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COMPOSITES THEORY AND PRACTICE

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MECHANICAL AND THERMAL PROPERTIES OF HEMP-LIME COMPOSITES

The paper presents the results of research concerning lightweight, ecological composites produced on the basis of building lime, cement and metakaolin, which are binders, as well as hemps used as a renewable raw material of agriculture. Tests of the physical and mechanical properties of lime-hemp composites were performed and their basic characteristics were determined, i.e.: absorptivity, bulk density, thermal conductivity, compressive and flexural strength, as well as the dynamic modulus of elasticity. The study was conducted to determine the use of lime-hemp composites to construct walls or to fill the frames of a wooden house. The results show that the lime-hemp composites produced are lightweight and have low thermal conductivity and apparent density. On the other hand, they are characterized by very low strength properties compared to traditional building materials. The dynamic mechanical properties of the shives reinforcing the composites depend on various factors such as shives loading, orientation and the nature of the shives-matrix interface region. The addition of ethylene-vinyl acetate copolymer as a plasticizing and strengthening admixture caused a considerable increase in the strength parameters of the composites.

Keywords: **hemp-lime composites, ecological building, thermal conductivity, compressive strength, flexural strength**

MECHANICZNE I TERMICZNE WŁAŚCIWOŚCI KOMPOZYTÓW WAPIENNO-KONOPNYCH

Przedstawiono wyniki badań lekkich, ekologicznych kompozytów wyprodukowanych na bazie wapna budowlanego, cementu i metakaolinu, stanowiących środki wiążące, oraz konopi wykorzystanych jako surowiec odnawialny z rolnictwa. Wykonano badania fizyczne i mechaniczne właściwości kompozytów wapienno-konopnych oraz wyznaczono ich podstawowe charakterystyki, tj.: nasiąkliwość, gęstość objętościową, współczynnik przewodzenia ciepła, wytrzymałości na ściskanie i zginanie, dynamiczny moduł sprężystości. Badania przeprowadzono w celu określenia możliwości wykorzystania kompozytów wapienno-konopnych do wznoszenia ścian lub też do wykonania z nich wypełnienia szkieletu drewnianego domu. Otrzymane wyniki dowodzą, że wytworzone kompozyty wapienno-konopne są lekkie i charakteryzują się niskim współczynnikiem przewodzenia ciepła oraz małą gęstością pozorną. Z drugiej strony cechują je bardzo niskie parametry wytrzymałościowe w porównaniu z tradycyjnymi materiałami budowlanymi. Dynamiczne właściwości kompozytów wzmocnionych paździerzami konopnymi zależą od różnych czynników, m.in. sposobu obciążenia, ich zorientowania w matrycy oraz naturalnego połączenia między paździerzami a osnową. Dodatek kopolimeru octanu winylu jako domieszki plastyfikująco-wzmacniającej spowodował znaczny wzrost parametrów wytrzymałościowych kompozytów.

Słowa kluczowe: **kompozyty wapienno-konopne, budownictwo ekologiczne, przewodność cieplna, wytrzymałość na ściskanie, wytrzymałość na rozciąganie przy zginaniu**

INTRODUCTION

Research on concrete made of hemp is part of a sustainable development policy in the building field. In order to reduce the associated greenhouse gas emissions and the resulting impact on the climate, it is necessary to select construction materials that can meet not only the performance specifications but also the lowest level of greenhouse gas emissions. For this reason, in recent years natural fibers have been widely investigated to be used as an alternative to carbon, glass, wooden or plastic fibers, in several composite applications for building construction [1]. One of such materials is hemp, which has been used as a composite material and increasingly in the construction of building envelopes. As regards hemp in buildings, it is increasingly used with a lime base binder for wall constructions [2]. Lime and its derivatives are the main ingredients in the binder used in the hemp-lime wall construction. Lime is a processed material widely used in the building industry and is produced by heating calcium carbonate in a kiln to a temperature of approximately 900ºC. Hemp-lime construction has been used in France since the 1990s [1, 3] but it has not been common in Poland.

