



Sustainable Thermal Insulation Biocomposites from Locally Available Hemp and Lime

Maris Sinka, Genadijs Sahmenko,
Riga Technical University

Abstract. The key focus of the presented research is on sustainable thermal insulation biocomposites which can be made from locally available hemp and lime. The main gains of the use of such material are given, with emphasis on CO₂ reduction. In the first stage samples of an artificial hydraulic lime using three different limes and three hydraulic additives are created and tested, the one with the highest compressive strength (DL60 lime with 40% metakaolin addition) are chosen for further research. In the second stage three different density mixes with the chosen binder are created, optimal hemp/binder ratio is determined, as well as compressive strength and thermal conductivity. Results indicate that created mixtures have good potential as self-bearing thermal insulation material used in low-rise buildings.

Keywords –hemcrete, hydraulic lime, low-carbon, sustainable materials.

I INTRODUCTION

Sustainable building materials are one of the most topical subjects today in building material industry due to the growing concerns about anthropogenic factor impact on CO₂ levels in atmosphere and its correlation with global temperature rise [1]. Globally manufacture of building materials is responsible for about 10% of all CO₂ emissions [2], which is the same in Latvia [3].

In more indirect way building materials are responsible for another source of CO₂ emissions – from energy consumed for building heating and cooling in the cases when building is made out of inefficient materials with high thermal conductivity values. Heating energy losses are even larger than material manufacture industry – together with electricity and water heating it generates 36% of all CO₂ emissions in Latvia, 50% in UK [4], 45% Canada, 40% USA, and 20% in China [5].

Therefore, building material industry needs to give its solution to this problem. One of the ways to answer these challenges would be to perfect and promote the use of biocomposite materials. Along with other great properties, a lot less CO₂ is created in manufacture process of these materials, because one of the two main components of the composite is made from biological ingredients, which has sequestered CO₂ in the growing process. As to even more lower their carbon footprint, the binder usually used is low-carbon too – either lime or clay. And as these materials are considered sustainable, their thermal conductivity coefficient is low enough to be compatible with traditional building materials.

There are many different low carbon dioxide biocomposites, such as hemp-lime, hemp-clay [6], straw-clay [7]. One of biocomposites which is particularly interesting in Latvia, because it can be made using locally available resources, is hemp-lime

self-bearing heat insulation material. Hemp shives and hydraulic lime are two main components of natural biocomposites. In Figure 1. biocomposite composition with three main CO₂ flows can be seen, which represent most significant carbon dioxide emission and absorption processes in biocomposite manufacture.

Hemp shives are inner part of hemp stalk, by chemical composition it is very similar to wood-pulp as it contains a lot of lignin. It is considered a by-product as the main purpose of hemp growing is obtainment of fiber and seeds. The chief market for hemp shives for now is their use as bedding material in horse stables, because of its outstanding moisture and smell absorption capabilities. It is due to this porous nature of hemp shives that it can be used as a filler in thermal insulating biocomposites, as it allows the material to have both great moisture regulating capabilities and low thermal conductivity.

Lime is an appropriate binder for biocomposites, because of its properties. First of all, it has a lot less embodied carbon in its manufacturing process as other binders, like concrete – for 1 ton of hydrated lime 337 kg of CO₂ are created, for concrete – 819 kg [8]. Secondly, when lime hardens, it reabsorbs carbon dioxide that was released in burning process from limestone, through carbonization. And third of all, its water vapor permeability makes it fully compatible with hemp shives, to create a material with good moisture regulating properties.

Hydraulic lime can be made by mixing air lime with hydraulic additives, to make it stronger and more appropriate as a self-bearing biocomposite binder. Most important properties of hydraulic additives are high amorphous SiO₂ amount and small particle size [walker]. Commonly used additives for lime are – silica fume [9], metakaolin [10], fly-ash [11], various ground glass [12] and brick [9].

