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Effect of Catalysts and Density of Bamboo Wool Cement Board on Physical and Mechanical Properties

Utjecaj katalizatora i gustoće cementne ploče od bambusove vune na njezina fizička i mehanička svojstva

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ABSTRACT • Bamboo wool cement board (BWCB) is an alternative to produce a new and sustainable material. Different types of catalysts are used for producing wood-cement composites that provide high properties. For this study, the effect of catalysts has been studied by using calcium chloride (CaCl_2) and calcium hydroxide ($\text{Ca}(\text{OH})_2$). The BWCB samples from *Dendrocalamus asper* (Schantz) of different density (0.60, 0.80 and 1.00 g/cm³) were produced by using portland cement as adhesive. The physical and mechanical properties of BWCB were investigated. It was found that BWCB gained a significant percentage of dimension stability due to the treatment by CaCl_2 catalyst. The water absorption was reduced up to 10 %, whereas water content decreased significantly in BWCB with $\text{Ca}(\text{OH})_2$. Flexural strength increased in BWCB with CaCl_2 , and thermogravimetric analysis showed that thermal stability of BWCB increased with CaCl_2 . Scanning electron micrographs of impact fracture samples are taken to study the mechanism of bamboo/cement interface adhesion due to catalyst. Thus, it can be concluded that the CaCl_2 might be a good catalyst for enhancing the properties of BWCB.

KEYWORDS: wool cement board; flexural properties; bamboo (*Dendrocalamus asper*); catalysts; mechanical properties

SAŽETAK • Cementna ploča od bambusove vune (BWCB) alternativa je za proizvodnju novoga pametnog i održivog materijala. U tom kompozitu mogu se upotrijebiti različiti katalizatori za postizanje boljih svojstava. U ovom je istraživanju proučavan učinak katalizatora kalcijeva klorida (CaCl_2) i kalcijeva hidroksida ($\text{Ca}(\text{OH})_2$) na fizička i mehanička svojstva ploča. Uzorci BWCB-a različite gustoće (0,60; 0,80 i 1,00 g/cm³) proizvedeni su od bambusa (*Dendrocalamus asper* (Schantz)) i portland-cementa kao ljepila. Ispitana su fizička i mehanička svojstva uzoraka BWCB-a. Utvrđeno je da su se upotrebom CaCl_2 kao katalizatora povećale dimenzijska stabilnost, čvrstoća na savijanje i toplinska stabilnost BWCB-a. Nasuprot tome, primjenom ($\text{Ca}(\text{OH})_2$) kao katalizatora upijanje vode smanjilo se do 10 %, a znatno se smanjio i sadržaj vode u BWCB-u. Lomne površine snimljene su

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pretražnim elektronskim mikroskopom kako bi se proučio mehanizam adhezije bambusa i cementa postignut uz pomoć katalizatora. Moguće je zaključiti da CaCl_2 može biti dobar katalizator za poboljšanje svojstava BWCB-a.

KLJUČNE RIJEČI: vlaknasta cementna ploča; čvrstoća na savijanje; bambus (*Dendrocalamus asper*); katalizatori; mehanička svojstva

1 INTRODUCTION

1. UVOD

Wood wool cement board (WWCB) composites are formed when the wood wool is reinforced by matrix, which consists of several materials such as cement, water and chemical as catalyst (Kochova *et al.*, 2017; Taiwo *et al.*, 2024). The use of WWCB has been rapidly increasing in various manufacturing industries such as building and construction due to its excellent thermal as well as acoustic insulation properties (Koh *et al.*, 2024). Advances have been made in the technology-based agricultural biomass in manipulating alternative materials to replace conventional materials, such as non-wood materials (Berger *et al.*, 2020). Many attempts have been made to produce wool cement board from non-wood materials such as oil palm fronds (Maynet *et al.*, 2021), straw (Lesieck *et al.*, 2023), sisal and coconut fiber (Asefa *et al.*, 2024; Kochova *et al.*, 2020), kenaf core (Wang *et al.*, 2021), bamboo fiber (Akinyemi and Osasona, 2017), agricultural residue (Bumanis *et al.*, 2024) and other non-wood materials.

Bamboo serves as an ideal alternative material in the construction industry due to its exceptional mechanical and chemical properties. Numerous studies on bamboo as a raw material for bamboo wool cement boards (BWCB) have highlighted its resilience and ability to be harvested much faster than traditional wood. The push for sustainable BWCB production is gaining momentum due to increasing demands for improved safety and environmental sustainability. Utilizing bamboo wool as reinforcement in concrete has proven to be highly beneficial; for example, incorporating 1 % bamboo wool fiber into cement has been shown to significantly enhance the bending strength of mortar (Gelana *et al.*, 2019).

However, cement boards from bamboo generally fail to achieve good mechanical properties (Maier *et al.*, 2020; Chen *et al.*, 2024; Taiwo *et al.*, 2024). The main reason for this limitation is the hydroxyl influence and some other polar batches in the fibers (Quintana *et al.*, 2024). Bamboo is also known to contain a significant amount of extractive substances, such as resins, waxes, lipids, tannins, silica, hexosan, pentosan, and starch (Wang *et al.*, 2016). These extractives are thought to interact with the cement solution, forming complex compounds with the metal ions present. This interaction is believed to contribute to the poor compatibility between portland cement and bamboo wool. As a result, extractives are recognized as inhibitors in the cement harden-

ing process (Delannoy *et al.*, 2020; Nazerian *et al.*, 2011). Enhancements in the mechanical properties of BWCB have been accomplished through the incorporation of catalysts (Yin *et al.*, 2021).

