ARTIFICIAL HYDRAULIC LIME BINDER AND ITS IMPACT ON PROPERTIES OF HEMP-LIME COMPOSITIONS

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Abstract. The rising global temperature is partly associated with the increase of anthropogenic carbon dioxide (CO_2) emissions. Major part of this CO_2 comes from building material industry and from energy consumed to maintain buildings. To solve this problem a building material that both has low thermal conductivity and emits low amount of CO_2 is needed. Hemp and hydraulic lime building materials are one of these materials, but they are not widely used partly due to insufficient research of their possible properties. The aim of this research was to find optimal composition of artificial hydraulic lime binder and to elaborate appropriate compositions of hemp-lime insulating material. The binder itself was also to be tested as multiple air limes were supplemented with different additives and the most appropriate for use in hemp-lime material was to be chosen – a dolomitic lime DL60 with 40% metakaolin additive. The ratio of hemp/binder 0.38 gave the best results – compressive strength of 0.221 MPa at 10% deformation and thermal conductivity of 0.0757 W/m^{2}k, which is considered a good result and shows a possibility for this material to be used as self-bearing thermal insulation building material.

Keywords: hydraulic lime, hemp shives, pozzolans, CO2 absorption, hemp, thermal insulation

1. Introduction

One of the challenges that have to be faced by the modern society is global increase of CO_2 and temperature growth that is associated with it. Nowadays, it is getting recognised that these two things are connected (Humlum *et al* 2013), the debate now shifts to the question of the extent to which carbon dioxide accumulation boosts the global temperature rise (Florides *et al* 2013), nevertheless it is acknowledged that we should reduce the anthropogenic CO_2 emissions to minimise the temperature ascent (Hook, Tang 2013).

Construction industry is one of the largest CO_2 emitters – for example in China, which is the largest carbon dioxide pollutant (Wang *et al.* 2013), construction industry is responsible for more than 15% of all greenhouse gas emissions (Xu *et al.* 2012). In the US, which is the second largest emitter (Benhelal *et al.* 2013), construction industry is responsible for the third highest carbon emissions among industrial sectors. Cement industry alone is responsible for 5-7% of global CO_2 pollution.

In more indirect way construction industry contributes to increasing quantity of CO_2 by failing to quickly apply building materials that can lower the amount of heat necessary to be produced as heating together with electricity and water heating generates 36% of all CO_2 emissions in Latvia, 50% in the UK (Bushbridge 2009), 45% in Canada, 40% in the USA, and 20% in China (Glaeser *et al.* 2009).

To deal with the problems mentioned above, the building material industry needs to develop solutions. One of the ways how to solve this problem is hemp-lime material, which is made of hemp shives and hydraulic lime. It has good thermal conductivity for heat loss reduction and it can be produced with low CO_2 amount. In Figure 1 hemp-lime composition with three main CO_2 flows can be seen, which represent most significant carbon dioxide emission and absorption processes in hemp-lime manufacturing.

The inner part of the hemp stalk is called hemp shives, which is a filler of hemp-lime material, by chemical composition it is similar to wood pulp because it contains a lot of lignin (Stevulova *et al.* 2012). As it does not have many applications, it is considered an industrial by-product from hemp fibre and seeds manufacture. The main usage of hemp shives is as a bedding material in horse stables due to their high moisture (Pejic *et al.* 2008) and smell absorptivity. It is due to their highly porous structure that hemp shives have these abilities and it is the reason why they are so appropriate as a thermal insulation building material.
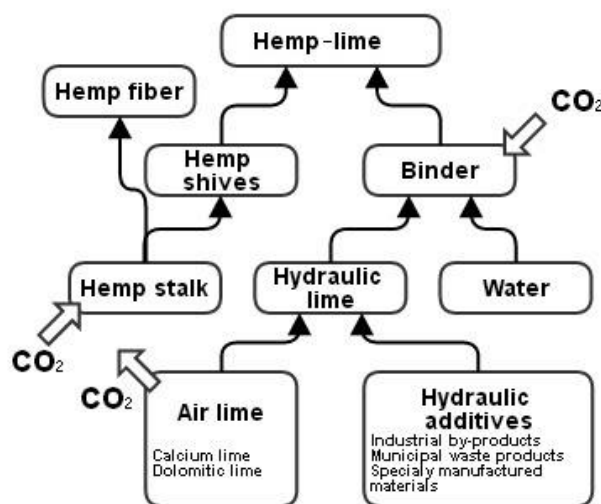

Fig. 1. Main CO_2 flows in the hemp-lime composite.