Hemp is a fast growing annual plant which is cultivated using different methods. The construction and performance of buildings using hemp-lime walls have been studied in detail by Bevan and Woolley [3]. Their study has identified a wide range of benefits including: exceptionally high levels of air tightness achieved through the monolithic wall construction; improved air quality due to the hygroscopic properties of the wall; and lower energy consumption attributed to the heat transfer process involving the sensible and latent thermal capacities of hemp-lime walls. It is usually used as material for insulating walls or insulation layers for floors and roofs.

The increasing scientific interest in natural fibers as a component of construction applications is also due to the good mechanical properties exhibited by natural fibers. Many researchers have approached the study of natural materials, especially investigating their thermal insulating properties. The most studied materials are jute [4], cork [5], corn cob [6], hay [7], sugarcane [7], wood wool and rock wool [8], cellulose loose-fill [9], flax [10, 11], straw bales [12] and hemp [3, 10, 11, 13]. The currently registered varieties of hemp in Poland and countries of the European Union are: Bialobrzeskie, Benico, Silesia, Tygra bred at the Institute of Natural Fibers in Poznan which is involved in comprehensive examinations of obtaining and processing natural raw fiber and herbal materials. These varieties represent a high economic value. They are not dangerous in terms of drug addiction under the Act on Counteracting Drug Addiction and they contain less than 0.2% Δ9THC. The principal components of the fiber cell walls are cellulose, hemicelluloses and lignin with pectin normally considered to be the main binder [14].

The research included in this paper aims at checking the possibility of using hemp in the construction of hemp-lime walls.

EXPERIMENTAL PROCEDURE

Mixture design and sample production process

For the analysis, six specimens were made. In the laboratory, the composite mixtures were prepared using: lime, hemp shives, perlite, portland cement, water, metakaolin, ethylene-vinyl acetate copolymer as a plasticizing and strengthening admixture in the quantity of 0.5% in relation to water weight. The abbreviated names of the composites and mix-proportioning of the composites used in the experimental program are shown in Table 1. The most pertinent parameter in this case seems to be the Hemp - to - Cement + Lime + Metakaolin ratio (H/(C+L+M)) and Perlite - to - Cement + Lime + Metakaolin ratio (P/(C+L+M)), the values of which are summarized in Table 1.

Industrial hemps come from the Institute of Natural Fibers and Herbal Plants in Poznan. The hemp shives are characterized by a very low bulk density (100÷104 kg/m^3) because of their highly porous structure. Also, the shives exhibit a high water absorption capacity: up to 410% of its own mass, after 48 h of immersion.

The granulometric analysis of Bialobrzeskie hemp shives was carried out in three dimensions (length, width, thickness) using a steel sliding calliper (accuracy: 0.02 mm), which was described in the work by Stikute et al. [15]. Research shows that the thickness of hemp shives is 1.8÷7 mm (max. 1.8÷3.1 mm), length 15÷56 mm (max. 15÷25 mm) and width 2.8÷8 mm (max. 4.1 mm). The hemp shives used in the test differed from those described in the above mentioned work in [15] as far as the length was concerned, which was 15÷150 mm. The shape and size of hemp shives are directly affected by mechanical treatment during hemp extraction at the plantation, manufacturing processes aiming at obtaining the desired dimensions of the shives as well as and their cleaning and calibration.

TABLE 1. **Composition of produced materials**
TABELA 1. **Skład wytworzonych kompozytów**

Material	Symbol, unit	C1	C2	C3	C4	C5	C6
Lime	L [kg/m^3]	106.38	139.21	147.37	153.17	176.77	189.70
Hemp shives	H [kg/m^3]	85.11	92.81	84.21	87.53	75.76	54.20
Perlite	P [kg/m^3]	42.55	46.40	63.16	65.64	101.01	135.50
Water	W [l/m^3]	212.98	371.22	421.06	437.64	505.06	542.00
Cement	C [kg/m^3]	21.28	32.48	48.42	50.33	58.08	62.33
Metakaolin	M [kg/m^3]	10.64	13.92	14.74	15.32	17.68	18.97
Ethylene-vinyl acetate copolymer	E_{vc} [kg/m^3]	-	-	-	2.19	-	-
W/(C+L+M) *	[%]	1.54	2.0	2.0	2.0	2.0	2.0
H/(C+L+M) **	[%]	60	50	40	40	30	20
P/(C+L+M) ***	[%]	30	25	30	30	40	50

