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Research on the properties of concrete with hemp shives

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Abstract: Nowadays a modern building must be energy efficient, i.e. distinguished by extremely low energy consumption. The building must be built according to the principles of sustainability, considering how it can be maximally friendly to the environment, and its life cycle should comply with the principles of the circular economy. Buildings with constructions made from natural origin materials are being built more and more in Lithuania. Such materials include fibrous hemp. The study presents the results of research on the properties of hemp shiv concrete made with binders of different compositions. The calcitic lime, composite portland cement, organic sapropel and mixtures of these materials were used as binding material for the research. Hemp shives are used for concrete fillers. The tests determined the compressive strength of hemp-shiv concrete, and the thermal conductivity of the concrete was tested under laboratory conditions. The research was performed based on standard methods and equipment.

Keywords: concrete, fibrous hemp, material properties

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Introduction

Fiber hemp means plants of the hemp (*Cannabis sativa* L.) species of the hemp family (*Cannabaceae*) that contain no more than 0.2 percent tetrahydrocannabinol in the dried material and are grown solely for industrial purposes (fiber and seeds) or horticulture.

The fiber hemp law of the Republic of Lithuania was adopted in 2013 (Law of the Republic of Lithuania on fibrous hemp, 2013). The permit to grow industrial

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fiber hemp in Lithuania came into force from 2014. Farmers did not take long to take advantage of this and a long-grown plant appeared in the country's fields, characterized by fast growth, yielding not only seeds from which valuable oil is pressed, but also fiber, shives. Coarsely chopped hemp stalks, hemp shives with fiber residues and cleaned hemp fiber can be used for building construction.

Hemp shives are obtained by processing the defoliated stalks. They are in the form of small, irregularly shaped particles with a length of 10-70 mm and a width of 2-2.5 mm. Bulk density of these particles is 100-120 kg/m^3, moisture content is 17-22%. Hemp shives have a very high water absorption – they absorb up to 450% of water in 8 hours. When processing hemp stalks, they are stored in water for a long time, so they do not need to be mineralized before mixing with mineral binders.

Hemp shives can be used as a filler in the production of low-density heat-insulating concrete (Kosinski et al., 2018; Kosinski et al., 2022). Most often, a frame system is used for this, when the frame of the building is filled with low-density and heat-conductive hemp concrete. Hemp concretes with higher density and strength are able to withstand higher loads, but they are more heat conductive (Balčiūnas et al., 2013; Seng et al., 2018). The hygroscopic properties of hemp concrete are studied by researchers (Benmahiddine et al., 2020; Bennai et al., 2019; Seng et al., 2019). A comprehensive review on the use of hemp in concrete is performed by researchers (Barbhuiya & Bhusan, 2022). Hemp concrete can be used not only as monolithic, but also in the form of blocks of various dimensions (Delannoy et al., 2018; Jami et al., 2019). In some countries of the world, for example, in France and Italy, hemp concrete blocks are already widely known and used in construction, but in Lithuania it is still a novelty, because the cultivation of fibrous hemp has been banned for many years.

Hemp concrete recipes have been developed in foreign countries (France, Australia, etc.), and special mixtures of binders, usually lime-based, are produced, but they are quite expensive (Jami et al., 2019; Pietruszka et al., 2019). There are no mixtures of binding materials suitable for use in the production of hemp concrete in Lithuania. It is necessary to create such mixtures using artificial and natural materials produced in the country. For example, sapropel can be used as a binding material.

Organic sapropel is a muddy sediment or sediment formed at the bottom of fresh, stagnant water bodies (lakes, ponds, peatlands). Contains a lot of organic matter in a colloidal state. Sapropel has binding properties (Obuka, 2021; Tronet et al., 2016). When it dries, sapropel becomes a sufficiently hard material, just like traditional binding materials (lime, cement). Therefore, we assume that sapropel, together with lime, should positively integrate into the mixture of hemp shiv and water. When sapropel dries, it should improve or at least not reduce the mechanical and thermal properties of hemp concrete.

The aim of the work is to evaluate the influence of binders and their mixtures on the mechanical and thermal properties of hemp concrete.

