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STUDY OF THE FUNCTIONAL PROPERTIES OF SUSTAINABLE MATERIALS BASED ON NATURAL BYPRODUCTS AND CO_2 ZERO-EMISSION BINDERS

ŠTUDIJ FUNKCIONALNIH LASTNOSTI TRAJNOSTNIH MATERIALOV, IZDELANIH NA OSNOVI NARAVNIH STRANSKIH PRODUKTOV IN VEZIV Z NIČELNO EMISIJO CO_2

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This is a study of some key properties of sustainable materials based on natural by-products (straw or hemp shives) and binders with zero CO_2 emissions (natural clay or CO_2-activated binders based on by-products), which can be used in the interiors of building structures in the form tiles and suspended ceilings to stabilize their thermal and moisture properties and to adjust the acoustic properties. It is specifically a study of the acoustic properties of these natural based ecological composites and a study of their reaction to fire. These properties are key, together with hygroaccumulation properties, for the use of these materials in the field of building structures. The aim of the work was to determine the dependence of the type and dosage of the binder on the resulting behavior of the composites from the point of view of fire, and then further reactions of the action of fire on organic particles during short-term exposure to a small flame. Furthermore, it is about the results of the study of acoustic properties, from the point of view of sound absorption, as well as on the adjustment/stabilization of the relative humidity or fluctuations in the production of water vapor in the room (e.g., different short-term occupancy of the spaces by people). The results of this study provide important insights for optimizing the use of ecological composites in construction applications.

Keywords: natural by-products, CO_2 emissions, reactions to fire, ecological composites

Prispevek je posvečen študiji nekaterih ključnih lastnosti trajnostnih materialov na osnovi naravnih stranskih proizvodov (slame ali konopljinih ostankov) ter veziv z ničelnimi emisijami CO_2 (naravna glina ali s CO_2 aktivirana veziva na osnovi stranskih proizvodov). Ti materiali se lahko uporabljajo v notranjosti gradbenih konstrukcij v obliki plošč in spuščenih stropov za stabilizacijo njihovih toplotnih lastnosti in zmanjševanje vlažnosti različnih prostorov. Materiali pogosto lahko služijo tudi za izboljšanje akustičnih lastnosti prostorov. Avtorji tega članka so izvedli predvsem študijo akustičnih lastnosti in odziva na ogenj izbranih ekoloških naravnih kompozitov. Te lastnosti so namreč, skupaj s higro-akumulacijskimi lastnostmi, ključne za uporabo teh materialov na področju gradbenih konstrukcij. Cilj te študije je bil ugotoviti odvisnost vrste in odmerka veziva na obnašanje kompozitov v primeru požara in nadaljnja reakcija prisotnih organskih delcev na delovanje ognja med kratkotrajno izpostavljenostjo majhnemu plamenu. Nadalje so avtorji v članku predstavili rezultate študije akustičnih lastnosti z vidika absorpcije zvoka. Avtorji so študirali še, kako se izbrani materiali prilagajajo/stabilizirajo relativni vlažnosti, oziroma vsebnosti vodne pare ter njenemu nihanju v prostoru (npr. različna kratkotrajna zasedenost prostorov z ljudmi). Rezultati te študije omogočajo pomembne vpoglede za optimizacijo uporabe naravnih ekoloških kompozitov v gradbeništvu.

Ključne besede: naravni stranski produkti, emisija CO_2, reakcije zgorevanja, ekološki kompoziti

1 INTRODUCTION

The construction industry is one of the key sectors that contributes to global carbon dioxide (CO_2) production, with total CO_2 emissions from this sector accounting for more than a third of the world's total CO_2 emissions.[1] A long-term effort, anchored within the EU in the Kyoto Protocol and the Paris Climate Agreement, and now part of the legislative requirements within the Green Deal for Europe package,[2–4] is the gradual reduction of these emissions, both in the production of building materials and construction, as well as across the entire life cycle of buildings.