* W/(C+L+M) = Water / Cement +Lime+Metakaolin weight ratio
** H/(C+L+M) = Hemp / Cement +Lime+Metakaolin weight ratio
*** P/(C+L+M) = Perlite / Cement +Lime+Metakaolin weight ratio

In lime composites, classic limestone sand was abandoned and replaced by expanded perlite class II EP180 and a 0÷4 mm grain size. The content of perlite was from 25 to 50% in relation to the quantity of binder (C + L + M). The compressive strength of perlite was 0.14÷0.40 MPa, bulk density 60÷80 kg/m^3 and had a thermal conductivity coefficient of 0.042 W/mK. Perlite causes significant changes in the physical and rheological characteristics of the products. Increasing the volume fraction of perlite and reducing sand results in lowering the strength parameters. In exchange thereof, the following qualities are improved: thermal insulation, fire resistance, lightness of the products, resistance to capillary rise as well as noise reduction.

A mixture of hydrated lime, Portland cement and metakaolinite was used as a binder. The hydrated lime complied with the requirements of PN-EN 459-1 and was characterized by a bulk density of 390÷410 kg/m^3. The chemical composition of the lime is as follows: CaO - 95.5%, MgO - 0.5%, CO_2 - 2.1%, SO_3 - 0.1%, free water - 1.5%. The Portland cement CEM I 42.5R had the following technical parameters: a specific surface of 3985 cm^2/g, the beginning of binding 190 min, the end of binding 250 min, compressive strength after 2 days - 30.4 MPa, flexural strength after 2 days - 5.41 MPa, water demand 28%, loss on ignition 3.44% by weight. The research on Portland cement CEM I 42.5R was conducted according to the Polish standards PN EN 197-1:2002 and PN-B-19707:2003. Metakaolin was added in the quantity of 0.1% by weight, lime of the following chemical composition: AL_2O_3 40-42%, SiO_2 51-53%, K_2O and Na_2O 1.3-1.5%, compounds of Fe, Ti, Mg 1.3-1.5%. Metakaolin is a pozzolanic additive, it contributes to early age strength and a denser cementitious matrix. Some of these additives also provide special reactivity. Calcium hydroxide accounts for up to 25% of the hydrated Portland cement, and calcium hydroxide does not contribute to the concrete strength or durability. Metakaolin combines with the calcium hydroxide to produce additional cementing compounds, the material responsible for binding concrete together.

Based on experiments, the optimal ratio W/(C+L+M) was determined at a level of 2.0. This relation in the initial mixture C1 was assumed to be 1.54, however, due to poor workability it was increased to 2.0 and 2.5. At the level of W/(C+L+M) = 2.5, the constituents in the molds segregated, therefore, the ratio of 2.0 was taken for further research. After having mixed the components thoroughly, hemp shives were gradually added in order to obtain homogeneous and workable mixtures. Once the mixture was placed in the molds, it was compacted on a vibrating table. The cubic and rectangular specimens were compacted in one layer while the cylindrical specimens in two layers. For a period of three days, the samples were placed in molds protected against water loss. After removing the samples from the molds, they were stored in air-dry conditions for a period of 25 days, until the time the tests were carried out (Fig. 1).