The object of the research is hemp concrete – the binding material is unslaked calcitic lime, composite portland cement and organic sapropel. Hemp shives are used as fillers for concrete.

The novelty of this work – to evaluate the effect of mineral hydraulic binder – portland cement and organic binder – sapropel on the properties of hemp concrete. The hypothesis – that hemp concrete with organic sapropel would have higher or equal strength, lower thermal conductivity.

1. Research methods

The influence of concrete binders on mechanical and thermal properties is determined by standard methods and equipment. Binding materials used to prepare the hemp concrete mixture: unslaked calcitic lime (Milled Quicklime CL90 Q manufacturer JSC "Naujasis kalcitas"), composite portland cement CEM II/A LL – 42.5N (manufacturer JSC "Akmenes cementas"), organic sapropel (from Dobele lake, Kaunas district). Cleaned hemp shives, length 3-25 mm (manufacturer JSC "Natūralus Pluoštas") are used for concrete fillers. Potable water was used to form the concrete mixture. Three-composition mixtures were prepared using a binder to aggregate (shiv) ratio of 2.2:1 for the hemp concrete tests (Table 1).

Table 1. Compositions of hemp shiv concrete mixtures (*created by authors*)

Index of mixtures	Ratio	Materials
KB1	2.2:1	2.2 parts by mass of quicklime (100%), one part of hemp shives
KB2	2.2:1	2.2 parts by mass of quicklime (90%) and cement (10%), one part of hemp shives
KB3	2.2:1	2.2 parts by mass of quicklime (90%) and sapropel (10%), one part of hemp shives

Unslaked calcitic lime was used as the main binding material. Lime was slaked with potable water during mixing. The amount of evaporated water was estimated by weighing and compensated. Part of samples were made using a binder mix where 10% of the lime was replaced by cement (CEM II/A–LL 42.5 N) or organic sapropel calculated on a dry weight basis. The mixtures are prepared in a forced mixing mixer.

The bulk densities of the materials used in the hemp concrete mixture were determined (Table 2). Bulk density is determined according to the standard (EN 1097-3:2002).

Table 2. Bulk densities (bulk weights) of materials for hemp concrete (*created by authors*)

Material	Bulk density (bulk weight), kg/m^3	
	free poured	hand squeezed
Calcitic ground quicklime	510	–
Cement CEM II/A–LL 42.5 N	1230	–
Hemp shives	113	136

In order to evaluate the amount of water in sapropel, its moisture content was determined by the drying method. Moisture content by mass was calculated using the formula:

$$w_m = \frac{m_v}{m_s} \cdot 100 = \frac{m_d - m_s}{m_s} \cdot 100\% \quad (1)$$

where m_v, m_s, m_d are respectively water content, the mass of the dry sample and wet sample

$$w_m = \frac{100.0 - 12.0}{12} \cdot 100 = 733.3\%$$

These tests show that in sapropel most of the mass is water, while the dry matter is only 12% of the wet sapropel mass. When mixing concrete with sapropel, its amount was calculated on the basis of dry matter, so the amount of water was reduced by the amount that is in the sapropel. The amount of water is calculated according to the formula:

$$V = 1.5 \cdot m_{sp} + 0.92 \cdot m_k + 0.32 \cdot m_c + 0.32 \cdot m_s \quad (2)$$

where m_{sp}, m_k, m_c, m_s are respectively the mass of shives, quicklime, cement and dry sapropel.

Specimens (cubes 10×10×10 cm) were made from hemp concrete mixtures for determining density and compressive strength. 3 samples were made from each mixture. Specially made tile-shaped plates 20×20×(4...5) cm for determination of the thermal conductivity coefficient. The mixture was compacted manually in the molds, using a wooden rod with a cross-section of 4×4 cm. Samples are taken from the molds after 1-2 days. One month in laboratory conditions hardened samples were weighed with an electronic scale, their dimensions were determined with an electronic caliper. The density of the samples was determined according to the standards (EN 12350-6:2019; EN 12390-7:2019).