Lime is an appropriate binder for hemp-lime material, because of its properties. First of all, a lot less carbon is emitted in its manufacturing process than producing other binders, such as cement – for 1 ton of hydrated lime 337 kg of CO2 are created, for cement –819 kg (Wilkinson 2009). Secondly, when lime hardens, it

reabsorbs carbon dioxide that was released in the burning process from limestone, through carbonization. And thirdly, excellent water vapour permeability of the hardened lime binder (Mosquera et al. 2004) makes it fully compatible with hemp shives to create a material with good moisture regulating properties.

Artificial hydraulic lime can be made by mixing air lime with hydraulic additives to make it stronger and more appropriate as a self-bearing hemp-lime binder. Most important properties of hydraulic additives are high amorphous SiO_2 amount and small particle size (Walker, Pavia 2010). Commonly used additives for lime are silica fume (Wilkinson 2009), metakaolin (Cerny *et al.* 2006), fly-ash (Vejmelkova *et al.* 2012), various ground glass (Wegian *et al.* 2011) and ground brick (Wilkinson 2009).

As for total CO2 emitted by hemp-lime material, 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 m 3 – 4 kg (Edwards 2007), 108 kg (Bushbridge 2009), 120 kg (Miskin 2009) – as they use different calculation methods, but one thing is clear – hemp-lime materials are carbon neutral or even negative.

The aim of this research first of all is to examine the effect of hydraulic additives on compressive strength on various air limes, to compare it with previously known hemp-lime binder strengths and to choose the most suitable for further research. Hemp-lime heat insulating materials are prepared with locally available resources in order to investigate their density, thermal conductivity and compressive strength. Various binder proportions are prepared to find the correlation between compressive strength, binder properties, density and thermal conductivity.

2. Materials and methods

2.1. Material properties

Three different commercially available air limes were used to find out the effect of lime content on hydraulic compound formation, composition of the limes are given in Table 1.

Table 1. Lime used in sample preparation.

Name	CaO+ MgO content , %	Acti -ve lime , %	Bulk density, kg/m³	Color	Producer
Hydrated lime CL90	≥ 90	≥ 80	627	white	Lhoist Bukowa, PL
Hydrated lime CL80	≥ 80	≥ 65	417	white	Krasnosolsk-strojmateriali
Quicklim e DL60	≥ 60	X	807	grey	Saulkalne, LV

Five different materials were used as hydraulic additives:

1. Silica fume or Microsilica (MS) – Elkem Microsilica 971 (undensified), Norway;
2. Metakaolin (MK) – industrial by-product, calcined at 800ºC kaolin clay, Lithuania;
3. Chamotte (CH) – mix for fireproof mortar, Ukraine;
4. Crushed fireproof brick (FB) – ground in laboratory ball mill at 300 rpm, 30 min;
5. Crushed hallow loadbearing (HB) – ground in the laboratory ball mill at 300 rpm, 30 min.

Hemp shives were obtained as by-product of hemp-fibre manufacture. Bulk density of the used hemp shives is 97 kg/m³. Particle size distribution of hemp material can be seen in Table 2 and in Figure 2.

Table 2. Particle size distribution of the used hemp shives

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

Fig. 2 Particle size distribution of used hemp shives.

2.2. Experimental methods

To test the ability of hydraulic additions to react with air, lime samples – prisms were made. Dimensions of the samples were 160x40x40 mm, oiled steel moulds were used. Mixing of specimens was done manually, water was 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 %), which was measured with the hygrometer.

