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The impact of modifying hemp shives with water glass on selected properties of hemp-cement-lime composite

RADOSŁAW CHOMICZ[1], PIOTR BORYSIUK[2]

[1]Faculty of Wood Technology, Warsaw University of Life Sciences – SGGW, Poland
[2]Department of Technology and Entrepreneurship in Wood Industry, Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences – SGGW, Poland

Abstract: *The impact of modifying hemp shives with water glass on selected properties of hemp-cement-lime composite.* The influence of the addition and modification of hemp shives with water glass on selected properties of the hemp-cement-limestone composite was investigated. Nine variants of composites were produced, differing in the volume content of hemp husks: 0%, 15%, 25%, 35% and 50%, modified or unmodified with water glass. For the produced composites, it was tested: density, compressive strength, MOR (bending strength), MOE (modulus of elasticity), thickness swelling and water absorption. Based on the conducted research, it was found that the increase in the addition of hemp shives results in a decrease in strength parameters and deterioration of the water resistance of hemp-cement-lime composites. In turn, the modification of hemp shives with water glass improves both the strength and physical properties (limited swelling in thickness and water absorption) of hemp-cement-lime composites compared to analogous composites based on unmodified hemp shives. The highest strength parameters and the best resistance to water are demonstrated by a hemp-cement-limestone composite containing a 15% volume share of hemp shives modified with a 5% addition of water glass.

Keywords: hemp-cement-lime composite, hemp shives, water glass, strength properties, physical properties

INTRODUCTION

Around the world, there is a broad acknowledgment of the imperative to decrease greenhouse gas emissions and lower energy consumption. In recent years, there has been increasing interest in the idea of constructing buildings with minimal or zero emissions, along with the adoption of construction methods that enable this goal. To safeguard our planet, it has become evident that alternative strategies must be devised to address our construction-related requirements (Bevan and Wooley 2008). A beneficial solution in this respect may be the use wood-based materials bonded together with mineral binder in the building industry as construction and finishing materials (Borysiuk et al. 2019). The physical and mechanical properties of cement-bonded particleboards make them suitable for industrial purposes, meeting the mechanical requirements for building applications (Cabral et al. 2018). These materials can be used in various applications including walls, partition walls, lower ceilings, facades, and floors (Keprdová and Křížová 2014). It is worth noting that cement bonded particle boards, apart from having good mechanical properties, are also characterized by resistance to unfavorable environmental conditions (Jorge et al. 2004, Melichar et al. 2021, Liow et al. 2022). It is also important that the flammability of cement-bonded particleboards decreases with an increase in the cement-wood ratio, making them less prone to ignition and reducing heat release rates (Yu et al. 2016, Hou et al. 2021).

The development of construction using natural resources such as hemp, flax, or plant residues from straw aims to reduce environmental degradation. These eco-friendly materials improve thermal, insulation, and ventilation parameters compared to traditional building materials (Brzyski et al. 2017). Brzyski (2016) also pointed to the positive properties of plant-based materials as an alternative to high-energy-demanding building materials. Besides wood, which is widely used in construction, plant residues such as hemp chips or straw are increasingly being utilized. Selected studies indicated that alternative raw materials such as sunflower stalks, technical hemp, straw, grapevine and jute can be used to partially or wholly replace wood in the production of cement-bonded particleboards, potentially decreasing manufacturing costs and ecological loads (Wang et al. 2013, Keprdová and Křížová 2014, Taş and Kul 2020).

In the 1980s in France, the concept of using hemp to create a lime-based composite emerged. During repair operations, holes in the walls were filled with straw, earth, and wicker. With the growing awareness of the benefits of using natural resources in construction, new materials are emerging, such as hempcrete, which is characterized by good vapor permeability and insulating properties (Pietruszka et al. 2019). The possibilities of using the composite has been presented by Brzyski (2016). It was mentioned that properly combined hemp fibres with lime are used as insulation material for roofs and floors in residential construction.

As already mentioned, wood-based materials, including boards with a mineral binder, constitute an extremely valuable material base that proves itself in the construction industry. However, many of these materials require further research to improve their parameters and eliminate drawbacks. One approach aimed at reinforcing the structure of wood-based panels will be the use of natural fibres in their composition. Hemp can be cited as an example (Trociński et al. 2023). The addition of hemp to cement boards has been shown to improve physical and mechanical properties (Rangavar 2017). Analogous relationships were obtained in research Filazi et al. (2023). The addition of hemp fibers to cement mortars enhances properties such as compressive strength, bending strength, and flexural strength, leading to strong, durable, and environmentally friendly composite materials

Trociński (2023) investigated the influence of the amount of added hemp fibres and the cross-linking temperature of the gypsum matrix on the properties of the produced gypsum composites. He showed that an increase in the fibre share extends the cross-linking time of the matrix, significantly increases it, and the density of the composites decreases. The best strength properties of hemp-gypsum composites were obtained with a hemp fibre content of 4%. At the same time, he pointed out that a further increase in the share of hemp fibres causes a significant deterioration of the strength parameters. Additionally, Trociński (2023) determined that increasing the temperature during cross-linking of the gypsum matrix negatively affects the strength characteristics of the produced composites. In turn, the insulating properties of the composites improved significantly with the increasing share of hemp fibres.

Trociński (2023) examined the impact of modifiers on hemp fibres later used in gypsum-fibres composites. It has been observed that impregnation of hemp fibres with a universal ground increased the tensile strength by 7% compared to the variant with non-impregnated hemp fibres. On the other hand, impregnation of hemp fibres with a deeply penetrating primer emulsion exhibits higher tensile strength by 30% compared to the variant with non-impregnated fibres. In turn, Akerman (1964) indicates that products such as water glass, paraffin, casein paints, and asphalt emulsions can be used to impregnate the fibre surface. He demonstrated that the low moisture resistance of gypsum fibreboard panels can be improved.

