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Characterization of Hemp-Lime Bio-Composite

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Abstract. Hemp-lime bio-composite (hempcrete) is a new building material consisting of two main constituents: hemp shiv and lime-based binder. Hemp shiv is a woody core of *Cannabis Sativa* plant obtained in decortication process and chopped into particles. Lime-based binder is a mix of binders with highest content of hydrated lime (other ingredients often present in a mix are: natural hydraulic lime, pozzolans, cement and others). Its natural origin, ability to create healthy indoor environment, good thermal properties and especially high ecological values (including low carbon emission in the entire life-cycle) makes it a sustainable alternative to commonly used materials in construction industry. Due to its mechanical properties hempcrete is not a load-bearing material. It is used as a filling material for single-layer walls with a structural frame and as an insulation material for existing walls, floors and roofs. Construction techniques include forming monolithic walls by compacting the mix in a formwork, spraying, bricklaying from precast blocks and prefabrication of entire wall elements. In this paper the results of mechanical and hygrothermal properties of the developed hemp-lime composites will be presented. The results will be used to obtain the hygrothermal characteristics of the building partitions applying numerical simulation methods.

1. Introduction

Construction has a huge share in overall energy use and consequently GHG emission. It is estimated that the production and transport of building materials is responsible for from 7 up to 9 % of global emission in western Europe [1]. Lowering its negative impact on the environment is one of the main challenges. To satisfy the sustainable development criteria, new constructions need to use recycled materials from existing buildings or bio-based materials which have a low carbon footprint [2,3,4,5,6]. Wider implementation of materials with organic infill such as hemp-lime composites seems to be one of the solutions as its current use is still inconsiderable in comparison with commonly used materials. Research on such materials should bring a better understanding of its properties and wider use in practice.

Hemp is a plant which played a significant role throughout ages in many countries around the world. Products such as fibres, seeds, flowers were widely used in numerous industries. There are historical traces of intentional use of hemp-binder composites for building purposes (e.g. India). In modern times it was applied for the first time during renovation works of historical wattle and daub buildings in north-east France in 1986. Due to unique properties, it worked well with other organic materials like old and



damp timber [2,4,5]. Success in renovation works led to the development of a technology and the use of the material in new buildings.

The material, so-called “hemperete”, has two main constituents: hemp shiv, obtained from Cannabis Sativa (industrial hemp) plant in a decortication process and chopped to particles of proper size; and special binder whose main ingredient is hydrated lime. There are four main building techniques using hemp-lime composites:

- bricklaying of precast hemperete blocks or bricks,
- tamping of the material in two-sided formwork in order to form a monolithic partition,
- spraying the material onto one-side formwork in order to form a monolithic partition or insulation layer,
- prefabrication of entire partitions.

Hemperete can be characterized as a non-load-bearing material with low mechanical strength, medium density and good insulating properties [7]. Other features are biological and chemical corrosion resistance, good fire resistance and high vapour permeability [7]. Due to low mechanical strength in most cases, hemperete is combined with a load-bearing structure – timber, steel or reinforced concrete frame. Less dense mixes in loose form are also utilized for horizontal insulation layers of roofs and floors [5]. Aforementioned ecological values of the material are the result of low embodied energy and low (or even negative) carbon footprint mostly due to organic infill (of fast-growing and absorbing huge amounts of CO₂ plant [8]) but also lime carbonatation which lowers final emission. Employing materials with low thermal conductivity also reduces the heating demand, thus decreases the ecological footprint of the building in the course of its operation [9]. In addition, the hemp-lime layer may absorb and expel heat and humidity in relation to the environment and act as a thermal storage by reducing the flow of energy through the wall [3,4,5,6,9,10]. This paper covers selected properties of hemp-lime bio-composites: compressive strength, thermal conductivity, sorption characteristics and vapour permeability. Microstructure of various composites is also shown.