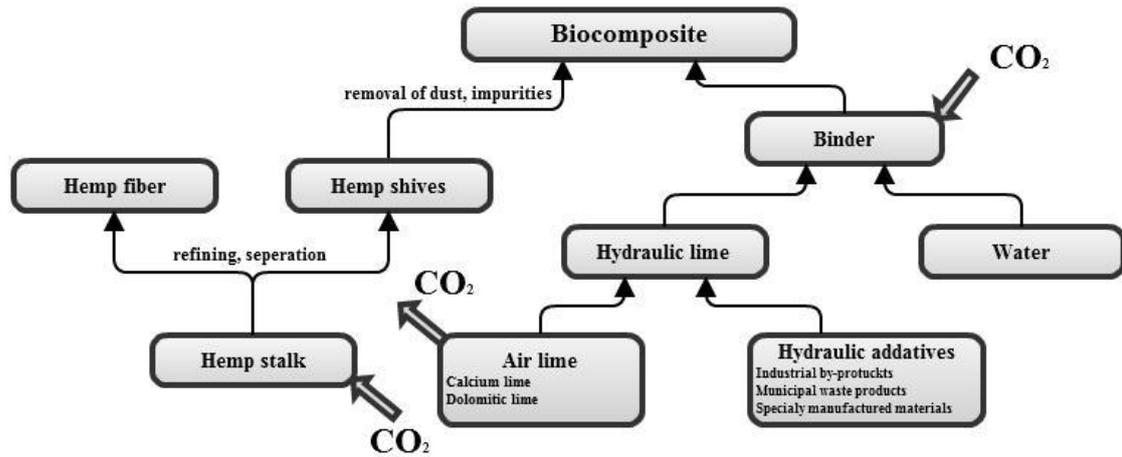


Fig. I. Composition of biocomposites with three main CO₂ flows

As for total CO₂ emitted by hemp-lime biocomposite, research shows that in fact this material absorbs, through growing of hemp stalk and carbonization of lime, more carbon dioxide than is emitted. Various researchers propose different amounts of CO₂ sequestered in full life cycle of material in 1 m³ – 4 kg [13], 108 kg [4], 120 kg [14] – as they are using different calculation methods, but one thing is clear – biocomposite made of hemp-lime mix is carbon neutral or even negative.

The aim of this research first of all is to examine the effect of three hydraulic additives on compressive strength on various air limes, to compare it with previously known biocomposite binder strengths and to choose the most suitable for further research. Then it will be mixed with hemp shives to investigate thermal conductivity and compressive strength of heat insulating biocomposites made from locally available resources. Various binder proportions will be used to test the correlation between compressive strength, binder properties, density and thermal conductivity.

II MATERIALS AND METHODS

A. Material properties

To find out the effect of lime content on formation of hydraulic compounds, three different commercially available air limes were used, their composition is given in Table I.

TABLE I
PROPERTIES OF USED LIMES

| Name | CaO+MgO content, % | Active lime, % | Bulk density, kg/m ³ | Color |
|---------------------------|--------------------|----------------|---------------------------------|-------|
| Hydrated lime CL90 | ≥ 90 | ≥ 80 | 627 | white |
| Hydrated lime CL80 | ≥ 80 | ≥ 65 | 417 | white |
| Quicklime DL60 | ≥ 60 | X | 807 | grey |

Three different pozzolanic additives were tested. First one - metakaolin which is obtained by burning kaolin clay at 800⁰ C. Other two are ground crushed bricks from building demolition waste recycling – one with fireproof capabilities, the other – hollow loadbearing brick.

Hemp shives were obtained as by-product of hemp-fiber manufacture. Bulk density of used hemp shives is 97 kg/m³. Particle size distribution of hemp material can be seen in Table II and in figure 1.

B. Experimental methods

To test the ability of hydraulic additions to react with lime 160*40*40 prisms were made using oiled steel moulds. Mixing of specimens were done manually, water were added as necessary to ensure a constant plastic consistency of mortar, so no mechanical vibration tools were needed.

After casting in moulds, specimens were covered with polyethylene film, kept for 7 days, then demoulded, sprayed with water and again covered with film to ensure constant high relative humidity (95 ± 5 %), with was measured with hygrometer.

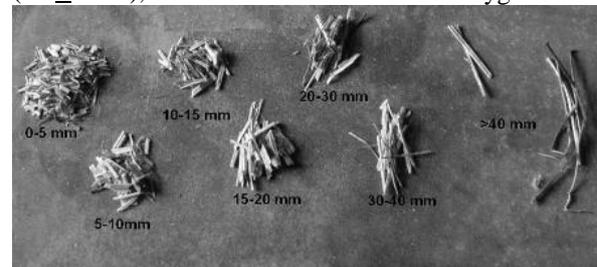


Fig. II. Hemp shive size

TABLE II
HEMP SHIVE GRANULOMETRY

| Length, mm | 0-5 | 5-10 | 10-15 | 15-20 | 20-30 | 30-40 | >40 |
|------------|-----|------|-------|-------|-------|-------|-----|
| % of mass | 27 | 15 | 14 | 19 | 13 | 8 | 4 |

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Compressive strength of the samples was measured after 28 days of curing, tolerance of force determination $\pm 1\%$. The binder with highest performance was selected for furtherer tests.