As part of research aimed at increasing moisture resistance, Skłodowska-Weigt (1967) investigated the use of silicone resins to protect gypsum binders from moisture. It was shown that the water absorption of the samples decreased from 13.5% to below 1% for a gypsum content of 35% and resin content ranging from 0.14% to 2.85%. In turn, Dobrowolska (2002) investigated the use of hydrophobic additives in the form of silicone resins to increase moisture resistance of gypsum particle board. It was observed that their introduction can significantly or completely limit water penetration. Along with the idea of using plant residues in the form of hemp fibres in wood-based materials, there has also been a suggestion to impregnate these fibres to improve their strength parameters. Patt and Schöler (1987) investigated the effect of modifying wood fibres with potato starch. It was demonstrated that adding 10-20% potato starch by weight of the fibres increases the bending strength parameters of fibreboard. Similarly, Thole et al. (1993) indicated that the addition of potato starch in amounts of 2-16% by weight of gypsum, along with a proper selection of wood particles, resulted in an increase in strength parameters of gypsum particleboards ranging from 45% (spruce particles) to 60% (oak particles). In her research, Dobrowolska (2002) also demonstrated that the modification of gypsum fibreboard panels with vinyl resin improves the bending strength of the panels by almost 87% compared to the unmodified variant. However, the modification of gypsum fibreboard panels with zinc sulphate reduced the bending strength parameters by 5% compared to the unmodified panel. In turn, with regard to cement-particle boards, Taş et al. (2021) indicated that polymer additives, such as poly carboxylic ether and melamine-based polymer, can also reduce water absorption and thickness swelling, and improve internal bond strength and bending stiffness of boards. The ratios of polymer additives to the wood cement mixture were 1%, 1.2% and 1.4% respectively. It is worth noting here that, the compatibility of wood and Portland cement can be affected by factors such as water-soluble polysaccharides, organic carboxylic acids, and the use of additives like calcium chloride and sodium silicate to improve compatibility (Wang et al. 2013, Liow et al. 2022, Yang and Li 2022).

Unfortunately, there is no direct information available on the specific effects of adding hemp to cement boards. However, based on the findings related to cement mortars and concrete mixes, it can be inferred that the addition of hemp to cement boards may lead to improvements in physical and mechanical properties, as well as potential challenges related to setting that can be mitigated with the use of lime (Diquélou et al. 2016, Rangavar 2017, Ferrández et al. 2023, Filazi et al. 2023).

In conclusion, the addition of hemp to cement boards offers environmental benefits, enhances structural properties, and presents economic advantages. However, challenges such as workability, mechanical strength, and binder properties need to be carefully addressed to fully realize the potential of hemp in cement board manufacturing.

MATERIALS AND METHODS

The material subjected to the study consisted of appropriately cut samples of hemp shives composite with cement-lime binder at volumetric ratios of 50%, 35%, 25%, and 15%. Five identical blocks were produced for each volumetric ratio variant. Additionally, for the purpose of the study, four similar variants were created, but the hemp shivs used in the composite mixtures were pre-modified with water glass at a 5% ratio relative to the mass of hemp shivs used in each variant. Furthermore, a "0%" variant was produced, consisting of a cement-lime mixture without hemp shivs. The composite was produced using an HK 6 BIS injector. For the purposes of the study, hydrated lime from Alpol company and cement mortar from Kreisel company were used. The creation of the composite required water glass from Dragon company. Hemp shives used to produce the composite were sourced from an organic farm of a local farmer. The hemp shives had a density of approximately 130 kg/m^3 and moisture content below 10%. The fractional composition of hemp shives is shown in fig. 1.

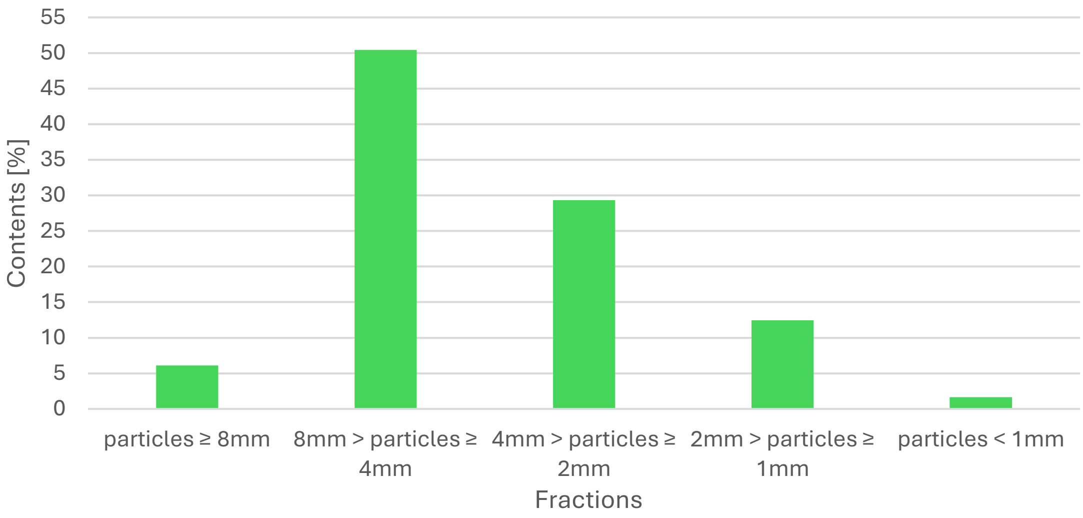

Fig. 1. Fractional composition of hemp shives.

The cement-lime blocks with hemp shivs had dimensions of 300x280x100mm. The research material was obtained by appropriately cutting hemp blocks designated for each experiment. For each experiment, 10 samples were prepared for each variant to ensure the reliability of the results.

Density test

The density study was conducted according to the PN-EN 323:1999 standard. For determining the density, properly prepared samples with nominal dimensions of 50x50x20mm were used (fig. 2).

Fig. 2. Density test sample.

MOR and MOE test

The test was conducted according to the PN-EN 310:1994 standard. Samples with nominal dimensions of 100x280x20 mm were used for testing (fig. 3). The spacing of the supports of the testing machine was 260mm. The strain rate was set at 10 mm/min.

Statistical analysis

In Statistica 13, a statistical analysis of the obtained results was conducted. The statistical analysis included one-way analysis of variance (ANOVA). Using Tukey's honestly significant difference test, the significance of differences between individual values was compared.

Fig. 3. Samples for MOR and MOE testing - after the test.

Compressive strength test

The test was conducted according to the PN-D-04102:1979 standard. Samples with nominal dimensions of 100x50x50 mm were used for testing (fig. 4). Before conducting the test, the load scale was set to 25 daN. The strain rate was set at 5 mm/min. The compressive strength was determined using the formula:

$$R_{cw} = \frac{P_c}{a \times b} \text{ [N/mm}^2\text{]}$$

Where:

R_{cw}- Compressive strength,

a, b - cross-sectional dimensions of the sample [mm],

P_c - crushing force

Fig. 4. Compressive strength test sample during testing.

