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COMPOSITE MATERIALS FROM HEMP AND HYDRAULIC LIME FOR USE IN BUILDING AND WOOD-CONSTRUCTIONS

Petr Hamšík, Pavel Král
Mendel University in Brno, Faculty of Forestry and Wood Technology
Brno, Czech Republic

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ABSTRACT

This paper deals with the results of the development of optimal composition of the composite material based on hemp and hydraulic lime for use in wooden and other constructions. The aim of the research is to design and test composite plate material with low water vapour diffusion resistance, resistant to moisture, weathering and fire while minimizing negative impacts on the environment. 14 panels of seven different formulas of composition were produced and tested. The formulas varied in amount of hemp reinforcement fibres (5 and 10 weight part), water-hydraulic lime ratio (υ = 0.6 and υ = 0.7), hydraulic limes by different producers and use or lack of use of waterglass as mineralization reagent. Mechanical properties (strength and modulus of elasticity in three-point bending), moisture impact, water vapour permeability and thermal conductivity were measured at test specimens made from the panels. The results of laboratory tests were statistically analysed and compared.

KEYWORDS: Hemp, hydraulic lime, plate composite materials.

INTRODUCTION

The demand in the construction industry of these days is to reduce energy consumption of building. This reductions energy consumption is one of the requirements and criteria in the concept of sustainable development, whose principle and objectives are defined in The Agenda 21 on Sustainable Construction (1999). One of the applied principles of sustainability in construction of buildings is the alternative material and energy design principles (Hájek 2005).

The aim of the research was to develop and test material suitable for external cladding exterior walls of wooden and other constructions. The request on this plate material was to use natural raw materials and materials close to natural ones with low resistance to water vapour diffusion and with good resistance to moisture, weather and fire at the same time. This would provide alternative material which combines properties of cement-based materials (e.g. cement-chip boards and cement-fibreboards) and gypsum-based materials (gypsum-fibre boards, gypsum-chip boards).

Materials based on cement are water and weather conditions resistant but too little permeable to water vapour. Gypsum-based materials are less resistant to water vapour diffusion but also less resistant to moisture and weather conditions (Hrázský and Král 2007; Adámek et al. 1997).

As reinforcement material of the developing material, hemp fibres (tow) were selected due to their high strength properties, resistance to moisture and environmental, social and economical benefits (potential produce in agriculture and rural areas). The bark of hemp stalk contains bast fibres which are among the longest natural soft fibres on Earth and compose of cellulose and hemi-cellulose Kubánek (2009).

Hemp as raw material is suitable for production of building materials. It is very stable, resistant to rupture and copes well with moisture and wetness. The hemp plant is able to reach the height of 4500 mm within 120 days. From one hectare, 12 tons of dry raw material can be harvested from which up to 8 tons of construction material can be produced. This is enough to build a small house. Rapid growth of hemp causes that the plants shade the soil which prevent weed from growing and so they need no herbicides. The plants contain substances that repel insects, so no insecticides are needed to protect them (Chybík 2009). Hemp can play a vital role in the move towards organic agriculture (Allin 2012).

From disadvantage Asprone et al. (2011) mentioned „as it was expected for natural fibers, results from both fiber and composite tests presented a high dispersion. This represents a critical issue for structural applications, where a design value for each mechanical property of the used materials is needed."

Fibre content by weight is the main factor that affects compressive and flexural properties of hemp fibre reinforced concrete (HFRC), regardless of the mixing method used (Li et al. 2006).

Hydraulic lime was chosen as a binder, because of it is fireproof. It has also been reported that it is stronger and more moisture resistant than lime is. At the same time, it is more flexible and water vapour permeable than cement is.

Hydraulic lime sets and hardens much faster than lime. It is possible to use it in the construction industry to produce mortars and concrete of lower strength grades used both in air and water. Hydraulic lime is applied wherever greater firmness of mortar or concrete is needed, which cannot be achieved with lime. It is characterized by greater resistance to weathering and thus longer durability in comparison to lime render. In contrast to cement, hydraulic lime retains the essential property of lime, i.e. plasticity (Adámek et al. 1997).