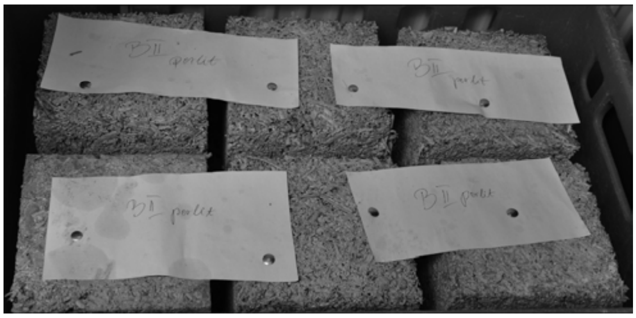


Fig. 1. Specimens for compressive strength test

Rys. 1. Próbki do badania wytrzymałości na ściskanie

COMPOSITES PROPERTIES

Apparent density and absorptivity

The apparent density test was performed in accordance with EN 12390-7:2001. Three cubic specimens from each batch with dimensions of 100x100x100 mm were used for testing. The absorptivity test was carried out according to standard PN-88/B-06250 on three cubic specimens of dimensions 100x100x100 mm from each batch.

Thermal conductivity coefficient

To determine the thermal conductivity coefficient, a plate apparatus was used. For that purpose, 3 plates of each concrete type were prepared. The dimensions of each plate were as follows: 300×300×50 mm. Research was conducted on 3% moist samples, which were obtained by material storage in a room with a relative humidity equal to 70% during a period of 4 weeks. In order to determine the thermal conductivity coefficient of the composite, two temperatures were applied: 20°C for a heating plate and 0°C for a cooling plate. The average temperature was 10°C. The operating rules consist in letting a specific heat flow through the sample and measuring the temperatures which occurred at a determined heat flow on the surfaces which let the heat in or out.

The apparatus worked with computer software which recorded the results of the measurements.

Compressive strength

Cubic composite samples with the following dimensions 150x150x150 mm were employed. The research was conducted according to EN 12390-3:2002 normative-compressive strength (Fig. 2a). Evaluation of the composite grade was elaborated using a compression tester by Controls within 3 MN after 28 days of maturation, when the average compressive strength was obtained by the samples.

Flexural strength

Examination of the composites was performed on 100x100x500 mm specimens. The research was conducted according to EN 12390-5:2009 normative - flexural strength (Fig. 2b). The test was done after 28 days of sample maturation. The samples were then loaded with a centrally placed force (3-point-bending). Spacing of the supports was 300 mm.

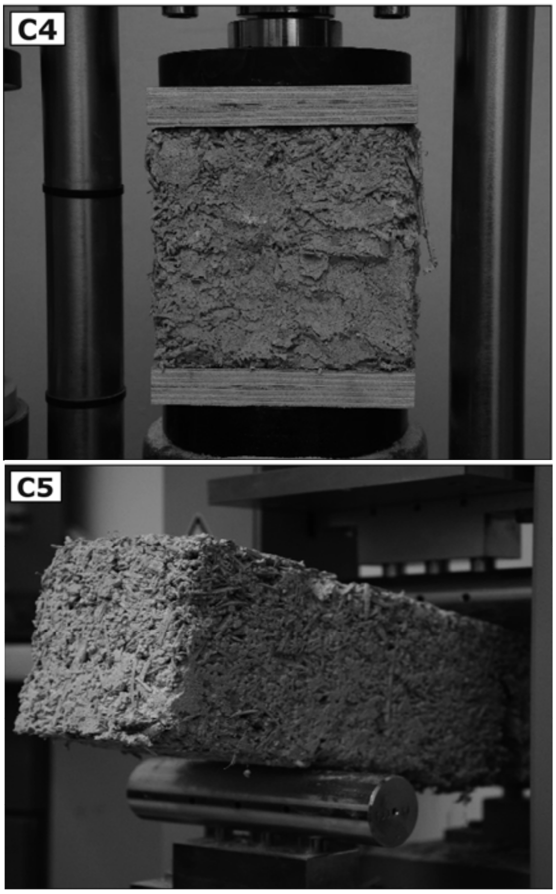
a)
b)


Fig. 2. Tests of composite samples with shives: a) compressive strength (C4), b) flexural strength (C5)

Rys. 2. Badania kompozytów z paździerzami: a) wytrzymałość na ściskanie (C4), b) wytrzymałość na zginanie (C5)

Dynamic modulus of elasticity

The test method for the dynamic modulus of elasticity of concrete in compression was performed on cylinders of 150 mm in diameter and a height of 300 mm maintaining the recommendation that in the case of cylindrical specimens, the length (l) should be at least twice the diameter of the specimens (d).