Thickness swelling and water absorption test

The thickness swelling and water absorption test after 2 and 24h soaking was conducted according to the PN-EN 317:1999 standard. Samples with nominal dimensions of 50x50x20 mm were used for testing (fig. 5). The water absorption was determined using the formula:

$$N_{2,24} = \frac{m_{2,24(2)} - m_1}{m_1} \times 100 \text{ [\%]}$$

Where:

$N_{2,24}$- water absorption after 2 or 24 hours of soaking in water [%],

$m_{2,24(2)}$- mass of the sample removed from water after 2 or 24 hours [g],

m_1- mass of the sample before immersion in water [g].

Fig. 5. Thickness swelling and water absorption test samples.

RESULTS

The average sample densities and corresponding homogeneous groups based on the Tukey test are shown in fig 6. The highest density, reaching 1846 kg/m^3, was exhibited by the variant with 15% hemp shives modified with water glass. The lowest density was observed in the variant with 50% hemp shives unmodified with water glass. A similar decrease in the density of composites (by over 16%) with an increase in the content of hemp particles was also noted by Ferrández et al. (2023). The largest differences in sample density between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives were observed in the 15% and 25% variants, amounting to 227 kg/m^3 and 231 kg/m^3 respectively, and were statistically significant (different homogeneous groups G, E and F, D). Analysing the results, it can be noted that increasing the volume fraction of modified hemp shives by 35% reduces the composite density by 31%. In the case of unmodified shives, the density decreases by 27%. It is worth noting that compared to the other variants, the density difference in the 50% variant is the smallest, at 1193 kg/m^3. It should be added that this difference is statistically significant (different homogeneous groups B, A). However, the largest difference in sample density between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives was observed in the 25% variant, amounting to 231 kg/m^3. Different homogeneous groups (F, D) indicate that these differences are statistically significant. It's worth noting that the variant not containing hemp shives had a density of 1789 kg/m^3, making it the second densest variant. An interesting observation is that the variant with 15% of modified hemp shives has a higher density than the variant without hemp shives (0% variant). Referring to the literature data (Pietruszka and Gołębiewski 2019), it was observed that the density of the variant with 15% content of hemp shives modified with water glass is higher by almost 60%, and for the variant with 50% content of hemp shives modified with water glass, the density is higher by 41%.

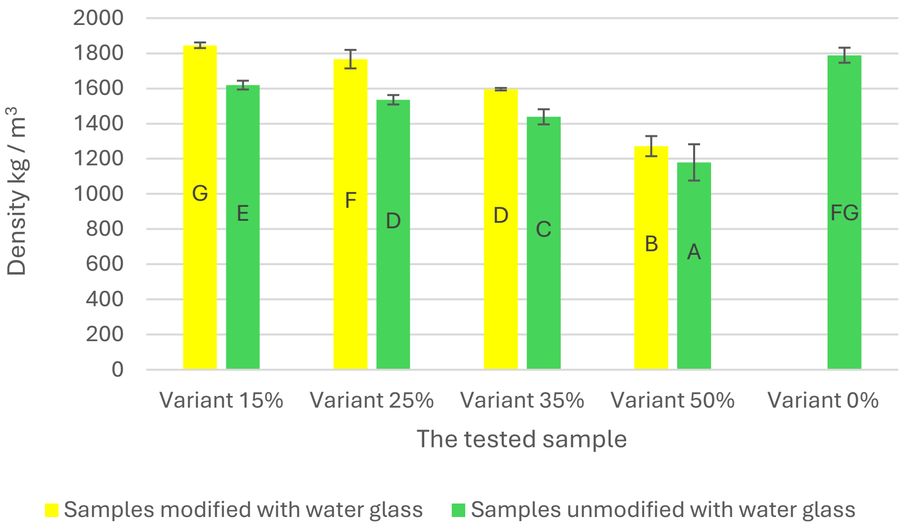

Fig. 6. Average density of samples; A, B, C, D, E, F, G - homogeneous groups based on Tukey's test.

Analysing the one-way analysis of variance (table 1), it can be concluded that both the addition of hemp shives and the addition of water glass were statistically significant. However, hemp shives played a decisive role in density, accounting for 81.5% of the influence, while the influence of glass was at 10.2%. The influence of unanalysed factors in the study amounted to only Error = 4.4%.

The average results for the bending strength of the samples and corresponding homogeneous groups based on the Tukey test are shown in fig. 7. The highest MOR value of 2.9 N/mm² was observed in the variant with 15% hemp shives content modified with water glass. The lowest MOR was exhibited by the variant with 50% hemp shives content, unmodified with water glass. A decrease in the MOR value of cement particleboards with an increase in the share of wood particles was also noted by Frybort et al. (2008). It is also worth noting that the increase in the content of hemp shives in hemp-cement-lime composites, resulting in a decrease in their MOR value, also results in a more differentiated crack pattern in the samples (fig. 8).

The largest differences in MOR between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives were observed in the 15%, 25%, and 35% variants. The differences in average MOR in the 15%, 25%, and 35% variants were 1.6 N/mm², 1.4 N/mm², and 1.5 N/mm², respectively, and were statistically significant (different homogeneous groups E, B and D, B and C, A). Analysing the results, it can be noted that increasing the volumetric content of modified and unmodified hemp shives by 35% reduces the bending strength of the composite by almost 80%. It is worth noting that compared to the other variants, the difference in MOR of the samples in the 15% variant is the largest at 1.6 N/mm². It should be added that this difference is statistically significant (different homogeneous groups E, B). Conversely, the smallest difference in MOR of the samples was observed in the 50% variant, amounting to 0.3 N/mm². The same homogeneous groups (A) indicate that these differences are not statistically significant. The bending strength of the variant without hemp shives (variant 0%) was 1.77 N/mm^2, making it only the fourth in terms of bending resistance. The variant with 15% content of modified hemp shives showed a 63% higher MOR compared to the 0% variant. An interesting observation is that the variant with a 35% volume fraction of hemp shives modified with water glass exhibits a higher MOR than the variant without hemp shives by 12%. The increased bending strength effect with the addition of water glass to hemp shives stems from a better bond between the hemp particles and cement, as confirmed by Yang and Li (2022) and Trociński (2023). Trociński (2023) in his study impregnated hemp fibres with a deeply penetrating primer emulsion, which enhanced the MOR properties by 20.6% compared to the reference variants.

