

Hemp Thermal Insulation Concrete with Alternative Binders, Analysis of their Thermal and Mechanical Properties

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Abstract. One of the main challenges that construction industry faces today is how to address the demands for more sustainable, environmentally friendly and carbon neutral construction materials and building upkeep processes. One of the answers to these demands is lime-hemp concrete (LHC) building materials – carbon negative materials that have sufficient thermal insulation capabilities to be used as thermal insulation materials for new as well as for existing buildings. But one problem needs to be overcome before these materials can be used on a large scale – current manufacturing technology allows these materials to be used only as self-bearing thermal insulation material with large labour intensity in the manufacturing process. In order to lower the labour intensity and allow the material to be used in wider applications, a LHC block and board production is necessary, which in turn calls for the binders different from the classically used ones, as they show insufficient mechanical strength for this new use. The particular study focuses on alternative binders produced using gypsum-cement compositions ensuring they are usable in outdoor applications together with hemp shives. Physical, mechanical, thermal and water absorption properties of hemp concrete with various binders are addressed in the current study.

1. Introduction

The construction industry has to satisfy the growing demand for sustainable and environmentally friendly construction materials. One of such materials is hemp-lime concrete (LHC) [1] – thermal insulation material with good thermal insulation properties (0.07 to 0.14W/m²K) [2][3], negative CO₂ emissions [4][5][6], excellent hydric properties[7][4], great acoustic capabilities [8], and good fire resistance [9].

At present, LHC material is mostly produced in-situ as a frame filling material for new low-rise buildings [10]. In order to decrease labour intensity in the manufacturing process, it is necessary to

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produce LHC blocks and boards. This way requires the binders different from the classically used ones, as they show insufficient mechanical strength for this new use.

Traditionally, pure lime or lime based binders with hydraulic additives [11] have been used for LHC materials. These materials show insufficient hardening of the core of the constructional element because of insufficient carbonation. This is an unacceptable property for LHC blocks and boards as they need to be sawn in right sizes on site.

One of the possible ways to improve mechanical stability of hemp composite is to use other types of binders which provide more homogenous material structure. In the current study, alternative binders based on gypsum composite are tested, to assess their applicability together with hemp shives; the mechanical, thermal and water absorption properties of hemp concrete materials are addressed.

2. Materials

2.1. Hemp Shives

Hemp shives are a by-product of hemp-fibre manufacturing process, they are the wooden inner core of the hemp stalk. They are separated from the outer long fibres, which are the primary product of hemp fibre production that is mainly used in the production of paper, textiles and biodegradable plastics [12]. Hemp shives are regarded as waste or by-product [13], it is used as bedding in horse stables or as thermal insulation building material.

Hemp shives have largely different physical properties, which are influenced by hemp breed, growing and harvesting conditions, processing technology, etc. In the current study, only one type of hemp shives is used focusing on different binders. The hemp shives used are from “Zalers” Ltd., flax and hemp processing company in Kraslava County. Granulometric composition, density, thermal conductivity and moisture content can be seen in table 1.

Table 1. Properties of shives.

Fibre	>20mm	10-20mm	0.63-10mm	Dust	Density, kg/m ³	Thermal cond. W/m*K	Moisture, %
3.3%	3.2%	8.0%	84.2%	1.2%	72.26	51.87	6.77%

2.2. Binders

Typically, lime is used as a binder in LHC materials. It can be pure hydrated lime, natural hydraulic lime or formulated lime – hydrated lime with added pozzolans to enhance hydraulic properties of the binders. Commonly used pozzolans are either natural (volcanic ashes, pumices) or artificial (silica fume, metakaolin). Natural hydraulic lime or formulated lime shows significantly higher strength than hydrated lime and in combination with hemp shives, hydrated lime lacks the mechanical rigidity required for it to be used as a binder for LHC building blocks [14].

