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Accelerated Aging of Hempcrete Insulation for Durability Assessment

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ABSTRACT

The construction sector contributes 37% of global emissions, making decarbonizing construction crucial. As operational carbon decreases over the next few decades, embodied carbon is becoming an increasingly significant area of investigation. One approach to reduce embodied carbon is shifting to bio-based building materials like hemp-lime insulation (hempcrete). However, their adoption depends on demonstrating long-term durability and compliance with building codes, especially in harsh northern climates. This paper addresses this gap by presenting the results from an ongoing accelerated aging study, in which key material properties were regularly monitored up to six months to assess the short-term performance of hempcrete. The study identifies key performance metrics and evaluates the effectiveness of different tests for durability assessment of hempcrete. Specimens were subjected to three hygrothermal weathering conditions with varying levels of relative humidity, and characterization tests included thermal conductivity, compressive strength, mold growth, and spectroscopy. The findings indicate that due to the material's inhomogeneity in particle size, destructive bulk-scale tests such as compression testing exhibit high variability, while inhomogeneity in the coverage of hurds with binder at the small-scale result in variability in infrared spectra. Minor changes in chemical composition were observed after 6 months, indicating potential dissolution of polysaccharides in the hemp shives at high humidities. On the other hand, non-destructive bulk-scale testing of specimens that are retained for the entire weathering period, such as thermal conductivity, yield more consistent results; after 3 months of aging, thermal conductivity remained stable with no statistically significant change over time. Over the course of the six-month aging period, no significant changes were observed in mechanical, thermal, chemical, or mold growth resistance properties of hempcrete, suggesting that a longer aging time or increase in weathering intensity is required to observe hygrothermal degradation to the point of failure for the purpose of service life prediction.

INTRODUCTION

Hempcrete, or hemp-lime, is a bio-composite material consisting of hemp shiv – a woody material obtained from the stalk of industrial hemp plants, and a lime-based binder. This low-carbon construction material serves as a non-structural thermal insulator and wall infill system, as scoped in Appendix BL of the 2024 International Residential Code (IRC), which applies to one- and two-family dwellings and townhouses (International Code Council 2024). This bio-aggregate material is

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considered a sustainable alternative to conventional petroleum-based insulation products, and research has shown that it has the potential to be a carbon-negative building material. The long-term carbon sequestration is achieved via biogenic uptake of CO₂ during photosynthesis, as well as via carbonation of the lime-based binder, which combined can counteract the emissions from hempcrete block production (Arehart, Nelson, and Srubar 2020; Arrigoni et al. 2017). Shifting to sustainably sourced bio-based materials is one of the main approaches to mitigate embodied carbon emissions in the construction sector, which accounts for at least 37 percent of global greenhouse gas emissions (United Nations Environment Programme 2023)). Further research must be done to advance the integration of these materials into building codes, standardize performance evaluations, and demonstrate scalability, to advance their widespread use.

The 2024 IRC references standards for fire resistance, thermal performance, and mechanical performance testing of hempcrete, and in general this material has been extensively characterized by different groups, as its formulation and production process are under continual modification and improvement. Recent optimizations under investigation range from thermally treating the hemp hurds to tailor hempcrete properties (D'Eusano et al. 2024), to employing vibration techniques for improved uniformity in pre-cast blocks (Mahmood, Kavcic, and Noel 2024). However, there is little information on long-term performance and durability of bio-based building materials, including hempcrete. In addition, standard methods to evaluate hempcrete performance properties are still under development. Recently, the ASTM D37.07 subcommittee on industrial hemp established a task group focused on hempcrete insulation for construction applications, whose scope involves developing standards for hemp hurd, binders, and hempcrete. Nonetheless, this material is already being used in buildings around the world. Indeed, the developmental trajectory of bio-aggregate materials has been described as “bottom up”, meaning their use on the construction site has driven development in the laboratory (Nozahic and Amziane 2013). For hempcrete to be more widely adopted, it is important to demonstrate that this is a durable and climate resilient building material that can fulfill its intended service-life, and that durability criteria be integrated into building codes. Currently there is no mention of hempcrete or hemp-lime in the Canadian National Building Code, and although hempcrete is present in the appendix in the International Residential Code, which is the basis for the building codes in 49 of the 50 states in the United States, there is no mention of durability requirements. Development and integration of durability standards for bio-based construction materials, including hempcrete, into building codes is an important area in need of further development. The goal of this study is to assess the durability of hempcrete and predict its service life, in an effort to contribute to the emerging body of knowledge that exists on this topic.