A catalyst is an additive mixed into cement to enhance the bonding strength between the binder and wood particles, ensuring optimal adhesion. It also accelerates water evaporation from the cement board, leading to a quicker hardening process and improved final results. Calcium chloride (CaCl_2) is an effective catalyst for hardening cement boards made with sawdust as the primary material (Saeed, 2023). Traditionally, the curing process for cement boards takes at least 28 days to reach full strength. However, the CO_2 injection method significantly reduces the hardening time compared to conventional approaches (Taskirawati *et al.*, 2019).

However, the problems in the manufacture of a cement-bonded composite requires 2-3 weeks for curing of cement. A catalyst can be used to accelerate the hardening reaction of cement with reinforcing materials. The chemical catalyst, such as calcium chloride (CaCl_2), magnesium chloride (MgCl_2) or calcium hydroxide ($\text{Ca}(\text{OH})_2$), was reported to be successful, with the curing time shortened to a few minutes (Andales *et al.*, 2019). The same authors also observed that additives have reduced the inhibitory effects of wood on the setting of portland cement. Furthermore, Ashori *et al.*, (2012) investigated the properties of cement-bonded composite boards with the addition of CaCl_2 using portland cement as adhesive. They showed that all properties of the boards were improved when the CaCl_2 content was increased from 3 to 7 %.

This study aims to evaluate the impact of different types of catalyst (CaCl_2 and $\text{Ca}(\text{OH})_2$) and bamboo wool board densities on the material's properties. The treatment seeks to develop lightweight yet durable bamboo-cement wool boards, offering an innovative solution to address home and building security challenges in Indonesia. The research is anticipated to produce partition wall products with a combination of lightness, strength, and compliance with standard requirements.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Materials

2.1.1. Materijali

This research is focused on betung bamboo (*Dendrocalamus asper*) obtained from Sumedang, West Java, Indonesia. The study utilized about 150 cm of the

Table 1 Properties of portland cement composite (PCC)**Tablica 1.** Svojstva kompozita portland-cementa (PCC)

Characteristics / Svojstva	Description / Opis
Air content of mortar, volume, % <i>sadržaj zraka u mortu, volumen, %</i>	4.0 – 8.0
Fineness, specific surface, m ² /kg <i>finoća, specifična površina, m²/kg</i>	400 – 480
Autoclave / <i>autoklav</i>	
- Expansion / <i>širenje, %</i>	0.05 - 0.35
- Shrinkage / <i>utezanje, %</i>	0.01 - 0.20
Compressive strength, kg/cm ² <i>Čvrstoća na tlak, kg/cm²</i>	
- 3 days / <i>3 dana</i>	160 - 180
- 7 days / <i>7 dana</i>	220 - 245
- 28 days / <i>28 dana</i>	290 - 340
Setting time, vicat <i>Vrijeme vezanja, vicat</i>	
- Initial / <i>početno, min</i>	130 - 165
- Final / <i>završno, min</i>	230 - 280
False set / <i>lažno vezanje</i>	70 - 77
SO ₃ , %	1.5 - 2.0
Chloride / <i>klorid, %</i>	0.001 - 0.01

basal section of each bamboo stem, known for its short and unevenly spaced internodes. This segment was cut into 40 cm lengths. A 50 kg bag of Portland cement CEMI 42.5N (PCC), obtained from the local market, was used as a binding material. The standard characteristics of the PCC are presented in Table 1. Calcium chloride (CaCl₂) and calcium hydroxide (Ca(OH)₂) were supplied by Bratachem Company, Indonesia, and were used as catalysts. The catalyst was added into the PCC system in order to improve the curing process and compatibility in the bamboo wool cement board system. Physical data of catalysts are shown in Table 2.

2.2 Preparation of bamboo wool

2.2. Priprema bambusove vune

Bamboo stalks, each 40 cm in length, are divided into two sections and processed into bamboo wool us-

ing a wool-making machine (Takekawa Iron Work, China). The produced bamboo wool is initially air-dried until its moisture content reaches approximately 15 %. It is then soaked in cold water for 48 hours before being dried again to reduce the moisture content back to 15 % (Figure 1).

2.3 Hydration test

2.3. Ispitivanje hidratacije

The hydration temperature was monitored inside an insulated box. The cement mixtures had a water-cement mass ratio of 0.5, while the cement/bamboo wool mixture followed a ratio of 6.9:1.0. A thermocouple wire was placed approximately at the center of each sample and connected to a Graphtec midi LOGGER GL220 for data recording. All experiments were conducted at room temperature. The variation in the time taken to reach the hydration temperature between the cement/water mixture, and the bamboo wool with cement/water mixture indicates the effectiveness of the cement hardening inhibitor. The following equation from Hofstrand *et al.*, (1984) was used:

$$I = 100 \cdot \frac{T - T_s}{T_s} \quad (1)$$

Where: *I* – inhibitory hardening; *T* – *T* time of hydration of bamboo wool-cement mixture; *T_s* – time of cement hydration (cement-water mixture).

