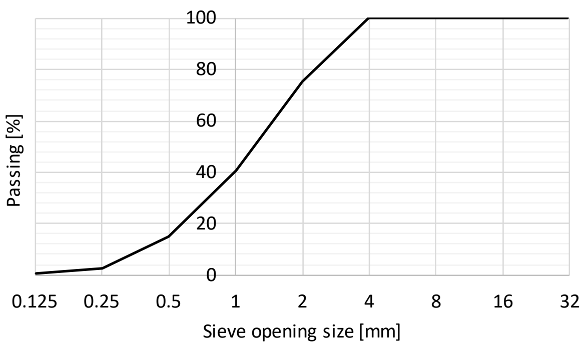


Fig. 3. Granulometric curves of sand

2.3 Mixture Proportions and Specimen Preparation

The experimental programme included cement-based mortars with varying biomass ash content and geopolymer mortars with different activators, with all replacements made on a volumetric basis to ensure consistent binder volume. The standard (cement-based) mortar mixtures were prepared using 1350 g of sand, 225 g of water, and a total binder content of 450 g. Biomass ash replaced cement in volume percentages of 0%, 25%, 50%, and 75%, yielding mixtures designated C100P0, C75P25, C50P50, and C25P75, respectively. In contrast, the geopolymer mixtures GP-KOH and GP-NaOH were formulated using 1350 g of sand and 380 mL of biomass ash, combined with an alkaline activator consisting of a 10 M hydroxide solution (KOH or NaOH) and sodium silicate (Na_2SiO_3) in a 1:2.5 ratio.

Mortar mixtures were cast into standard three-gang prismatic moulds and demoulded after 24 h. The specimens were then labelled and cured in water until testing, while geopolymer mortars were stored at room temperature. Flexural and compressive strengths were determined at 28 days in accordance with HRN EN 1015-11:2019 [32]. Each mixture was represented by three prisms, with standard deviations below 10% of the mean values.

3. RESULTS AND DISCUSSION

3.1 Classification and Characterisation on Biomass Ash

The chemical composition of the biomass ash (Table 1) reveals a material dominated by CaO (78.6%), with comparatively low concentrations of SiO_2 (4.22%), Al_2O_3 (0.96%), and Fe_2O_3 (1.82%).

Table 1. Chemical composition of cement and ash

Material	Cement	Biomass ash
P_2O_5	0.18	0.98
Na_2O	<0.10	<0.10
K_2O	1.09	5.45
CaO	62.00	78.60
MgO	3.14	3.25
Al_2O_3	4.29	0.96
TiO_2	0.33	1.95
Fe_2O_3	2.79	1.82
SiO_2	19.75	4.22
MnO_2	0.05	0.22
SO_3	6.37	2.59

When evaluated against ASTM C618 [36], the sum of SiO_2 + Al_2O_3 + Fe_2O_3 amounts to approximately 7.00%, which falls well below the 50% minimum required for Class F fly ash and the 70% minimum required for Class C fly ash. Consequently, the biomass ash investigated in this study does not qualify as a conventional supplementary cementitious material (SCM) under either ASTM C618 classification. This finding is significant: it confirms from a compositional standpoint alone that the ash cannot be expected to contribute to strength development through conventional pozzolanic pathways. The high CaO content (78.6%) warrants separate discussion. Calcium-rich ashes can exhibit hydraulic or latent-hydraulic behaviour, potentially contributing to cementitious reactions by forming calcium silicate and calcium aluminate phases. However, in the absence of sufficient reactive SiO_2 and Al_2O_3, the calcium content cannot be fully leveraged for C-S-H formation. The ash may therefore be better characterised as a non-conventional calcium-rich SCM rather than a pozzolan in the classical sense. This is consistent with the low pozzolanic activity index reported in Section 3.2 and underscores the need for alternative activation strategies, such as the alkaline activation explored in the geopolymer systems of this study. The heavy metal content in the ash was determined in accordance with ISO/TS 16996:2015 Solid biofuels — Determination of elemental composition by X-ray fluorescence [37], and is presented in Table 2.