Durability assessment of hempcrete is an emerging field, and, to the authors' knowledge, no studies have focused on the short-term performance assessment of hempcrete aged in static hygrothermal conditions. Consequently, the level of degradation expected within six months was uncertain at the beginning of the experiment. Nonetheless, service life prediction was considered during the planning phase, and three conditions were strategically selected to account for the possibility that failure might occur under all conditions. For the data collected to be used in future service life analyses, one environmental variable was kept constant, while the other was varied. Due to the sensitivity of bio-based materials to moisture and the importance of evaluating their durability under hygrothermal conditions, temperature was selected as the consistent variable and maintained at 104 °F (40 °C), while relative humidities were adjusted to 40%, 50%, and 70% RH in each of the three chambers, respectively. In order to evaluate changes in key performance properties over a six-month period, these exposure conditions were chosen to intensify in-situ conditions in order to accelerate degradation, while ensuring that unrealistic degradation mechanisms were not introduced. For this reason, the highest relative humidity (RH) was selected to stay below the critical threshold for mould growth, which is known to be 80% RH on hempcrete and woody materials when temperatures are above 68 °F (20 °C) (Raamets et al. 2021; Hukka and Viitanen, 1999). The higher temperature of 104 °F (40 °C) was selected to introduce a level of acceleration to the laboratory aging, while also limiting the possibility of mould growth, as the most suitable temperature range for fungal growth is between 68 °F – 95°F (20 °C – 35 °C) (Koh et al. 2022). These conditions are reasonable as hempcrete used for thermal insulation in real-world construction is unlikely to remain moist for prolonged periods of time in continental climates such as Canada's and the Eastern United States, due to its excellent vapour permeability. Hygrothermal modeling of hempcrete assemblies in a southern Ontario climate have shown that the water content in both an exposed face-sealed mass wall and a vented rain screen wall system follow regular seasonal fluctuations, drying out between watering incidents and displaying no sign of condensation or water accumulation during the multi-year simulation period (Dhakal et al. 2017). It is worth noting that this behaviour may not extend to all climates, as mould growth simulation results from masonry and timber-frame hempcrete walls have shown an increased risk for mould growth in temperate European climates (Koh et al. 2022). In such climates, a durability assessment protocol in which higher humidities

are used and mould is allowed to grow may be warranted; this highlights the importance of designing protocols and selecting conditions representative of the climate in which the material is intended to be used.

METHODOLOGY

Commercially available hempcrete blocks were cut into the required specimen sizes for the tests using a masonry table saw and a horizontal band saw. Prepared specimens were then divided into control specimens and aging specimens. Specimens destined for aging were placed in three constant climate chambers with controlled temperature and RH set to 104 °F (40 °C) and 40%, 50%, and 70% RH, respectively. Except for heat flow meter specimens which have only been aged for 3 months to date, all other specimens have been aged for a total of 6 months, and were removed at defined intervals (1, 3, 6 months) for characterization of material properties. Both unaged (control) and aged specimens were tested for thermal performance, mechanical performance, chemical composition, and mold growth resistance on the surface.

