DURABILITY AND HYGROTHERMAL PERFORMANCE OF BIO-BASED MATERIALS IN NORTHERN EUROPEAN CLIMATE

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Abstract

Bio-based building materials (3BMs) are one of the solutions for how the construction industry can mitigate its negative environmental impact because of energy consumed in material production and due to the insufficient thermal insulation of buildings, as, in general, these materials sequester CO_2 in them and have low thermal conductivity. One of the obstacles that these materials must overcome in order to become more widely accepted is the general belief that they are inferior to traditional building materials in terms of durability – mostly biodegradation. The objective of this study is to assess biodegradation of 3BMs in real operating conditions. In order to achieve it, this article analyses the in-situ hygrothermal performance of 3BMs in the Northern European climate, situated in various parts of the structure, to measure their operating conditions with relative humidity sensors when subjected to humid continental climate conditions. The results are then used to simulate the humidity conditions in the laboratory for the biodegradation tests. Several hemp-based materials are tested as well as traditional construction materials for reference. The materials are inoculated with a mixture of six different fungi that are typical to 3BMs and kept in the set laboratory conditions. After a period of 45 days and 4 months the pH values of materials are tested, fungal growth is evaluated, and genus determined according to macromorphological and micromorphological characteristics. Preliminary results indicate that 75% RH is a safe level for 3BMs with mineral binder, but when exposed to 99% RH for longer periods fungal growth is observed, but only when reduced binder content is used and pH level drops below pH 9.30. The overall results indicate that 3BMs are usable in Northern European climate conditions.

Keywords:

Hemp concrete, hemp-lime concrete, durability, biodegradation, hygrothermal performance

1 INTRODUCTION

Bio-based building materials (3BMs) – self bearing insulation materials made from porous organic filler, usually agricultural waste, and mineral binder - are one of the solutions for how to mitigate the negative environmental impact from the construction industry by providing low carbon and energy efficient building materials [Fang 2018]. It has been shown through various research projects using Life Cycle Assessment (LCA) that the use of 3BMs in buildings lowers their overall impact [Penaloza 2016] mostly through CO_2 sequestration during the growth of the bio-based component of 3BMs and the use of low embodied energy binders [Arrigoni 2017; Pretot 2014; Sinka 2018]. And as the organic fillers are fast-growing compared to forest products, they don't require a long rotation period, and can store more carbon [Pittau 2018].

These materials also exhibit excellent hygrothermal properties of low thermal conductivity from 0.07 to 0.1 W/m·K [Collet 2014], high vapour permeability of 10^{*11} – 10^{-10} kg/m·s·Pa [Moujalled 2018] and a high moisture buffering capacity of MBV>2 [Collet 2013]. These properties allow the provision of good thermal performance and indoor climate [Costantine 2018]. But as these materials are used without a vapour-tight barrier [Latif 2018] the relative humidity inside the wall can reach 80-90% [Moujalled 2018; Rahim 2017], which can be considered a critical moisture level for the growth of mould [Johansson 2012].

The bio-based filler component of 3BMs is also the main source of concern regarding the durability of these materials compared to traditional mineral based building materials; 3BMs are more susceptible to the growth of mould [Palumbo 2017; Viel 2019] due to their organic origins.

In this research the hygrothermal performance of 3BM – hemp-lime concrete with different binders are tested in real conditions in Latvia using a specially designed measurement system that also measures relative humidity at various depths of wall construction. This data is analysed to determine the relative humidity levels at which the 3BMs must operate. These results are, in turn, used to set boundary RH conditions for the biodegradation tests, where the samples with identical mixtures to the measured walls are inoculated with a blend of 6 different fungi and incubated to determine the resistance from mould.

2 MATERIALS AND METHODS

2.1 Materials and mixtures

In this research two different binders were used – experimental (FHL) and commercial (HL). Experimental binder (FHL) consists of 60% hydrated lime CL90 produced by *Lhoist Poland Ltd* and 40% metakaolin that is a by-product of porous glass production by *"Stiklaporas" UAB* in Lithuania. Commercial binder (HL) used in hemp-lime construction in Latvia consists of 70% hydrated lime, 20% hydraulic lime and 10% additives (HL).