During the experiment 3 different compositions of biocomposites were made. To test the influence of material density on thermal conductivity and compressive strength, various binder proportions were tested.

Drum mixer were used to mix the samples. First of all hemp shives were put in the mixer with half of the necessary amount of water and mixed for 3 minutes. Then the binder was added, mixed for 2 minutes, and after all – the rest of the water. Preparation continued until the binder was evenly distributed, which took 3-4 minutes. The mixed compositions were cast in oiled steel moulds with dimensions of 100*100*100mm for compressive strength testing, and in 350*350mm water-proof plywood moulds for thermal conductivity testing. Material were cast in three layers, moderately tamping each layer, polyethylene film were placed on top to prohibit fast drying of the samples, then a steel plate with weight on top of it all for even compaction.

The film and weight were removed after 3 days, specimens were demoulded after 7 days of curing. Hardening conditions were $20 \pm 2^{\circ}\text{C}$ temperature and $55 \pm 10\%$ relative humidity.

To assess material density, before tests specimens were weighted and their dimensions were measured. Compressive tests were performed using universal testing machine Zwick Z100 (maximal applicable force – 100 kN). Pressure on specimens was applied in the same direction as compaction, by rate 10 mm/min, force – deformation diagram was recorded during the test. As biocomposites with relatively low compressive strength can exhibit relatively large deformations without noticeable breaking point,

maximal compressive strength is measured at 10% deformation (in this case at 10 mm of absolute deformation).

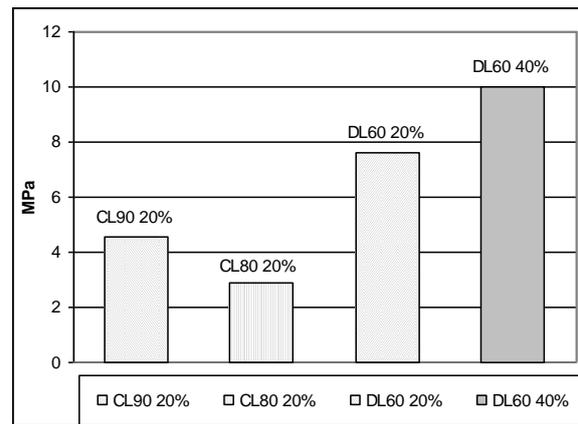


Fig. III. Compressive strength of various limes with metakaolin addition.

Thermal conductivity was determined using Fox 600 heat flow measuring device. Sample was fixed horizontally. During the test temperature of lower surface was $+20^{\circ}\text{C}$ and 0°C of upper surface (mean temperature $+10^{\circ}\text{C}$). Heat transmission coefficient was determined considering constant heat flow between two sides of sample.

III RESULTS AND DISCUSION

A. Composition of Lime binders

The testing of binders were done in two stages. During the first stage optimal amount of metakaolin were determined in combination with most suitable lime. During the second stage two different ground brick additions were examined to clarify their hydraulic properties.

TABLE III

ARTIFICIAL HYDRAULIC LIME MIXES

| Sample name | Lime | Lime, g | Meta., g | Brick1, g | Brick2, g | Sand, g | Water, g | Hydraulic add., % |
|----------------------------|------|---------|----------|-----------|-----------|---------|----------|-------------------|
| CL90 20% | CL90 | 240 | 60 | 0 | 0 | 600 | 266 | 20.0% |
| CL80 20% | CL80 | 240 | 60 | 0 | 0 | 600 | 300 | 20.0% |
| DL60 20% | DL60 | 240 | 60 | 0 | 0 | 600 | 200 | 20.0% |
| DL60 40% | DL60 | 180 | 120 | 0 | 0 | 600 | 200 | 40.0% |
| DL60 | DL60 | 300 | 0 | 0 | 0 | 600 | 200 | 0.0% |
| DL60 +10% meta +10% brick1 | DL60 | 240 | 30 | 30 | 0 | 600 | 200 | 20.0% |
| DL60 + 28.5% brick1 | DL60 | 214.5 | 0 | 85.5 | 0 | 600 | 200 | 28.5% |
| DL60 +10% meta +10% brick2 | DL60 | 240 | 30 | 0 | 30 | 600 | 200 | 20.0% |
| DL60 + 28.5% brick2 | DL60 | 214.5 | 0 | 0 | 85.5 | 600 | 200 | 28.5% |
| CL90 + 20% brick1 | CL90 | 240 | 0 | 60 | 0 | 600 | 300 | 20.0% |
| CL90 + 20% brick2 | CL90 | 240 | 0 | 0 | 60 | 600 | 300 | 20.0% |