Thermal conductivity of 12" × 12" × 2" (30 cm × 30 cm × 5 cm) specimens was determined in triplicate using a heat flow meter (Figure 1a) according to ASTM C518, at four mean temperatures: 14 °F, 32 °F, 50 °F, 68 °F (-10 °C, 0 °C, 10 °C, 20 °C). Mechanical performance of 6" × 6" × 3" (15.2 cm × 15.2 cm × 7.6 cm) specimens under axial compressive load was determined in quadruplicate according to ASTM C165 using a crosshead speed of 0.14 in./min (3.6 mm/min) (Figure 1b). Chemical analysis was performed using Fourier-Transform Infrared (FT-IR) spectroscopy with an attenuated total reflectance (ATR) accessory containing a diamond crystal (Figure 1c). Spectra were collected between 4000 – 400 cm⁻¹ as the average of 32 scans at a resolution of 4 cm⁻¹, and were obtained in decuplicate from selected hemp shives recovered from crushed blocks after compression testing. Mold growth resistance was evaluated in accordance with ASTM C133, using pine as the reference material. Each 3" × 3" × 1" (7.5 cm × 7.5 cm × 2.5 cm) hempcrete specimen was inoculated with 25 × 0.0007 fl oz (20 µl) spore suspension (0.02 fl oz, 500 µl) in a 5 × 5 grid pattern within a defined template to ensure the area of inoculation was consistent across triplicate samples (Figure 1d).

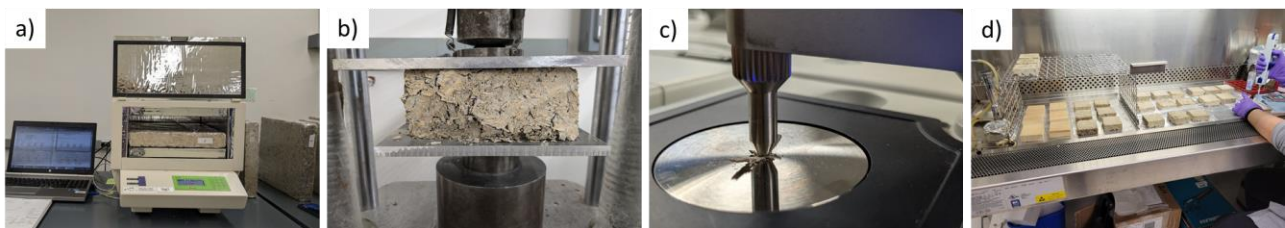


Figure 1 Characterization techniques used to assess short-term performance of hempcrete: (a) thermal conductivity via heat flow meter, (b) compression testing, (c) infrared spectroscopy, (d) mold growth resistance.

RESULTS AND DISCUSSION

Thermal performance

The thermal conductivity was measured at four mean temperatures and at three aging intervals to monitor the effect of aging on both the thermal conductivity at a given temperature, and on the temperature dependence of the key property. Results from the unaged specimens show a very low temperature dependence on thermal conductivity, as shown in Figure 2. Upon accelerated aging at the three hygrothermal weathering conditions for three months, little change was observed in the thermal conductivity of hempcrete; the trends with aging are displayed in Figure 3, which shows the average results of triplicate specimens, where standard deviation is represented by the error bars. Statistical analysis of the results was performed using a series of twelve single-factor analysis of variance (ANOVA) tests, grouping triplicate specimens for each of the three aging conditions and each of the four mean temperatures. ANOVA results confirmed that there is no significant change in thermal conductivity with aging time at any of the aging conditions, nor any of the mean temperatures, as the F statistic – the test statistic for a one-way ANOVA, was lower than the $F_{critical}$ value for all tests. This result indicates that

short-term hygrothermal aging has no significant impact on the thermal performance of hempcrete, as monitored via thermal conductivity testing. This key property remains stable for up to three months of aging under static conditions of 40% RH, 50% RH, and 70% RH at 104 °F (40 °C).