Filler – hemp shives are described in previous research, as well as both binders [Sinka 2017]. Two different compositions are used in the research - HL and FHL with a mass ratio of shives:binder:water 1:2:2.

2.2 Wall assemblies

Three different wall assemblies that are constructed using previously described mixtures are examined in this paper and shown in Tab. 1 - 200 mm thick hemp-lime experimental panel without internal and external finishes (A) using FHL mixture, wall of existing hemp-lime building consisting of wind barrier membrane, 250 mm hemp-lime layer (with mixture HL) and 50 mm thick wood wool insulation (B), and 80 mm hemp-lime blocks (FHL mixture) used to insulate an existing 200 mm thick vertical wooden stud building wall (C).

2.3 Wall moisture measurements

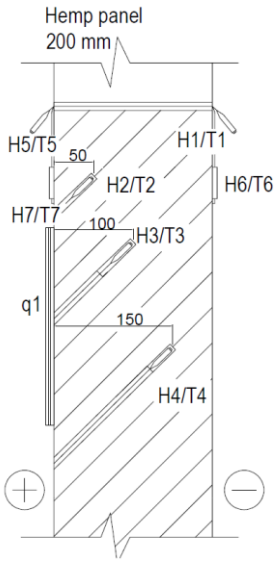
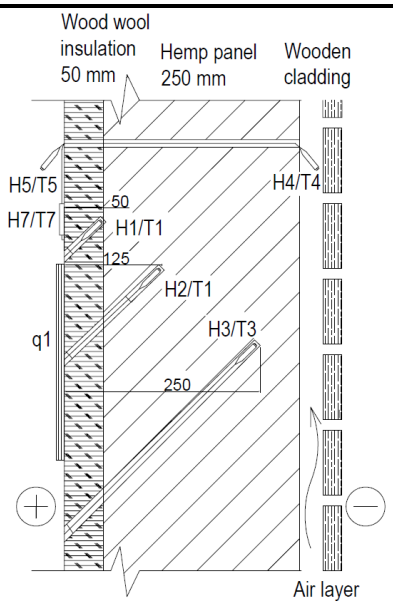
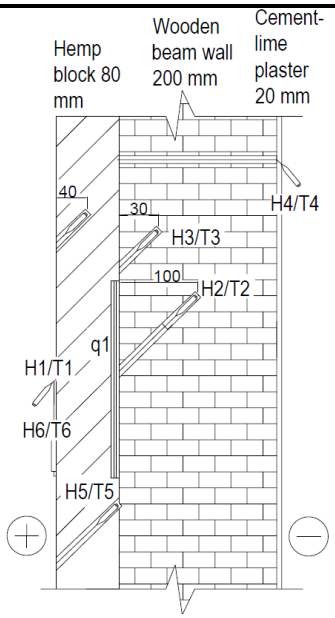
The device for wall in-situ measurements were specially designed and produced, it consists of 7 temperature/humidity sensors and 1 heat flow sensor. The data is logged and sent through the 4G network to the server.

The main components of the system are the microcontroller *MSP430F2274*, computer *Raspberry Pi* and the temperature and humidity sensors *SHT75* which consist of two sensors in a single housing, are highly accurate (±0.3°C; ±2%) and come fully calibrated and have low power consumption.

The placement of sensors differs for all three types of walls, see Tab. 1. For the first wall type (A) two sensors were placed on the outside – the first on the surface, the second – at 100 mm from the wall to record outside conditions, three sensors in the panel at different depths – 50, 100 and 150 mm, and two sensors indoors. For the second wall type (B) the outdoor temperature sensor was placed in the air barrier, three sensors in the panel at different depths – 50, 125 and 250 mm, and two sensors indoors. For the third wall type (C), one sensor was placed on the outside, two sensors are placed in the wooden part of the wall – one is placed on the borderline between the blocks and the existing wall, one – in the hemp-lime blocks, and two – indoors.