The compressive strength was determined by testing the samples (up to 10% deformation) with a mechanical testing machine. The direction of compression is parallel to the direction of formation. The compressive strength is determined according to the standards (EN 12390-3:2019; EN 826:2013).

The coefficient of thermal conductivity was determined using a FOX 200 heat flow meter. The device is designed to measure thermal conductivity according to standard (EN 12667:2001).

Device characteristics:

- Size of the samples – base dimensions of samples: 200 × 200 mm; thickness up to 51 mm.
- Temperature range – –20-75°C.
- The accuracy of the temperature is ±0.01°C.
- The accuracy of the coefficient of absolute thermal conductivity is ±2%.
- The reproducibility is ±0.5%.
- The thermal conductivity coefficient range is 0.005-0.35 W/(m·K).

The device is equipped with thin film heat exchangers, digital thickness gauges and temperature controller. The device operation is based on solid state cooling/ heating. FOX 200 is an universal device and is particularly suitable for measureing the thermal conductivity of porous materials. The thickness is measured with an accuracy of 0.025 mm.

2. Results and their discussion

The research results on concrete made with hemp shiv fillers shows, that with a 2.2:1 mass ratio of binding material and fillers, the concrete has a density of 459-497 kg/m^3. Concrete has a higher density, if the binder is composed of 90% quicklime and 10% cement. Hemp concrete with a 10% sapropel mixture binder has a lower density (Fig. 1).

Compressive strength testing results show that the concrete with hemp shives and a quicklime binder has a compressive strength of 693 kPa. The load bearing capacity of the concrete containing a 10% cement binder is slightly increased and the compressive strength is 698 kPa. A decrease in strength is observed for concrete with a binder mixture composition of 90% quicklime and 10% sapropel. In this case, the compressive strength of the concrete is 572 kPa (Fig. 1). During the study, it was observed that sapropel as a binding material reduces the load bearing capacity.

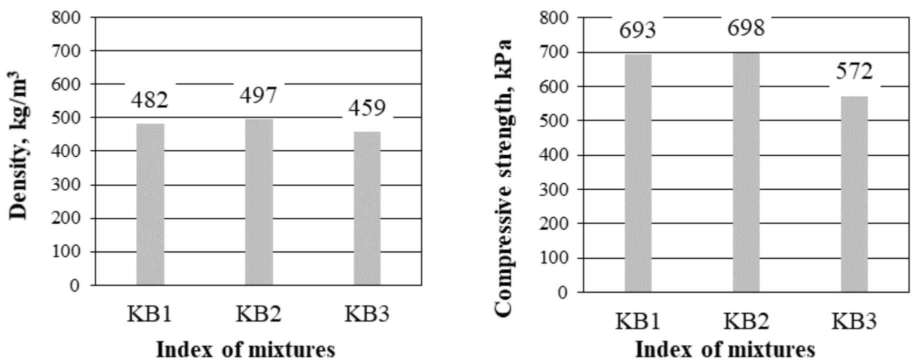

Fig. 1. Density and compressive strength of air-dried hemp shiv concrete (*created by authors*)

The dependence between concrete density and compressive strength was established. It can be seen (Fig. 2) that there is a reliable relationship between concrete density and compressive strength: as concrete density increases, strength increases.

The thermal conductivity coefficient was determined while studying the properties of hemp shiv concrete. The results of the thermal conductivity test show that the highest conductivity is in the concrete made from mineral origin of binding material. Concrete with sapropel has lower thermal conductivity (Table 3).

The dependences the thermal conductivity coefficient – compressive strength and density – thermal conductivity coefficient were established (Fig. 3).