Compressive strength of the samples (4 samples for each composition) was tested after 28 days of curing in accordance with standard (LVS 459-1:2011), tolerance of force determination +1%. The binder with highest performance was selected for furtherer tests.

During the experiment three different hemp-lime compositions were made, to test the influence of material density on thermal conductivity and compressive strength, various binder proportions were tested.

Table 3. Composition to test the reactivity of the limes

Sample name	Lime, type	Lime, g	Meta., g	Sand, g	Water, g	Hydr. add., %
C0	CL90	300	0	600	266	0%
C1	CL90	285	15	600	266	5.0%
C2	CL90	270	30	600	266	10.0%
C3	CL90	240	60	600	266	20.0%
C4	CL80	300	0	600	300	0%
C5	CL80	285	15	600	300	5.0%
C6	CL80	270	30	600	300	10.0%
C7	CL80	240	60	600	300	20.0%
C8	DL60	300	0	600	200	0%
C9	DL60	285	15	600	200	5.0%
C10	DL60	270	30	600	200	10.0%
C11	DL60	240	60	600	200	20.0%

Table 5. Composition of dolomitic lime with metakaolin

Sample name	Lime, type	Lime, g	Meta., g	Sand, g	Water, g	Hydr. add., %
DL0	DL60	350	0	700	240	0%
DL1	DL60	332.5	17.5	700	240	5.0%
DL2	DL60	315	35	700	240	10.0%
DL3	DL60	280	70	700	240	20.0%
DL4	DL60	245	105	700	240	30.0%
DL5	DL60	210	140	700	240	40.0%
DL6	DL60	175	175	700	240	50.0%
DL7	DL60	140	210	700	240	60.0%
DL8	DL60	105	245	700	240	70.0%
DL9	DL60	70	280	700	240	80.0%

Drum mixer was used to mix the samples. First of all, hemp shives were put in the mixer with a 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 was added. 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 100x100x100 mm for compressive strength testing, and in 350x350 mm water-proof plywood moulds for thermal conductivity testing. Material was cast in three layers, moderately tamping each layer, polyethylene film was placed on the top to avoid fast drying of the samples, then a steel plate with the weight was placed on the top for even compaction.

The film and weight were removed after 3 days, specimens were demoulded after 7 days of curing. Hardening conditions were: 20 ± 2^0C temperature and $55\pm10\%$ 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 the specimens was applied in the same direction as compaction, by rate 10 mm/min, force – deformation diagram was recorded during the test.

Thermal conductivity was determined using Fox 600 heat flow measuring device. The sample was fixed horizontally. During the test temperature of lower surface was +20ºC and 0ºC of upper surface (mean temperature +10ºC). Heat transmission coefficient was determined considering constant heat flow between two sides of sample.

3. Results and discussion

3.1. Composition of lime binders

The testing to find the most suitable binder for hemp-lime material was done in several stages. The first stage included testing of air lime reactivity, the second – searching for the most appropriate hydraulic additive and the third stage involved finding of the right dosage.
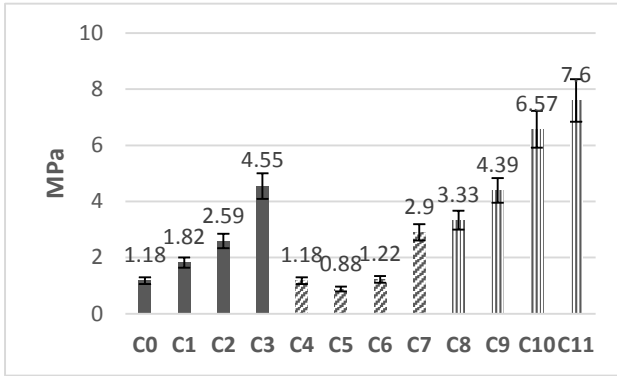
Table 4. Composition to test the reactivity of the additives