Determination of the dynamic modulus of elasticity of the samples was performed using the dynamic method based on resonance frequency measurements made by means of a frequency counter C311-R (Fig. 3). The test was conducted at approximately a 1V output voltage based on ASTM C666 and ASTM C215. In the test, the accelerometer was installed on the cylinder composite specimen with a silicone coating and was attached to the data acquisition system. A small diameter steel ball was used as the impact source in the test. The ball hit the top surface of the cylindrical specimen, the accelerometer measured the vertical motion and the data were obtained by a computer program. According to this setup, the data were recorded from the data acquisition system and both the amplitude-time and amplitude-frequency graphs were obtained. Based on the amplitude-frequency graph, the peak value, which shows the resonant frequency value of the composite specimen, was obtained.

The dynamic modulus of given a specimen is calculated using:

$$E_{DM} = 4L^2 n^2 \rho$$

where: E_{DM} - dynamic modulus of elasticity [GPa], L - specimen length [m], n - frequency [kHz], ρ - apparent density [kg/m^3].

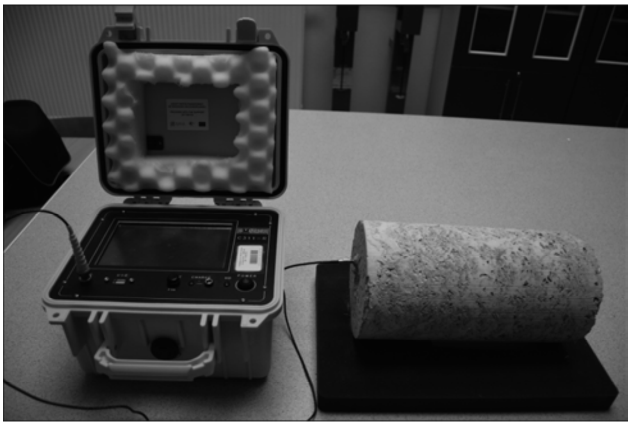


Fig. 3. Dynamic modulus of elasticity test on hemp-lime composite specimen

Rys. 3. Badanie dynamicznego modułu sprężystości kompozytu wapienno-konopnego

RESULTS AND DISCUSSION

Physical properties

The physical properties of the composites adopted for the examination are shown in Figures 4 and 5.

The results show that the quantity of hemp shives significantly affects an increase in absorptivity and has an effect on a decrease in the density of the composites (Fig. 4). The drop in density is from 7 to 42.4% and it increases with the quantity of hemp shives added from 30 to 60% respectively, compared to samples C6 with the lowest contents of hemp shive of 20%. Based on the study, one can conclude that the produced composites have a density from 265.8÷461.2 kg/m^3. The addition of shives in the quantity of 60% resulted in an increase in absorptivity by 35%. The absorptivity of the samples is very high and varies from 98.5 to 150.5%.

It was found that as absorptivity increased and composite density decreased, there was a gradual decrease in thermal conductivity from 0.111 to 0.094 W/mK (Fig. 5). In order to meet the technical requirements [16] which should be fulfilled by the walls of residential buildings in respect to the heat transfer coefficient $U = 0.25$ W/m^{2}K, a composite wall made of C1 with the highest content of hemp shives (60%) and the lowest thermal conductivity λ should have a thickness of 0.37 m. It was found that the same single-layer wall in an energy-saving building should have a thickness of 0.47 m, and in a passive building 0.63 m, respectively. A wall produced from composite C2 with coefficient $\lambda = 0.094$ W/mK, should have the following thicknesses: 0.39 m, 0.49 m, 0.65 m. For other composites, C3-C6, the wall thickness should be 0.44 m, 0.55 m, 0.73 m respectively.