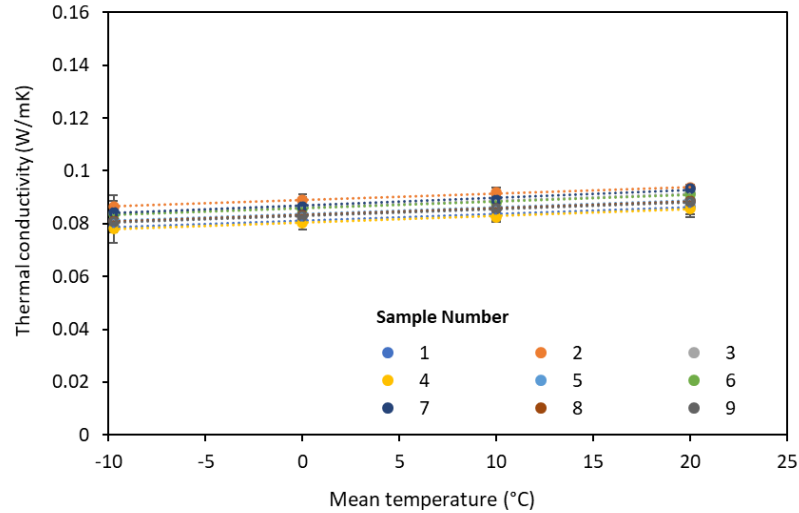


Figure 2 Thermal conductivity of nine unaged hemp-lime specimens at four mean temperatures.

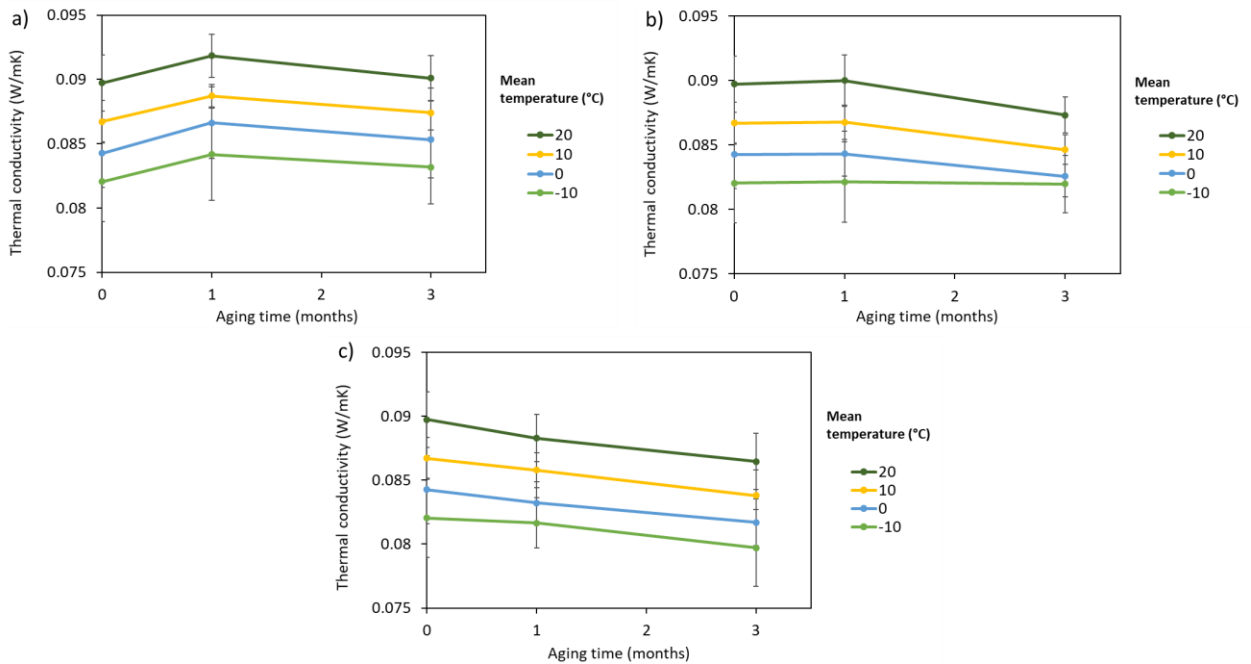


Figure 3 Evolution of thermal conductivity of hemp-lime aged at 104 °F (40 °C) and (a) 40%, (b) 50% and (c) 70% RH.