2.4 Preparation of bamboo wool cement board

2.4. Priprema cementne ploče od bambusove vune

Bamboo wool cement boards (BWCB) were produced with target densities of 0.60 g/cm³, 0.80 g/cm³, and 1.00 g/cm³. The catalysts, CaCl₂ and Ca(OH)₂, were used at a concentration of 2 %. After being soaked in cold water for 48 hours, the bamboo wool was redried to a moisture content of around 15

Table 2 Catalyst used for the bamboo wool cement board system**Tablica 2.** Katalizatori upotrijebljeni za cementnu ploču od bambusove vune

Type of catalyst <i>Vrsta katalizatora</i>	Description / Opis
Calcium chloride (CaCl ₂) <i>kalcijev klorid (CaCl₂)</i>	Physical properties / <i>Fizička svojstva</i> - Appearance: White, odorless, powder in the form of granules or flakes / <i>izgled: bijeli prah bez mirisa, u obliku granula ili pahuljica</i> - Density / <i>gustoća</i> : 2.15 g/cm ³ - Melting point / <i>talište</i> : 772 °C - Boiling point / <i>vrelište</i> : 1,935 °C Chemical properties / <i>Kemijska svojstva</i> - Water-soluble: Dissolves in water to give both ions / <i>topljivost u vodi: topljiv u vodi uz stvaranje oba iona</i>
Calcium hydroxide (Ca(OH) ₂) <i>kalcijev hidroksid (Ca(OH)₂)</i>	Physical properties / <i>Fizička svojstva</i> - Appearance: white-and-beige powder, odorless, crystalline in the form of hexagonal crystal structure / <i>izgled: bijelobež prah bez mirisa, heksagonalne kristalne strukture</i> - Density / <i>gustoća</i> : 2.24 g/cm ³ - Melting point / <i>talište</i> : 580 °C Chemical properties / <i>Kemijska svojstva</i> : - Water-soluble: Dissolves not very soluble in water / <i>topljivost u vodi: slabo topljiv u vodi</i>



Figure 1 Manufacturing process of bamboo wool: a) bamboo stalks, b) bamboo strips, c) wool-making machine Takekawa Iron Work, d) bamboo wool, e) bamboo wool soaked in cold water, f) bamboo wool after being soaked

Slika 1. Proces proizvodnje bambusove vune: a) stabljike bambusa; b) trake bambusa; c) stroj za izradu vune Takekawa Iron Work; d) bambusova vuna; e) bambusova vuna namočena u hladnoj vodi; f) bambusova vuna nakon namakanja

% and then weighed to meet the specified target densities. The bamboo wool was then treated with a catalyst solution, where the catalyst accounted for 2 % of the total water used per panel sheet. To evaluate the

effect of the catalyst on BWCB properties, a catalyst-to-bamboo wool ratio of 4 % of the bamboo wool weight was used. The catalyst-treated wool was mixed with cement, and the specific proportions of

Table 3 Proportions of cement, bamboo wool, water and catalyst based on the target density of BWCB

Tablica 3. Udjeli cementa, bambusove vune, vode i katalizatora na temelju ciljane gustoće BWCB-a

Density, g/cm ³ Gustoća, g/cm ³	Bamboo wool, g Bambusova vuna, g	Cement, g Cement, g	Water, ml Voda, ml	Catalyst, g Katalizator, g
0.60	300	525	600	12
0.80	400	700	800	16
1.00	500	875	1000	20

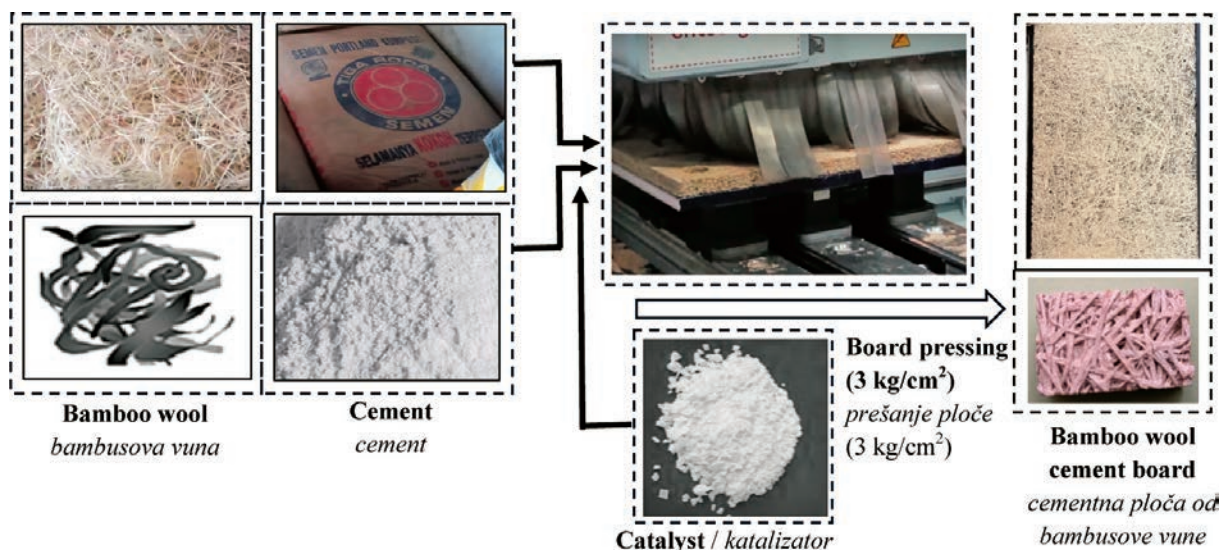


Figure 2 Manufacturing process of bamboo wool cement board (BWCB)