In the frame of this work, hemp composites with different mineral binders were produced and compared. Standard (reference) compositions were prepared using the following binders:

- NHL 2 is feebly hydraulic natural hydraulic lime (St. Astier);
- DL60 is dolomitic lime, produced locally by “Saulkalne” Ltd in combination with pozzolanic admixture – metakaolin – obtained by burning of kaolin clay at 800⁰ C [14];
- GCP is a gypsum-cement-pozzolanic composition, which was elaborated and was widely used in 1970’s and 1980’s. Such compositions combine rapid hardening of the gypsum binder and water

resistance of a cement binder. In this case, gypsum with addition of cement CEM II 42.5N from “Cemex” Ltd. and metakaolin is used, as well as with “Tradical” Ltd. HB commercial lime binder.

Table 2. Compositions of mixtures.

Type	Hemp shives	DL 60	NHL2	Gypsum	Cement	Metakaolin	Tradical HB	Water	Shives:binder ratio
DL	1	0.83	-	0.08	-	0.27	-	1.8	0.85
NHL	1	-	2	-	-	-	-	1.86	0.50
NHL-W	1	-	2.5	-	-	-	-	2	0.40
GCP	1	-	-	1.2	0.4	0.4	-	2	0.50
GCP-W	1	-	-	1.38	0.46	0.46	-	2.08	0.40
GC-TR	1	-	-	1	0.32	0.32	0.58	2.08	0.45

3. Methods

3.1. Preparation, mixing and moulding

Before the mixing process, moulds are prepared. They are made of moisture-resistant plywood, dimensions 350x350 mm, before the tests the moulds are greased with formwork oil to minimize friction when the samples are demoulded.

All ingredients are measured in weight and weighed using electric scales. Mixing is done using laboratory drum mixer, first the shives are mixed with the half of all the necessary water, then the binder and the rest of the water are added. Total mixing time is 3 minutes for each mixture.

Compositions of mixtures can be seen in table 2. Traditionally when using natural hydraulic lime, the shives: binder ratio of around 0.4 – 0.5 is used, so in the current study ratios of 0.4 and 0.5 were chosen. The quantity of the water added was set to achieve wet mixture that sticks together when pressed.

Dolomitic lime have also been used as a binder for LHC [15], but has shown weakness of inner strength of material, as LHC blocks with dolomitic lime have rigid outer shell but when sawn in pieces show an unbounded inner core, which is attributed to chemical reaction between organic hemp shives and alkaline lime binder. So in the present study, an admixture of metakaolin and gypsum is added to enhance the early strength of the material.

Cement has also been used as a binder for hemp concrete materials and has shown promising results regarding mechanical strength, but the weakness of the cement is its environmental impact, which is a lot more significant than that of a lime binder. This impact could be minimized if same strength material could be produced with higher shives: binder ratio, which would mean a lower amount of binder used.

Gypsum is another type of the mineral binder. As it is soluble in water [16], it has limited use compared to the hemp concrete binder, as it is used only as indoor plaster [17] with hemp fibre additions for enhancement of flexural strength [19], or as foam gypsum with hemp fibre reinforcement [18]. In order to use gypsum as a binder for hemp concrete it needs to be improved by addition of cement [16] and pozzolans [17]. These additions decrease the initial strength of gypsum, but in the long term improve its strength and durability in outdoor applications. This gypsum-cement-pozzolan (GCP) mixture, on the other hand, has much higher initial strength than lime or cement binders, and lower alkalinity of the binder decreases the amount of organic hardening retardants emitted from shives.

Two different shives: binder ratios are used for GCP mixtures – 0.4 and 0.5 and one mixture with ratio 0.45 where some of the binder is replaced with commercially available Tradical HB binder designed for use with hemp shives. It consists of hydrated lime with pozzolanic admixtures.

During the mixing it was observed that some of the mixtures form lumps during the process. This formation of has also been observed by other authors [20], and in the current study it was mostly detected during the mixing of DL sample – the lumps can be seen in figure 1. This can be explained by the higher shives: binder ratio.



Figure 1. Compositions with different binders – (from the left) - GC-TR, GCP, DL, GCP-W.

