CONVERTING BEECHWOOD BIOMASS INTO BUILDING MATERIALS: PROPERTIES OF MORTARS WITH BIOCHAR AS A SAND SUBSTITUTE

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ABSTRACT

The construction sector is responsible for a significant share of global greenhouse gas emissions, while the extraction of natural aggregates is increasingly unsustainable. In this context, biochar, a porous carbon-rich material obtained by biomass pyrolysis, has attracted attention as an eco-friendly additive in cementitious composites. This study investigates the effects of beechwood biochar as a partial replacement for natural sand in mortars. Five mortar series were prepared with biochar contents ranging from 0 to 20 wt.%, while keeping a constant cement mass and adjusting the water content according to the mixture composition. Specimens were tested for density, compressive and flexural strength, pull-off adhesion strength, and capillary water absorption at different curing ages. The results revealed a systematic decrease in density and strength with increasing biochar content, reflecting the low density and high porosity of biochar particles. Nevertheless, mortars with up to 10 wt.% biochar exhibited acceptable mechanical performance for potential application in non-structural elements, while offering benefits in terms of lower density and valorisation of renewable biomass waste. The findings highlight the potential of beechwood biochar as a sustainable partial aggregate replacement, contributing to circular economy strategies in the construction industry.

Keywords: *biochar, mortar, beechwood, mechanical properties, pull-off strength, sustainability*

INTRODUCTION

The construction sector is a major contributor to global greenhouse gas emissions, with cement production alone accounting for nearly 5 % of the world's CO_2 emissions (as highlighted by the meta-analysis of cement composites) [1, 2]. Concurrently, the extraction of natural aggregates such as sand and gravel is increasingly unsustainable due to environmental degradation and resource depletion. These challenges necessitate the development of low-carbon, eco-friendly building materials.

Biochar, a porous, carbon-rich material produced by the pyrolysis of biomass, has emerged as a promising sustainable additive in cementitious composites. Its large surface area, chemical stability, and carbon sequestration ability make it attractive for reducing the environmental impact of construction materials [3 - 5].

Recent studies demonstrate the multifaceted benefits of incorporating biochar into mortars and concretes. A 2024 meta-analysis found that modest dosages (< 2.5 wt.%) of plant-based biochar can enhance 28-day compressive strength by 3 - 13 %, especially when produced under controlled pyrolysis conditions [1, 2]. Another study optimized biochar particle size (~ 51 µm) and dosage (~ 2.7 %) to improve mechanical performance through densification of the microstructure and enhanced hydration [6]. A 2023 review [7] reported that biochar addition generally enhances mechanical, thermal, and durability performance while promoting carbon neutrality. A 2025 review [5] revealed that low (1 - 2 %) dosages of timber or wood waste biochar can reduce setting times and improve density and porosity profiles, illustrating the importance of feedstock characteristics and pyrolysis conditions. In a 2024 experimental study, mixed biochar (rice husk + sawdust) at 10 % replacement increased compressive strength by 24 % and achieved 6 % CO_2 sequestration during accelerated carbonation curing [8]. On the industry front, researchers at the Royal Melbourne Institute of Technology in 2024 demonstrated that coffee-ground-based biochar (up to 15 % replacement for sand) increased concrete strength by 30 %, reduced cement demand by up to 10 %, and supported circular waste valorisation [9].

Beech (Fagus sylvatica) is among the most widespread hardwood species in Central and Southeast Europe, where forestry and wood-processing industries generate considerable amounts of residues. Valorisation of these residues through biochar production represents a sustainable pathway, but unlike agricultural feedstocks such as rice husk or coffee grounds, hardwood-derived biochars, and particularly beech wood, remain underexplored in cementitious applications. Despite growing interest, limited research has addressed the use of beechwood biochar specifically as a partial replacement for aggregate in mortars, distinct from its role as a supplementary cementitious material or as a fine filler. The motivation for this study is to characterize the mechanical and durability properties of mortars series with varying degrees of substitution with beechwood biochar (0 - 20 wt.%) in terms of compressive and flexural strength, adhesion (pull-off) strength, water absorption and density. The findings were discussed with respect to optimal substitution levels, application potential, and alignment with sustainable construction goals.

EXPERIMENTAL

Raw materials

A Portland composite cement CEM II/B-M (S-L) 42.5R produced by *Lafarge Beočin* (Serbia) was used as the binder. The fine aggregate was natural river sand (0/4 mm), with granulometry verified according to SRPS EN 1015-1 [10]. Tap water of potable quality was used for mixing and curing.