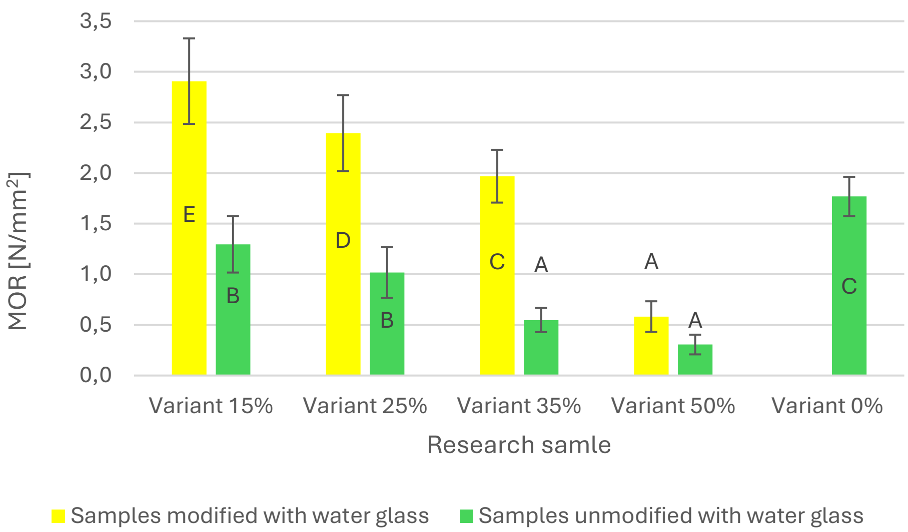

Fig. 7. Average MOR values of the tested composites; A, B, C, D, E - homogeneous groups based on Tukey's test.

0% 15% 25% 35% 50%

Fig. 8. Example images of cracks in samples of individual composite variants.

The average results for the modulus of elasticity under static bending of the samples and corresponding homogeneous groups based on the Tukey test are shown in fig. 9. The highest value of MOE, reaching 4278 N/mm², was exhibited by the variant with 15% hemp shives content modified with water glass. The lowest MOE was observed in the variant with 50% hemp shives content modified with water glass. A decrease in the MOE value of cement particleboards with an increase in the share of wood particles was also noted by Frybort et al. (2008). The largest differences in average MOE between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives were observed in the 15%, 25%, and 35% variants. The differences in the average values of MOE were 3911 N/mm², 1189 N/mm² and 795 N/mm², respectively, and were statistically significant (different homogeneous groups D, A and C, A and B, A). Analysing the results, it can be observed that increasing the volumetric content of modified hemp shives by 35% decreases the MOE of the composite by 95%. It is noteworthy that compared to the other variants, the difference in MOE of samples in the 15% variant is the largest, amounting to 3911 N/mm². It should be noted that this difference is statistically significant (different homogeneous groups D, A). The smallest difference in MOE of samples was observed in the 50% variant, amounting to 86 N/mm². The same homogeneous groups (A) indicate that the differences are not statistically significant. It is worth noting that for samples not modified with water glass, the MOR values for all variants are similar. It was observed that in the variant with 50% volume fraction of hemp shives, cement composites with the addition of modified hemp shives exhibited a lower MOE compared to composite variant containing unmodified hemp shives. The MOE of the variant without hemp shives (variant 0%) was 550 N/mm^2, making it only the fourth in terms of MOE. The variant with 15% volume fraction of modified hemp shives showed a MOE nearly 678% higher than the 0% variant. An interesting observation is that the variant with a 35% volume fraction of hemp shives modified with water glass exhibits a MOE nearly 91% higher than the variant without hemp shives. The effect of a higher MOE with the addition of water glass to hemp shives results from a better bonding of hemp particles with cement, as also confirmed Yang and Li (2022) and Trociński (2023). Trociński (2023) in his study impregnated hemp fibres with a deeply penetrating primer emulsion. He showed that the modification of hemp fibres contributed to an increase in the MOE value compared to the reference material by 36.6%.

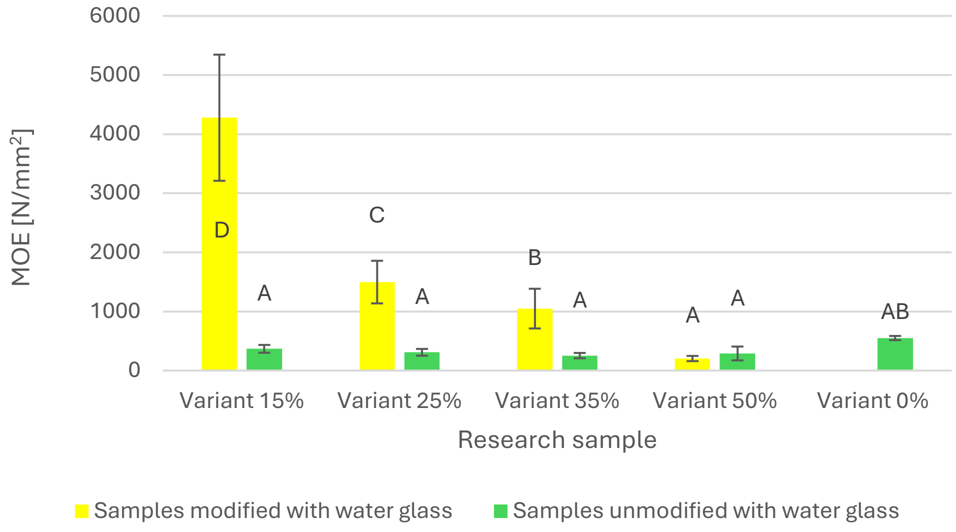

Fig. 9. Average MOE values of the tested composites; A, B, C, D - homogeneous groups based on Tukey's test.

Analysing the one-way analysis of variance (table 1), it can be concluded that both the addition of hemp shives and the addition of water glass were statistically significant in the study of MOR and MOE. However, hemp shives played a decisive role in both the MOR and MOE, accounting for 44.9% (for MOR) and 34.9% (for MOE) of the influence. The influence of water glass was at 30.9% (for MOR) and 22.3% (for MOE). The influence of unanalysed factors in the study (Error) for MOR and MOE was only 8.3% and 7.7%, respectively.