After mixing, the mixture was put in moulds, filling in layers slightly tamping each layer by hand. In the end, a plate with around 10 kg weight was put on top. Demoulding was done on the next day leaving the samples horizontally, after they gained enough strength they were raised up vertically. Samples were kept in laboratory conditions (20 ± 2 °C and 40 ± 10 %RH) and weighted until they didn't show any change in weight, which was on average about a month after demoulding.



Figure 2. Water absorption test – GCP-W (left) and DL (right) samples.

3.2. Testing of the samples

When the weight of the samples stabilized, their thermal conductivity was measured. This was done using LaserComp's FOX600 heat flow meter, according to the guidelines of LVS EN 12667. After these tests, the samples were left in laboratory conditions for two years – from April 2013 till April 2015, to allow the binders to fully set and for lime to carbonate.

After this period, the samples were tested for compressive strength and water absorption. First of all, the samples were sawn into four 170x170 mm pieces. This process already allowed making some conclusions, as inner cores of DL, NHL and NHL-W samples were soft and only partially bounded, the NHL sample was too damaged during the process and was not used for further tests. Gypsum-based mixtures showed similar rigidity throughout the sample.

After cutting and preparing the test samples, water absorption test according to LVS EN 1609 standard was carried out. It required samples to be weighed, immersed in water 10 mm deep for 24 hours, then dried for 10 minutes by placing them on a sieve at 45° angle and weighed again. The result expressed as water absorbed in kg on immersed area can be seen in table 3.

Table 3. Results of the tests.

Mix name	Shives:binder ratio	Density, kg/m ³	Water absorption, kg/m ²	Compr. strength, kPa	Compr. strength (W), kPa	Thermal conductivity, W/m*K	Compr. strength ratio
DL	0.85	290	16.085	0.081	0.030	0.069	2.667
NHL	0.50	320	-	-	-	0.084	-
NHL-W	0.40	355	20.079	0.067	0.047	0.093	1.437
GCP	0.50	310	14.800	0.126	0.059	0.088	2.137
GCP-W	0.40	325	10.615	0.200	0.082	0.097	2.422
GC-TR	0.45	300	10.874	0.146	0.079	0.082	1.870

After the water absorption test, compressive strength was tested for all samples, the maximum strength was registered as 10% deformations according to LVS EN 826 guidelines. The tests were done using ZWICK Z100 universal testing machine, with applied pressure at 10mm/min, force-deformation diagram was recorded. The tests were done for both water saturated (Compr. strength (W)) and dry samples (Compr. strength), the results are summarized in table 3.

4. Results and discussion

4.1. Water absorption

Differences in water absorption can be seen in both figure 2 and figure 3. From table 3 it can be seen that density doesn't correlate with water absorption as it could be expected, because the sample with highest density (NHL-W) has the higher water absorption, but the lowest one (DL) doesn't have the lowest absorption.

Water absorption somewhat correlates with compressive strength, this could be explained by the differences of the binder nature. As more hydraulic binders (containing more cement) showed similar rigidity throughout the material, the lime binders were softer in the inner core and more porous, which allowed larger water uptake. This water uptake of lime-based binders should be taken in account when considering the protection of LHC construction (mortar, overhang, etc.).