Table 2. Heavy metal content in biomass ash

Quality Characteristics	Biomass ash
As	28.80
Cd	2.12
Co	<0.50
Cr	24.10
Cu	47.20
Mn	910.00
Mo	8.87
Ni	15.80
Pb	28.90
Sb	<0.50
V	18.60
Zn	196.00
Hg	1.05

Biomass ash derived from the combustion of wood fuel should not be directly applied to agricultural areas as a soil amendment, as is occasionally done, according to a comparison of the data shown in Table 2 with the maximum permitted amounts of heavy metals in Table 3.

Table 3. Allowable amounts of heavy metals in soil according to [38]

Heavy metal/soil type	Sandy soil	Silty loam soil	Clay loam soil
Cd	0-0.5	0.5-1	1-2
Pb	0-50	50-100	100-150
Ni	0-30	30-50	50-75
Hg	0-0.5	0.5-1	1-1.5
Zn	0-60	60-150	150-200
Cu	0-60	60-90	90-120
Cr	0-40	40-80	80-120

The ashes exceeded permissible Cd limits for all soil types, with elevated Zn and Hg in sandy and silty loam soils, indicating potential environmental and health risks for direct agricultural use. Incorporation into cementitious composites is therefore a more suitable option, enabling immobilisation of hazardous elements while enhancing mechanical and durability performance.

3.2 Pozzolanic Activity Index

Table 4 summarises the findings of the compressive strength tests conducted on prisms containing quartz sand.

Table 4. Compressive strength of mortar prisms with quartz sand

Prism type	Individual strength (MPa)	Mean strength (MPa)
Reference	65.92; 65.24; 59.95	63.70
Biomas ash	16.53; 18.25; 17.13	17.30

The testing results indicate that the biomass ash specimens reached a mean compressive strength of 17.30 MPa after 90 days, which is significantly lower than the 63.70 MPa recorded for the reference specimens. Based on these values, the calculated pozzolanic activity index (PA) is 27%. This value is substantially lower than the 85% threshold required at 90 days, indicating that the investigated ash does not meet the standard criteria for pozzolanic materials in this context. As a result, its contribution to strength development in the cement-based system is negligible, and its use as a cement replacement primarily results in reduced strength. While chemical analysis identified a high CaO content, this parameter alone is insufficient to confirm pozzolanic activity. Also, a low pozzolanic activity index suggests a limited contribution of the ash to later-age hydration processes. Consequently, substantial long-term strength recovery through pozzolanic reaction is not expected, and the reduction in mechanical performance observed at higher replacement levels is likely to persist with prolonged curing. Latent hydraulic behaviour should be distinguished from pozzolanic activity. The latter refers to the reaction of a material with calcium hydroxide in a cementitious system, whereas latent hydraulic behaviour describes its ability to develop cementitious properties only under favourable activation conditions. Accordingly, the low pozzolanic activity index of the investigated ash indicates limited reactivity as a cement replacement, but does not preclude its response in an alkali-activated system.

Beyond chemical composition, the coarser particle size of the biomass ash relative to cement is an additional contributing factor: pozzolanic reactivity is strongly governed by the specific surface area available for chemical reactions, and finer particles with greater surface exposure react more rapidly and completely. The granulometric data already indicate that the biomass ash is substantially coarser than cement, and this difference alone is sufficient to partially explain the reduced reactivity, independent of chemical composition. This low reactivity, despite the high CaO content observed in the chemical analysis, means that the ash will not contribute positively to strength development in cement-based systems through pozzolanic action, but will instead dilute the binder, as confirmed by the compressive strength trends.

3.3 Fresh Mortar Consistency

The consistency test results for the fresh mortar mixtures are presented in Table 5. The testing procedure was carried out in accordance with HRN EN 1015-3:2000/A2:2008 [39] and is illustrated in Fig. 4.