Table 1. Analysis of variances results of mechanical properties of hemp-cement-lime composite

factors / interaction	Density		MOR		MOE		Compression strength	
	p	X	p	X	p	X	p	X
hemp share	0.0000	81.5	0.0000	44.9	0.0000	34.9	0.0000	57.6
water glass addition	0.0000	10.2	0.0000	30.9	0.0000	22.3	0.0000	20.3
hemp share * water glass addition	0.0000	3.9	0.0000	15.8	0.0000	35.1	0.0000	18.2
Error		4.4		8.3		7.7		3.8

p – significant with α=0.05; X – percentage of contribution

The average results for compressive strength of the samples and corresponding homogeneous groups based on the Tukey test are shown in fig. 10. The highest compressive strength value of 14.7 N/mm^2 was exhibited by the variant with 15% content of hemp shives modified with water glass. The lowest compressive strength was observed in the variant with 50% content of hemp shives modified with water glass. Significant differences in compressive strength between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives were noted in the 15%, 25%, and 35% hemp shive content. The differences in average compressive strength among the 15%, 25%, and 35% variants were 9.53 N/mm^2, 4.91 N/mm^2, and 4.06 N/mm^2, respectively, and were statistically significant (different homogeneous groups F, B and E, B and C, A). Analysing the results, it can be observed that increasing the volume fraction of modified hemp shives by 35% reduces the composite's compressive strength by 92%. It's worth noting that compared to other variants, the difference in compressive strength in the 15% variant is the largest at 9.53 N/mm^2. This difference is statistically significant (different homogeneous groups F, B). The smallest difference in compressive strength among the samples was observed in the 50% variant, which was 0.12 N/mm^2. The same homogeneous groups (A) indicate that these differences are not statistically significant. Referring to the literature (Elfordy et al. 2008, Brzyski et al. 2017), it was noted that the obtained compressive strength values are generally higher than those cited in the literature. The compressive strength of the variant without hemp shives (variant 0%) was 8.05 N/mm^2, making it only the third in terms of compressive strength. The variant with 15% volume fraction of modified hemp shives showed a compressive strength nearly 83% higher than the 0% variant. An interesting observation is that the variant with a 25% volume fraction of hemp shives modified with water glass exhibits a compressive strength over 18% higher than the variant without hemp shives. Also in this case, the effect of higher compressive strength after adding water glass to hemp shives results from better bonding of hemp particles with cement (Yang and Li 2022).

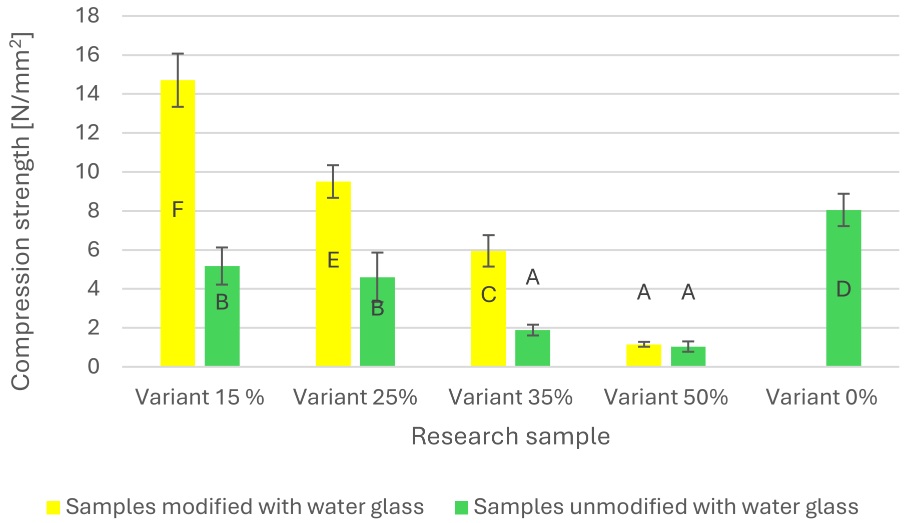

Fig. 10. Average compression strength values of the tested composites; A, B, C, E, F - homogeneous groups based on Tukey's test.

Analysing the one-way analysis of variance (table 1), it can be concluded that both the addition of hemp shives and the addition of water glass were statistically significant in the study of compressive strength. Hemp shives played a decisive role in compressive strength, accounting for 57.6% of the influence, while the influence of water glass was at 20.3%. The influence of unanalysed factors in the study was only Error = 3.8%.

The average results for water absorption of samples after 2 hours of soaking and corresponding homogeneous groups based on the Tukey test are shown in fig. 11. The highest water absorption value after 2 hours of soaking, reaching 15.9%, was observed in the variant with 50% unmodified hemp shives. The lowest water absorption was exhibited by the variant with 15% hemp shives modified with water glass. The largest differences in water absorption after 2 hours of soaking between hemp cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives were observed in the 15% and 25% variants. The differences in average water absorption after 2 hours of soaking in the 15% and 25% variants were 3% and 3.8%, respectively, and were statistically significant (different homogeneous groups A, B). Analysing the results, it can be noted that increasing the volume fraction of modified hemp shives by 35% increases the composite's susceptibility to water absorption by 150%. It is worth noting that compared to the other variants, the difference in water absorption after 2 hours of soaking in the 25% variant is the highest, at 3.8%. It should be added that this difference is statistically significant (different homogeneous groups A, B). The smallest difference in water absorption after 2 hours of soaking was observed in the 35% variant, amounting to 0.4%. The same homogeneous groups (B) indicate that these differences are not statistically significant. It is worth noting that for variant samples containing 15%, 25% and 35% of unmodified hemp shives, the water absorption after 2 hours of soaking in water for all variants is at a similar level. It was observed that the difference in water absorption after 2 hours of soaking for the variant with 50% hemp shives content differs significantly from the other variants. The water absorption after 2 hours of soaking in water for the variant without hemp shives (variant 0%) was 6.90%, making it the variant with the least water absorption. The variant with 50% volume fraction of modified hemp shives showed a higher water absorption after 2 hours of soaking in water than the 0% variant by approximately 130%. An interesting observation is that the remaining variants with unmodified hemp shives exhibit similar water absorption values after 2 hours of soaking in water and show a higher water absorption than the 0% variant by nearly 40%. The factor that reduces the water absorption of hemp shives is the use of a modifier in the form of water glass, which was also confirmed by Trociński (2023). In his research, he found that the modifier reduced the water absorption of composites with hemp fibers by 31% compared to variants with unmodified fibers.