Mechanical performance

Due to the heterogeneous nature of hempcrete, a high level of variation was seen in the compression curves, especially after the limit of proportionality in the plastic deformation region. This may also be influenced by the deformation behaviour of hempcrete under compressive loads, as it continuously deforms rather than breaking (Walker, Pavia, and Mitchell 2014). Figure 4 (a) shows this variability among eight unaged hempcrete specimens. From these curves, it was noted that the linear portion displays a similar slope, therefore these regions were fitted as shown in Figure 4 (b), and the compressive modulus of elasticity was taken as the slope of the linear fit.

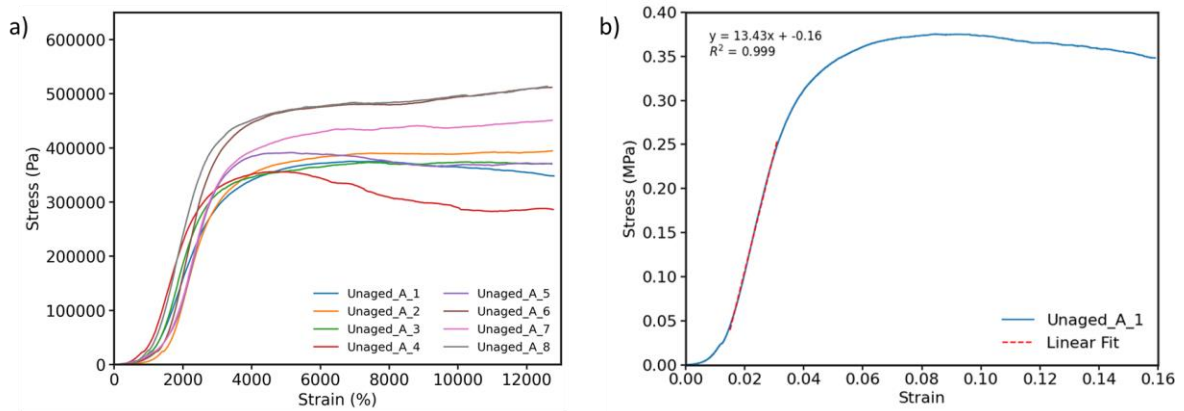


Figure 4 (a) Compression curves for eight unaged hempcrete samples, (b) compression curve of unaged specimen with a linear fit on the elastic region.

Moving forward, taking the compressive modulus rather than the ultimate strength is expected to minimize variability in the data caused by the heterogeneity of the sample. Nonetheless, the results shown in Figure 5 reveal that sample variability is still present, as indicated by the error bars which represent standard deviation among four replicates. Such variability may be due to the relatively broad and skewed size distribution of the hurd. A hurd sample was collected from the commercial blocks by carefully deconstructing the block and washing away the binder, then drying in a 122 °F (50 °C) oven for one week to achieve a bone-dry state. The distributions in Figure 6 show a positive skew in length (major axis), width (minor axis) and area, indicating the presence of more hurds on the larger side than would be expected in a normal distribution. It has been previously demonstrated that average hemp hurd size has an impact on compressive properties of hempcrete (Stevulova et al. 2012; Niyigena, Amziane, and Chateaneuf 2018). As such, it follows that hempcrete with a non-uniform particle size distribution with two separate fractions (0.06 in² and 0.06in²-0.12in², or < 40 mm² and 40-80 mm²) is expected to yield variable results.

Chemical composition

ATR FT-IR spectra for hempcrete contains a mixture of contributions from both hemp and binder, which appear in different ratios due to local variations in binder coating. This variability in surface coverage translates to variations in observed peaks as seen in Figure 7 and Figure 8. In addition, peak assignment in the mid-infrared region is complex due to the absorptions of both hemp and binder in that region. To confirm the peaks attributable to the bulk of the hemp hurd, a shiv was cut open, exposing the inner woody core free of binder, and three spectra were collected from it. The average spectrum is shown in Figure 7 with notable peak assignments. Although this method does not account for all peaks attributable to hemp, as the epidermis of an aggregate particle has been shown to have unique peaks, it is beneficial to separate the majority of the organic and inorganic vibrations. The two new prominent peaks observed when analyzing the composite are attributed to calcite; these are present at 874 and 1414 cm⁻¹, arising from the symmetric bending and antisymmetric stretching of carbonate