Sensors were placed in the walls after their construction, 12mm holes were drilled, sensors placed inside, the rest was filled with wood wool, the end of the opening was sealed with impermeable sealant.

Tab. 1: Wall types used in the research and their description

Wall type	A	B	C
Cross-section of the wall			
Mixture type	FHL	HL	FHL
Total wall structure thickness, mm	200	300	280
Biocom-posite thickness, mm	200	250	80

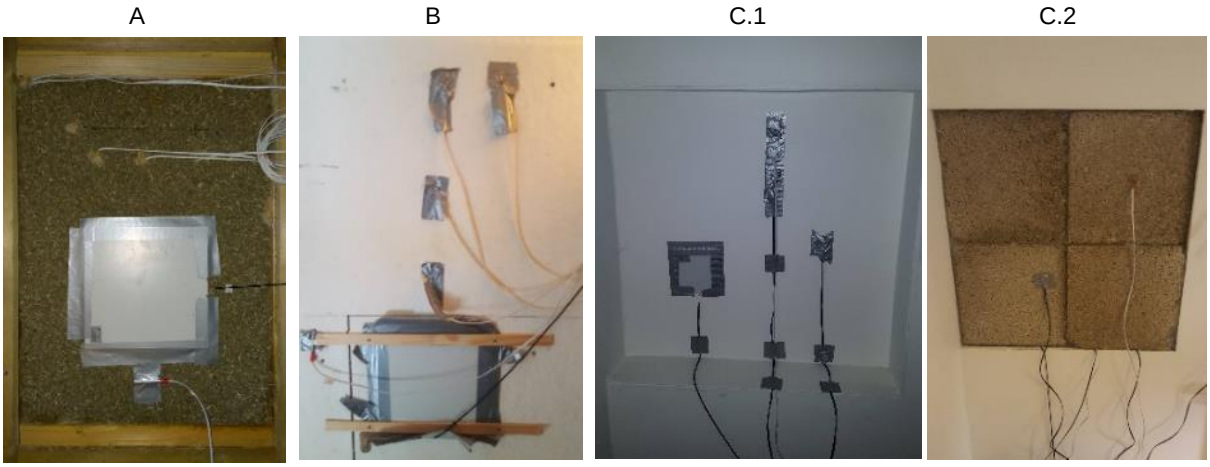


Fig. 1: Pictures of experimental walls (see Table 1); C.1 and C.2 corresponds to type C without and with hemp block installed on inner surface

2.4 Biodegradation tests

Biodegradation tests were performed by artificially inoculating material samples with 6 different types of fungal spores and incubating samples in 75% and 99% RH – boundary relative humidity levels were chosen after wall moisture measurement tests for two periods - 45 days and 4 months. 75% RH humidity was ensured by a sodium chloride saturated salt solution which provides 75.47 ± 0.14 RH at 20 °C and was kept in the climate chamber together with the samples. 99% RH was provided by spraying each sample with 3 ml of sterile water two times a week. Assessment of fungal growth was performed visually using the scale from 0 to 4 according to the ASTM C 1338-96 Standard test method for determining the fungi resistance of insulation materials and facings:

0 No growth detected microscopically
1 Microscopical growth present
2 Microscopical growth covering the whole surface
3 Macroscopical (visible to the naked eye) growth present
4 Macroscopical growth covering >80% surface

After the visual assessment, 1.0 ± 0.5 g samples were separated from large samples, washed with sterile water and incubated on an agar medium for 5-7 days. After incubation the fungal genus was identified according to macromorphological (appearance of colonies) and micromorphological (mycelium, conidia and spore shape) characteristics.