Beechwood biochar was supplied by Basna d.o.o. (Serbia), accompanied by a technical data sheet (AR-23-FR-014189-01) prepared according to DIN EN ISO/IEC 17025:2018 [11]. The feedstock was beech wood residues with an initial moisture content of 13.5 %. The material was produced by pyrolysis under limited oxygen conditions, dried, ground, and sieved to match the fine fraction of natural sand.

Mixture design and specimen preparation

Five mortar series were prepared by replacing natural sand with beechwood biochar in different mass ratios (0 - 20 %). The compositions of the mixtures are shown in Table 1.

Table 1. Mix proportions of mortar series (per batch, 768 cm³)

Mortar series	Cement [g]	Sand [g]	Biochar [g]	Water [g]	Biochar (replacement for sand) (wt.%)
A	450	1350	0	225	0
B	450	1215	135	360	10
C	450	1080	270	495	15
D	450	945	405	630	17.5
E	450	675	675	900	20

The amount of water in each mixture was calculated as the quantity required to achieve workable consistency during mixing, based on preliminary tests and the higher water absorption of porous biochar particles compared to natural sand. Mixing was carried out in a laboratory mixer with a capacity of 8 L, equipped with a rotating bowl and fixed blades. The procedure lasted approximately 10 minutes. First, the required quantities of sand and biochar were dry-mixed for 1 minute. Half of the mixing water was then gradually added over 4 minutes, followed by the addition of cement and the remaining water. The mixture was homogenized for an additional 5 minutes until a workable consistency was achieved. Fresh mortar was cast into moulds previously coated with mineral oil. Each mould was filled in three layers; after placing each layer, vibration was applied on a vibrating table. After final filling, vibration was continued for an additional 30 seconds, excess mortar was removed, and the surface was levelled with a straightedge. Specimens were demoulded after 24 h and cured in water at 20 ± 2°C until testing.

Testing methods

The following tests were conducted on the hardened mortar specimens:

- Density - determined after 2, 7, and 28 days by measuring the mass and volume of dried prisms 40 × 40 × 160 mm, according to [12]. Tests were performed using a digital balance with a precision of 0.01 g.
- Compressive and flexural strength - tested after 2, 7, and 28 days using an Amsler testing machine, following [13]. Flexural strength of prisms (40 × 40 × 160 mm) was determined by three-point bending, after which the two halves were subjected to compressive strength testing.
- Adhesion (pull-off strength) - measured on mortar layers (~ 10 mm thickness) applied onto cubic substrates (150 × 150 × 80 mm), following [14]. A digital pull-off tester (model 58-C0215, Controls, Italy) was used with 50 mm steel dollies.
- Capillary water absorption - determined during the first 3 h of immersion, according to [15]. The lateral surfaces of cubic specimens (150 × 150 × 80 mm) were sealed with epoxy, and only one surface was exposed to water. Specimens were periodically weighed using a digital balance with a precision of 0.01 g.

Three specimens per mixture were tested, and average values are reported.

RESULTS

Density and classification

The density of hardened mortar, determined after 2, 7, and 28 days is presented in Figure 1.

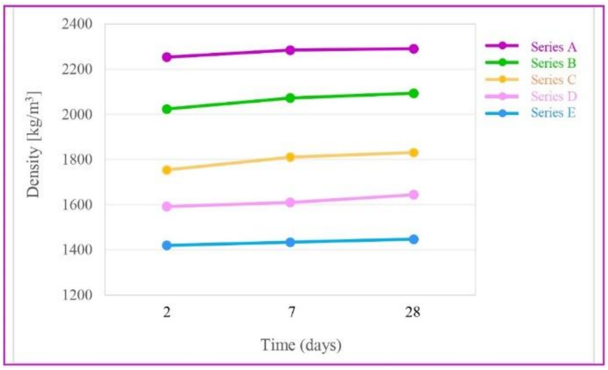


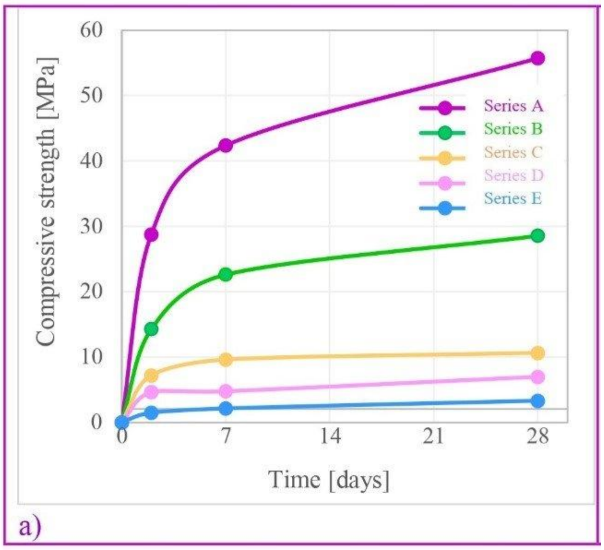
Figure 1. Density of hardened mortar, determined after 2, 7, and 28 days