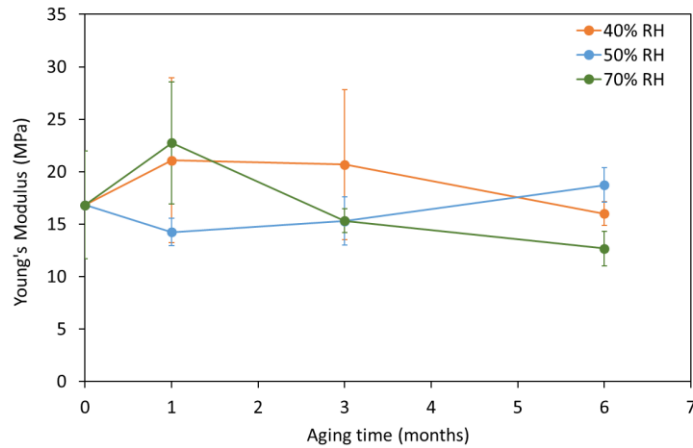


Figure 5 Evolution of hemp-lime compressive modulus over time under different RH conditions at 104 °F (40 °C).

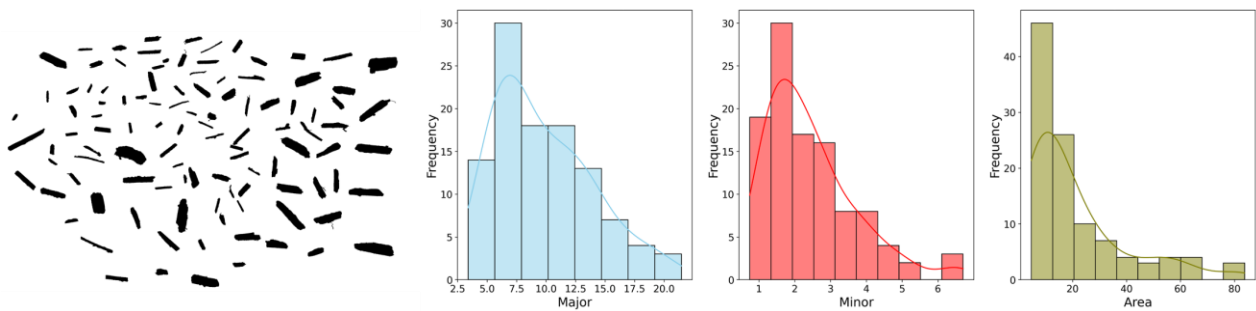


Figure 6 Binary mask of hemp hurds image and related particle size distribution histograms for length (major axis), width (minor axis), and area. Units for the independent variables are mm and mm².

(CO₃²⁺) in calcite, respectively (Sheridan et al. 2020). After six months of hygrothermal aging, little change is observed in the chemical composition of the hempcrete in the three conditions. The most notable changes are in the hempcrete aged at 70% RH, as seen in Figure 8. There is a slight flattening or decrease in sharpness of the O-H peak centered around 3400 cm⁻¹, which could indicate that in the high RH condition, polysaccharides in the hemp shives may be dissolving. This spectral change has been observed to a greater extent in immersion aging studies (Sheridan et al. 2020), and it will be interesting to observe whether this flattening trend continues further in the high RH condition after longer aging times. The second minor change is an increase in intensity of the peak centered around 1465 cm⁻¹. This peak appears as a “shoulder” on the 1414 cm⁻¹ calcite peak in the samples aged at 40% RH and 50% RH, as well as in the unaged sample. As this is the spectral region containing multiple peaks from hemp shiv (1200 – 1600 cm⁻¹, Figure 7), it is difficult to conclusively determine whether this small change in peak shape is due to the presence of newly formed compounds during aging, or if the position where the spectra were collected simply included a greater area of exposed hurd. The spectra also shows that the unaged control hempcrete has strong calcite peaks present, which did not change significantly with aging, indicating that the natural cement binder had already undergone carbonation prior to aging. This is expected for hempcrete that was obtained through commercial channels, as it had sufficient time to react with atmospheric CO₂ during the curing, transport, and storage phases of its manufacturing process.