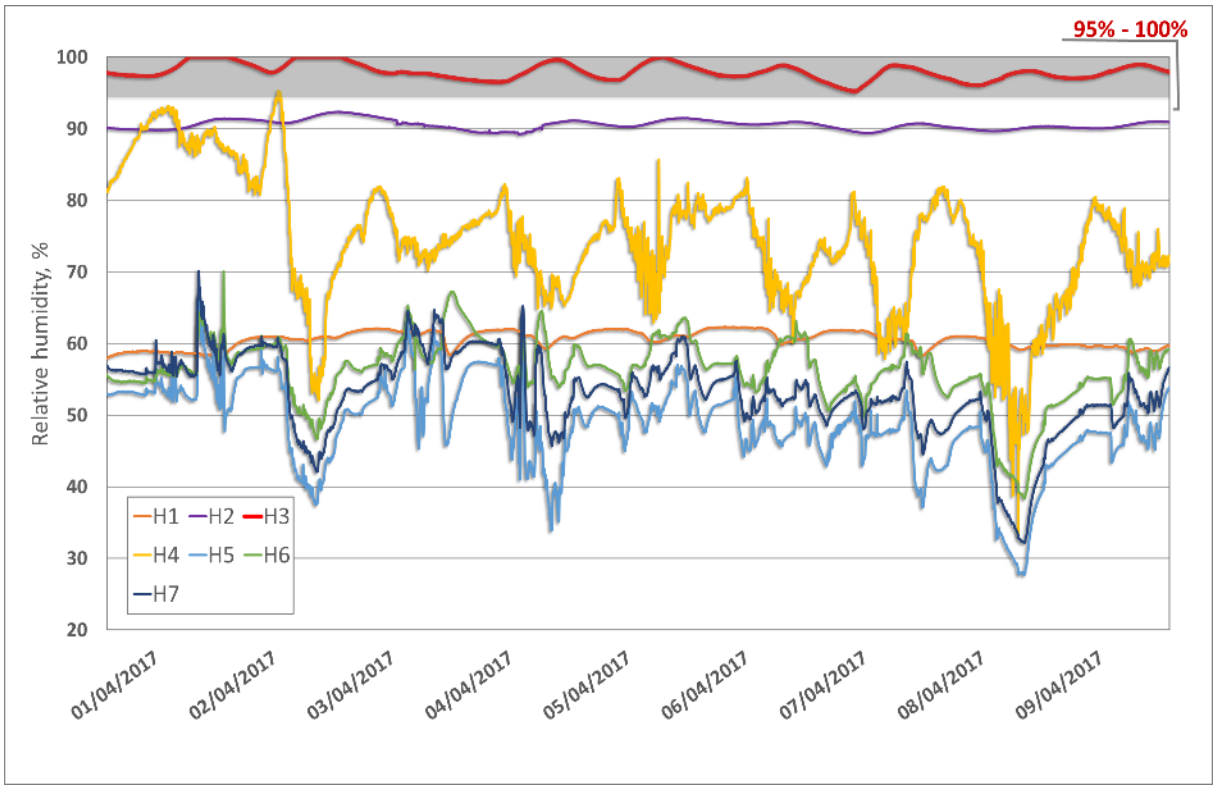


Fig. 2: Relative moisture measurements inside wall type B from 1st to 9th of April 2017

Tab. 2: Maximum humidity range of all wall types outer layers

Wall type	A	B	C
Drying - winter	95-99%	90-99%	-
Drying - summer	80-90%	85-95%	-
Operating - winter	68-77%	65-80%	64-70%
Operating - summer	64-75%	52-64%	55-60%

For each material the microbiological stability was determined for inoculated specimens (marked with F) and control specimens (marked with K). Three different concentrations of binders – 100 %, 50 % and 20 % – were tested for both mixtures at 99% RH.

The six following different fungal spores were used for inoculation:

- *Aspergillus versicolor*
- *Penicillium chrysogenum*
- *Alternaria alternata*
- *Cladosporium herbarum*
- *Chaetomium sp.*
- *Trichoderma asperellum*

After the fungi were grown in Petri dishes, suspension in distilled water from their spores and mycelium were produced. Suspensions were prepared and mixed to OD_{545} 0.16. The samples were inoculated with 3 ml fungal suspension.