A uniform increase in density is observed in Figure 1, resulting from controlled curing under identical conditions for 28 days. According to the standard [16], mortars with bulk density ≥ 2000 kg/m³ are classified as normal mortars, while those with lower density are considered lightweight mortars. Based on this criterion, Series A (0 %) and B (10 %) fall into the category of normal mortars, whereas higher substitution levels (≥ 15 %) produced lightweight mortars (Series C, D, and E) due to the porous structure and lower bulk density of biochar.

Mechanical strength

The reference mixture (Series A) exhibited the highest compressive strength. The mortar with 10 % biochar (Series B) still reached 28.5 MPa after 28 days, which is adequate for structural applications. However, mortars with higher substitution levels showed a considerable reduction in compressive strength, indicating their unsuitability for load-bearing use (Figure 2a).

Flexural strength decreased with the increase of biochar content (Figure 2b). After 28 days, flexural strength dropped from 8.1 MPa (Series A) to 6.0 MPa (Series B), and further to 1.0 MPa at 20 % replacement (Series E).



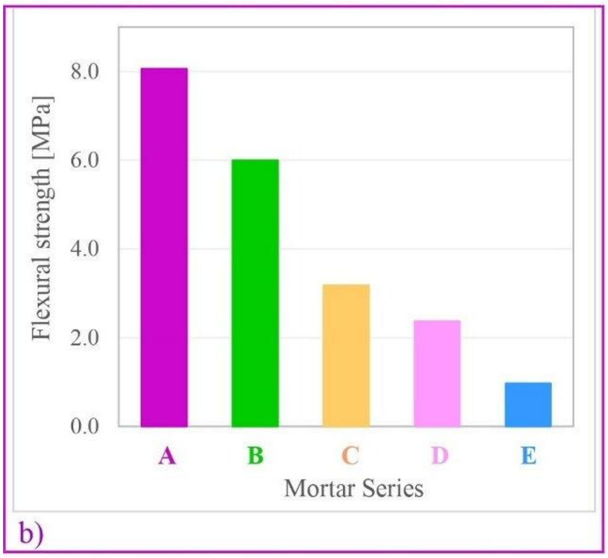


Figure 2. Mechanical strength: a) development of compressive strength over time, b) flexural strength of 28-day mortar

Adhesion (Pull-off test)

The obtained results of adhesion testing are presented in Table 2. Adhesion values followed the same trend: the reference mortar achieved 4.1 MPa, whereas Series B showed 2.01 MPa. Mortars with 15 – 20 % biochar replacement dropped below the standard requirement of 1.5 MPa, limiting their applicability in structural elements.

Visual inspection during testing indicated that the predominant mode was cohesive failure within the mortar layer, while adhesive failures at the mortar-substrate interface were occasionally observed in mixes with higher biochar content (Series D and E).

Table 2. Results of adhesion testing by the pull-off method

Mortar series	P_{mean} [kN]	f_t, pull-off, mean [MPa]	Relative pull-off strength [%]
A	8.20	4.10	100.00
B	4.02	2.01	49.00
C	2.80	1.40	34.11
D	2.00	1.00	24.40
E	0.96	0.48	11.71

P_{mean} - average pull-off load; f_t, pull-off, mean - mean pull-off tensile strength; Relative pull-off strength - strength relative to reference Series A

Water absorption

All series of mortar specimens during the water absorption testing are shown in Figure 3.

Figure 3. Mortar specimens during capillary water absorption testing

The water absorption results are presented in Figure 4. The curves start from the first experimental measurement interval, while by definition absorption is zero at t = 0 (SRPS EN 1015-18).

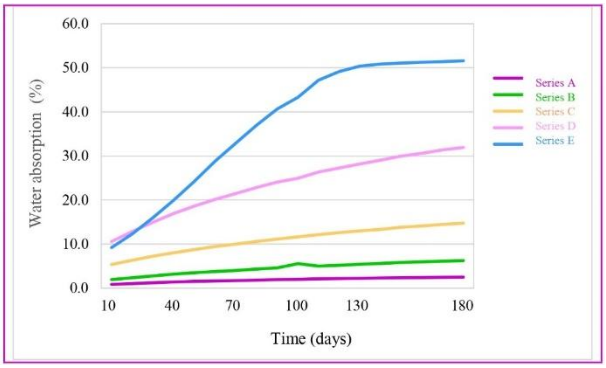


Figure 4. Water absorption vs. time

Capillary absorption increased with biochar content, reaching up to 55 % of sample mass in Series E within 3 h. The curve for Series E approached apparent saturation during the test interval, while the other series continued to absorb water without reaching a plateau. This reflects the higher pore volume available in mixtures with increased biochar content.