Slika 2. Proces proizvodnje cementne ploče od bambusove vune (BWCB)

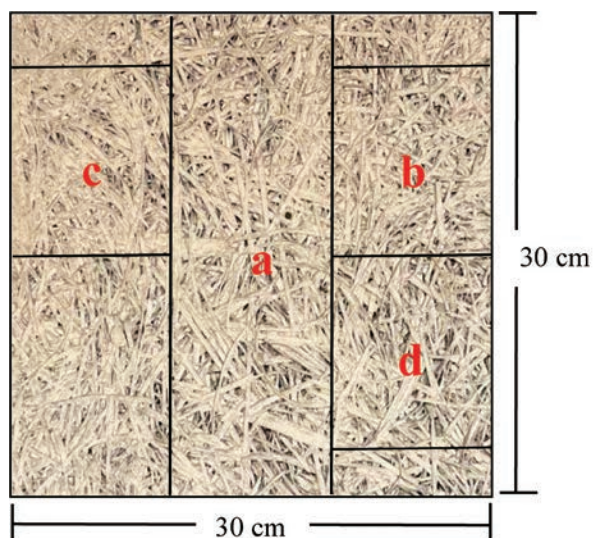


Figure 3 Process for dividing test samples: a) flexural strength test (30 cm × 10 cm × 1.5 cm); b) thickness swelling test (10 cm × 10 cm × 1.5 cm); c) water absorption and thickness shrinkage test (10 cm × 10 cm × 1.5 cm); d) density and water content test (10 cm × 15 cm × 1.5 cm)

Slika 3. Postupak izrade ispitnih uzoraka: a) ispitivanje čvrstoće na savijanje (30 cm × 10 cm × 1,5 cm); b) ispitivanje debljinskog bubrenja (10 cm × 10 cm × 1.5 cm); c) ispitivanje upijanja vode i utezanja (10 cm × 10 cm × 1.5 cm); d) ispitivanje gustoće i sadržaja vode (10 cm × 15 cm × 1.5 cm)

cement, bamboo wool and water for each target density are outlined in Table 3.

The mixture of cement, bamboo wool, water, and catalyst was formed into sheets measuring 30 cm × 30 cm × 1.5 cm, and specific pressure applied in the pressing machine was 3 kg/cm² and maintained for 24 h. The molded bamboo wool boards were then hydrated in a well-ventilated area (25 °C, 45-65 % RH) for 21 days to ensure better curing of the cements (Figure 2). Six bamboo wool cement boards were produced for each individual recipe.

Each BWCB sheet is trimmed into sections corresponding to the dimensions needed for the specific property tests. The preparation of the BWCB test samples adheres to the ASTM D 1037-78 standard, as shown in Figure 3.

2.5 Properties of BWCB

2.5. Svojstva BWCB-a

2.5.1 Physical properties

2.5.1. Fizička svojstva

The evaluation of BWCB physical properties is conducted in accordance with ASTM D 1037-78 standards. Thickness swelling is determined by measuring the test sample thickness at four points prior to soaking, as illustrated in Figure 4.

After measuring the thickness, the test sample was submerged in cold water for 24 hours, followed by a second thickness measurement. The thickness swelling was then calculated using the following formula:

$$\text{Thickness swelling} = [(T_2 - T_1)/T_1] \cdot 100 \% \quad (2)$$

Where: T_1 – initial thickness (cm) and T_2 – thickness after 24-hour soaking (cm)

The water absorption test is a continuation of the thickness swelling test, based on the weight gain after being soaked for 24 hours, which is then compared to the initial weight. The amount of water absorption is calculated using the formula:

$$\text{Water absorption} = [(B_2 - B_1)/B_1] \cdot 100 \% \quad (3)$$

Where: B_1 – initial weight (g) and B_2 – weight after soaking (g).

2.5.2 Mechanical properties

2.5.2. Mehanička svojstva

Mechanical properties were evaluated using a 3382 Instron UTM with a 100 kN capacity (Instron, Norwood, MA, USA). The samples, measuring 30 cm × 10 cm × 1.5 cm, underwent flexural tests at a cross-head speed of 1.15 mm/min and a span of 40 mm, in accordance with ASTM D790-02.

2.5.3 Morphological properties

2.5.3. Morfološka svojstva

The samples were examined using a SEM (Leo Supra 50 VP, Carl Zeiss, SMT, Germany) to study the microscopic structure and fracture surfaces caused by the flexural tests. Prior to analysis, small samples, 1–2 mm thick, were coated with a 10 nm gold layer by sputtering and vacuumed for 20 minutes. SEM images were taken at an accelerating voltage of 15 kV.