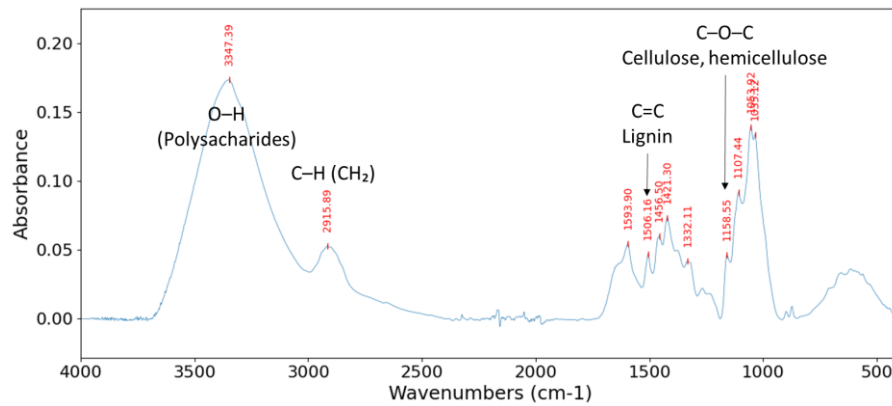


Figure 7 Average FT-IR spectrum collected from the core of a hemp shiv.

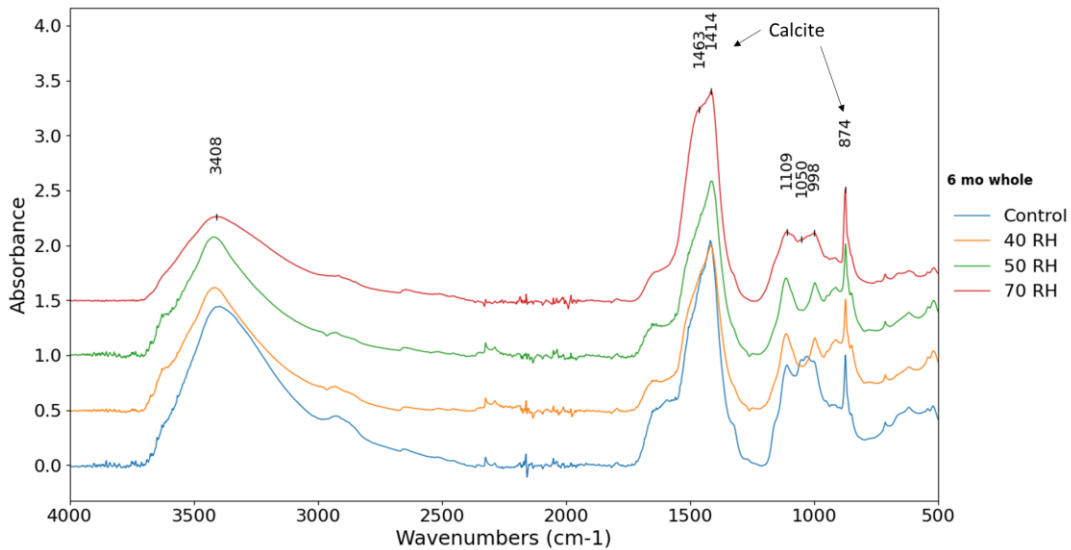


Figure 8 FT-IR spectra of hempcrete aged at 104 °F (40 °C) and 40 %, 50%, and 70% RH for 6 months.