Table 5. Mortar consistencies

Mortar	Consistency (cm)
C100P0	19.50
C75P25	16.00
C50P50	15.00
C25P75	15.50

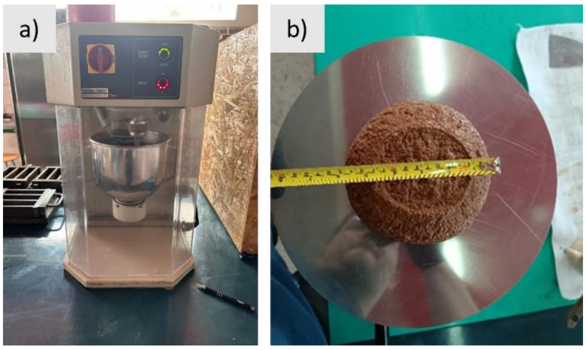


Fig. 4. Experimental setup: a) the mixer for preparing mortar mixtures, b) determination of mortar consistency on a flow table [33]

As shown in Table 5, increasing ash content reduced mortar consistency and workability due to ash's higher water absorption than sand. This outcome was expected, as the ash had a higher water demand than cement, thereby reducing the amount of free water available in the mixture and making the fresh mortars stiffer. Regarding the geopolymer mortars, it was not possible to measure their consistency because they exhibited an extremely rapid setting time. Although this prevented measurement of consistency, it also indicates a pronounced interaction between the biomass ash and the alkaline activators. The mortar mixtures were cast into three-gang moulds.

3.4 Flexural Strength

At 28 days, flexural and compressive strengths of the prisms shown in Fig. 5 were determined in accordance with HRN EN 1015-11:2019 [32] for hardened masonry mortar.

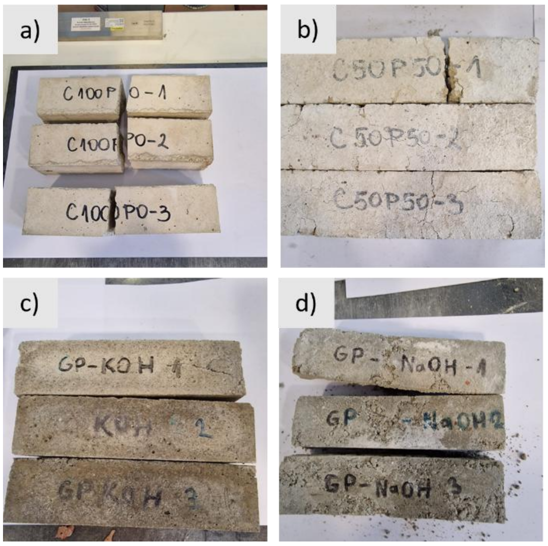


Fig. 5. Prism appearance of: a) cement mortar, b) mortar with partial replacement of cement by biomass ash, c) geopolymer mortar GP-KOH, d) geopolymer mortar GP-NaOH [33]

The process for determining the flexural and compressive strengths of these mortar prisms is illustrated in Fig. 6.

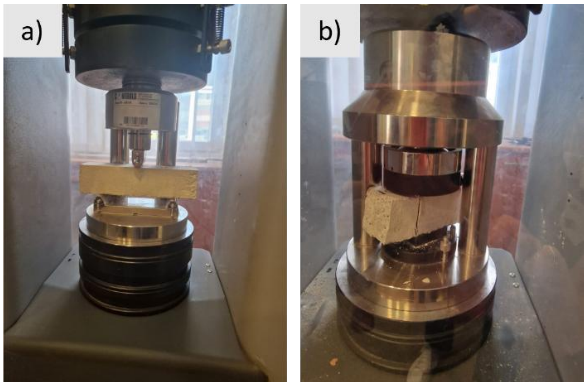
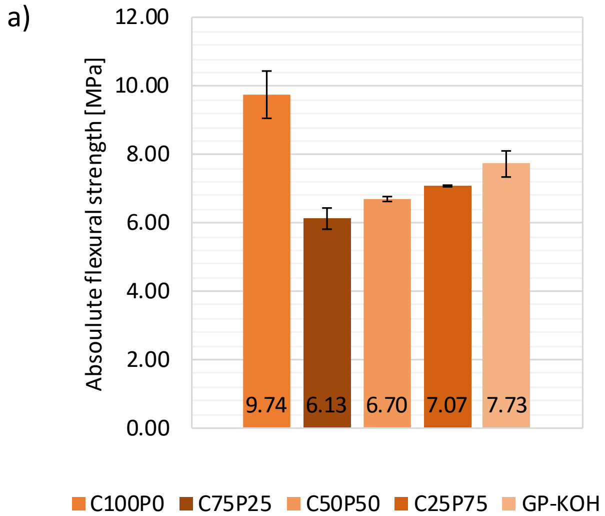


Fig. 6. Testing of mortar properties: a) flexural strength, b) compressive strength testing [33]

The resulting flexural strength data are presented in Fig. 7.