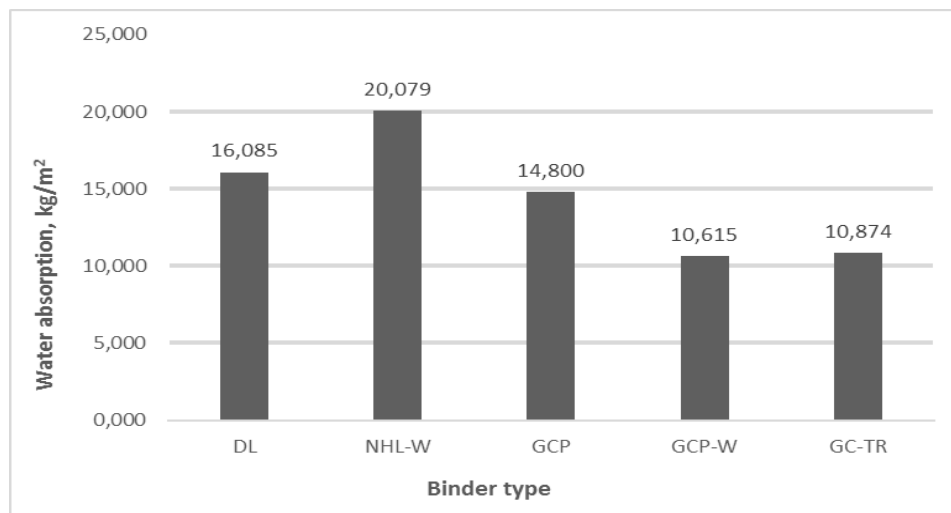


Figure 3. Water absorption dependence on the binder type.

4.2. Thermal conductivity

As can be seen from figure 4, thermal conductivity is in direct correlation with density. This has also been shown by other authors [21]. The obtained results of 0.069 W/m*K at 292.32 kg/m³ are slightly lower than those of other authors – 0.074 W/m*K at 269 kg/m³ [21] and 0.086 W/m*K at 250 kg/m³ [22].

This can be explained by looking at figure 4 – all the lime-based materials are below the trend line and all gypsum-based are above. This can be explained by the differences in the inner core of the materials, which was unhardened and porous in the lime material, but rigid and monolithic – in the gypsum-based materials. This unhardened and porous structure ensured that there were fewer chemical and physical bounds between the particles, which in turn lead to the production of materials with lower thermal conductivity.

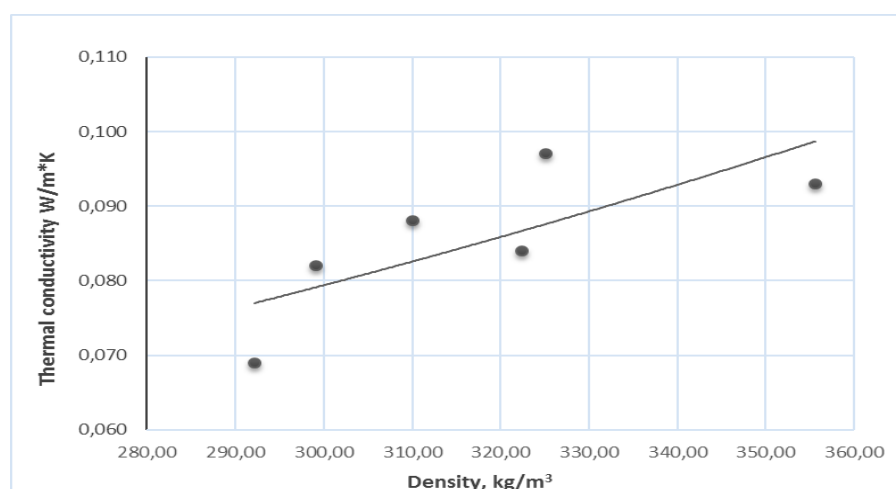


Figure 4. Thermal conductivity and density of compositions.

4.3. Compressive strength

After sawing of the samples, first conclusions about the strength of the samples were made. First, lime-based samples display poor inner strength, as in previous tests [14], but in this study the samples were cured for 2 years in laboratory conditions, but had not displayed any significant improvement. It means that low carbonisation is not the reason for this low strength as previously thought, as the samples did not carbonate for two years.

Insufficient water amount as the reason of low material strength has been put forward as one of the theories [23], but this theory should be dismissed. As it can be seen from table 2, the amount of spare water for NHL and GCP samples was similar, but the GCP samples show a rigid inner core. The main reason for the unhardened lime binder is that chemical compositions – pectins and other organic compounds are emitted in the reaction between organic hemp shives and alkaline lime binder environment [24] [25]. And these polysaccharides serve as retarders of lime and cement binding reactions, in the case of NHL binders not only temporarily slowing the process but permanently stopping it [26].