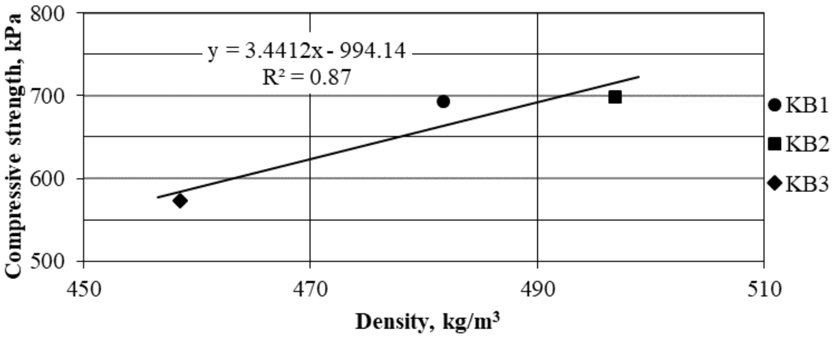

Fig. 2. Relationship between density and compressive strength of concrete with shiv fillers (*created by authors*)

Table 3. Thermal conductivity coefficients of air-dried hemp shiv concrete (*created by authors*)

Concrete composition no. (ratio of binders and fillers; see Table 1)	Thermal conductivity coefficient of air-dry samples, W/(m·K)
KB1 (2.2:1)	0.114
KB2 (2.2:1)	0.108
KB3 (2.2:1)	0.096

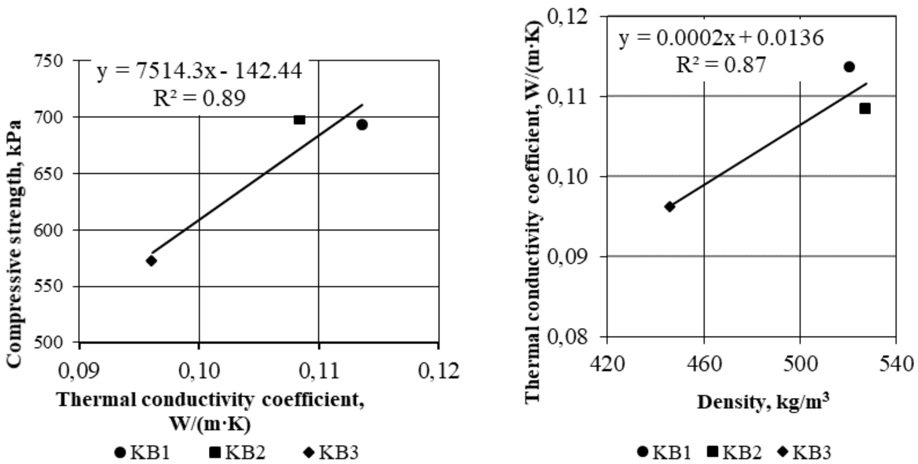

Fig. 3. Relationships between thermal conductivity – compressive strength and density – thermal conductivity of concrete with hemp shives (*created by authors*)

The graphs and equations presented in the figures show that there are reliable relationships between thermal conductivity and compressive strength, density and thermal conductivity, i.e. with increasing compressive strength, density, thermal conductivity coefficient increases.

Similar results are obtained when compared with literature reports (Balčiūnas et al., 2013). In concrete both the strength and the coefficient of thermal conductivity depend on the density: as density increases, the strength and thermal conductivity increase. Hemp shiv concrete containing organic sapropel has a lower density, but its strength has decreased by about 21%. This shows that our assumption did not come true, i.e. the binding properties of sapropel are weaker than those of lime. In terms of thermal conductivity, our assumption came true – the addition of sapropel reduced the coefficient of thermal conductivity by 16%.

Conclusions

It was found that with a 2.2:1 mass ratio of binder and fillers, the concrete has a density of 459-497 kg/m^3, a compressive strength of 572-693 kPa and a thermal conductivity coefficient of 0.096-0.114 W/(m·K).

Compressive strength testing results show that concrete containing organic sapropel with hemp shiv fillers is weaker than concrete with mineral binders. It was found that after replacing 10% of lime cement or sapropel, the compressive strength of concrete with hemp shives is 698 and 572 kPa, respectively – its strength has decreased by about 21%.

The results of the thermal conductivity test show that concrete with mineral binding materials has the highest conductivity, while concrete with sapropel has lower thermal conductivity. Concrete with 90% lime and 10% sapropel has the lowest thermal conductivity. The addition of sapropel reduced the coefficient of thermal conductivity by 16%.

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