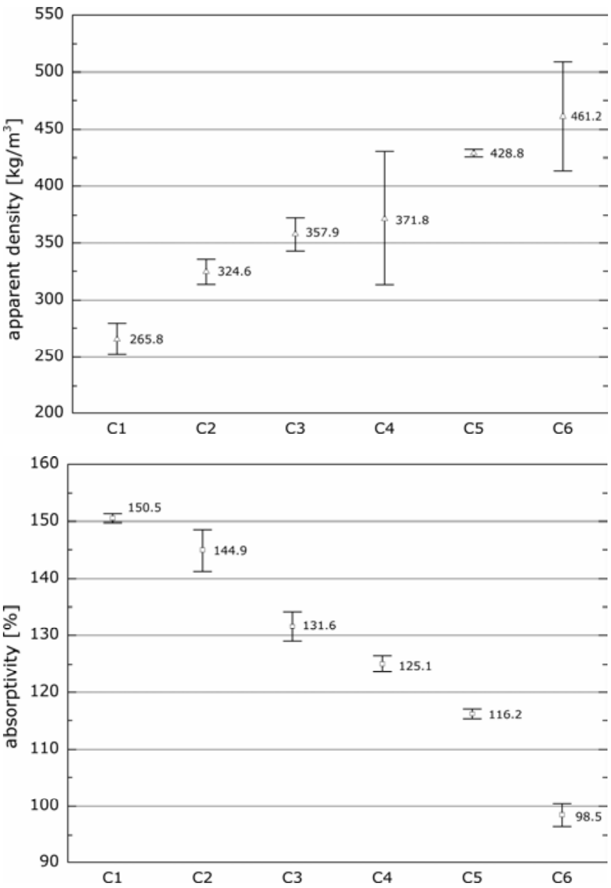


Fig. 4. Apparent density and absorptivity of tested composites

Rys. 4. Gęstość objętościowa i nasiąkliwość badanych kompozytów

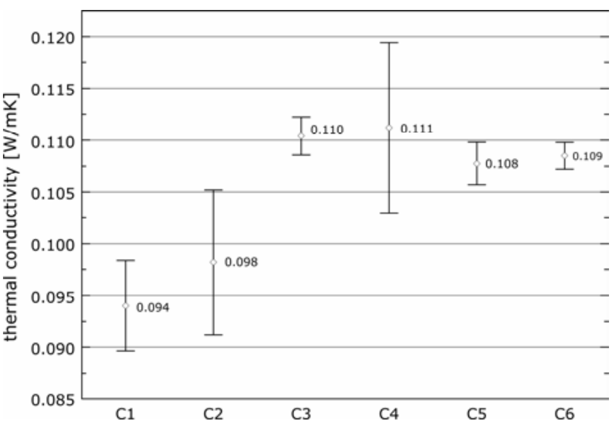


Fig. 5. Thermal conductivity coefficient of composites

Rys. 5. Współczynnik przewodzenia ciepła kompozytów

Studies [17] showed that regardless of the material formulation or setting processes, the results indicated that the final product had a low apparent density (300 < ρ < 600 kg/m^3) and high porosity > 65%. Consequently, they demonstrated a thermal conductivity at ambient conditions (23°C, 50% RH), which ranged from 0.07 to 0.20 W/mK [18] and from 0.069 to 0.115 W/mK [19]. Due to the low density and the high porosity of hemp shives, the combination of hemp and starch binder produces a building material with properties that differ from those of conventional concrete. This material is of lower density and lower thermal conductivity. According investigation [20], the thermal conductivity varies from 0.067 to 0.085 W/mK. This value decreases considerably in the function of the hemp shives proportion in the starch-hemp concrete. The results referring to density and thermal conductivity obtained in the study are comparable to the results of other researchers. Nevertheless, the test results concerning absorptivity are definitely higher than those obtained in study [20], and they vary from 6.30 to 25.81%, at a 40% hemp shives content.