A large portion of CO_2 emissions in the construction industry come from the production of building materials, approximately 39 % by 2023 (of which 28 % are operational emissions (heating/cooling) and 11 % are embodied carbon emissions from materials production), especially binders such as cement and other materials, the production of which is energy intensive and also releases bound CO_2.[5,6] In response to this situation, much of the current research is focused on the use of alternative binders with zero CO_2 emissions, such as clay mineral-based binders or CO_2-cured binders based on industrial by-products.[7]

The research work presented in this contribution focuses on CO_2-zero composites, which are composed of an alternative binder combined with easily renewable organic-based fillers, with the goal of creating panels that could be used as infill materials for non-load-bearing

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building components, such as suspended ceilings or vertical interior elements.[7]

The aim is to develop materials that are capable of absorbing acoustic energy and moisture in building interiors and, in the case of moisture, evaporating it back into the air when needed for a healthy indoor environment. These are porous composites created by combining an organic fibrous binder of natural origin and an inorganic binder, which is also sorption active. The resulting composite should combine the favorable properties of both input material groups: it should be highly porous and sorption-active, and the organic binder should be protected against degradation and fire by the inorganic binder, thus creating a material with a favorable fire-reaction class that can be used in the interiors of all types of buildings.

2 EXPERIMENTAL PART

As part of the experimental work, two basic types of binders were selected: a clay-based binder and a carbonated slag binder. Both types of binders had zero or negative CO_2 emissions. For the clay binders, three types of clays were selected, differing in their chemical and mineralogical compositions:

- Clay A contained a predominant share of the clay mineral illite,
- Clay B contained a predominant share of the clay mineral kaolinite,
- Clay C contained a predominant share of the clay mineral montmorillonite.

The CO_2-cured binder used steelmaking ladle slag of fraction 0/8 mm, processed using a Retsch BB200 jaw crusher and a ball mill with steel grinding bodies to achieve a specific surface area (fineness) of 3000 cm^2/g, with a specific density of 3.02 g/cm^3. Mineralogically, it consists of β-C_2S, γ-C_2S, C_3S, MgO, merwinite, gehlenite, akermanite, and brownmillerite. The chemical composition was determined experimentally using XRF analysis: 30–60 % CaO, 2–35 % SiO_2, 5-35 % Al_2O_3, 1–10% MgO, and up to 15 % FeO (Fe_2O_3). This slag was designated as binder D. The selection of these binders was motivated by their potential to reduce CO_2 emissions and their ability to create strong and durable building materials.

Three types of organic fillers were selected based on their availability: crushed wheat straw (fraction 1/8 mm), spruce shavings (fraction 2/8 mm), and crushed industrial hemp shives (fraction 1/8 mm). These materials were chosen for their availability, high sorption activity, and ability to compensate for volume changes in the binders. These materials were processed to approximately the same particle size using sieve screening. For hemp shives and straw, a finer sieve (1 mm) was chosen because the fine particles of these fillers had a different shape index compared to the shavings (see **Figures 2** and **3** below). To achieve similar particle sizes for all the filler types, a 1-mm sieve was used for the straw and hurds, while a larger 2-mm sieve was used for the shavings.

From the selected materials, production mixtures of sorption-active composites were then prepared. The clays and plant materials were mixed in a volumetric ratio of filler to binder equal to 70:30. The amount of mixing water was kept as low as possible to ensure that the resulting mixture was workable while preventing water segregation during the slight compaction of the mixture into molds. The amount of water varied depending on the specific binder and the absorbency of the filler, with the binder-to-water ratio ranging from 1:0.8 to 1:1.25.

During mixing, the water was first combined with the binder, and then the plant fillers were coated with this suspension. This method ensured even coverage of the plant particles with the binder, which is crucial for achieving the desired properties of the final material.