2.6 Data analysis

2.6. Analiza podataka

A one-way analysis of variance (ANOVA) and Duncan's multiple range test were used to analyze the

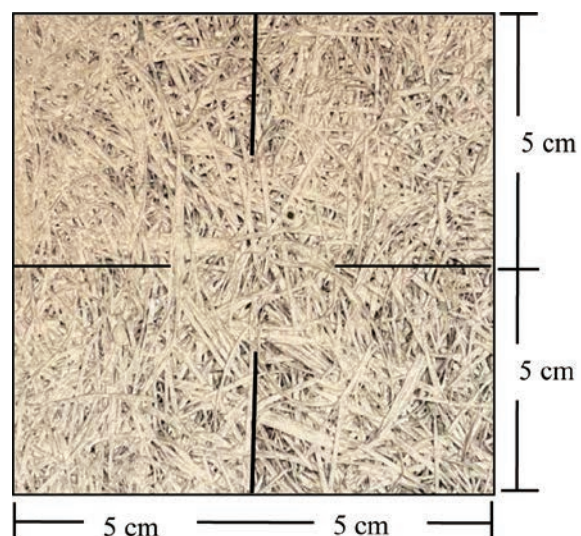


Figure 4 Procedure for measuring thickness swelling of the test sample

Slika 4. Postupak mjerenja debljinskog bubrenja

data. All statistical tests were performed using SAS at a 95 % confidence level.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Hydration temperature

3.1. Temperatura hidratacije

The highest hydration temperature was observed at 8 h for the cement-water mixture, reaching 66 °C, and at 10 h for the cement-bamboo wool mixture, reaching 45.5 °C. According to the studies by Yin and Li (2024), the maximum hydration temperature of the cement and bamboo powder mixture is considered favorable, as it exceeds 41 °C. This can occur because bamboo betung (*Dendrocalamus asper*) has a higher hemicellulose content (27 %) (Fatriasari *et al.*, 2014). High hemicellulose content can inhibit the bond between bamboo-forming material and cement (Snoeck *et al.*, 2015).

Based on the percentage of the inhibitory effect of 25 % for cement hardening from the research results, it can be concluded that the treatment of soaking bamboo wool in cold water for 48 hours is quite effective in dissolving substances that inhibit cement hardening with bamboo wool. The components of bamboo extractives cause the inhibitory effect or retarding degree of cement hydration (Andreola *et al.*, 2024). On the other hand, da Gloria *et al.* (2021) suggested the sugars and starches present in bamboo have been identified as the most critical compounds causing incompatibility between bamboo and cement.

3.2 Physical properties analysis

3.2. Analiza fizičkih svojstava

3.2.1 Thickness swelling properties

3.2.1. Debljinsko bubrenje

Figure 5 shows that the percentage of thickness swelling in BWCB decreases as the density increases after being soaked in cold water for 24 hours. The

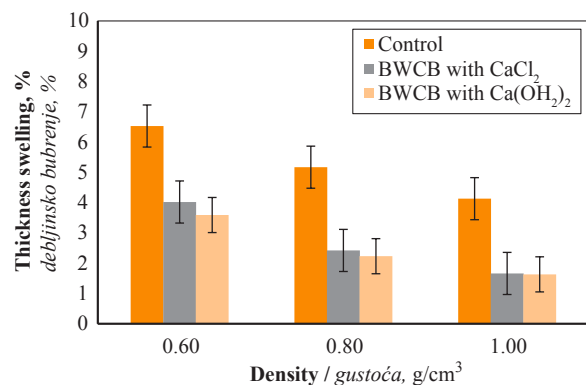


Figure 5 Thickness swelling of BWCB samples as a function of density

Slika 5. Debljinsko bubrenje uzoraka BWCB-a s obzirom na gustoću

highest average thickness swelling, 3.81 %, occurs at a density of 0.60 g/cm³, while the lowest, 1.65 %, is observed at a density of 1.00 g/cm³. Furthermore, Ca(OH)₂ is a more effective catalyst than CaCl₂, as the boards treated with Ca(OH)₂ demonstrate a lower thickness swelling value (2.48 %) compared to those treated with CaCl₂ (2.70 %).

Statistical analysis indicates that the use of Calcium Chloride (CaCl₂) and Calcium Hydroxide (Ca(OH)₂) catalysts at the same concentration (2 %) has no significant effect on the thickness expansion of BWCB. However, the board density has a highly significant impact on thickness swelling. Higher densities are associated with reduced thickness swelling, likely due to the increased cement content, which improves the boards dimensional stability. These findings are consistent with Adelusi *et al.* (2021), who reported that a higher matrix content in panel production leads to a lower percentage of thickness swelling.

Duncan's two-mean difference test revealed significant differences among treatments B1 (low density), B2 (medium density), and B3 (high density) at the 95 % confidence level. This indicates that density variations affect the thickness swelling of the panels after 24 hours of soaking in cold water. Low-density BWCBs contain more void spaces compared to high-density ones, allowing greater water absorption. Increasing the board density reduces these voids, thereby improving its thickness swelling and water absorption properties. On the other hand, higher-density BWCBs display lower thickness swelling percentages, likely due to their denser, more compact structure, which hinders water penetration during soaking (Sewar *et al.*, 2024).

Furthermore, moisture exposure in natural fiber-reinforced cement board samples can lead to the leaching of water-soluble compounds and the degradation of fibers or particles into low molecular weight byproducts, which may weaken the bond between the fibers and the cement in the composite material (Choi, 2022). The absorption of water by materials is closely linked to the durability of composites, as it facilitates the introduction of harmful substances into the composite. This is considered one of the primary causes of reinforcement bar corrosion, cracking, and structural expansion. Zhao *et al.* (2019) examined the impact of incorporating pineapple leaf fibers and ramie fibers on the capillary water absorption of cement mortar. They found that as the natural fiber content increased, the water absorption of the mortar also rose, primarily because the natural fibers created pathways for water infiltration.