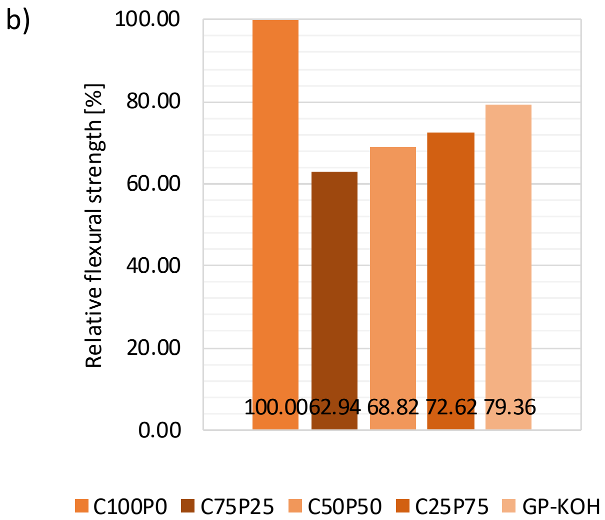


Fig. 7. Flexural strength test of mortars: a) absolute, and b) relative values

As presented in Fig. 7, the measured flexural strength increased with increasing biomass ash content. However, this trend is inconsistent with the low pozzolanic activity of the analysed ash and therefore cannot be explained by additional C-S-H formation or significant matrix densification. The observed increase is more plausibly related to the failure mechanism of the specimens during testing rather than to a genuine improvement in material behaviour. This interpretation contrasts with the findings of Ardhira et al. [28], who reported significant improvements in flexural strength in ambient-cured geopolymer mortars. Optimal additions of 10% SCBA and 5% RHA increased flexural strength by 10.6% and 3.5%, respectively. Similarly, Prochoń et al. [30] found that phosphate-bearing additions in biomass fly ash geopolymers led to increased flexural strength at 7, 28, and 56 days. However, this improvement was accompanied by a significant increase in porosity. In contrast, the apparent increase in flexural strength observed in the present conventional mortars should not be attributed to a beneficial effect of biomass ash. The recorded values were substantially influenced by the atypical failure mode observed during testing. The anomaly in recorded flexural strength can be attributed to the atypical failure mode observed in the biomass ash specimens, as shown in Fig. 8. Rather than exhibiting a distinct, complete flexural fracture, the specimens showed only partial cracking while continuing to bear load. Following the formation of the initial crack, the specimen remained partially supported by the apparatus's lower metal plate, altering the stress distribution as force was applied. This unintended contact resulted in the measurement of an additional load that did not reflect pure flexural behaviour.

Fig. 8. Failure of biomass ash mortar prisms during flexural strength testing [33]

This represents an important experimental consideration that may have influenced the measured flexural strength values, potentially affecting their reliability. Since no displacement sensors or load–displacement curves were recorded during testing, the occurrence and extent of this effect could not be identified or corrected during the experimental procedure. In addition, flexural tests were not repeated, further limiting the ability to verify the consistency of the results. Consequently, the reported flexural strength values should be interpreted with caution and considered as indicative rather than strictly quantitative. Importantly, this limitation is confined to the flexural testing procedure; the compressive strength results remain unaffected and fully valid, as they were obtained using a different testing configuration that did not exhibit the observed artefact.

3.5 Compressive Strength

The results of the compressive strength tests are presented in Fig. 9.