Clay samples were cured by gradual drying at a maximum temperature of 40 °C. This process ensured slow and even curing without excessive stress or cracking. Samples made with the CO_2-cured binder were further exposed to specific conditions for 24 h (temperature: 22 °C, relative humidity: 75 %, CO_2 content: 70–85 %) to activate the binder and complete the curing and stabilization of the material.

The physical and acoustic properties of the composite samples were then tested. The tests primarily involved determining the sound-absorption coefficient in an impedance tube according to ISO 10534-1. From the perspective of material behavior in contact with fire, selected tests were performed from the set used to classify the fire reaction class according to EN 13501-1. Specifically, the small flame test was conducted according to EN ISO 11925-2, and the gross heat of combustion was determined according to EN ISO 1716.

3 RESULTS

A sieve analysis was first conducted on the organic materials to determine the particle size distribution. For more detailed analysis, macroscopic imaging and scanning electron microscopy (SEM) were performed, allowing a thorough characterization of the surface and structure of the individual materials. These analyses provided key information about the morphology of the plant residues, which is crucial for understanding their interaction with the selected binders.

Given that the materials were separated using sieves ranging from 2 mm to 8 mm or 1 mm to 8 mm, it is evident (**Figure 1**) that all three fillers contained approximately up to 10 % residual undersize fraction below the bottom sieve through which the fillers were separated. Overall, the particle size of the straw and hemp was similar, although the straw contained more fine particles. Wood shavings had coarser particles, but they had a different shape index (especially in the finer particles), so

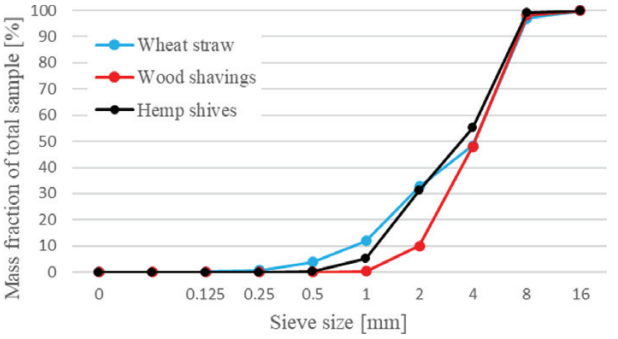

Figure 1: Sieve analysis of selected natural fillers

the overall structure and granulometry of the fillers were approximately comparable (**Figures 2** and **3**).

Table 1: Bulk density in fresh state (kg/m^3)

Binder	Filler		
	Wheat straw	Wood shavings	Hemp shives
A	1090	1270	1100
B	1190	1340	1170
C	1150	1320	1170
D	1290	1410	1260

Table 2: Bulk density after curing and drying (kg/m^3)

Binder	Filler		
	Wheat straw	Wood shavings	Hemp shives
A	670	840	650
B	780	850	780
C	750	940	660
D	830	860	720

Test samples were produced from the selected binders and organic fillers, and the bulk density and key properties related to fire reaction and acoustic performance were determined.

As part of the monitoring of acoustic properties, the dependence of the sound-absorption coefficient on frequency was determined for individual materials, see **Figure 4**. The measured values were compared with each other, and a single-number sound absorption rating was calculated according to EN ISO 11654.

The measured values were compared with each other, and a weighted sound-absorption coefficient was determined. Classification of the materials was carried out according to the sound absorber classification in line with EN ISO 11654, see **Table 3**.

