Resilient Structures and Sustainable Construction
Edited by Pellicer, E., Adam, J. M., Yepes, V., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-4-8

A STUDY OF HEMPCRETE PROPERTIES USING NATURAL HYDRAULIC LIME – MIX DESIGN, MECHANICAL PROPERTIES, AND MICROSTRUCTURE

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In the article, an analysis of tensile strength fiber hemp and hemp fiber linkage analysis in the cement matrix is presented. The average tensile strength of the fibers of untreated hemp amounts to 764 MPa and the calculated modulus of elasticity amounts to 30 GPa. A test of pulling fibers from the cement matrix has shown that when increasing the length linkage, the maximum pulling force increases while the clamping strength does not significantly change. In the laboratory, a mixture of hemp concrete where a portion of mineral aggregate was replaced with hemp hurd was prepared. Results of the examination of the microstructure of hardened lime binder have shown that the hardened NHL mixture is porous and vapor-permeable while the hardened HL mixture is thick and compact. The goal was to create a prototype hemp concrete mixture that can be used for production of prefabricated elements with tensile strength between 10 and 25 MPa.

Keywords: Composites, Hemp fibers, Hemp concrete.

1 INTRODUCTION

Hemp concrete, or Hempcrete, is biocomposite, ecological material, that consists of a mixture of hemp hurds, mineral aggregate and binder. The binder can be cement, lime or a mixture of both. Conventional hemp concretes that are most commonly used in construction practice are concretes using natural hydraulic lime (NHL) as a binder. They can be classified as: Lightweight Hempcrete, Wall Hempcrete, Floor Hempcrete, Hemp Plaster. Since the need for hemp concrete is on the rise, there are many modifications of hemp concretes known in the construction practice with mostly cement as a binder and various additives. In this article, we will show experimental work comprising of: research on mechanical properties of hemp fibers, which are used for the production of hemp concretes, research on hemp fibers clamping in the cement matrix, research on microstructure and physical properties of binders and producing a prototype of the mixture of hemp concrete with the aim of producing prefabricated elements.

2 RESEARCH ON MECHANICAL PROPERTIES OF HEMP FIBERS

2.1 Tensile Test of Industrial Hemp Fibers

Tensile test on five samples of untreated industrial hemp fibers was made on the universal machine for static and dynamic mechanic testing of materials Zwick Roell Z010 Testing

Machine. For analysis of the results Zwick Test Xpert software was used. Tensile test was executed so that the hemp fibers were clamped in the jaws of the machine and were monotonically loaded by the constant speed of moving the head of the test machine in the direction of the force of 0.01 mm/s until they break. The test was executed on untreated industrial hemp fibers. The specimens were completely untreated natural fibers of different lengths and diameters. Tensile strength of hemp fibers was determined as the ratio between maximum force and the corresponding surface of the fibers. Since the hemp fibers are of very irregular geometry, to determine a cross-sectional area of fibers an equation from literature was used (Asprone *et al*. 2011).

$$A = \frac{P}{l\gamma} \tag{1}$$

where P represents the weight of the fiber, l the length of fiber and γ specific weight of fiber, in Eq. (1). Table 1 shows the results of tensile tests.

Table 1. Tabular presentation of the results of the tensile tests.

Sample	**F(N)**	**ε (%)**	**σ (MPa)**	**E (GPa)**
1	38.34	3.65	641	20.4
2	50.67	2.40	847	42.4
3	36.77	3.31	615	25.2
4	54.18	4.51	906	30.0
5	48.59	3.25	813	30.9
Average	45.71	3.42	764	29.8
Standard deviation	7.73	0.76	129	8.21

2.2 Pull – Clamping Test of the Fibers

For the test, 24 samples were prepared. Completely untreated, natural hemp fibers were used for this test as well. The purpose of the test was to determine clamping strength between cement matrix and various lengths of clamping. In literature, which addresses such tests, the test is called one sided test pulling. When the pull length reached 30 mm, pull test was stopped. For the test, a cement matrix made from fine grained concrete was used. This fine-grained concrete was mixed from cement CEM I 42.5 N and standard sand. Water/cement ratio was 0.5, weight ratio binder/aggregate was 1:1. Samples were built in special molds, as shown on the Figure 1.

Figure 1. Molds for pull – clamping test samples.