DISCUSSION

The experimental results demonstrated a systematic effect of beechwood biochar on the mechanical and durability properties of mortars. The overall trends can be explained by the porous nature and low-density of biochar particles, their influence on the microstructure, and the water demand of the mixtures.

Density. A gradual decrease in bulk density was observed with increasing biochar replacement. This is consistent with the intrinsic low density of biochar and its higher porosity compared to natural sand. Similar reductions in density have been reported for mortars with wood-derived and agricultural biochars [5, 17].

Compressive strength. The compressive strength decreased with increasing biochar content, but mortars with up to 10 wt.% substitution still achieved values above 28 MPa after 28 days. This level is sufficient for certain non-structural applications. The reduction in strength can be attributed to weaker particle packing and increased water demand, which leads to higher porosity in the hardened matrix. A meta-analysis [1, 2] showed that moderate biochar contents (< 2.5 wt.%) may even increase compressive strength, but higher dosages generally reduce it, in line with the present results. Comparable conclusions were drawn in a recent review [7].

Flexural strength. Flexural strength followed a similar decreasing trend, with a more pronounced reduction compared to compressive strength. This behaviour is expected, since flexural performance is particularly sensitive to microstructural discontinuities. An experimental study [6] highlighted the role of biochar particle size distribution in mitigating these effects, suggesting that further optimization of beechwood biochar fineness could improve performance. Similar observations in other studies have linked this reduction to increased porosity and weaker interfacial bonding in biochar-modified mortars [6, 7].

Adhesion (pull-off strength). A marked reduction in adhesion to the substrate was recorded, with relative pull-off strength dropping to less than 50 % of the reference series at higher substitution levels. This decrease reflects the weak interfacial bond and high porosity of biochar particles. Comparable findings have been reported for mortars with agricultural biochars [7, 17]. The present study highlights adhesion as the most sensitive parameter affected by biochar addition, which requires further research on surface treatments or admixtures to improve bonding.

Water absorption. The increase in capillary water absorption with higher biochar contents is explained by the porous structure of the biochar, which facilitates capillary transport. Similar behaviour was observed in other studies on timber- and crop-derived biochars [5, 7], confirming that increased porosity is a common effect regardless of the feedstock. In the present study, Series E (20 wt.% biochar) exhibited an apparent saturation within the 3-hour test interval, reflecting its large accessible pore volume and rapid filling during the initial capillary stage. Other series with lower biochar contents continued to absorb water without reaching a plateau after 3 h, indicating that their saturation would likely occur over longer times due to slower filling of the finer pores. This suggests that high biochar dosages accelerate the early uptake phase, while lower dosages prolong the absorption process.

Water demand and sustainability aspects. It should be noted that higher biochar contents required proportionally higher water additions to ensure workable consistency, due to the absorption capacity of porous biochar particles. Although this represents a limitation, the absolute water quantities remain relatively small, and recycled process water is commonly used in practice. In terms of sustainability, the net effect remains positive, since the valorisation of beech wood residues and the reduction in natural aggregate consumption outweigh the additional water demand [4].

In summary, the results demonstrate that beechwood biochar decreases density, strength, and adhesion at higher dosages, but up to 10 wt.% replacement the mortars still show acceptable performance for non-structural applications. This supports the potential of beechwood biochar as a viable aggregate substitute in the context of sustainable construction.

CONCLUSION

This study evaluated the influence of partial replacement of natural aggregate with beechwood biochar on the properties of cement mortars. The results showed that:

- Mortars with 10 % biochar achieved compressive strength above 28 MPa after 28 days, retained acceptable flexural strength, and met adhesion requirements, making them suitable for structural use.
- Higher substitution levels (>15 %) led to a significant reduction in mechanical properties, but produced lightweight mortars with increased water absorption capacity, which could be advantageous for non-structural, insulating, or internal-curing applications.
- The incorporation of biochar reduces the consumption of natural resources and contributes to carbon sequestration, thereby reducing the ecological footprint of mortar production.

Overall, beechwood biochar demonstrates potential as a sustainable additive in cement mortars, with optimal substitution levels depending on the desired balance between mechanical performance and environmental benefits. Future research should focus on improving the interfacial bonding of biochar particles and exploring admixtures to enhance strength and durability.

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