2. Materials and samples

Two different mixes were prepared (Table 1) – both using hemp shiv „Białobrzskie” cultivated and processed in north-east Poland (the material has not declared functional properties for construction purposes). In the first mix T a special binder for hemperete production „Tradical PF 70” was used (75% of hydrated lime, 15% of hydraulic lime, 10% pozzolans and other minor additives). For the second mix B, so-called „builder’s mix” of commonly available binders was used (75% of hydrated lime, 15% of hydraulic lime and 10% of cement CEM II/B-V 42,5 N).

Table 1. Characteristics of samples prepared for tests

	Proportions H:B:W	Binder	Initial density [kg m ⁻³]
T750	1 : 2 : 2.9	Tradical PF 70	750
T650	1 : 2 : 2.9	Tradical PF 70	650
T550	1 : 2 : 2.9	Tradical PF 70	550
B650	1 : 2 : 3.1	„builder’s mix”	650
TL550	1 : 1.5 : 2.18	Tradical PF 70	550

First the possibility of manual compression of the mix was tested and three densities of the fresh mix were chosen – 750 kg m⁻³ (the highest possible), 650 kg m⁻³ (the medium) and 550 kg m⁻³ (the lowest that guarantee integrity of the sample). Both mixes (T and B) were prepared in the same procedure: first, the binder was mixed with water for 2-3 minutes then hemp shiv was added and mixed together for another 5-6 minutes (to obtain a homogeneous mixture). The samples were created by tamping the mix

manually with the use of wooden rammer: in steel forms (10 x 10 x 10 cm) for compressive strength tests and in plywood forms (30 x 30 x 10 cm) for other tests (when required, smaller samples for testing were cut out from these blocks). Forms were opened after 1 ÷ 2 hours and samples were moved to curing chamber for first 28 days (temperature $18^{\circ}\text{C} \pm 2^{\circ}\text{C}$, relative humidity $90\% \pm 10\%$). Rest of the time samples were stored in temperature $23^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and relative humidity $55\% \pm 10\%$.

3. Experimental part

The experimental programme consisted of mechanical strength, density, thermal conductivity, sorption and vapour permeability tests.

3.1. Compressive strength

The mechanical strength of hemp-lime composites is considered as a secondary feature. In typical applications, material must carry its own load only. Strength tests help to examine the correctness of binding process (Figure 1).

The compressive strength of the material noted in literature is contained in a wide range [11,12,13,14,15,16], generally from 0,05 to 0,9 MPa. Analysis of previous research indicates that compressive strength depends on characteristics of the binder (higher share of hydraulic binders results in faster strength gain) [11], characteristics of the hemp shiv (bigger share of short particles results in higher strength) [15], proportions of these components [12] (higher share of shiv results in lower strength), density (being a result of compaction method and level) [13] and method of mix preparation as well as curing conditions [16].

Due to the lack of standards regarding testing of mechanical properties of hemp-lime composites, the research methodology was based on studies carried out so far by other researchers (especially [11]). The tests were conducted in accordance with EN 12390-4 [17], 90 days after samples production. Due to slight inequities on the surface of samples, fiberboard washers were applied. In the compressive strength test, samples were subjected to an axial compressive force in the same direction they were created. The stress increase was 1 kN cm^{-2} per minute. Initially under the stress samples behaved quasi-elastic (the stress-strain graph was linear), than the curve lost linearity – that point was interpreted as ultimate strength. Final strength was calculated as an average of 3 samples of each type.



Figure 1. Compressive strength test of T750 hemp-lime composite

3.2. Density measurement of samples

The density of the dry samples was determined according to EN 1602 [18]. Before the test, the samples were dried at temperature 100°C , next conditioned at temperature $(23 \pm 2)^{\circ}\text{C}$ and relative humidity below 5% until a constant mass of the sample was obtained. Five samples of every type of material were tested and the mean values of density for each type of material are presented.

3.3. Thermal conductivity λ

Tests were performed in accordance with EN 12667 [19]. Before the test samples were conditioned to achieve a constant weight under constant temperature (23 ± 2) °C and relative humidity 0, 50, 80 and 90%. Measurements of thermal conductivity λ were carried out in the steady-state conduction by the hot plate method, with a FOX 314 apparatus. The measurements were made at the average sample temperature of 10 °C, the difference in temperature at the sample thickness of 20 K and heat movement from bottom to top, on samples with dimensions (300 x 300 x 100) mm. Three samples of every type of material were tested and the mean values of thermal conductivity for each type of material are presented.