More authors (Troëdec et al. 2009; Bydžovský and Dufek 2009; Keprová and Bydžovský 2009) state that some organic constituents of cellulosic reinforcement materials (wooden and hemp chips, fibres etc.) could have negative influence on hardening process of hydraulic binders and on the strength of connection between the reinforcement and the matrix. It can be caused especially by sacharides. Bydžovský and Dufek (2009) tested this influence on specimens from mixtures with three different of mixing water. The first one was an extract from sawdust, second one an extract from hemp and the third one tap water. It has been found that in the early stages of maturation the hydration process was slightly delayed, but the final strength after 28 days was not different. (ibid.). Keprová, Bydžovský (2009) state about use of hydraulic lime and hemp hurds: "Three different compositions were designed. Connective component was the same in all mixtures, what was different was just pre-treatments of hemp hurds, which were left without treatment or mineralized by slaked lime or sodium waterglass." Mixtures no. 2 and 3 were the strongest, also due to mineralization, which limited the inhibiting effect of hemp hurds on setting and hardening of the mixture.

MATERIAL AND METHODS

Manufacturing a prototype panels and test specimens

Two different hydraulic limes with minimum compressive strength of 5 MPa (after 28 days) were used as a binder for the production of the plates. Trassit Plus - high-hydraulic lime binder manufactured by Baumit company was used first. The manufacturer states: Composition: lime, latent hydraulic elements - trass, additives; grain size: more than 95 % of particles smaller than 0.09 mm; content of CO_2: <10 %; compressive strength after 28 days: ≥ 5.0 MPa; tensile strength after 28 days: ≥ 1.5 MPa. The second one was "Hydraulic lime HL 5 - only for building purposes (type VH 3) manufactured by the Research Institute of Building Materials (VUSTAH), in Brno, the Czech Republic.

Hemp fibres (tow) were used as reinforcing fibrous material. They were short waste fibres exhausted from a production line of hemp insulation in the CANABEST, company, the Czech Republic.

The mixing water was tap water from a municipal water supply system. Overall quantity of water in mixtures consisted from two parts. One part was set by water-hydraulic lime ratio υ = 0.6 or υ = 0.7 which determined amount of water for hydration process and making slush from hydraulic lime. The water-hydraulic lime ratio υ = 0.6 represents 60 weight parts of water and υ = 0.7 represents 70 weight parts of water. The second part of the total amount of water in the mixtures was calculated to be twice the weight of dry hemp fibres added to the mixture. The second part was added to saturation of hemp by water because of large water absorption capacity of hemp.

As the mineralization reagent waterglass (34 – 38 % aqueous solution of sodium silicate) was used. In some test panels 5 weight parts of waterglass were added and in some others no waterglass was added.

Seven different formulas were suggested for the mixtures. For each formula, two panels with dimensions 92 x 60 x 1.5 cm were made.

Formulas 1 - 4 consisted of the Trassit Plus hydraulic lime (Baumit), hemp fibres, water and waterglass. Individual formulations differ in the amount of hemp (5 and 10 weight parts) and in the water-hydraulic lime ratio (υ = 0.6 and υ = 0.7 i.e. 60 and 70 weight parts). Formula 5 differed from formula 4 in adding no waterglass as mineralization. The volumes of the other components were the same as in formula 4. Formula 6 contained just the Trassit Plus hydraulic lime (Baumit) and water. It was the formula for comparison with the others with hemp reinforcements. Formula 7 differed from the others in using the Hydraulic lime HL 5 (VUSTH) instead of the Trassit Plus (Baumit). The volume of the other components in the mixture was the same as in formula 4.

Tab. 1: Composition of the mixtures - formulas 1 – 6 in weight parts.

Formula	Hydraulic lime Trassit Plus	Hemp fibers	Water		Waterglass
			For hydraulic lime	For hemp	
No.	Weight parts	Weight parts	Weight parts	Weight parts	Weight parts
1	100	5	60	10	5
2	100	5	70	10	5
3	100	10	60	20	5
4	100	10	70	20	5
5	100	10	70	20	-
6	100	-	50	-	-

Tab. 2: Composition of the mixtures – formula 7 in weight parts.

Formula	Hydraulic lime HL 5 (VUSTAH)	Hemp fibers	Water		Waterglass
			For hydraulic lime	For hemp	
No.	Weight parts	Weight parts	Weight parts	Weight parts	Weight parts
7	100	10	70	20	5

Waterglass was, except for formulas 5 and 6, mixed in the total amount of water meant for both hydraulic lime and hemp and then hemp fibres, were inserted, except formula 6. When the hemp was soaked, hydraulic lime was added and all components were mixed for 10 minutes in a bucket with a power hand stirrer. The mixture was poured into a mould, spread by a levelling roller (a pinned plastic roller), smoothed by a hand smoother and covered by PE foil. The filled moulds were stacked on one another and left for 28 days in a room with standard laboratory conditions. After that, test specimens were made from the plates which were removed from the moulds and cut by a circular saw. The specimens for the bending test in "wet" conditions were dipped in water for 24 hours = wet specimens. The other test specimens, for the tests in dry conditions, were dried at 103 ± 2°C to achieve 0 % of moisture content. After that, the specimens meant for dry conditions were weighed and air-conditioned to equilibrium moisture content under standard laboratory conditions = dry specimens.