But this organic chemical reaction influences the gypsum-based binder far less, because, firstly, gypsum doesn't create alkaline environment, it is pH neutral, so the organic compounds are created in lower amounts. Secondly, gypsum has fast initial setting times, which allows it to harden before the organic compounds are even created, as lime samples have shown that these retardation processes happen during several first days of setting of the LHC [14].

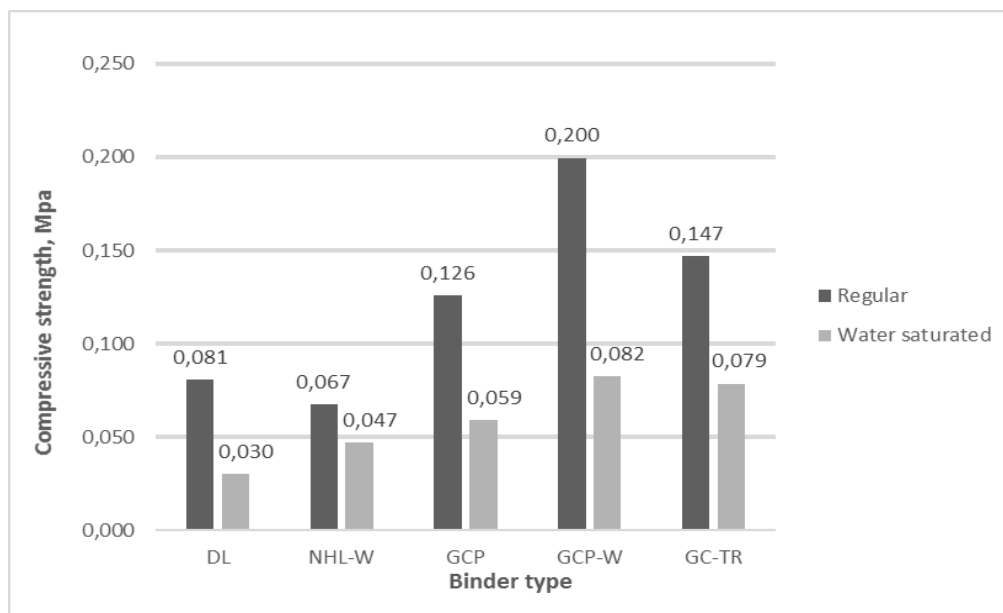


Figure 5. Compressive strength of regular and water saturated materials.

Results of the compressive strength testing can be seen in figure 5 and table 2. The top achieved results (0.2 MPa at 325kg/m³) is similar to other tests [27][28][14], but as the density was achieved with extra binder, but not pre-compression of the material, the results from previous tests suggest that similar results could be achieved with lower amount of the GCP binder and pre-compression of the material.

It can also be seen from the results that addition of 14% gypsum to DL binder didn't have a significant influence on the strength, tests with different ratios is necessary to make final conclusions, but for now it seems that gypsum content was insufficient to neutralize the negative effect of emergence of organic compounds.

From figure 5 it can also be concluded that addition of cement and pozzolanic mixtures to the gypsum binder had positive effect on its resistance to water solubility, as the compressive strength ratio of regular: water saturated samples was higher than that of NHL-W, but lower than DL.

5. Conclusions

The following conclusions can be summarised within the study:

- Weakness of the inner core of LHC material that has been attributed to insufficient carbonization and low water content is most likely the fault of organic polysaccharide compounds that are emitted in the reaction between hemp shives and alkaline binders.
- As gypsum-based binders create less alkaline environment and have high early strength, organic sugar binding retarders do not affect these binders significantly.
- Gypsum binders can be enhanced with addition of cement and pozzolanic mixtures to be useable as binders for outdoor conditions.
- As thermal conductivity showed correlation with density as observed previously, it can be suggested that pre-compression of the material could lead to lesser amount of binder used at similar densities which could improve the materials' environmental impact.
- Water absorption is largely based on the type of binder used – the more hydraulic the binder, the less water is absorbed.

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