Table 3: Weighted sound-absorption coefficient α_w [-] / sound-absorption class

Binder	Filler		
	Wheat straw	Wood shavings	Hemp shives
A	0.15/E	0.20/E	0.10/ unclassified
B	0.20/E	0.30/D	0.15/E
C	0.30/D	0.35/D	0.30/D
D	0.25/E	0.25/E	0.30/D

During the small flame test, none of the materials exhibited flaming combustion, whether tested on the edge or the surface of the samples, during the 30-second flame exposure. Therefore, additional parameters were determined to allow for comparison between the samples. These included: height of charring/surface exposure and

Figure 2: Optical microscope (magnification 6.4×); a1) Wheat straw, a2) Wood shavings, a3) Hemp shives

Figure 3: Scanning electron microscope (magnification 50×); b1) Wheat straw, b2) Wood shavings, b3) Hemp shives

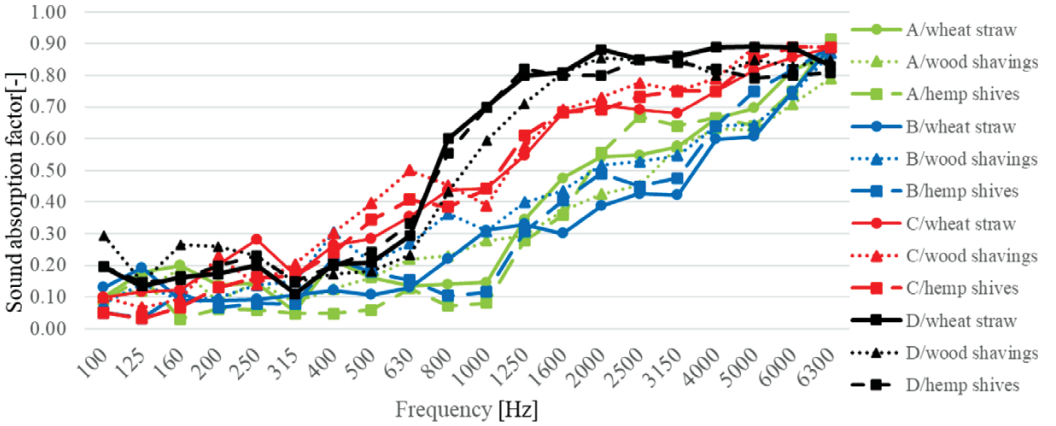

Figure 4: Dependence of the sound-absorption coefficient on frequency

Table 4: Evaluation of the single-flame source test

Sample/material	Flaming burning (YES/NO)	Hot spot (touch of flame) (YES/NO)	Smoke (YES/NO)	Height of charring/ surface exposure (mm)	Height of charring/ edge exposure (mm)
A/ Wheat straw	NO	NO	NO	46	31
A/ Wood shavings	NO	NO	NO	47	29
A/ Hemp shives	NO	NO	NO	43	41
B/ Wheat straw	NO	NO	NO	38	31
B/ Wood shavings	NO	NO	NO	43	26
B/ Hemp shives	NO	NO	NO	41	31
C/ Wheat straw	NO	NO	NO	31	33
C/ Wood shavings	NO	NO	NO	26	13
C/ Hemp shives	NO	NO	NO	31	16
D/ Wheat straw	NO	YES	YES	56	41
D/ Wood shavings	NO	YES	YES	54	42
D/ Hemp shives	NO	YES	YES	53	39

height of charring/edge exposure. All these properties are shown in **Table 4**.

Table 5: Values of gross heat of combustion (MJ/kg)

Binder	Filler		
	Wheat straw	Wood shavings	Hemp shives
A	3.628	1.776	4.327
B	3.188	3.543	5.414
C	2.576	1.756	2.484
D	2.002	2.802	3.343
No binder	16.366	18.2265	17.183

The values of the gross heat of combustion, determined for each material, are shown in the following **Table 5**. The samples after testing are shown in the **Figure 5**.