3.4. Sorption curves

Tests were carried out in accordance with EN ISO 12571 [20]. Samples were placed under constant temperature conditions of 23 °C and relative air humidity of 0%, 50%, 80% and 90%, respectively until their mass were stabilized. Measurements of mass change were made every 24 hours. Five samples of every type of material were tested and the mean values for each type of material are presented.

3.5. Water vapour permeability

Determining the coefficient of water vapour diffusion resistance, μ , the tests were performed in accordance with EN 12086 [21]. Prior to the tests, the samples were conditioned at a temperature of (23 ± 5) °C and relative humidity (50 ± 5)% until the mass stabilized in three consecutive weighing (change in mass within ± 5 %). The samples, diameter 128 mm, thickness 100 mm, were then placed in metal dishes on the bottom of which a drying agent (CaCl_2) was used. Measurements of the change in weight were recorded at an interval of 12 hours. The tests were terminated when five consecutive changes in the mass per unit time were constant and housed within a tolerance of ± 5 % of the average for each sample tested. The determination of the water vapour diffusion resistance factor, μ , in steady-state conditions were calculated acc. to p. 8.6 EN 12086 [21]. Five samples of every type of material were tested and the mean values of water vapour diffusion resistance for each type of material are presented.

4. Results and discussion

Figures 2 and 3 show the structure of pure hemp shiv (without binder) and hemp-lime bio-composite. Stem cells of hemp shiv, which form the porous structure, may be observed. We can also observe the transverse diaphragm pores, which have influence on the material thermal conductivity, since increasing material porosity increases the material insulation properties.



Figure 2. Pure hemp shiv (without binder)

Adhesion of binder to the hemp shives has influence on the behaviour of the composites under loading. When forming the composite structure, it is important to get reliable contact zones to ensure adequate material strength characteristics. At the initial phase of the sample loading, the compressive strength is determined by the binder. Incorrect mixing or compacting of the samples may lower the effectiveness of the connection. In addition, the contact area between both materials can crack in the course of composite drying [3,4,5,6,9,10,11,12,13,15]. This may be caused by the different characteristics of particular components and different volume changing processes during drying, which may weaken the contact area between the matrix and the filler.



Figure 3. Hemp-lime bio-composite images

Results of compressive strength test didn't show big data dispersion between the samples of each type. Standard deviation values were in range from 0,01 to 0,02 [MPa] and variation coefficient didn't exceed 0,11.

As expected higher density of samples resulted in higher compressive strength – dependence in considered range is close to linear. The type T samples showed better results than type B. The TL550 mix was slightly stronger than T550. Presented results are generally similar to those noted in the literature [11,12,13,14,15,16] and lower than declared by European hempcrete producer (around 0,9 after 90 days for similar mixes) presumably because of lower hemp quality (presence of a greater amount of silty parts in the shiv may lower hempcrete strength [8]), slight composition differences and possible methodology differences. Visual inspection of the samples after destruction indicates that the process of binding inside was not completely finished. Results are summarized in Table 2.

Table 2. Characteristics of hemp-lime bio-composite

		RH [%]				Compressive strength [MPa]
		0	50	80	90	
T750	Density [kg m ⁻³]	412	434	439	452	0.60
	Thermal conductivity [W m ⁻¹ K ⁻¹]	0.098	0.113	0.111	0.123	
T650	Density [kg m ⁻³]	366	384	388	399	0.42
	Thermal conductivity [W m ⁻¹ K ⁻¹]	0.088	0.102	0.105	0.111	
B650	Density [kg m ⁻³]	346	361	366	375	0.21
	Thermal conductivity [W m ⁻¹ K ⁻¹]	0.084	0.094	0.100	0.106	
TL550	Density [kg m ⁻³]	317	336	341	349	0.25
	Thermal conductivity [W m ⁻¹ K ⁻¹]	0.084	0.098	0.096	0.108	
T550	Density [kg m ⁻³]	309	324	328	335	0.21
	Thermal conductivity [W m ⁻¹ K ⁻¹]	0.080	0.091	0.096	0.101	

Obtained density of the dry hemp-lime composites varied from 309 kg m⁻³ for T550 material to 410 kg m⁻³ for the T750 type material (Table 2) and a significant decrease in the initial density shown in Table 1 of the composites can be observed. Such a difference is the result of water evaporating during the samples drying while leaving the untouched material shape.