Samples stayed covered with polyethylene foil for in the mold for 24 hours, then the mold was removed and the samples were placed in a climate chamber at a temperature 20°C and relative humidity 98% for six days. For the pull test the universal machine Zwick Roell Z010 Testing Machine was also used. Speed of the head moving was 2 mm/min, free length of the fiber was 15 mm. An estimate of the apparent shear strength τ_{app} (Miller *et al*. 1987) was calculated according to Eq. (2):

$$\tau_{app} = \frac{F_{max}}{\pi d_f l_e} \tag{2}$$

Where F_{max} mean maximum pull-out force, d_f equivalent diameter of the fibers and l_e length of the fiber clamping (mm). Tabular presentation of the pull force results is shown in Table 2, calculated results which were obtained on the basis of the pull test are shown in Table 3.

Table 2. Tabulated summary of pull test results.

l_e (mm)	10	20	30	40
Sample	**F_{max}(N)**	**F_{max}(N)**	**F_{max}(N)**	**F_{max}(N)**
1	2.91	5.83	5.23	13.20
2	4.02	4.13	7.16	10.77
3	3.39	4.82	6.01	12.61
4	2.72	6.43	4.98	7.26
5	3.81	4.02	7.32	12.03
6	3.79	4.77	7.82	11.93
Average	3.44	5.00	6.42	11.30
Standard deviation	0.53	0.95	1.18	2.14

Table 3. Calculated parameters from the results of the pull test.

l_e (mm)	**τ_{app} (MPa)**	**l_c (mm)**
10	0.142	0.323
20	0.136	0.363
30	0.247	0.422
40	0.218	0.448

3 RESEARCH ON MICROSTRUCTURE AND PHYSICAL PROPERTIES OF BINDERS

Microstructure control was executed on hardened sample from cement paste and hardened sample made with lime binder with a standard consistency using optical stereo microscope Olympus SZX and scanning electron microscope Quanta 3D. Cement sample were made from pure Portland cement CEM I 42.5 N. Lime sample were made from natural hydraulic lime NHL(5) and hydraulic lime. For every type of binder, five samples were made. Hardened cement sample were kept at a temperature 20°C and relative humidity of 98% for 28 days, hardened lime sample were kept in standard lab conditions for an equal period of time. After the process, the fracture patterns of samples were visually examined and such findings were made: there were no cracks on the hardened cement sample, there was one microcrack on one hardened NHL sample and there were multiple microcracks on every hardened HL sample. The microstructure of the fractured surfaces, which was controlled by scanning electron microscope is shown in Figure 2.

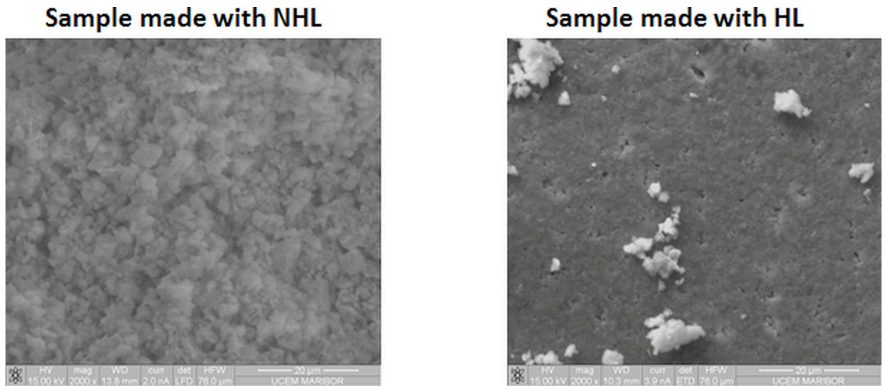

Figure 2. The microstructure of the fracture of the sample from the NHL - SEM (SEI) (left), the microstructure of the fracture of the sample from the HL - SEM (SEI) (right).

4 MAKING OF THE PROTOTYPE MIXTURE OF HEMP CONCRETE WITH THE AIM OF MAKING PREFABRICATED ELEMENTS

When making hemp concrete firstly a commercial mixture was made, that mixture is widely known and usually used when building houses from natural materials. The mixture consists of lime and cement binder, hemp hurd and water. Such material is used as a filler for wooden skeleton structures where it is intended as isolation because of its low compressive strength. Hemp lime composite is usually divided in one part binder, 1.5 part water and four parts of hurd. The binder consists of four parts of natural hydraulic lime and one part of cement (Sekolovnik and Lubej 2016). Compressive strength results of hemp concrete are shown in Table 4.

Table 4. Compressive strength “Hempcrete – Hemp Lime Composite”.

Specimen	$\rho(kg/m^3)$	$f_{c,\,cube}$
1	650	0.10
2	674	0.16
3	686	0.18
Average	-	0.15

4.1 Concrete Mix of Hemp and 0/4 mm Aggregate

For hemp concrete production, a mixture of mineral aggregate with fractions of mineral aggregate 0/4 and 4/8 mm was made. Shares of individual fractions were determined using the EMPA maximum curve. In the first mixture, a part of mineral aggregate of 4/8 mm granulation was replaced with hemp hurd. Calculation of volume of the 4/8 mm aggregate:

- m_{agr} = 415 kg (mass of the 4/8 mm aggregate)
- ρ_{agr} = 2.7 kg/dm3 (density of the aggregate)

In the next step, aggregate volume represented the volume of the hurd from which mass of the hurd that replaced 4/8 mm aggregate in the mixture was claculated.