4 DISCUSSION

Based on the conducted experiments, it was found that materials with clay binders achieve bulk densities in the fresh state of 1100–1350 kg/m^3, while after drying or curing, these bulk densities range between 650 kg/m^3

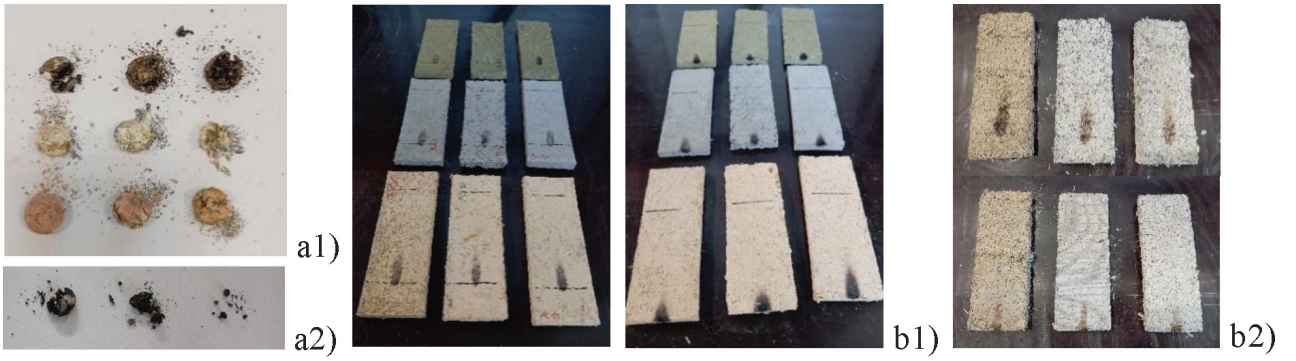

Figure 5: Samples after tests used to classify fire reaction classes; the determination of gross heat of combustion; a1) clay binder, a2) CO_2-cured binder; the single-flame source test; b1) clay binder, b2) CO_2-cured binder

and 950 kg/m^3. Materials with CO_2-cured binders show a bulk density in the range 1250–1400 kg/m^3 in the fresh state and 750–850 kg/m^3 after curing. Overall, it can be seen that each binder coats the filler in a different way, and there is no simple relationship between bulk density and the type of binder or filler. Overall, the bulk densities can be considered comparable. The use of wood shavings as a filler result in the densest microstructure of the final material for both binder types, as evidenced by the highest bulk densities measured in both fresh and dried states. This behaviour is consistent across clay-based binders and the carbonated slag binder, indicating that the structural contribution of wood shavings outweighs the influence of the binder type on material densification. In contrast, straw-filled composites exhibit the most predictable volumetric behaviour during drying, with a relatively narrow range of bulk density reduction of approximately 35–39 %, regardless of the binder used. This suggests that straw provides a balanced interaction with the binder matrix, leading to a stable and reproducible drying response. When hemp shives are combined with clay-based binders, the most pronounced volumetric changes during drying are observed, with bulk-density reductions ranging from approximately 33 % to 43 %. This wider variability points to a higher sensitivity of the hemp shive–clay system to moisture loss, potentially related to the higher porosity and water-absorption capacity of the shives and their interaction with the clay matrix during drying. A comparison of bulk densities across all mixtures further demonstrates that the choice of filler has a dominant influence on the final bulk density compared to the choice of binder, for both clay-based binders and the carbonated slag binder. Material characteristics are governed by the filler selection.

The measured dry bulk densities of the composites (≈650–940 kg/m^3) fall within a well-documented range for bio-based composites with plant-derived fillers. Review studies focusing on the use of hemp in cementitious and mineral composites report comparable ranges of bulk density, emphasizing that the resulting density strongly depends on the granulometry of the filler, its water absorption capacity, and the filler-to-binder ratio, as well as on the method of sample preparation and compaction.[8,9] These findings are consistent with the results of the present study, in which the dominant influence of the filler type on the bulk density of the final material was confirmed.