To evaluate the biodegradation of the samples a reference bio-based insulation was chosen for the tests – commercially available wood fibre flexible insulation.

3 RESULTS AND DISCUSSION

3.1 Wall moisture measurement results

Wall moisture measurements were performed for three different types of wall, each having relative humidity sensors located at different depths of the wall. The maximum humidity range of the outer layers depending on the season can be seen in Tab. 2. As for two of the wall types (A and B) measurements were started shortly after manufacture – initial moisture levels were high, and this drying period is represented separately from the operating period after drying in Tab. 2.

Measurements for wall type A – experimental panel – were started right after the manufacture of the panel in February, thus it showed elevated moisture levels for the first several months, and it took 5 months for a 200 mm panel without any finishing to dry out and reach equilibrium moisture - 55-65% RH for the inner layer. These measurements indicate that a long drying period is necessary for these materials, which requires it to withstand several months with relative humidity above 90%. It must be considered that no external finishing was applied to the panel, increasing water vapour permeability; the panel was also only 200 mm thick. The drying time is only extended with thicker layers and additional covering of the inner and outer surface. After the drying period, outer sensors measure humidity levels of 68 to 77% in winter periods and 64 to 75% RH in summer periods (Tab. 2.).

Measurements for the second wall type B – located in an existing hemp-lime building – were started 6 months after the completion of the building, thus some moisture content is still locked in the wall from the manufacturing process. A section of all humidity measurements can be seen in Fig. 2 – period from 1st to 9th of April 2017. As can be seen from this graph – RH of the outer layer remains quite high in this period – above 95%. In the first winter period the humidity varies between 90 and 99%, in the following summer it drops slightly to 85 – 95 % (Tab. 2.). At the end of the following winter, humidity

Fig. 3: From the left: FHL-100, FHL-50, FHL-20

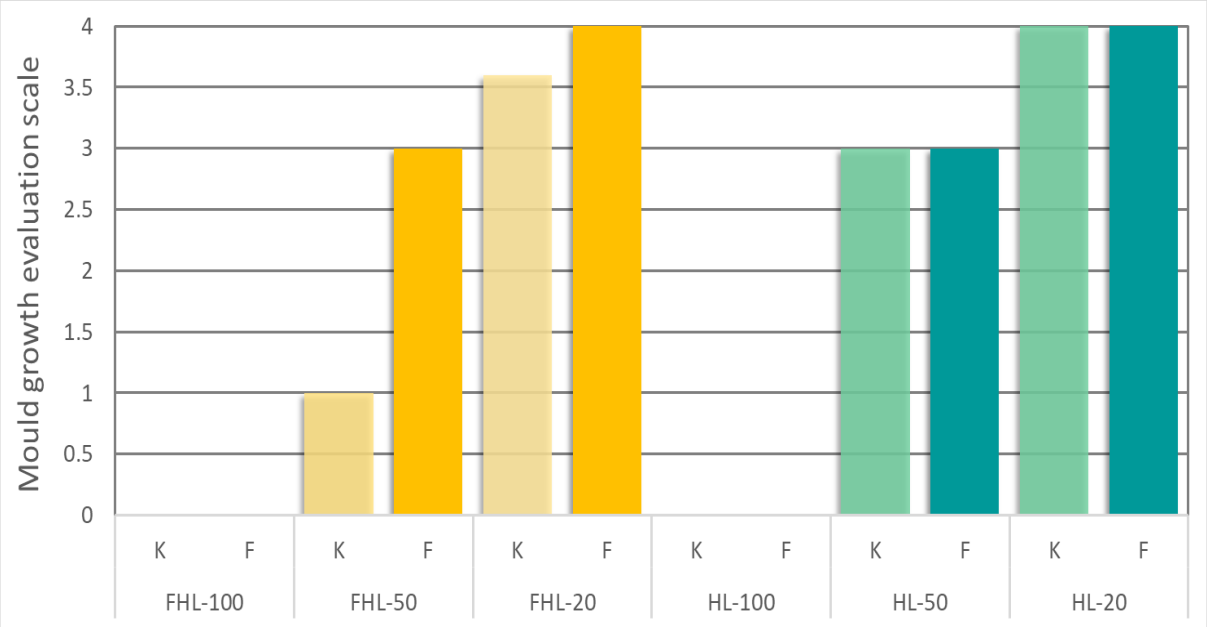


Fig. 4: Mould growth evaluation of FHL and HL samples with various ratios of binder