Measuring physical properties

Bending strength and elasticity were measured by 3 point bending tests according to the ČSN EN 310 (1995) standard using the test specimens 50 x 400 x 15 mm in both wet and dry conditions. The moisture content was determined by the gravimetric method according to ČSN EN 322 (1994). The thermal conductivity was measured on the test specimens 300 x 300 x 30 mm made from two pieces of plates of formula 4. Measuring was conducted according to the ČSN 72 7012-3 (1994) standard with medium temperature of measurement was +10°C and gradient of temperature 10°C. The water vapour permeability was measured according to ČSN EN ISO 12572 (2002) called under conditions B - i.e. temperature 23±1°C and gradient of air humidity φ = 0 / 85 %. It was measured on flow of water vapour through an area with a diameter of 100 mm on specimens from plates of formulas 2 and 7 and on specimens from the cement-chip board CETRIS Basic (producer: CIDERM Hranice na Moravě, the Czech Republic).

Statistic analysis

The measured data were statistically analysed by the Statistica 8 and the Calc 2.0 (OpenOffice). An exploratory data analysis (EDA) was done, assessment of basic characteristics and comparisons were made by Anova, Mann–Whitney U tests, Wald–Wolfowitz tests and Kolmogorov–Smirnov tests.

RESULTS AND DISCUSSION

The strength and elasticity in bending, the moisture content and the density of panels

Tab. 3: MOR – the modulus of rupture in the three-point bending, moisture and density of the "wet specimens" (the specimens dip in water for 24 hours before the testing). The "minimal number of specimens ($nmin^{\pm 10\ \%}$)" is estimation of minimal number of the specimens which will be necessary to determine the arithmetic mean of the MOR with accuracy of ±10 % on the significance level α = 5 %.

Formula	Moisture of tested samples	Density at moisture w = 0 %	Number of measurements	Bending elasticity			
				Arithmetic mean	Sample standard deviation	Minimal number of samples	Median
	w	ρ_0	n	MOE	σ^{MOE}	$n_{min}^{\pm 10\ \%}$	MOE_{med}
No.	(%)	(kg.m⁻³)	(-)	(N.mm⁻²)	(N.mm⁻²)		(N.mm⁻²)
1	60.3	905	5	2985	304	20	2974
2	68.1	872	5	1706	942	565	1680
3	61.9	862	6	2212	1497	464	1514
4	70.4	808	6	1095	622	214	1338
5	69.1	834	6	1345	455	76	1292
6	49.8	1099	5	2390	3628	30	3659
7	75.7	793	6	1253	193	16	1281

Tab. 4: MOE – the modulus of elasticity in the three-point bending tests of the wet specimens (the specimens dip in water for 24 hours before the testing). The minimal number of specimens ($nmin^{\pm 10\ \%}$ is estimation of minimal number of the specimens which will be necessary to determine the arithmetic mean of the MOE with accuracy ±10 % on the significance level α = 5 %.

Formula	Moisture of tested samples	Density at moisture w = 0 %	Number of measurements	Bending elasticity			
				Arithmetic mean	Sample standard deviation	Minimal number of samples	Median
	w	ρ_0	n	MOE	σ^{MOE}	$n_{min}^{\pm 10\ \%}$	MOE_{med}
No.	(%)	(kg.m⁻³)	(-)	(N.mm⁻²)	(N.mm⁻²)		(N.mm⁻²)
1	60.3	905	5	1.5	0.33	40	1.5
2	68.1	872	5	1.0	0.23	39	1.1
3	61.9	862	6	1.7	0.60	85	1.5
4	70.4	808	6	1.0	0.48	141	1.1
5	69.1	834	6	1.4	0.29	28	1.4
6	49.8	1099	5	-	-	-	-
7	75.7	793	6	1.3	0.21	19	1.3

Tab. 5: MOR – the modulus of rupture in the three-point bending, moisture and density of the "dry specimens" (the specimens conditioned on air in standart laboratory conditions). The "minimal number of specimens ($nmin^{\pm 10\ \%}$)" is the estimation of minimal number of the specimens which will be necessary to determine the arithmetic mean of the MOR with the accuracy ±10 % with the significance level α = 5 %.