Sample name	Lime, type	Lime, g	Add.1	Add.1, g	Add.2	Add.2, g	Sand, g	Water, g	Hydraulic add., %
D0	DL60	350	-	-	-	-	700	240	0%
D1	DL60	280	MT	35	FB	35	700	240	20.0%
D2	DL60	250	-	-	FB	100	700	240	28.5%
D3	DL60	280	MT	35	HB	35	700	240	20.0%
D4	DL60	250	-	-	HB	100	700	240	28.5%
D5	DL60	280	MT	35	CH	35	700	240	20.0%
D6	DL60	250	-	-	CH	100	700	240	28.5%
D7	DL60	332.5	MT	17.5	-	-	700	240	5.0%
D8	DL60	315	MT	35	-	-	700	240	10.0%
D9	DL60	280	MT	70	-	-	700	240	20.0%
D10	DL60	341.75	-	-	MS	8.75	700	240	2.5%
D11	DL60	332.5	-	-	MS	17.5	700	240	5.0%
D12	DL60	341.75	-	-	MS	35	700	240	10.0%
D13	DL60	332.5	MT	8.75	MS	8.75	700	240	5.0%
D14	DL60	341.75	MT	17.5	MS	8.75	700	240	7.5%
D15	DL60	332.5	MT	35	MS	8.75	700	240	12.5%

Fig. 3. Strength results of various air limes with metakaolin.

In the first stage of the research all three air limes were mixed with hydraulic additive – metakaolin – to test their
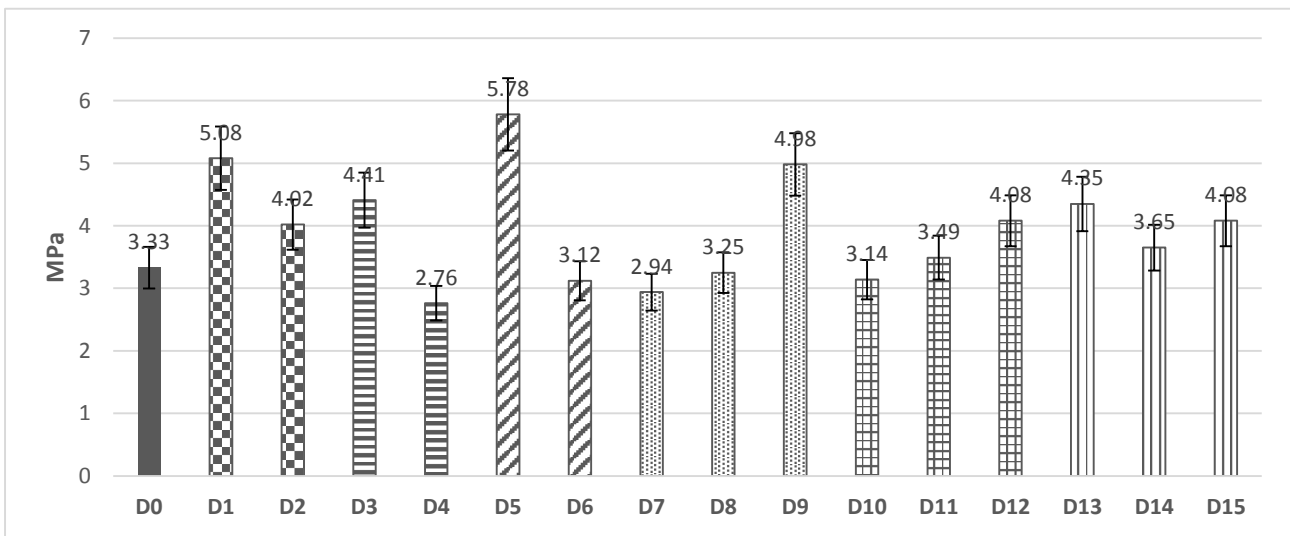
reactivity. Mix compositions are summarized in Table 3. For every type of lime four different metakaolin proportions were used – 0, 5, 10 and 20% of the total binder mass. Binder with sand ratio of 1:2 was used for all specimens. The amount of water necessary was determined by visually controlling and keeping consistent the flow of all binders.

The second stage was aimed at determining the most appropriate hydraulic additive for DL60 lime, which was the most active in the first stage, all five hydraulic materials were used in different compositions summarised in Table 4.