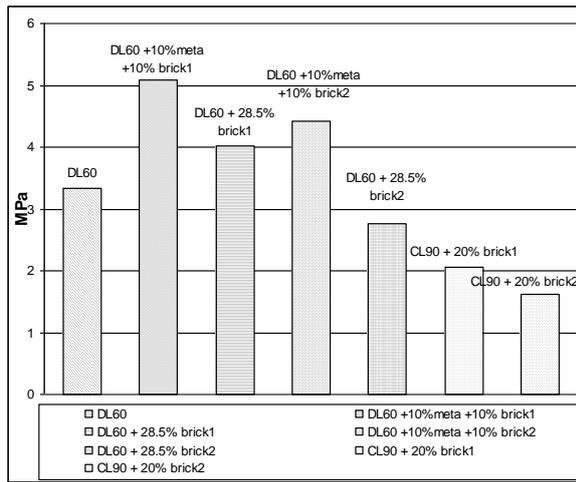


Fig. IV. Compressive strengths of binders with various additives.

Proportions of mix compositions are summarized in Table III.

Results of the first experimental stage are shown in Fig. 3. It shows that CL80 lime has the lowest ability to react with hydraulic additions, which is due to its lower amount of active $\text{Ca}(\text{OH})_2$ [15]. Result of CL90 with 20% metakaolin shows good result (4.55 MPa) which is about the same as in similar researches [10]. The best result is generated by DL60 lime with 40% metakaolin addition – 9.98 MPa. The results of second experimental stage are summarized in Fig. 4. As shown, none of the compositions can match the best results of the first stage. It can be seen that both ground brick additives have little hydraulic activity, and works more as a microfiller. Of course it can be beneficial to supplement lime or some more active hydraulic additive not compromising the result, but in this particular research binder with the best compressive strength is needed, so for furtherer research DL60 lime with 40% metakaolin is chosen.

B. Producing Biocomposites

Three compositions of hemp shives and hydraulic lime binder (DL60 with metakaolin) were produced, mix proportions are summarized in Table IV. The most commonly applied hemp/lime proportion by weight was used in mix 2. – 0.38,[14], the other two are with lower and higher ratio, to test the effect of density on compressive strength and thermal conductivity.

As can be seen from Fig. 5, which is force-deformation diagram for compositions from Table IV – increasing the amount of hemp shives above 0.38

TABLE IV

BIOCOMPOSITE CHARECTARISTICS

| Nr. | Hemp/binder ratio | Density, kg/m ³ | Compressive strength, MPa | Thermal conductivity λ , W/m ² K |
|-----|-------------------|----------------------------|---------------------------|---|
| 1. | 0.31 | 337 | 0.222 | 0.0867 |
| 2. | 0.38 | 328 | 0.221 | 0.0757 |
| 3. | 0.47 | 312 | 0.179 | 0.1010 |