Formula	Moisture of tested samples	Density at moisture w = 0 %	Number of measurements	Bending elasticity			
				Arithmetic mean	Sample standard deviation	Minimal number of samples	Median
	w	ρ_0	n	MOE	σ^{MOE}	$n_{min}^{\pm 10\ \%}$	MOE_{med}
No.	(%)	(kg.m⁻³)	(-)	(N.mm⁻²)	(N.mm⁻²)		(N.mm⁻²)
1	6.9	941	20	1.4	0.26	15	1.5
2	5.5	915	17	1.0	0.30	43	0.9
3	6.8	858	19	2.0	0.43	22	1.9
4	5.6	849	20	1.9	0.25	8	1.9
5	5.7	892	16	2.5	0.61	27	2.4
6	5.6	1095	10	-	-	-	-
7	5.6	845	20	2.2	0.52	24	2.2

After taking out the plates from mould after 28 days, panels formula 6 were cracked and so inapplicable for practical use. To this reasons in the tables there are no values of the MOR and the MOE to the formula 6.

Tab. 6: MOE – the modulus of elasticity in the three-point bending tests of the "dry specimens" (the specimens conditioned on air in normal laboratory conditions). The "minimal number of specimens (nmin$^{\pm 10\ \%}$)" is the estimation of minimal number of the specimens which will be necessary to determine the arithmetic mean of the MOE with the accuracy ±10 % with the significance level α = 5 %.

Formula	Moisture of tested samples	Density at moisture w = 0 %	Number of measurements	Bending elasticity: Arithmetic mean	Bending elasticity: Sample standard deviation	Bending elasticity: Minimal number of samples	Bending elasticity: Median
	w	ρ_0	n	MOE	σ^{MOE}		MOE_{med}
No.	(%)	(kg.m^{-3})	(-)	(N.mm^{-2})	(N.mm^{-2})	$n_{min}^{\ 10\ \%}$	(N.mm^{-2})
1	6.9	941	18	1305	222	13	1338
2	5.5	915	13	757	256	55	686
3	6.8	858	19	1191	143	7	1186
4	5.6	849	18	1235	251	19	1303
5	5.7	892	16	1807	547	42	1906
6	5.6	1095	10	1134	404	124	1056
7	5.6	845	20	1237	213	13	1256

Comparison of MOR and MOE measured at wet and dry conditions

There is no significant difference between the MOR of the wet and dry specimens except the specimens formula 5. The specimens of the formula 5 (without waterglass) had significantly higher bending strength in the "dry" condition. It is possible to presume that the waterglass in the mixture had an impact on the water resistance (Fig. 1). The comparison of the modulus of elasticity (MOE) did not show any significant differences between the tests of the "wet" and "dry" specimens (Fig. 2).

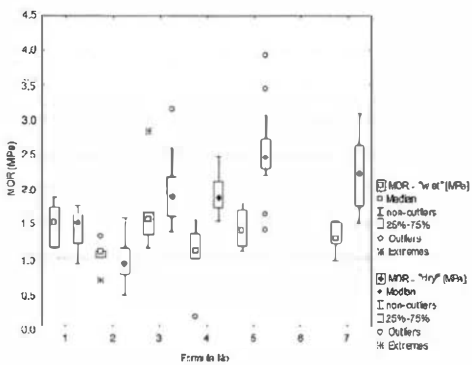

Fig. 1: The bending strength (MOR) of "wet" and "dry" specimens.

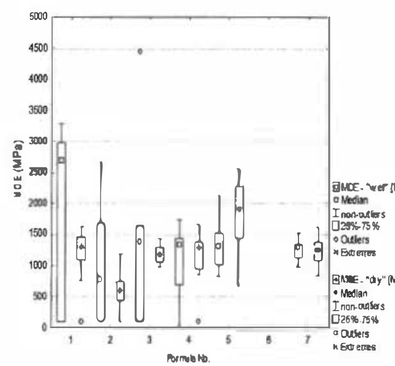

Fig. 2: The bending elasticity (MOE) of the "wet" and "dry" test specimens.