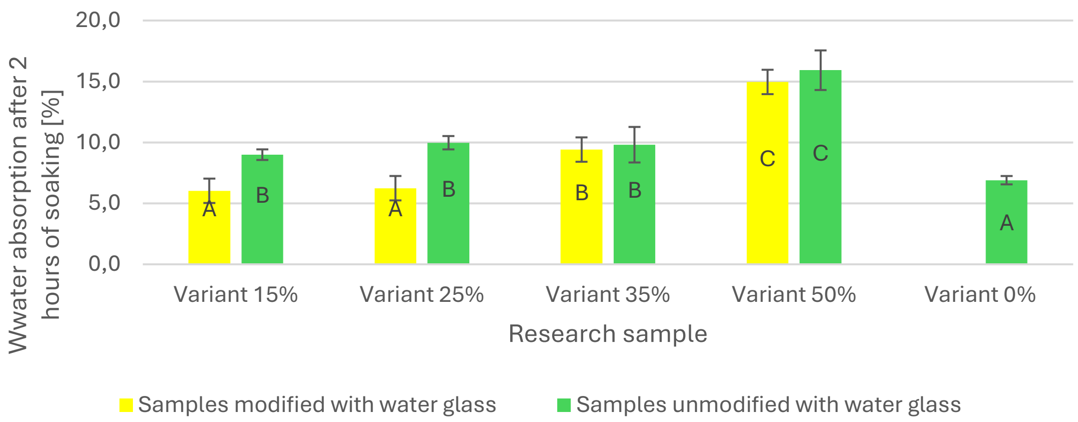

Fig. 11. Average water absorption after 2 hours of soaking the tested composites; A, B, C – homogeneous groups based on Tukey's test.

The average results for water absorption of samples after 24 hours of soaking and corresponding homogeneous groups based on the Tukey test are shown in fig. 12. The highest water absorption value after 24 hours of soaking, amounting to 17.35%, was exhibited by the variant with 50% hemp shives content, unmodified with water glass. The lowest water absorption of 6.92% was observed in the variant with 15% hemp shives content, modified with water glass. The decrease in the absorbability of composites along with the reduction in the content of hemp shives is a direct result of the reduced availability of shives on the surface of the composites (fig. 13). It was noted that the largest differences in sample water absorption after 24 hours of soaking in water between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives were observed in the variants of 15% and 25%. The differences in the average water absorption after 24 hours of soaking in the variants of 15% and 25% were 2.58% and 3.2%, respectively, and were statistically significant (different homogeneous groups A, B). Analysing the results, it can be observed that increasing the volume fraction of modified hemp shives by 35% increases the susceptibility to water absorption of the composite by nearly 150%. It is worth noting that compared to the other variants, the difference in water absorption after 24 hours of soaking in the 25% variant is the largest at 3.2%. It should be added that this difference is statistically significant (different homogeneous groups A, B). The smallest difference in water absorption after 24 hours of soaking in the samples was observed in the 50% variant, amounting to 0.09%. The same homogeneous groups (C) indicate that the differences are not statistically significant. It is worth noting that for variant samples containing 15%, 25% and 35% of unmodified hemp shives, the water absorption after 24 hours of soaking for all variants fluctuates at a similar level. It was observed that the difference in water absorption after 24 hours of soaking for the variant with 50% hemp shives content differs significantly from the other variants. It is worth noting that the variant not containing hemp shives (variant 0%) had a water absorption of 7.33%, making it the third in terms of lowest water absorption.

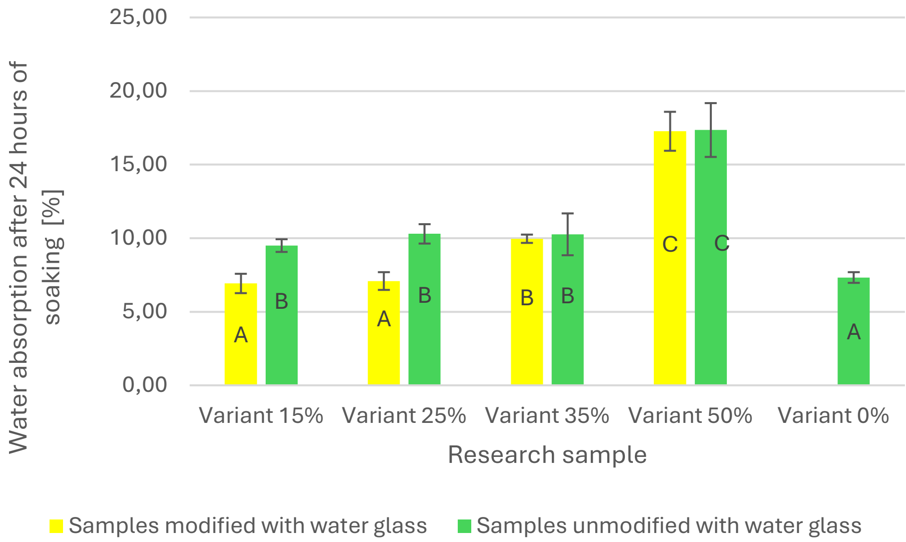

Fig.12. Average water absorption after 24 hours of soaking the tested composites; A, B, C – homogeneous groups based on Tukey's test.

Analysing a one-way analysis of variance (Table 2), it can be concluded that both the addition of hemp shives and the addition of water glass were statistically significant in the water absorption test after 2 and 24 hours of soaking. The addition of hemp shives played a decisive role in water absorption, accounting for 83.1% of the impact after 2 and 88.7% of the impact after 24 hours of soaking, respectively. In turn, the effect of modifying hemp shives with water glass was 5.6% after 2 and 2.6% after 24 hours of soaking, respectively. It is worth emphasizing that this impact is comparable to the impact of factors not analysed in the study (Error = 6.6% after 2 and 5.5% after 24 hours of soaking).