In the third stage the right dosage of the most suitable additive – metakaolin – was found, it was used form 0 up till 80% of the total binder mass, compositions are given in Table 5.

Fig. 4. Results of reactivity (mortar compressive strength) of various additives.
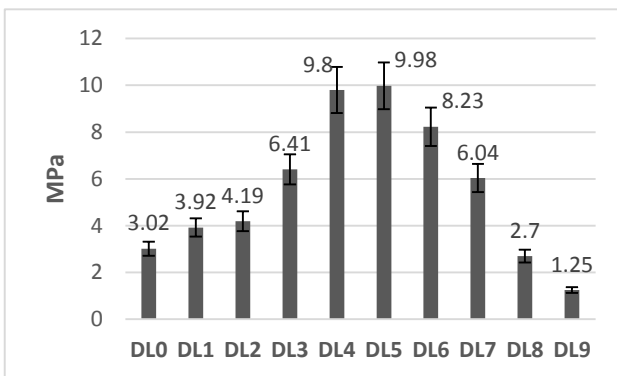
Fig. 5. Compressive strength of dolomitic lime with metakaolin.

3.2. Compressive strength of the binder

Results of the first stage of research are shown in Fig. 3. As it can be seen, addition of metakaolin significantly increases compressive strength of the binder, 20% addition to CL90 lime increases its strength almost four times, for CL80 lime about 2.5 times, but the highest value is achieved with DL60 lime with 20% metakaolin – 7.6 MPa which compared to similar tests (Vejmelkova, et al. 2012) is above average, so for the next stages of

research dolomitic lime was chosen.

From the results of the second stage (Fig. 4) it can be concluded that crushed brick and chammoete can be used only for replacement of more active hydraulic additive, as alone these materials contribute very little to strength increase. It can also be seen that microsilica alone or with metakaolin increase binder's compressive strength, but not as significantly as 20% MT addition.

Results of the third stage are shown in Fig. 5 and as it can be seen the highest value is achieved with 40% metakaolin addition to DL60 lime – after 28 days of curing – almost 10 MPa. This mixture will be used in further research as the binder for hemp-lime material.

3.3. Characteristics of hemp-lime compositions

In Table 5 mix proportions of three different shives/lime ratio compositions can be seen. The binder used is DL60 with 40% metakaolin addition. The ratios used are 0.31, 0.38 and 0.47 hemp/lime ratio by weight. The most commonly used out of all three is 0.38 (Miskin 2009), the other two are on both sides of the ratio scale – to test the effect that density has on compressive strength and thermal conductivity.

Table 5. Hemp-lime characteristics

Nr.	Hemp/ binder ratio	Density, kg/m³	Compressive strength, MPa	Thermal conductivity λ, W/m*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

It can be seen in Table 5 that hemp/lime ratio has the expected effect on density as higher ratio also means lower density. To test the compressive strength of the specimens, they were crushed on a Zwick 100 universal testing machine, which recorded a force-deformation diagram during the test. The force at 10% relative deformation (10 mm) is considered as the compressive strength of the samples. It can be observed that lowering the ratio below 0.38 does not provide any extra compressive strength – 0.222 MPa for ratio 0.31 and 0.221 MPa for 0.38, increasing it does reduce it significantly to 0.179 MPa at 0.47. It can be explained that for this sieve granulometry the ratio of 0.38 is optimal as the binder can cover all the sieves to make an effective contact zone, increasing the amount of binder does not give any effect as the contact zone does not significantly change, but using smaller amount of binder creates spots with no binder coverage, which leads to lower compressive strength. It is possible to increase the compressive strength by adding even more binder, but it

will have a negative effect on thermal conductivity. The results obtained (around 0.2 MPa for 330 kg/m³) can be considered as acceptable for using this material as a single layer self-bearing monolithic thermal insulation for low-rise buildings (Sinka *et al.* 2012).