Impact of the water-hydraulic lime ratio and the ratio of hemp on the bending strength

The test specimens formula 1 with lower ratio of hemp and water (υ = 0.6) had higher strength than the specimens formula 2 which had the same ratio of hemp but higher ratio of water (υ = 0.7) (Fig. 3). In contrast, the specimens with the higher proportion of hemp has no detectable differences in strength between the specimens formula 3 with the lower water ratio (υ = 0.6) and recipe 4 with the higher water ratio (υ = 0.7). Generally, the higher water ratio causes lower viscosity of the mixture and thus better miscibility and the mixture also better fills the mould. On the other hand, more water in the mixture causes bigger porosity in a solidified matrix. The bigger porosity has influence on the strength of the matrix and thus also on strength of composite as a whole. The strength of specimens with the higher water ratio was probably significantly lower just at the specimens formula 2 because of lower volume of hemp reinforcement and higher volume of hydraulic lime than in formula 3 and 4. The higher volume of hydraulic lime matrix caused biggest influence by its porosity on strength of the whole composite.

The strength of specimens was higher with the higher ratio of hemp reinforcement in the both water-hydraulic lime ratios. More than 10 portions of hemp were originally planned, but during the first pre-tests of stirring mixtures it was found out that it is a problem to stir the mixture with a markedly higher ratio (above 10 %) of hemp fibres. The hemp fibres made clumps and clots with less connectivity of the fibres between each other.

One of possible next researches is to use hemp fibres which are only several millimetres long. Because of this, it might be possible to rise the ratio of the fibres, which could enhance miscibility and connectivity among the particular fibres.

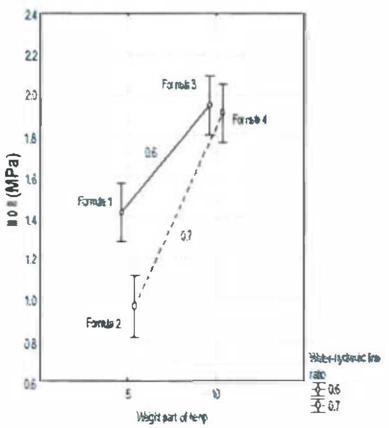

Fig. 3: The influence of the water-hydraulic lime ratio and the ratio of hemp on the bending strength of the "dry" test specimens.

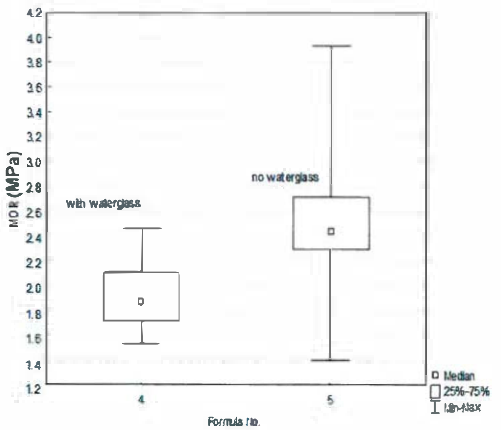

Fig. 4: The bending strength of the specimens with and without waterglass (formula 4 and 5).

The influence of the mineralization agent on the bending strength

As the information about influence of mineralization agents varies (Bydžovský and Dufka 2009; Keprdová and Bydžovský 2009), 5 weight parts of waterglass were added in formulas 1 – 4 and 7. And for comparison, in formula 5 no waterglass was added. The mixture of formulas 4 and 5 consisted of the Trassit Plus hydraulic lime and 10 weight parts of hemp. Water-hydraulic lime ratio in formula 4 and 5 was υ = 0.7. As an extra ingredient, waterglass was added to the mixture formula 4. The results of the bending tests did not prove significant influence on the bending strength of the tested specimens (Fig. 4 and Tab. 7).

Tab. 7: The statistic tests of the bending strength (MOR) of the specimens formula 4 (with waterglass) and specimens formula 5 (without waterglass).

Test	P value
Mann-Whitney U test	0.054789
Wald–Wolfowitz test	0.054585
Kolmogorov–Smirnov test	p < .05

Comparison of bending strength of specimens from the Trassit Plus hydraulic lime (Baumit) and the HL 5 Hydraulic lime (VUSTAH)

Comparing the test specimens with the Trassit Plus hydraulic lime (formula 4) to the specimens with HL 5 Hydraulic lime (formula 7) did not show a significant difference in bending strength (Fig. 5, Tab. 8).