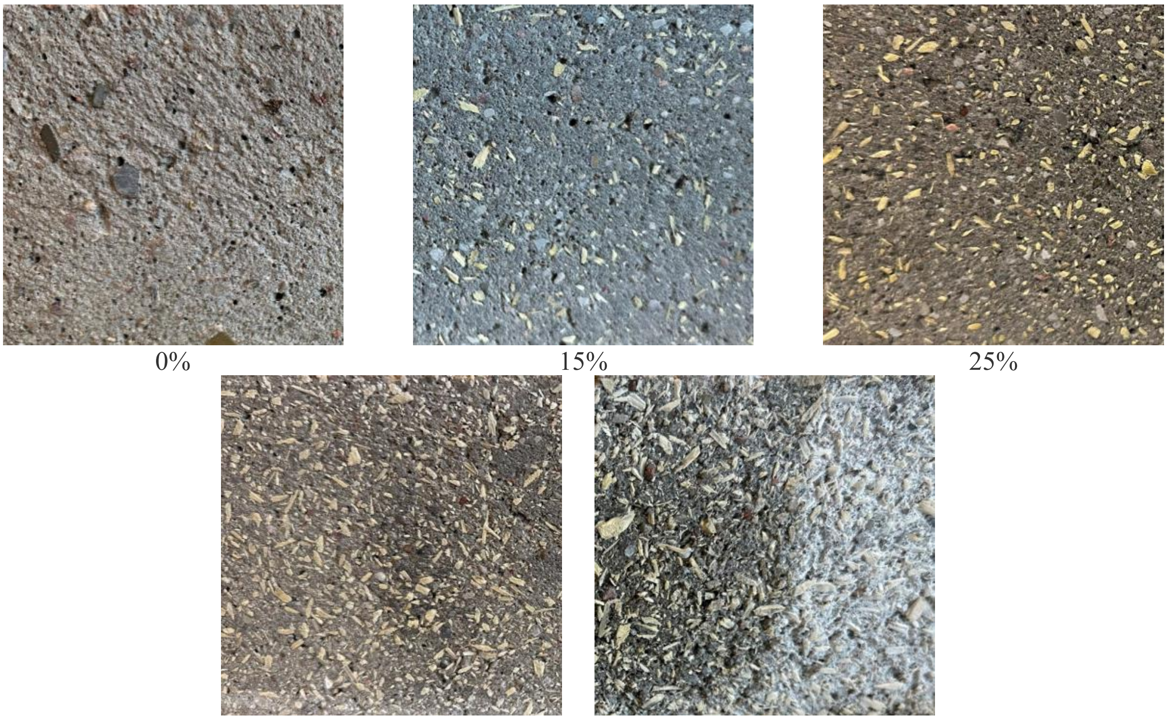

Fig.13. Examples of the surface appearance of samples of individual variants of hemp-cement-limestone composites.

Table 2. Analysis of variances results of physical properties of hemp-cement-lime composite

factors / interaction	Thickness swelling				Water absorption			
	2h		24h		2h		24h	
	p	X	p	X	p	X	p	X
hemp share	0.0000	41.6	0.0000	43.3	0.0000	83.1	0.0000	88.7
water glass addition	0.0000	17.3	0.0000	23.8	0.0000	5.6	0.0000	2.6
hemp share * water glass addition	0.0007	8.4	0.0000	11.7	0.0000	4.7	0.0000	3.2
Error		32.7		21.2		6.6		5.5

p – significant with α=0.05; X – percentage of contribution

The average results for thickness swelling of samples after 2 hours of soaking in water and corresponding homogeneous groups based on the Tukey test are shown in fig. 14. The highest thickness swelling value after 2 hours of soaking, reaching 0.73%, was observed in the variant with 50% unmodified hemp shives. The lowest thickness swelling value was exhibited by the variant not containing hemp shives (variant 0%). The largest difference in thickness swelling value after 2 hours of soaking between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives was observed in the 50% variant. The difference in the average thickness swelling value after 2 hours of soaking in the 50% variant was 0.39% and was statistically significant (different homogeneous groups A, B, C, D). Analysing the results, it's worth noting that increasing the volume fraction of hemp shives modified with water glass from 15% to 50% increases the composite's susceptibility to thickness swelling by 142%. The smallest difference in swelling value after 2 hours of soaking between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives was observed in the 15% variant, amounting to 0.11%. It should be noted, however, that the same homogeneous groups (A) prove that this difference is not statistically significant. The thickness swelling value after 2 hours of soaking for the variant without hemp shives (Variant 0%) was 0.13%, making it the variant with the lowest thickness swelling. The variant with 50% volume fraction of modified hemp shives showed higher thickness swelling after 2 hours of soaking than the 0% variant by approximately 162%. However, all thickness swelling values show minimal values, indicating that the cement-lime composite with modified and unmodified hemp shives with water glass exhibits good dimensional stability and is not significantly prone to thickness swelling after 2 hours of soaking in water.

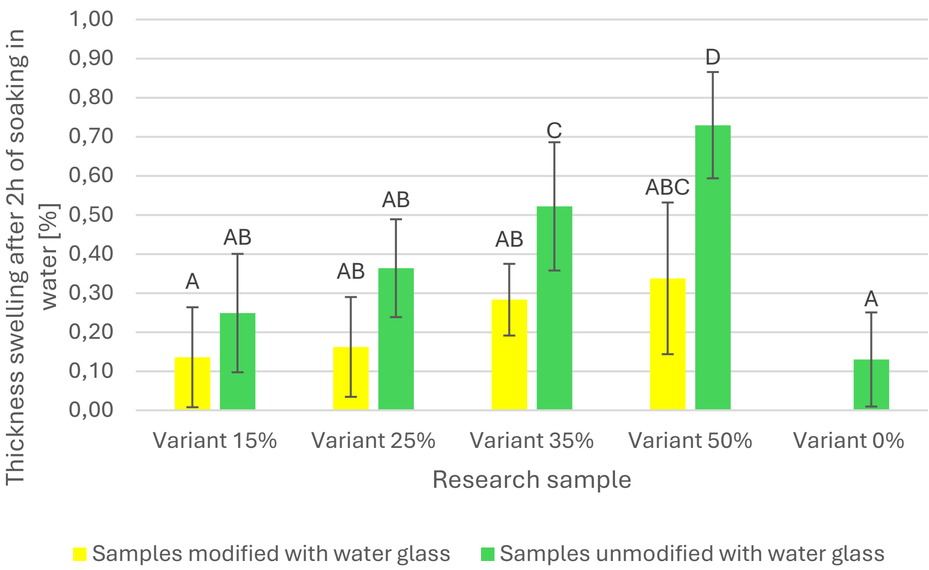

Fig. 14. Average thickness swelling after 2 hours of soaking the tested composites: A, B, C, D – homogeneous groups based on Tukey's test.

The average results for thickness swelling of samples after 24 hours of soaking in water and corresponding homogeneous groups based on the Tukey test are shown in fig. 15. The highest thickness swelling value after 24 hours of soaking, reaching 1.06%, was observed in the variant with 50% unmodified hemp shives. The lowest thickness swelling value of 0.16% was exhibited by the variant without hemp shives (variant 0%). The largest difference in thickness swelling values after 24 hours of soaking between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives was observed in the 50% variant. The differences in the average thickness swelling value after 24 hours of soaking in the 50% variant were 0.63% and were statistically significant (different homogeneous groups B, C, E). Analysing the results, it is worth noting that increasing the volume fraction of hemp shives modified with water glass from 15% to 50% increases the composite's susceptibility to thickness swelling by 95%. The smallest difference in thickness swelling values after 24 hours of soaking between cement composites with the addition of hemp shives modified with water glass and composite variants containing unmodified hemp shives was observed in the 15% variant, amounting to 0.17%. It should be noted, however, that the same homogeneous groups (B) prove that this difference is not statistically significant. The variant with 50% volume fraction of modified hemp shives showed greater thickness swelling after 24 hours of soaking than the 0% variant by approximately 169%. It is worth noting that the differences in thickness swelling values between samples soaked for 2 hours and samples soaked for 24 hours are very small. All swelling values exhibit negligible values, indicating that the cement-lime composite with modified and unmodified hemp shives with water glass demonstrates good dimensional stability and is not significantly prone to thickness swelling after 24 hours of soaking in water.