In terms of acoustic properties, the developed composites exhibit lower sound absorption at low frequencies, which is reflected in the single-number sound-absorption value. However, this is due to the small thickness of the test samples. It is expected that these composites will be used, for example, in the form of acoustic panels with a limiting thickness of around 20 mm, which was the chosen thickness for this test. The samples exhibit somewhat different behavior. Samples with CO_2-cured binders show a rapid increase in sound absorption from 630 Hz onwards, but at lower frequencies, they achieve average or below-average values. In terms of single-number values, the best performance was observed in samples with binder C (based on montmorillonite), and it can be stated that when used as interior cladding in building constructions, these composites will also fulfill an acoustic function and significantly influence the acoustic parameters of the spaces where they are installed, especially the reverberation time. On the other hand, the lowest absorption values were observed in samples with binder A and samples with binder B combined with straw and hemp shives.

The measured sound-absorption coefficient values ($\alpha_w \approx$ D/E) correspond well with generally published trends for porous bio-based materials of relatively small thickness. The reported absorption coefficients for hemp–lime composites typically range between 0.24 and 0.53 in the frequency band up to 2500 Hz, indicating that higher open porosity and lower bulk density generally lead to increased sound absorption.[10] Further studies confirm that open porosity and micro-pores of the filler play a key role, particularly in the mid- and high-frequency ranges, while sound-absorption efficiency at low frequencies is generally limited for thin elements.[11]

An important finding is that the ratio between binder and filler has a significant impact on the gross heat of combustion of the materials. The best values were achieved using clay C (based on montmorillonite), and these materials were the only ones to meet the 3 MJ/kg criterion for classification into fire-reaction class A2, regardless of the type of organic filler used. In terms of the individual organic fillers, the highest gross heat of combustion values were achieved by spruce shavings, but after mummification, the materials with these shavings achieved the lowest gross heat of combustion values in most cases. It is evident that the gross heat of combustion partially correlates with the bulk density of the composites, but the correlation coefficient is lower than 0.5.

From the perspective of behavior under small flame testing, the materials were found to have comparable performance. During the 30-second test, no ignition occurred. When observing the degree of charring in the samples, it was found that the worst values were exhibited by the samples with binder D (CO_2-cured binder), where there was a lower degree of particle coating by the binder. Among the clay binders, binder C (based on montmorillonite) showed the best results on average, while binder A (based on illite) showed the worst results.

From the perspective of reaction to fire, the literature on plant-based composites repeatedly highlights a strong dependence of flammability on bulk density, organic content, and the degree of mineralization of the organic phase. Experimental studies on hemp- and clay-based composites covering a wide range of densities (up to approximately 1500 kg/m^3) show that more pronounced flaming combustion occurs primarily in very lightweight mixtures with bulk densities below approximately

500 kg/m^3, whereas denser and better mineralized materials exhibit only limited surface charring and a short or no flaming phase.[12] These observations are consistent with the results of the present study, in which no flaming ignition was observed during the small flame test for the tested composites.

Overall, it can be concluded that clay-based materials are more suitable for applications where mummification of organic fillers and fire resistance are important. Clay-bonded materials demonstrated excellent performance in fire tests and exhibit better mechanical stability compared to CO_2-cured binder materials, which, however, excel in sound absorption.

5 CONCLUSIONS

The research shows that building materials with alternative binders exhibit interesting properties in terms of both acoustics and fire reaction, making it possible to use these materials (for example, in the form of panels) to improve the parameters of indoor living spaces in buildings. It was found that clay binders have a better ability to coat organic particles, with binder C (based on montmorillonite) showing the best results across all the experiments performed.

Materials with CO_2-cured binders display good acoustic properties, but their structure is less cohesive, and the particle coating is poorer, which had a negative impact in the small flame test.

Overall, the developed composites with alternative binders, due to their low bulk density, are suitable not only as infill ceiling elements but also as vertical interior elements. Their ability to stabilize the internal microclimate, especially in terms of humidity, should continue to be monitored and optimized. Clay materials, with a predominant share of the clay mineral montmorillonite, meet the criteria for fire reaction class A2 and represent a promising alternative to traditional building products, with a low environmental impact and suitable technical properties.

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