3.2.2 Water absorption properties

3.2.2. Upijanje vode

The data in Figure 6 indicates that the water absorption of BWCB, after 24 hours of soaking in cold

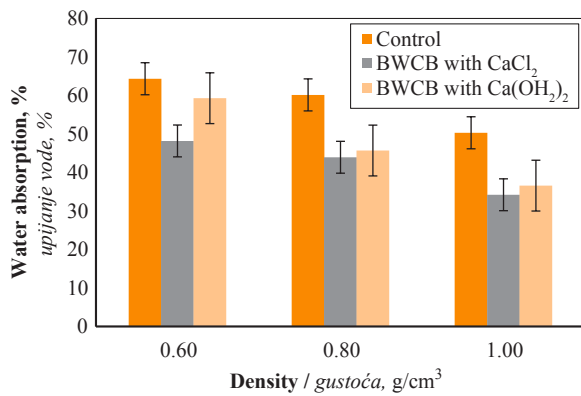


Figure 6 Water absorption of BWCB samples as a function of density

Slika 6. Upijanje vode BWCB uzoraka s obzirom na gustoću

water, decreases as panel density increases, regardless of the catalyst type used. Panels with a density of 0.60 g/cm³ exhibit the highest average water absorption at 51.25 %, while those with a density of 1.00 g/cm³ show the lowest at 35.40 %. The density of bamboo cement boards has a direct effect on their water absorption properties (de Araújo *et al.*, 2011). Lower-density boards have more interconnected pores or air pockets due to lower compaction during production. These voids act as capillaries, allowing water to rapidly enter and spread within the board (Awoyera *et al.*, 2023). Similarly, Zhao *et al.*, (2019) studied cement-based composites reinforced with natural plant fibers, specifically pineapple leaf fiber and ramie fiber. Their findings revealed that the tested composites exhibited significantly higher capillary absorption and chloride diffusion coefficients compared to plain composites, with the differences becoming more pronounced as the fiber volume fraction increased.

Furthermore, BWCB produced with a CaCl₂ catalyst have a lower water absorption percentage compared to those made with a Ca(OH)₂ catalyst. CaCl₂ catalyst speeded up the hydration reaction of cement. Faster hydration can lead to denser microstructure in the board, meaning fewer pores and capillaries are left

open (Yin and Li, 2022). As a result, water absorption is reduced because denser structures are less permeable. The catalyst can also enhance bonding between the wool bamboo and the cement matrix, thus creating a tighter interface and reducing voids to prevent water penetration (Figure 7).

Statistical analysis reveals that using CaCl₂ and Ca(OH)₂ catalysts, both at a concentration of 2 %, has a highly significant impact on the water absorption capacity of BWCB. CaCl₂ proves to be more effective, resulting in a lower water absorption rate of 42.11 % compared to 45.53 % for boards using Ca(OH)₂. This difference is likely due to the faster hardening reaction facilitated by CaCl₂ in the cement-bamboo mixture, which reduces water absorption since hardened cement does not retain water (Selvan, 2021). Conversely, boards using Ca(OH)₂ may harden more slowly, retaining more water during the same period.

The results of the statistical analysis showed that treatment A1 (CaCl₂) was significantly different from A2 (Ca(OH)₂) at the 5 % test level. In accordance with the results of studies by Taskirawati *et al.* (2019), CaCl₂ as a catalyst gave better results compared to Ca(OH)₂ although the difference was not that great. The density of BWCB significantly influences its water absorption capacity, with higher density boards exhibiting lower water absorption. This is likely because high-density boards have greater wool coverage by cement, resulting in fewer pores. Consequently, less water is absorbed by the wool, as hardened cement does not retain water. Water absorption in panels is affected by the surface area not covered by adhesive and the volume of voids between particles (Mayer *et al.*, 2022).

Duncan's two-mean difference test indicated significant differences among treatments B1 (low density), B2 (medium density), and B3 (high density) at the 5 % significance level. As panel density increases, the percentage of water absorption decreases, aligning with the observed trend in panel thickness expansion after 24 hours of immersion in cold water.