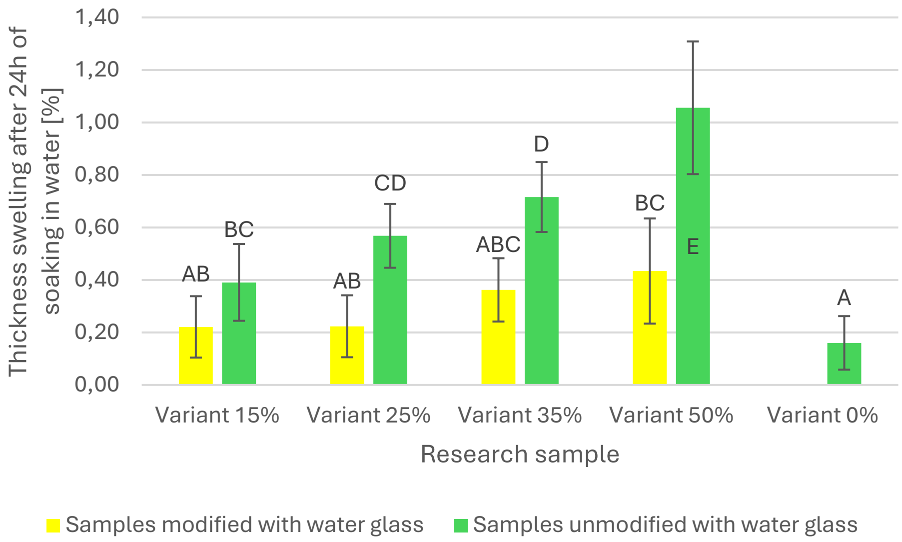

Fig. 15. Average thickness swelling after 2 hours of soaking the tested composites: A, B, C, D, E – homogeneous groups based on Tukey's test.

Analysing the one-way analysis of variance (Table 2), it can be concluded that both the addition of hemp shives and the addition of water glass had a statistically significant effect on the tested values of swelling in thickness after 2 and 24 hours of soaking in water. The addition of hemp shives played a decisive role in the thickness swelling values, accounting for 41.6% of the influence after 2 and 43.3% of the influence after 24 hours of soaking, respectively. In turn, the impact of water glass modification was 17.3% after 2 and 23.8% after 24 hours of soaking, respectively. However, it is worth noting that, as in the case of soaking capacity, these values were lower or comparable to the influence of factors not analysed in the study (Error = 32.7% after 2 and 21.2% after 24 hours of soaking).

CONCLUSIONS

Based on the tests carried out on the hemp-cement-lime composite with the volume content of hemp shives in the range (0 - 50%) modified and unmodified with water glass, the following conclusions can be drawn:

1. An increase in the content of hemp shives in the composite results in a decrease in its density, with lower density recorded in the case of composites containing hemp shives not modified with water glass
2. The increase in the content of hemp shives in the composite results in a decrease in its strength parameters: MOR, MOE and compression strength.
3. Modification of hemp shives with water glass significantly improves the strength parameters of hemp-cement-lime composites.
4. The highest strength parameters are demonstrated by a hemp-cement-lime composite containing a 15% volume share of hemp shives modified with a 5% mass addition of water glass.

5. The increase in the content of hemp shives in the composite increases its water absorption and thickness swelling.
6. Modification of hemp shives with water glass in the hemp-cement-lime composite has a positive effect on reducing its water absorption and thickness swelling.
7. The best resistance to water (lowest water absorption and thickness swelling in thickness) is demonstrated by a hemp-cement-lime composite containing a 15% volume share of hemp shives modified with a 5% addition of water glass.
8. Considering the individual factors (the share of hemp shives, the addition of water glass) affecting the properties of the hemp-cement-lime composite, the share of hemp shives has a higher percentage impact, and both factors have a statistically significant impact.

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Streszczenie: *Wpływ modyfikacji paździerzy konopnych szkłem wodnym na wybrane właściwości kompozytu konopno-cementowo-wapiennego.* Badano wpływ dodatku i modyfikacji paździerzy konopnych szkłem wodnym na wybrane właściwości kompozytu konopno-cementowo-wapiennego. Wytworzono dziewięć wariantów kompozytów różniących się zawartością objętościową łusek konopi: 0%, 15%, 25%, 35% i 50%, modyfikowanych i niemodyfikowanych szkłem wodnym. Dla wytworzonych kompozytów badano: gęstość, wytrzymałość na ściskanie, MOR (wytrzymałość na zginanie), MOE (moduł sprężystości), spęcznienie na grubość oraz nasiąkliwość. Na podstawie przeprowadzonych badań stwierdzono, że zwiększenie dodatku paździerzy konopnych powoduje obniżenie parametrów wytrzymałościowych i pogorszenie wodoodporności kompozytów konopno-cementowo-wapiennych. Z kolei modyfikacja paździerzy konopnych szkłem wodnym poprawia zarówno właściwości wytrzymałościowe, jak i fizyczne (ograniczone spęcznienie na grubość i nasiąkliwość) kompozytów konopno-cementowo-wapiennych w porównaniu do analogicznych kompozytów opartych na niemodyfikowanych paździerzach konopnych. Najwyższymi parametrami wytrzymałościowymi i najlepszą wodoodpornością charakteryzuje się kompozyt konopno-cementowo-wapienny zawierający 15% objętościowy udział paździerzy konopnych modyfikowanych 5% dodatkiem szkła wodnego.

Słowa kluczowe: kompozyt konopno-cementowo-wapienny, paździerze konopne, szkło wodne, właściwości wytrzymałościowe, właściwości fizyczne

Corresponding author:

Radosław Chomicz,
ul. Nowoursynowska 159, budynek 34
02-787 Warszawa, Poland
email: s196944@sggw.edu.pl