Strength properties

The strength properties of six hemp-lime composites adopted for the examination are shown in Figures 6 and 7. Generally, it is clear that the mechanical behavior of hemp concrete reflects that of its components.

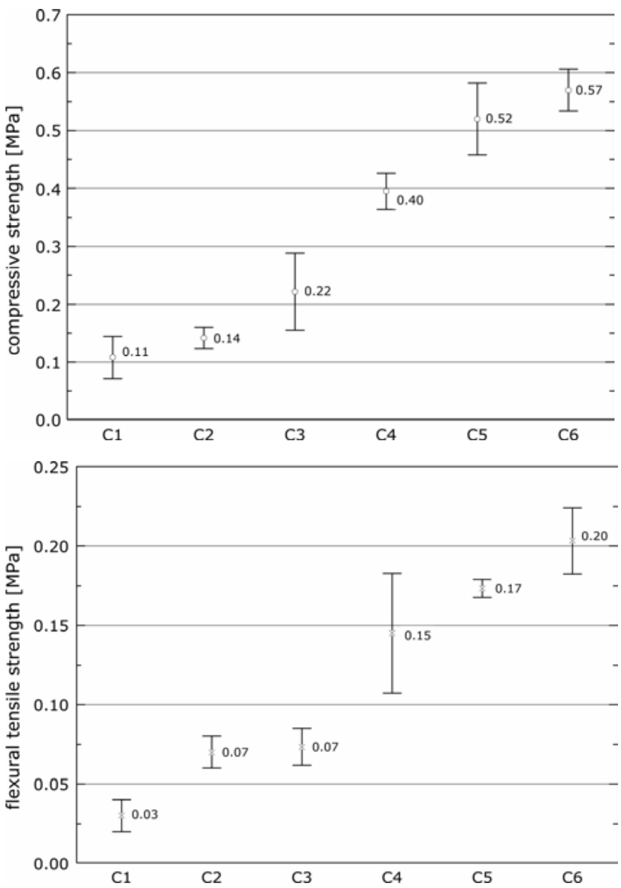


Fig. 6. Average compressive strength and flexural strength after 28 days

Rys. 6. Średnia wytrzymałość na ściskanie i zginanie po 28 dniach

Generally, regardless of the compaction type applied to the specimen, the more H/(C+L+M) and P/(C+L+M) ratios decrease, the higher the compressive and flexural strength. The higher the content of lime and cement, the lower the strength parameters. Thus, it can be concluded that the addition of hemp shives has a negative effect on the composite strength. The compressive strength is nearly 6.5 times higher, flexural strength almost 7 times higher for the composite (C6) with the lowest ratios H/(C+L+ M) and P/(C+L+M) in relation to composite C1. It should be noted that the strengthening chemical admixture vinyl acetate-ethylene copolymer, used in composite C4 caused more than a double increase in strength parameters.

The compressive strengths of composites produced from hemp shives and starch [20] range from 0.8 to 1.5 MPa, depending on the mixture design and concrete density. Flexural strengths obtained in tests vary from 0.04 to 0.10 MPa. However, composites produced from hemp shives (40 vol.%), hydrated lime (24 vol.%), Portland cement (0; 2.5; 5 vol.%), zeolite (0; 2.5; 5 vol.%), MgO - cement (0; 29 vol.%), water (31 vol.%) obtained a compressive strength in the range of 0.23÷1.89 MPa. The highest compressive strength was found in the case where the quantity of MgO in cement was 29 vol.%, without using Portland cement, zeolite and hydrated lime [19].