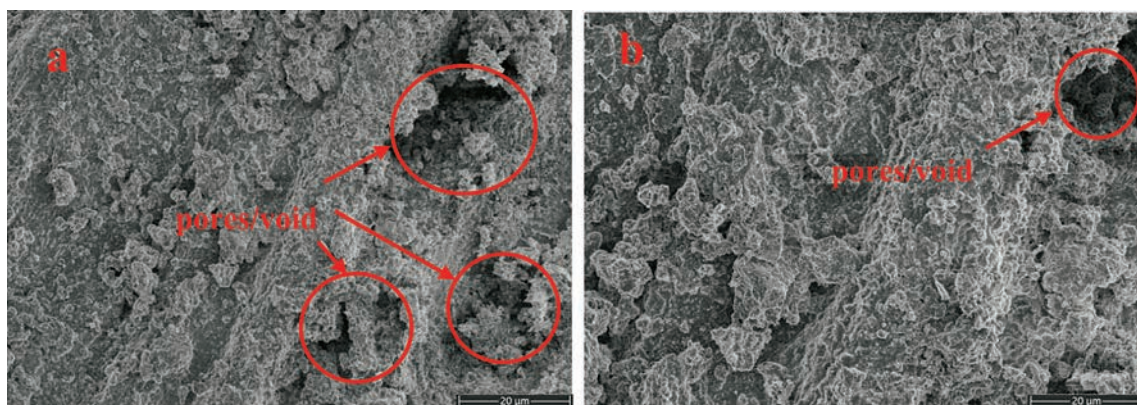


Figure 7 SEM microscopy of BWCB: a) with Ca(OH)₂; b) with CaCl₂

Slika 7. SEM mikrografija: a) BWCB-a s Ca(OH)₂; b) BWCB-a s CaCl₂

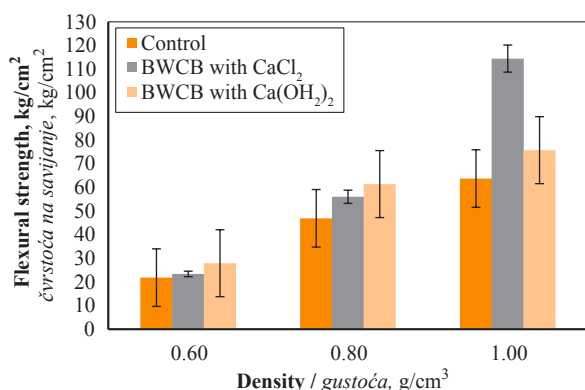


Figure 8 Flexural strength of BWCB samples as a function of density

Slika 8. Čvrstoća na savijanje BWCB uzoraka s obzirom na gustoću

3.3 Analysis of mechanical properties

3.3. Analiza mehaničkih svojstava

Figure 8 presents the flexural strength of BWCB across two catalyst types and three target density levels, demonstrating that increased density leads to higher flexural strength. Panels with a density of 1.00 g/cm³ achieve the highest average flexural strength of 95.11 kg/cm². Moreover, the CaCl₂ catalyst proves to be more effective in enhancing flexural strength compared to the Ca(OH)₂ catalyst.

In general, the internal catalyst effect of wool bamboo increases the compactness of the cement matrix, which improves the flexural strength of the samples. The results confirmed that the catalyst with cement is very effective for stabilizing the bamboo wool in matrix. The studies by Suresh and Murugaiyan (2021) suggested using calcium chloride to improve the natural fiber stabilization of matrix cement. Meanwhile, the bridging effect of wool bamboo cannot be ignored, as it can hinder the propagation of cracks in the matrix and increase the fracture energy.

Statistical analysis indicates that the use of CaCl₂ and Ca(OH)₂ catalysts significantly impacts the flexural strength of BWCB, as F-count exceeds F-table. The average flexural strength of boards made with the CaCl₂ catalyst is 64.62 kg/cm², compared to 55.02 kg/cm² for those using the Ca(OH)₂ catalyst.

The results of Duncan's Two-Mean Difference Test showed that treatment A₁, (CaCl₂) was significantly different from treatment A₂ (Ca(OH)₂) at the 95 % test level. This means that the use of different catalysts affects the value of the BWCB flexural strength, where the flexural strength of the bamboo wool board using the Ca(OH)₂ catalyst is lower than that of the CaCl₂ catalyst. From the viewpoint of the average density value of the BWCB produced as a result of this type of catalyst treatment, the smallest value was obtained with the Ca(OH)₂ catalyst, namely 0.77 g/cm³,

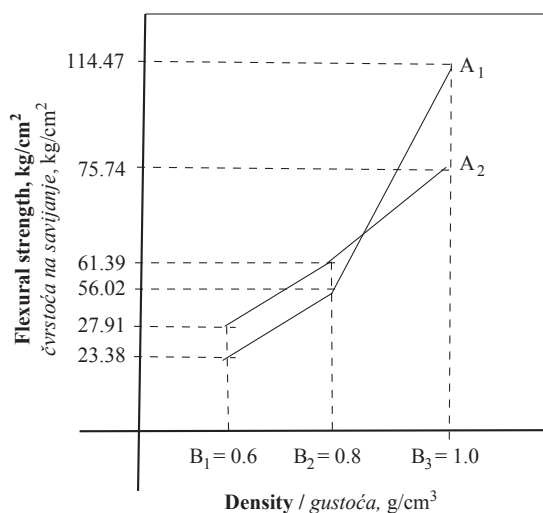


Figure 9 Interaction graph between factors A and B

Slika 9. Graf interakcije između faktora A i B

while the value obtained with the CaCl₂ catalyst was 0.79 g/cm³. Accordingly, it can be assumed that a better flexural strength value is found in BWCBs that have a higher density.

Meanwhile, treatments B₁ (low density), B₂ (medium density), and B₃ (high density) show significant differences at the 5 % test level, indicating that variations in density influence the flexural strength of bamboo wool boards. Higher density boards exhibit greater flexural strength. This aligns with Šipušić *et al.* (2022), who noted that increasing density reduces the cavities within the wool board. These cavities serve as weak points in the material under load, as they prevent effective load transfer between particles. The low (B₁), medium (B₂), and high (B₃) densities, when combined with CaCl₂ (A₁) and Ca(OH)₂ (A₂) catalysts, significantly impact the flexural strength of BWCBs. This indicates that variations in density affect the flexural strength of the boards using both CaCl₂ and Ca(OH)₂ catalysts. However, only the CaCl₂ catalyst at a density of 1.00 g/cm³ significantly improves the flexural strength of the BWCB, while densities of 0.60 g/cm³ and 0.80 g/cm³ show no significant effect. This is likely because higher density reduces the number of cavities in the panel, leading to an increase in flexural strength. Additionally, both types of catalysts exhibit a similar effect on flexural strength at each density level, except at a density of 1.00 g/cm³. The effect of the interaction between the two types of catalysts and varying densities on flexural strength can be better understood through the graph presented in Figure 9.