As shown in Table 2, thermal conductivity of investigated hemp-lime composites depends on the material density (material type) and moisture content. The thermal conductivity results for the tested samples varied in a range from 0.080 W m⁻¹K⁻¹ to 0.12 W m⁻¹K⁻¹ for a dry T550 sample and T750 material conditioned at 90% RH, respectively. Observed increase of thermal conductivity goes together with increase of sample density and water content in the samples, what is observed for many materials [3,4,5,6,9,10,11,12,13,15]. Pure hemp shiv (without binder) had the lowest thermal conductivity of 0.046 W m⁻¹K⁻¹ (for a dry sample) and density about 92 kg m⁻³.

The hemp-lime bio-composites gained moisture content in the range of 16–25 kg m⁻³ for 50% RH and 27–42 kg m⁻³ for 90% RH, for the samples of the lowest and the highest densities, respectively (Table 3).

Concerning the water vapour diffusion resistance factor μ , the obtained values were in the range from 29 to 24 for the T750 and T550, respectively. Such values are characteristic for vapour-permeable materials e.g. lime-cement mortars or gypsum board. This means that water vapour can flow freely through the internal structure of such composites. Obtained results indicate that the impact of the type of binder on hemp shiv concrete permeability is not evident. It is expected, that the large interparticular spaces between hemp particles strongly contribute to permeability, while the concrete micro/macro pores contribute to permeability to a lesser extent.

Table 3. Characteristics of hemp-lime bio-composite

		RH [%]		
		50	80	90
T750	Water content [kg m ⁻³]	25	29	42
T650	Water content [kg m ⁻³]	20	24	34
B650	Water content [kg m ⁻³]	17	21	30
TL550	Water content [kg m ⁻³]	20	25	34
T550	Water content [kg m ⁻³]	16	20	27

5. Conclusion

The research on the prospective application of hemp shiv acquired from Polish crops showed a promising potential as an eco-friendly and sustainable building material. The characteristics of these composites are determined by the composition of the employed hemp-lime mixture. Properties of the material are not sufficient for typical load-bearing walls as well as typical thermal insulation layers: mechanical properties are rather too low (their increase will result in worsening of more important insulation properties) and thermal conductivity is over two times higher than for insulation materials. Material can be utilized in a specific applications: formation of “breathable” single-layer walls matching thermal insulation requirements, containing load-bearing structure inside, and as an infill material (similar to aerated concrete) additionally insulated. Other applications are: renovation of old buildings (often containing bio-based materials as a structure or infill) and making of additional vapor-permeable outer or inner thermal insulation layers on existing partitions.

Analysis of the obtained results enables to formulate the following conclusions:

1. The best thermal properties (low value of thermal conductivity) were obtained by using T550 composite. However, for the other tested composites the λ values are promising for the materials application as an appropriate filling material for timber frame constructions of the external walls, even without additional insulation.
2. The best compressive strength results were obtained by using T750 composite, because of formation of the highest area of contact zones.
3. Hemp-lime bio-composite images have shown that quite a homogeneous structure was obtained using these composite which can be used for the construction of external walls, preventing the growth of mold and mitigating the negative impact of interstitial condensation.
4. The density of the hemp-lime composite and related thermal conductivity are both determined by the content of lime and hemp in the mixture. The increase of filler content simultaneously raises the apparent density and increases thermal conductivity coefficient.
5. All the hemp-lime composites, due to relatively low water vapour diffusion resistance factor μ (between 24–29), may be appropriate materials for the external walls, when using the suitable external and internal plasters providing diffusive openness of the whole barrier.

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