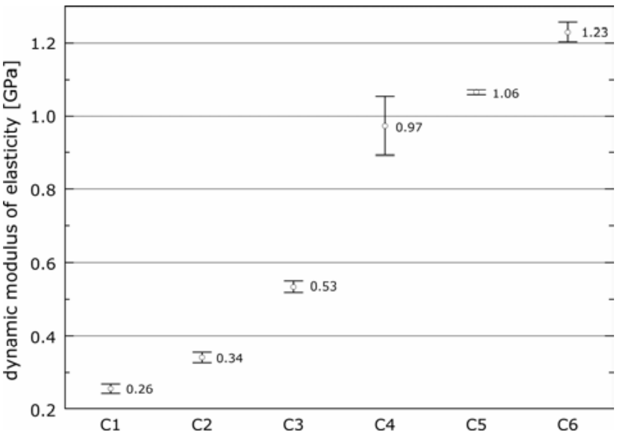


Fig. 7. Average dynamic modulus of elasticity after 28 days

Rys. 7. Średni dynamiczny moduł sprężystości po 28 dniach

Dynamic modulus E_{DM} is the most important property to evaluate the load bearing capacity of a composite material [21]. Based on the findings (Fig. 7), an adverse effect of the addition of natural shives on the dynamic modulus of elasticity can be observed. With an increasing addition of shives from 20 to 60%, the dynamic modulus gradually decreases, and is 5 times lower for composite C1. Almost a double increase was observed in the case of using an admixture of ethylene vinyl acetate copolymer in composite C4.

Gomes et al. [22] carried out research on several types of mortars consisting mainly of clay, and other components namely: sand, powder hydrated air-lime, natural hydraulic lime, Portland cement, Roman cement and natural shives. The mortars also contained the addition of 0, 5, 10 or 15% binder, and 0 or 5% hemp shives. Four types of binder were used: powder hydrated air-lime, natural hydraulic lime, Portland cement CEM II/BL 32.5 N and Roman cement. The following results were obtained: dynamic modulus from 0.214 (10 or 15% Portland cement and 5% shives) to 1.239 (10% Roman cement and 5% shives), flexural strength from 0.06 to 0.25 MPa (10% Roman cement and 5% shives), compressive strength from 0.11 to 0.58 MPa (10% Roman cement and 5% shives). The highest strength parameters were obtained when eliminating lime from the mortar and using cement, in particular 10% Roman cement with a 5% addition of shives [22].

A similar dependency was found in studies presented in this paper, and namely with an increased quantity of Portland cement, the strength parameters of the lime-hemp composites increased.

The tests on plasters based on zeolite, lightweight aggregate, furnace slag, Portland cement and hydrated lime described in [23] showed that vinyl acetate copolymer (VA) is a significant factor which affects the mechanical properties of plasters. Mortars with the highest content of polymer (0.9% by weight) were characterized by higher strength parameters, the highest frost resistance and resistance to salt crystallization.

A similar regularity was also noticed in the study presented. The vinyl acetate-ethylene copolymer used in composite C4 caused more than a double increase in strength parameters.

SUMMARY

The proposed compositions of hemp composites from cultivar hemp grown in Poland and lime-based binders show physical properties similar to those of contemporary thermal insulation or energy-efficient materials and can be used in combination with load-bearing frames to build wall structures. Other important aspects of this type of material are lower production costs with respect to traditional building materials.

Its behavior crucially depends on its composition and compaction during manufacturing. The thermo-physical characterization of the hemp-lime composites has shown potentially very good properties that could allow its exploitation in many applications in the building sector. However, the addition of hemp-lime leads to low resistance to compression, flexural and dynamic modulus in comparison with the building materials generally applied. The dynamic mechanical properties of shives reinforced composites depend on various factors such as shives loading, orientation and the nature of the shives-matrix interface region. The addition of ethylene-vinyl acetate copolymer as a plasticizing and strengthening admixture caused a considerable increase in the strength parameters of the composites and it improved the workability of composite C6. The increase was also affected by a not much higher content of lime (by 3 kg/m^3) and cement (by 0.70 kg/m^3) in relation to the composition of composite C3, yet the decisive influence on the improvement of the strength properties was the use of the ethylene-vinyl acetate copolymer. Its use in the manufacture of this type of composite was found to be reasonable.

Future research could be focused on the use of additives, which could increase the mechanical durability of hemp shives composites, in order to eliminate a wooden frame as the load-bearing structure of a wall.

Acknowledgement

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