Mold growth resistance

A network of hyphae (mycelium) and clusters of spores growing from the hyphae were observed in all specimens, including the pine reference material, the unaged hempcrete, and hempcrete aged at all three hygrothermal conditions (Figure 9). Most importantly for this test, the mold growth in the aged specimens was not greater than that observed on the reference pine material, satisfying the passing criteria for ASTM C133. This result indicates that hygrothermal aging up to 6 months under three different relative humidities had no significant effect on the microbial resistance of hempcrete. As all specimens were sterilized prior to the test, bringing them to the same baseline starting point for mold growth, this allowed for a true examination into whether hygrothermal degradation of the hempcrete itself affected the ability of mold spores introduced onto the material to grow, relative to the unaged control hempcrete and the reference material.

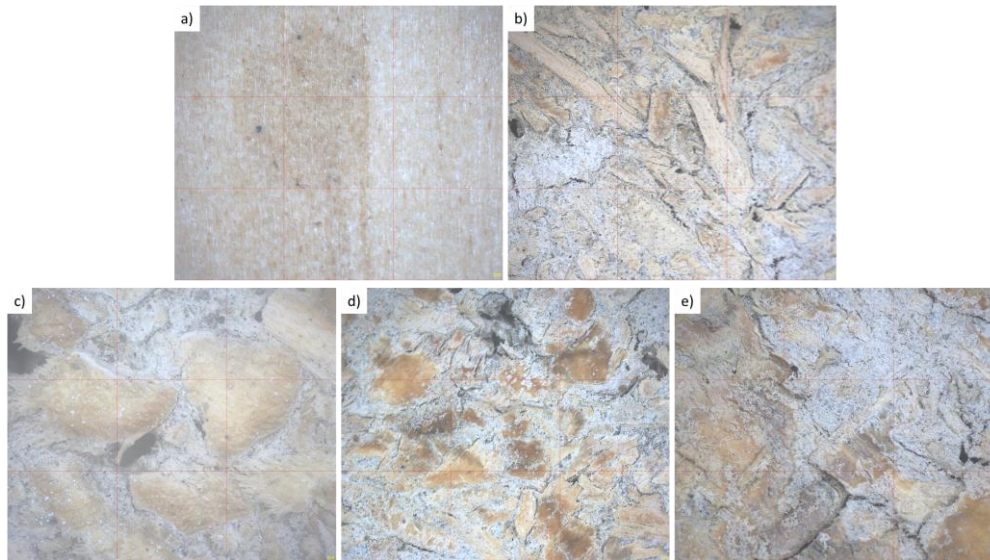


Figure 9 Optical micrographs of (a) pine, (b) unaged hempcrete, and hempcrete aged for 6 months at 104 °F (40 °C) and (c) 40% RH, (d) 50% RH, (e) 70% RH, after the incubation period.

CONCLUSION

A commercial hempcrete with natural cement binder was aged for 6 months under three hygrothermal aging conditions in which temperature was kept constant at 104 °F (40 °C) and relative humidity was varied at 40%, 50%, and 70%, staying under the threshold for microbial growth during the aging. Four characterization methods were selected to capture changes in thermal and mechanical performance – key performance metrics for hempcrete, as well as mold growth resistance and chemical composition, which are important to better understand the degradation and deterioration mechanisms of hempcrete exposed to moderate and high humidity conditions. There was no significant change in thermal conductivity measured at four mean temperatures in hempcrete specimens aged up to three months. The short-term stability of this property under the three aging conditions indicates this material retains its key property as a thermal insulator, and the non-destructive nature of this test ensures that the effect of aging can be accurately monitored by testing the same specimens after each aging time interval. Variability in the mechanical testing results was attributed to a non-normal distribution in hemp shiv sizes, and young's modulus was proposed as a key property to monitor with aging due to the variability in ultimate compression strength. While minor changes in chemical composition with aging indicate that polysaccharides may be dissolving in the highest humidity exposure condition, none of the weathering conditions caused deterioration that affected mold growth resistance. Although the lack of significant changes in these key properties after 6 months of hygrothermal aging demonstrates acceptable short-term performance of the material, indicating promise for its use in dry and moderately humid climates, the intensity of aging conditions may need to be increased, or the duration of the current conditions extended, to observe a full degradation curve up to the point of failure for these properties, as this is crucial for service life prediction studies.

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