had dropped to 65-80%, and the summer after that to 52-64%, representing the operating conditions after drying. From the measurements it can be seen that extended periods of drying are necessary for panels that have internal and external finishing installed right after manufacturing. It can take up to two years for the complete stabilisation of internal moisture.

The third wall type C is an existing vertical stud construction wall, that has been insulated from inside with fully dried hemp-lime blocks. Measurements of the wall were started before the installation of insulation and showed RH inside the wooden wall at levels of 40-50%. After the installation of insulation, the H3/T3 sensor (3 cm in the wooden wall) shows the highest RH levels of around 65% during the summer months and reaching 75% in early winter. H6/T6 sensor on the border of the hemp-lime insulation blocks and existing wall shows 60% RH in summer and 70% RH in winter.

3.2 Biodegradation test results

For the biodegradation tests two different conditions are chosen after wall moisture measurements – 75% RH representing typical operational conditions and 99% RH representing elevated moisture levels due to drying. The temperature for both humidity levels is 20 °C ± 2 °C. Both HL and FHL mixtures were tested at 75 and 99% RH.

For 75% RH tests, samples were tested at 45 days and 4 months. On HL and FHL inoculated (F) and control (K) samples, no fungal growth was observed in this period. Also, after incubation on an agar medium no fungal genus was determined. This can generally be explained by two reasons. First, at humidity levels of 75% only a few genera of fungi can grow and generally moisture levels up to 75% are considered safe for most building materials [Moller 2017]. Second, the materials show highly alkaline pH values – pH 12.40 for the HL mixture and pH 11.99 for the FHL mixture that provides protection from biodegradation [Udawattha 2018].

Regarding the reference wood fibre material, it showed macroscopical growth of mould on both the control and inoculated samples and were evaluated as level 3 according to ASTM C 1338-96. Two fungal genera were determined after incubation on an agar medium – *Trichoderma* and *Aspergilus niger. Trichoderma* is the genus of fungi that covers most of the sample surface, as it is distinguishable by its green colour [Mousumi Das 2019]. It must be noted that all of the fungal growth occurred in the first few days of incubation. Also, wood fibre insulation shows an acidic pH level – 3.63. This indicates that the pH value has a significant influence on the biodegradation resistance of materials and overall the proposed bio-based building materials have adequately high pH levels for their use up to 75% RH.

For 99% RH tests the samples were evaluated after 45 days. The test also included FHL and HL samples with reduced binder amount – 50% (FHL-50 and HL-50) and 20% (FHL-20 and HL-20) of the original binder content. This reduction was chosen to test reduced binder and lower the influence of the pH level on biodegradation of the chosen materials.

From the achieved results it can be seen that both inoculated and control samples for both materials at 100% binder content didn't show any growth of mould (Fig. 4.), and even no genus of fungi was determined. This is because of two possible reasons – fungi have lost both the shape of the cells and their viability, and this is possible because the fungi have long been in an unsuitable, alkaline environment or at least part of the inoculum gradually soaked deeper into the material due to the constant wetting to maintain the necessary moisture levels.

From the results it can also be seen that samples with reduced binder content show significantly higher growth of mould – FHL samples exhibiting slightly lower biodegradation. An increase in the growth of mould with a decrease in binder content can be seen in Fig. 3 where FHL inoculated samples with three different binder contents can be seen.