Figure 9 depicts the effect of the interaction between factor A (catalyst type) and factor B (three density levels) on the flexural strength of bamboo wool board. This interaction aligns with the findings by Hirschmüller *et al.* (2021), who noted that interactions are represented by non-parallel lines in an interaction graph.

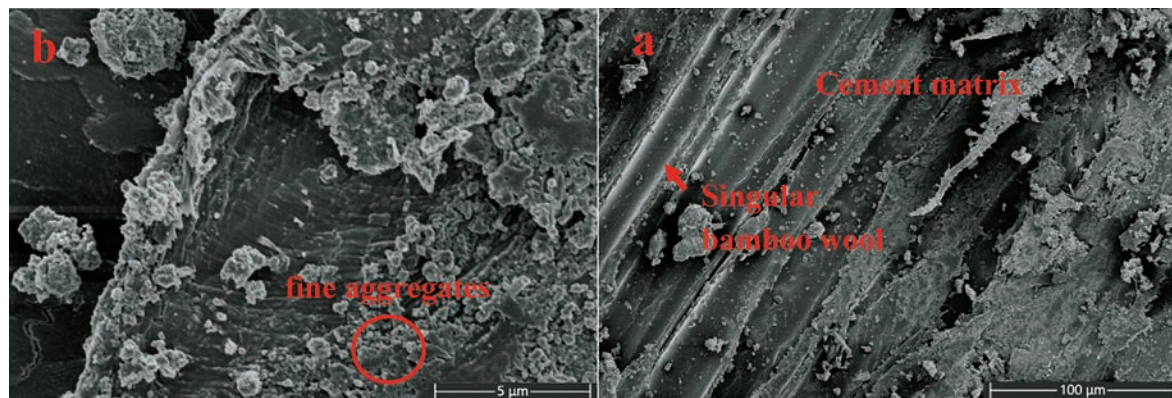


Figure 10 SEM microscopy: a) of BWCb control; b) BWCb with catalyst
Slika 10. SEM mikrofografija: a) kontrolnog BWCb-a; b) BWCb-a s katalizatorom

3.4 Analysis of morphological properties

3.4. Analiza morfoloških svojstava

The SEM microscopy results for the BWCb control and BWCb with catalyst are shown in Figure 10. The SEM image in Figure 10a displays a compact and uniform bond between the cementitious matrix and bamboo wool fiber. The fiber coating of hydration products is also clearly visible, indicating strong fiber-matrix adhesion.

Figure 10b shows the characteristic interface between the cement and the bamboo wool with catalysts, which acts as an accelerator in hardening the board, so that the bond between the cement will be better if the hardening is good (Chen *et al.*, 2023). Electron microscopy of bamboo wool cement containing catalyst particles reveals a uniform distribution within the cement binder. However, clumping is still present, albeit with a lower volume of agglomerates. Moreover, in the analyzed BWCb with catalyst, no significant porosity was observed in the interfacial region, only indicating the presence of catalyst near the fibers. This analysis indicates that both catalyst types exhibit excellent chemical compatibility with cement, with the CaCl_2 catalyst showing exceptional performance in improving BWCb properties. This conclusion is supported by SEM testing, which was used to analyze the morphology and microstructure of bamboo wool-reinforced cement composites. The SEM images revealed a homogeneous and dense cement matrix. However, the SEM images of the BWCb displayed a coarser surface, more uniform bamboo wool strands, and a smoother overall texture.

The findings suggest that both types of catalysts exhibit strong chemical compatibility with cement. Additionally, the CaCl_2 catalyst demonstrates outstanding performance in enhancing BWCb. The morphology and microstructure of bamboo wool-reinforced composites cement were examined and analyzed, supported by SEM test. SEM image detected that the cement matrix products were homogenous and dense. However, the SEM images of the BWCb

showed the coarser surface and more equal strands of bamboo wool and a smoother surface. The results of BWCb with catalyst indicated that the capillary porosity decreased due to the cement matrix curing and increased the compatibility between the cement and bamboo wool. The longevity and weathering resistance were also enhanced (Soroushian *et al.*, 2012).

These studies revealed that the mechanical properties of BWCb containing CaCl_2 surpass those of BWCb with $\text{Ca}(\text{OH})_2$. Gradual water addition during stirring helps improve the dispersion of catalyst particles. He *et al.* (2019) developed cement-based photocatalyst composites by mixing the photocatalyst with cement slurry through stirring. The findings suggest that both types of catalysts exhibit strong chemical compatibility with cement. Additionally, the CaCl_2 catalyst demonstrates outstanding performance in enhancing BWCb.

4 CONCLUSIONS

4. ZAKLJUČAK

Density is a key factor influencing the thickness swelling of BWCb, with higher densities resulting in reduced thickness expansion. The choice of catalyst also plays a significant role in determining the properties of BWCb. Calcium hydroxide, when incorporated into the bamboo wool and cement mixture, delivers better mechanical properties compared to calcium chloride. Additionally, the interaction between BWCb density and catalyst type has a notable impact on its physical and mechanical characteristics. Catalysts exhibit strong compatibility with the cement matrix used in BWCb production. SEM morphological analysis further highlights the significant effect of catalysts on the cement structure.

The use of catalysts with cement can make crinkled cement composites flatter, resulting in the decrease of pore intensity. The results presented herein indicated a significant improvement in physical and mechanical properties.

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