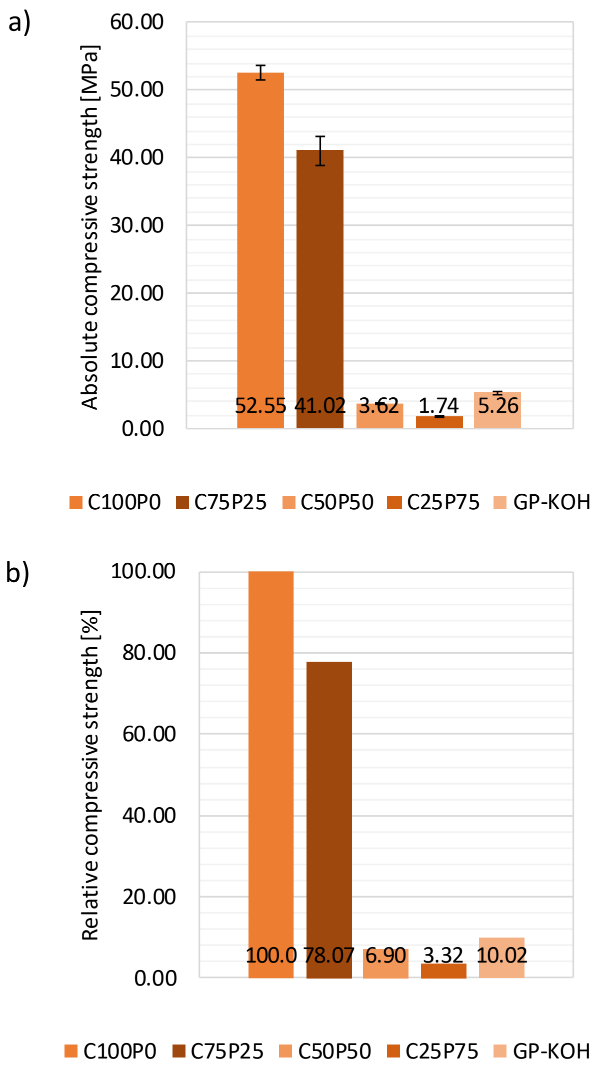


Fig. 9. Compressive strength test of mortars: a) absolute, and b) relative values

As shown in Fig. 9, the reference cement mortar achieved the highest compressive strength, reaching 52.55 MPa. A progressive decrease in compressive strength is observed as biomass ash content increases, indicating that partial or total replacement of cement adversely affects the mortar's load-bearing capacity. This trend is consistent with the ash's low pozzolanic activity, which limited its contribution to hydration and resulted primarily in binder dilution. At higher replacement levels, this effect was accompanied by increased porosity and a less effective binding matrix, leading to a pronounced loss of strength. The mixture containing 75% biomass ash exhibited a compressive strength of only 1.74 MPa, while the geopolymer mortar reached 5.26 MPa. According to HRN EN 1998-1:2011 [40], which governs the design of structures in seismic regions, mortars intended for masonry applications in seismically active areas must achieve a minimum compressive strength of 5 MPa. Based on this criterion, mixtures containing up to 25% biomass ash, as well as the geopolymer mortar, satisfy the prescribed requirement, whereas mixtures with higher ash contents do not meet the standard. This finding is practically relevant because it identifies a clear limit for conventional cement replacement with the investigated ash and, at the same time, confirms that the same ash can still be used in an alternative binder system that meets the minimum requirement for masonry applications in seismic zones. From a relative perspective, the comparison with the reference mortar further confirms the limited suitability of this ash as a high-volume cement replacement in conventional mortars. However, the geopolymer results show that the same material retained sufficient reactivity under alkaline activation to achieve a compressive strength above the threshold required for masonry applications in seismic regions, even with room-temperature curing. This distinction is one of the main findings of the study. The investigated biomass ash performed poorly as a direct cement replacement because of its low pozzolanic reactivity, but it showed meaningful alkali-activation potential when used as the primary precursor in a geopolymer system. The results therefore demonstrate that the suitability of biomass ash cannot be assessed solely on the basis of its behaviour in Portland cement mortars, but should also be considered in relation to alternative binder systems. The decreasing compressive-strength trend observed in the present cement-based mortars is consistent with Hubert et al. [26], who also reported an overall loss of performance with increasing wood biomass fly ash content and found that, even at 10% substitution, compressive-strength losses of 13% in masonry mortars and 20% in rendering mortars occurred after 90 days. A similar reduction in compressive strength with increasing incorporation of biomass fly ash was reported by Archer de Carvalho et al. [27] for metakaolin-based geopolymer mortars. However, their optimised formulation with 39% biomass fly ash was still predicted to reach about 30 MPa after 7 days under ambient curing. By contrast, Ardhira et al. [28] showed that, in a properly designed geopolymer system, 10% SCBA and 5% RHA increased compressive strength by 25% and 13.91%, respectively, relative to the control mixture. Together with the positive compressive strength development reported by Prochoń et al. [30] in phosphate-modified biomass fly ash geopolymers, these comparisons indicate that the mechanical role of biomass ash depends strongly on binder chemistry and activation route, rather than on ash presence by itself. All reported standard deviations are below 10% of the mean values, indicating good repeatability of the experimental results and confirming the reliability of the measurements. Overall, the results show that the investigated biomass ash is not suitable for high-volume direct cement replacement in conventional mortars, but remains technically promising in alkali-activated formulations and at low replacement levels, where minimum strength requirements can still be met. The progressive reduction in compressive strength with increasing ash substitution is consistent with the low pozzolanic activity index (27%) and with the ASTM C618 non-compliance discussed previously. Because the ash cannot contribute to cementitious hydration product formation at meaningful levels, higher substitution levels lead to greater binder dilution, which impairs mechanical performance. The authors propose that increased porosity accompanying binder dilution is a contributing mechanism to the observed strength reduction. However, it must be acknowledged that no direct microstructural or porosity measurements, such as scanning electron microscopy (SEM), X-ray diffraction (XRD), or thermogravimetric analysis (TGA/DTG), were performed in this study. The porosity-related explanation should therefore be treated as a working hypothesis rather than a demonstrated finding. Future work should incorporate microstructural characterisation to confirm or refine this interpretation.