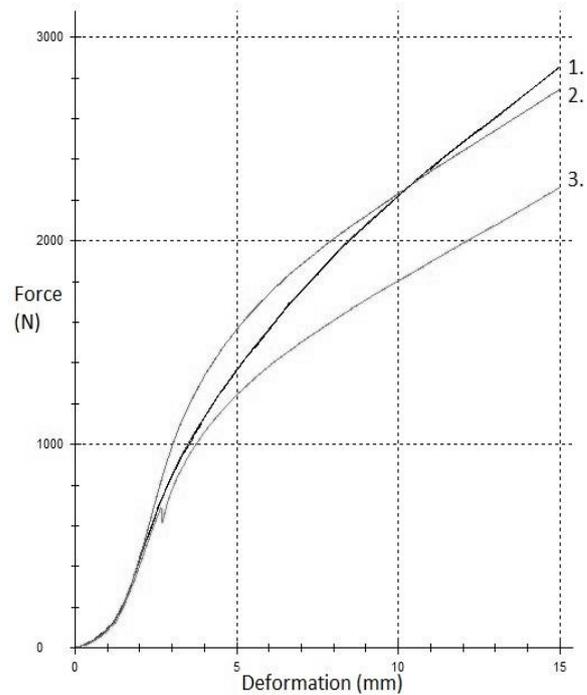


Fig. V. Force-deformation diagram of biocomposites

has a direct negative effect on compressive strength, as for lowering below 0.38 does not show any effect. This trend can also be seen in Table IV where applied force at 10% deformation is given. It can be explained that proportion of 0.38 is very optimal for this shive granulometry as binder can cover all shives, thus giving the required strength. Increasing the amount of shives creates spots with no binder, which leads to lower compressive strength, but increasing the amount of binder a little does not give notable strength rise, as area of contact zone between hemp shives does not significantly change. Of course, there is a proportion after which the compressive strength rises, but it also has its effect on thermal conductivity. If compared to other studies, then compressive strength of around 0.2 MPa for 330 kg/m³ density samples is considered good and acceptable for using as thermal insulation material in low-rise buildings [16].

The results of thermal conductivity coefficient λ are also given in Table IV, and are compared to results of previous tests in Fig. 6. As can be seen from the figure, all three samples stand very close to exponential trendline, which means that all three mixes made are comparable to the ones tested before, whose results are considered as acceptable and usable in further development of thermal insulation biocomposites [16].

IV CONCLUSIONS

1. As the most suitable binder for biocomposites DL60 lime with 40% metakaolin addition was found, as it gave the highest compressive strength value.
2. CL90 lime showed lower results with metakaolin then DL60 lime, but it performed better than

- CL80 lime, because of higher amount of active lime.
- Ground brick showed little hydraulic activity, and could only be used to replace lime for cost saving, but could not increase compressive strength significantly enough to be used in further research.
 - The optimal hemp/binder ratio for this granulometry of shives is 0.38, as more shives decreases compressive strength, and less does not increase it noticeably.
 - The achieved result – hemp/lime biocomposite with compressive strength of about 0.2 MPa for 330 kg/m³ density is acceptable for use as self-bearing thermal insulation material in low-rise buildings.
 - The thermal conductivity coefficients that were achieved stand very close to the exponential trendline of results from previous studies, which means that they are compatible and usable.
 - The aim of this study was achieved as optimal natural binder composition was elaborated and sustainable thermal insulation biocomposites were created.

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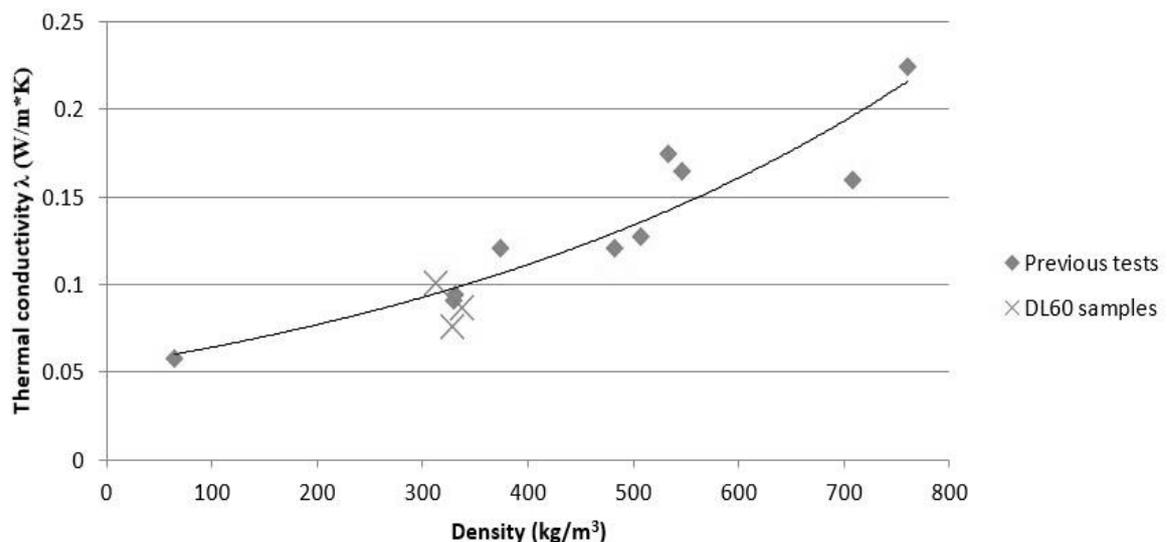


Fig. VI. Thermal conductivity correlation with density