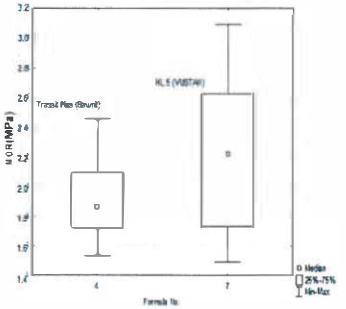

Fig. 5: Influence of type of hydraulic lime on bending strength (MOR): formula 4 and 7.

Tab. 8: The statistic tests of the bending strength (MOR) of the specimens formula 4 (with the hydraulic lime Trassit Plus) and the specimens formula 7 (with the Hydraulic lime HL 5).

Test	P value
Mann-Whitney U test	0.000520
Wald–Wolfowitz test	0.007715
Kolmogorov–Smirnov test	p < .001

Resistance to water vapour diffusion

Tab. 9: The resistance to water vapour diffusion of the test specimens formula 4 (hydraulic lime Trassit Plus - Baumit), formula 7 HL 5 Hydraulic lime (VUSTAH) and the cement-chips board "CETRIS Basic" (producer: CIDERM Hranice na Moravě, a.s.).

Formula No./ Material	Number of samples	Resistant to water vapour permability		Thickenss of samples	
		Mean	Sample standard dev.	Mean	Sample standard dev.
	(pcs.)	μ (-)	(-)	(mm)	(mm)
4 (Trass. sitPlus)	3	33.6	1.68	15.98	0.55
7 (Hyd. Lime HL 5)	3	17.3	2.23	17.76	1.12
CETRIS Basic	1	78.0	-	16.40	-

The specimens with hydraulic lime proved significantly lower resistance to water vapour permeability. The test formula 7 specimens with the HL 5 Hydraulic lime (VUSTAH) reached half the resistance in comparison to the formula 4 specimens with the Trassit Plus hydraulic lime (Baumit) and 4.5 times lower resistance in comparison to the CETRIS Basic cement-chips board (Tab. 9).

From the point of view of low resistance to water vapour and strength properties the HL 5 Hydraulic lime (VUSTAH) is more favourable than the Trassit Plus (Baumit).

Thermal conductivity

When comparing the thermal conductivity of the sample formula 4, which was determined on 0.182 $W.m^{-1}.K^{-1}$, with thermal conductivity of wood in radial direction, e.g. fir 0.147 $W.m^{-1}.K^{-1}$, oak 0.200 $W.m^{-1}.K^{-1}$ Požgaj et al. (1997), the thermal conductivity of the tested material was such as wood.

Tab. 10: Thermal conductivity of the specimen formula 4 containing the Trassit Plus hydraulic lime, 10 weight parts of hemp and waterglass.

Formula 4	Thermal conductivity $\lambda (W.m^{-1}.K^{-1})$
Mean	0.1822
Number of measurements	3
Sample standard deviation	0.0032

CONCLUSIONS

The aim of the research of plate materials made mainly from hydraulic lime and hemp was optimize their quality for wooden constructions. The strength and modulus of elasticity in three-point bending, moisture impact, water vapour permeability and thermal conductivity were measured at test specimens made from the panels of seven different formulas of composition.

Hydraulic lime has generally lower strength properties than cement, and it is therefore expected that the new hydraulic-lime based materials have lower strength properties than the cement-based materials. However the bending strength of the new hydraulic-lime based materials was much lower than it had been expected. The hydraulic-lime-based panels had almost the same bending strength properties both in the "dry" and the "wet" conditions. The waterglass has no significant influence on the bending strength of the tested specimens.

The tests confirmed that the water vapour resistance of hydraulic-lime-based materials is lower than the water vapour resistance of cement-based materials. It has turned out that using the HL 5 Hydraulic Lime (produced by the VUSTAH, a.s, Brno) is more convenient in terms of mechanical strength and lower diffused resistance of steam.

It has been confirmed that higher rate of hemp increases bending strength of the composite. It is assumed that bending strength will continue to grow to a certain limit if the proportion of hemp reinforcing component increases. One of the possible directions in further researches is to increase the proportion of hemp fibres as the reinforcement in the mixture. Increasing the hemp fibres ratio together with good miscibility is possible by using shorter fibres and by changing the technology of mixture layering and pressing. Another way is to test different setting and hardening conditions. Thermal conductivity of the tested material is $\lambda = 0.1822$ $W.m^{-1}.K^{-1}$.

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Petr Hamšík, Pavel Král
Mendel University in Brno
Faculty of Forestry and Wood Technology
Zemědělská 1
613 00 Brno
Czech Republic
Corresponding author: petrham@centrum.cz