3.6 One-Way Analysis of Variance

To evaluate whether the observed differences in mechanical properties among the investigated mixtures are statistically significant, a one-way Analysis of Variance (ANOVA) was performed. This method enables comparison of mean values across multiple groups and determines whether any differences between them are greater than would be expected by chance alone. In this study, ANOVA was applied to both flexural and compressive strength results in order to assess the influence of mixture composition on the measured responses. Prior to the analysis, the data were grouped according to mixture type, and basic descriptive statistics were calculated for each group (Table 6). These values provide insight into the distribution and variability of the results and serve as a basis for statistical testing. The null hypothesis assumes that there are no statistically significant differences between the group means, while the alternative hypothesis suggests that at least one group differs from the others.

Table 6. Summary statistics for One-Way ANOVA groups

Group	Count	Sum	Average	Variance
Flexural strength				
C100P0	3	29.22	9.74	0.4759
C75P25	3	18.39	6.13	0.0867
C50P50	3	20.11	6.7033	0.0080
C25P75	3	21.22	7.0733	0.0004
GP-KOH	3	23.19	7.73	0.1603
Compressive strength				
C100P0	3	157.65	52.55	1.2772
C75P25	3	123.07	41.02	4.5281
C50P50	3	10.87	3.62	0.0136
C25P75	3	5.23	1.74	0.0056
GP-KOH	3	15.79	5.26	0.0706

The results of the one-way ANOVA for both compressive and flexural strength, presented in Table 7, indicate a statistically significant effect of mixture composition. In both cases, the calculated F-values exceed the critical value F_{crit}=3.478, while the p-values are significantly lower than 0.05. This confirms the rejection of the null hypothesis and demonstrates that the differences between group means are statistically significant. Notably, the effect is more pronounced for compressive strength, as indicated by the substantially higher F-value.

Table 7. One-Way ANOVA results

Source	df	MS	F	p-value
Flexural strength				
Between Groups	4	5.8208	39.79406	4.12E-06
Within Groups	10	0.1463	-	-
Compressive strength				
Between Groups	4	1737.465	1473.618	8.35E-14
Within Groups	10	1.1790	-	-

4. CONCLUSION

This study investigated the mechanical performance of mortars incorporating biomass ash as a partial or complete replacement for cement, including both conventional cement-based systems and alkali-activated geopolymer formulations. The results revealed that the investigated biomass ash exhibits a low pozzolanic activity index of 27%, which falls substantially below the 85% threshold prescribed by the relevant standard, indicating negligible reactivity within conventional cementitious systems. Chemical analysis confirmed that the sum of SiO_2 + Al_2O_3 + Fe_2O_3 amounts to approximately 7%, which does not satisfy the minimum requirements of ASTM C618 for either Class F or Class C fly ash. The high CaO content (78.6%), while noteworthy, could not be leveraged for effective C-S-H formation due to the insufficient concentrations of reactive silica and alumina, further characterising the ash as a non-conventional calcium-rich material rather than a classical pozzolan.