Lower binder content samples also show lower pH levels – FHL-50 pH 9.24, FHL-20 pH 9.17, HL-50 pH 8.68, HL-20 pH 8.61. It can be seen from the results that a decrease in binder content and pH value corelates with an increase in the growth of mould. This also explains the difference between FHL and HL samples at a reduced binder amount.

Tab. 3: Genus of fungi identified on the samples

	Control (K)	Inoculated (F)
FHL-100	None	None
FHL-50	*Scopulariopsis, Cladosporium, Aspergillus, Paecilomyces*	*Scopulariopsis, Cladosporium, Aspergillus, Paecilomyces*
FHL-20	*Acremonium, Paecilomyces*	*Cladosporium, Scopulariopsis*
HL-100	None	None
HL-50	*Scopulariopsis, Paecilomyces*	*Aspergillus, Cladosporium, Paecilomyces*
HL-20	*Scopulariopsis, Paecilomyces*	*Paecilomyces, Chaetomium, Penicillium, Trichoderma, Cladosporium, Coprinus comatus, Scopulariopsis, Stachybotrys*
WF	*Paecilomyces*	*Trichoderma*

Regarding the genus of fungi, the following were found on the reduced binder content HL samples (Tab. 3): *Paecilomyces, Chaetomium, Penicillium, Trichoderma, Cladosporium, Coprinus comatus, Scopulariopsis, Stachybotrys.* And the following on the FHL samples: *Scopulariopsis, Cladosporium, Aspergillus, Paecilomyces*. Only some of these fungal spores were inoculated, suggesting that some were already present in the raw materials, e.g. hemp shives, or were introduced in the mixing or testing process.

The reference wood fibre insulation shows the same level of growth of mould – 3 – as at 75% RH, suggesting its inapplicability to increased moisture conditions.

Overall it can be seen that the proposed bio-based material with both HL and FHL binder can be used in construction in the Northern European climate as it can even withstand highly evaluated levels of moisture which can be relevant at the drying stage of the material.

4 CONCLUSIONS

The following conclusions can be drawn from the results:

1. The moisture measurements indicate that during the drying period of freshly manufactured hemp-lime panels the relative humidity of inner material layers remain high – 90-99%. The duration of the period is dependent on several factors, one of which is the internal and external finishing of the panels. Measurements show that a 200 mm panel without any finishing can dry out in 5 months; a 250 mm panel with additional internal insulation and external finish can retain some moisture from manufacturing for up to two years.
2. During the operating period (after the drying) the moisture of the inner layers of the hemp-lime concrete didn't exceed 75-80% RH regardless of the season.
3. For the biodegradation tests two different moisture levels were chosen – 75% RH representing typical operational conditions and 99% RH representing elevated moisture levels due to drying. Biodegradation tests with the artificial inoculation of six different fungi were performed using reference wood fibre insulation and the same 3BMs as in moisture measurements with varied binder content.
4. At 75% RH both 3BM mixtures – HL and FHL – didn't show any biodegradation due to the limited number of fungi that can grow at such moisture and high pH values - pH 12.40 for HL mixture and pH 11.99 for FHL mixture. Reference wood fibre insulation had a pH value of 3.63 and showed fungal growth, mostly with *Trichoderma* genus.
5. At 99% RH neither 3BM mixtures showed any growth on 100% binder content samples but showed level 1 to 4 growth on 50% and 20% binder samples, as these had lower pH values ranging from 9.24 to 8.61 Only some of the fungi genus found were inoculated, suggesting that some were already present in the raw materials. The reference wood fibre insulation showed growth of mould of level 3, suggesting its inapplicability to increased moisture conditions.
6. Overall it can be seen that the proposed 3BMs can be used in construction in the Northern European climate as they can even withstand highly evaluated levels of moisture which can be relevant at the drying stage of the material.

5 ACKNOWLEDGMENTS

This research was done with financial support of European Regional Development Fund, project "Development, optimization and sustainability evaluation of smart solutions for nearly zero energy buildings in real climate conditions" (1.1.1.1/16/A/192).

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