- ρ_{pez} = 0.125 kg/dm^3 (hurd density)
- V_{pez} = 154 dm^3 (hurd volume)

Based on the calculation 415 kg of aggregate in the mixture was replaced with 19.3 kg of hemp. On first sight the difference seems enormous, because mass of the hurd represents only 4.7 % of the mass of aggregate that was replaced. Despite the obvious difference in mass, the volume of the aggregate is the same as the volume of the hemp. The reason for being that the density of the aggregate (2.7 kg/dm^3) is significantly higher than the density of hurd (0.125 kg/dm^3). Mass of the 0/4 aggregate in this mixture was obtained with the help of EMPA maximum graininess curve. Collective mass of the 0/8 mm aggregate used for production of concrete cubes amounted to 1,595 kg, from which there was 1,180 kg 0/4 mm aggregate and 415 kg 4/8 mm aggregate. Sift through a sieve amounted to 60.35 % which means that the mass of the 0/4 aggregate is 1,013 kg. Compressive strength results of hemp concrete with 0/4 mm aggregate are given in Table 5.

Table 5. Compressive strength Hemcrete – Hemp Lime Composite.

Specimen	ρ (kg/m^3)	$f_{c.\ cube}$
1	1937	24.4
2	1930	23.6
Average	-	24.0

4.2 Concrete Mix of Hemp Hurd and 2/4 Aggregate

In this mixture, we wanted to increase the amount of hemp hurd. Regarding the first mixture where hemp replaced 4/8 mm aggregate, in the second mixture 0/2 mm aggregate was replaced in addition to that. That means that the only aggregate that stayed in the mixture was 2/4 mm aggregate which allowed a higher compressive strength than 0/2 mm aggregate to be achieved. In the mass of the aggregate, which amounted to 1,013 kg, 380 kg of the 0/2 mm aggregate (37 % from the total) was replaced and 633 kg 2/4 mm aggregate was left (63 % from the total). Mass of the hurd was calculated after determining the volume of the aggregate that was replaced, as already described in section 4.2. Volume calculation of 0/2 mm aggregate:

- m_{agr} = 380 kg (mass of the aggregate 4/8 mm)
- ρ_{agr} = 2.7 kg/dm^3 (density of the aggregate).
- Volume 141 dm^3 is the same for both aggregate and hemp hurd.
- Hemp hurd mass calculation using the volume:
  - ρ_{pez} = 0.125 kg/dm^3 (hurd density)
  - V_{pez} = 141 dm^3 (hurd volume).

Table 6. Compressive strength of hemp hurd with 2/4 mm aggregate.

Specimen	ρ (kg/m^3)	$f_{c.\ cube}$
1	1,698	12.1
2	1,700	11.2
Average	-	11.7

According to the calculation 380 kg of 0/2 mm aggregate in the mixture was replaced with 17.6 kg of hurd. Here also applies that the mass difference is enormous but the volume is the same for both aggregate and hurd (Sekolovnik and Lubej 2016). Compressive strength of hemp concrete with 2/4 mm aggregate is shown in Table 6.

5 RESULT ANALYSIS

In the tensile test of individual fibers a linear behavior up to the burst was shown. The average tensile strength was 764 MPa, which is comparable to the tensile strength of reinforced steel. Elasticity module that averages at 30 GPa allows good mechanical compatibility of hemp fibers with masonry construction when trying to strengthen or restore them (Kovač and Ivanič 2016).

The pull test showed that when increasing the length of clamping maximum pulling force increases, while strength of the clamping does not significantly change. Critical fiber length also does not significantly change. From these findings, we can conclude that strength of clamping and critical length of the fiber are two material constants of the composite system (Kovač and Ivanič 2016). With that research, the hypothesis that it is possible to construct prefabricated elements with a mix of lime and cement binder from hemp concrete is confirmed. Based on the result analysis we can conclude that with increasing the amount of hemp and decreasing the amount of aggregate in the concrete its compressive strength decreases. The lime amount also has a great impact on the compressive strength, because with an increase of added lime compressive strength decreases (Sekolovnik and Lubej 2016). Results of the examination of the microstructure of hardened lime binder have shown that the hardened NHL mixture is porous and vapor-permeable while the hardened HL mixture is thick and compact.

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