From a particle size perspective, the biomass ash was found to be substantially coarser than cement, with only 55% of particles passing 239 µm compared to 100% for cement. Since pozzolanic reactivity is strongly governed by specific surface area, this coarser gradation is expected to further reduce reactivity independently of chemical composition. The absence of Blaine or BET surface area measurements is acknowledged as a limitation, and future research should include such characterisation for a more comprehensive assessment.

In terms of fresh mortar consistency, increasing biomass ash content progressively reduced workability due to the ash's higher water demand relative to cement. Geopolymer mortars exhibited an extremely rapid setting time, which, while preventing consistency measurement, confirmed a pronounced reactivity of the biomass ash when activated by alkaline solutions.

With respect to compressive strength, a progressive and statistically significant reduction was observed with increasing ash substitution, consistent with the dilution of the binder and the ash's limited contribution to hydration product formation. The reference cement mortar achieved 52.55 MPa, whereas mixtures with 50% and 75% ash content reached only 3.62 MPa and 1.74 MPa, respectively. According to HRN EN 1998-1:2011 (Eurocode 8), the minimum compressive strength required for masonry mortars in seismically active areas is 5 MPa. Based on this criterion, only mixtures containing up to 25% biomass ash (41.02 MPa) met the prescribed standard among the cement-based formulations. Increased porosity accompanying binder dilution is proposed as a contributing mechanism, though this hypothesis requires confirmation through future microstructural investigations, such as SEM, XRD, or TGA/DTG analyses, which were not performed in the present study.

A key finding of the study is the contrasting behaviour of biomass ash in alkali-activated systems. The geopolymer mortar activated with KOH and sodium silicate, cured at room temperature, attained a compressive strength of 5.26 MPa, thereby satisfying the minimum threshold for masonry applications in seismic regions. This confirms that the ash possesses meaningful alkali-activation potential despite its poor performance as a direct cement replacement. The suitability of biomass ash, therefore, cannot be assessed solely on the basis of its behaviour in Portland cement systems, but should also be evaluated in the context of alternative binder formulations.

Regarding flexural strength, the apparent increase in measured values with higher ash content was attributed to an atypical failure mode during testing, in which specimens continued to bear load after initial cracking due to unintended contact with the testing apparatus. In the absence of load–displacement recordings and without repeated testing, these values should be considered as indicative rather than strictly quantitative. This limitation is confined to the flexural testing procedure and does not affect the validity of the compressive strength results.

Regarding the environmental suitability of the ash, the heavy metal content analysis revealed exceedances of permissible limits for cadmium in all soil types, with elevated zinc and mercury concentrations in sandy and silty loam soils. Direct agricultural application is therefore not recommended. Incorporation into cementitious composites represents a more appropriate valorisation pathway, enabling the immobilisation of hazardous elements while contributing to a circular-economy approach.

One-way ANOVA confirmed that the differences in both compressive and flexural strength among the tested mixtures are statistically significant, with p-values far below 0.05, further validating the influence of mixture composition on mechanical performance.

In summary, the investigated biomass ash is not suitable for high-volume direct cement replacement in conventional mortars due to its low pozzolanic reactivity and the resulting reduction in strength. However, it demonstrates technical feasibility at replacement levels up to 25% and shows considerable promise as a precursor in alkali-activated systems. Future research should focus on optimising geopolymer formulations, incorporating microstructural characterisation, conducting durability assessments, and evaluating the long-term behaviour of these systems, particularly in the context of seismic performance requirements.

ACKNOWLEDGMENTS

The results presented in this scientific paper have been obtained through the research activities within the projects: 2023-1-HR01-KA220-HED-000165929 "Intelligent Methods for Structures, Elements and Materials" [https://im4stem.eu/en/home/], co-funded by the European Union under the program Erasmus+ KA220-HED—Cooperation partnerships in higher education, and “Valorisation of Waste Materials for the Development of Sustainable Concrete”, funded by University North, Croatia.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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