Table 6. Hemp-lime corrected characteristics

Nr.	Hemp/ binder ratio	Density, kg/m3	Compressive strength, MPa	Thermal conductivity λ, W/(m*K)
1.	0.31	340	0.222	0.0753
2.	0.38	328	0.221	0.0722
3.	0.47	289	0.179	0.0696

The results of thermal conductivity test can also be seen in Table 5. As expected the 0.31 sample produced a higher conductivity then 0.38 sample, because of lower amount of air pores, but the 0.47 showed even higher conductivity then 0.31, which could be due to the fact that the specimen of the 0.47 sample was about two times wider and that not all of the water evaporated until the testing.

This was confirmed with repeated tests after 3 months of drying in indoor conditions. Final corrected results can be seen in Table 6. The differences in material density were even more noticeable and thermal conductivity showed the results that were expected – that the specimen with the lowest density will also have the lowest thermal conductivity coefficient.
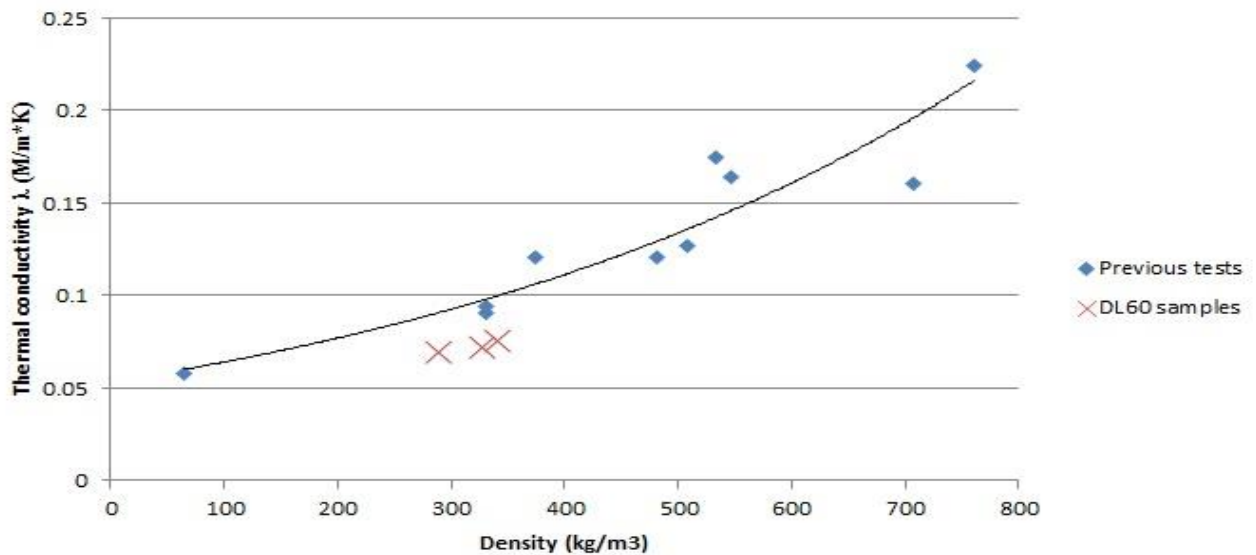
Fig. 6. Hemp-lime material thermal conductivity.

But if compared to results of previous tests in Fig. 6., it can be seen that the samples are a little bit below exponential trendline. And from that it can be concluded that the mixes created is considerable as acceptable and usable in development of hemp-lime thermal insulation materials (Sinka, Sahmenko 2013).

Conclusions

From the results of the first stage of experiment it can be concluded that the most rapid increase in compressive strength can be achieved using DL60 lime together with metakaolin – 40% by mass. CL90 and CL80 air limes showed lower reactivity, CL80 results were the lowest, which is explained with smaller amount of free lime. Other additives did not achieve high enough results to be

used in hemp-lime materials, but have possible uses in the development of restoration mortars.

The results of the second stage showed that the chosen binder is suitable for hemp-lime materials, as it demonstrated compressive strength and thermal conductivity that is considered as acceptable for these materials.

The aim of this study was achieved as optimal natural binder composition was elaborated and sustainable thermal insulation material was created.

Further research in this field would require a more in-depth research on other hemp-lime properties to facilitate comparing different binders used.

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