MOISTURE AND FLEXURAL BEHAVIOUR OF HEMP MAT FOAM STRUCTURAL INSULATED PANEL SPECIMENS

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ABSTRACT

The use of structural insulated panels (SIPs) for wall and roof assemblies in residential and commercial buildings is a well-known construction technique. SIPs typically use a combination of either expanded polystyrene foam (EPS) or polyurethane foam (PUR) as the core material. The covering or skin is predominantly oriented strand board (OSB). The OSB is either bonded to the foam with adhesive in the case of EPS, while polyurethane is used to provide adhesion with PUR SIPs. This paper presents the results of research that investigated the use of industrial hemp mat used as a skin for soy-based polyurethane foam panels. A series of tests were conducted to investigate moisture resistance and flexural behaviour on hemp mat foam panels. Moisture absorption behaviour was evaluated on three specimen types: uncoated, earth plaster and tung oil treated hemp mat. The absorption coefficient A_w was determined for all specimens. The tung oil treated specimens exhibited a water absorption coefficient that was 5.3% of that for untreated hemp mat panel specimens. Flexural tests were conducted on dry specimens with earth-plastered hemp mat, tung oil coated hemp mat, OSB and, untreated hemp mat skins. Tung oil provided resistance to tension failure and increased capacity to withstand considerable deformation without tensile failure in flexural specimens. Compared with pure foam specimens, untreated hemp mat improved flexural performance by 16.3%.

KEYWORDS

industrial hemp, moisture absorption, flexural behaviour, structural insulated panels

1.0 INTRODUCTION

Hemp is a fast growing annual plant. It is a natural fibre and a member of the family Cannabis Sativa. The bast fibre from processed industrial hemp provides reinforcement for many composite products. These bast fibres are one of the longest natural soft fibres, rich in cellulose.

As a result of increased interest with sustainability, hemp fibre composites have experienced and received much attention from a variety of industries. Hemp is abundant and

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possesses excellent insulating properties: renewable, biodegradable, low density, and has a high strength to weight ratio. Historically, hemp was used for ropes primarily for naval applications, which attests to its inherent strength. More recently, these natural fibres have found uses in automotive interiors, buildings, and general construction. The use of hemp is now found in insulation materials for residential and commercial construction offering a more natural option for builders. In addition, natural fibres are increasingly replacing synthetic fibres in composite materials. This provides opportunities for agricultural producers to find new markets for by-products that otherwise may be considered waste.

However, there are still some major challenges with natural hemp fibres. One of them is their ability to resist moisture. Since moisture absorption capacity can be high, natural fibres are still restricted from exterior applications. Hemp fibres can be easily altered when exposing them to different types of environments, such as ambient moisture, water, chemicals, sunlight, heat, and radiation. All of these factors cause changes in the microstructure and the chemical composition of polymer matrix composite materials (Shahzad et al. 2011). These modifications in turn cause changes in properties such as strength, modulus, impact, and fatigue (Shahzad et al. 2011).

Natural fibre composites are more susceptible to environmental attacks than synthetic fibre composites because of their structure. Natural fibres are hydrophilic and when exposed to moisture, the fibres will swell and may eventually mold. To investigate hemp fibre resistance to water absorption, this study focused on two surface treatments: Tung-oil and earth plaster. Tung oils are extracted from Tung trees, known as Vernicia fordii. Tung oil and earth plaster were chosen for this study as representative of materals that are sustainable, natural and in the case of earth plaster, locally available. The use of earth plasters for interior finishes can provide moisture buffering and the potential to improve indoor air quality by absorbing pollutants. Tung oils are naturally water, food and alcohol resistant and used for interior and exterior applications. The effect of moisture on the performance of hemp-based products used in construction is important from the perspective of long-term durability. In general, if materials can be maintained in a dry-service condition; their service life is considered to be 50 years as evidenced in wood frame buildings.

Another aspect of this study was to characterize the behaviour of coated panel specimens using flexural tests. Standard four-point loading was used to determine such parameters as stress at maximum load, initial stiffness, and the ability to absorb energy.

These tests provided a basis to compare the relative performance of the coatings and provide an initial baseline.

1.1 Study Objectives

The fundamental objectives of this study were to:

1. Determine the water absorption coefficient of natural hemp fibre mat
2. Determine water absorption coefficients of treated hemp surfaces and compare with the untreated hemp fibre water absorption coefficient.
3. Study if the surface treatments increase the hemp panel's dry-strength structural capacity
4. Compare the flexural performance of foam billets with samples with hemp matt and oriented strand board (OSB) skins

2.0 LITERATURE REVIEW

A brief review of literature on hemp fibre composites is presented to provide background on the properties of natural fibre composite materials.

2.1 Physical properties of natural fibres

Hemp fibre is a bast fibre, which belongs to the Cannabis family. It is an annual plant that grows in temperate climates (Edwards et al. 1997). Depending on their origin, natural fibers can be grouped into seed, bast, leaf and fruit qualities. Bast and leaf (the hard fibers) qualities are the most commonly used in composite applications. Examples of bast fibers include hemp, jute, flax, ramie, and kenaf. Leaf fibers include sisal and banana leaf fibers (Williams and Wool 2000).

Desirable properties for fibres include excellent tensile strength and modulus, high durability, low bulk density, good moldability and recyclability (Mohanty et al. 2001). These advantageous properties are related to the internal structure and chemical composition of fibres. Natural fibres have an advantage over glass fibres in that they are less expensive, abundantly available from renewable resources, and have a high specific strength (Mohanty et al. 2001). Natural fibres have densities of about one half of glass fibres. These fibres can withstand processing temperatures up to 250°C. They are fully combustible without the production of either noxious gases or solid residues (Sreekala et al. 2000).

Natural fibre exhibits considerable variation in both cross section and individual filament length. The qualities of the fibre depend on factors such as size, maturity and processing methods adopted for the extraction of fibre (Mohanty et al. 2001). In addition, processing techniques can have major influence on the physical properties of fibre composites. Table 2.1 presents a comparison of selected mechanical properties of some natural fibres.

2.2 Chemical composition of natural fibres

Natural fibres are complex in structure. They are composed of many organic compounds. Table 2.2 summarizes three specific natural fibres and their chemical composition (Williams and Wool 2000).

TABLE 2.1. Properties for natural fibres (Williams and Wool 2000).

	Flax	Hemp	Jute	Sisal
Density (kg/m^3)	1500	1480	1450	1450
Elastic Modulus (GPa)	100	70	2.5-13	9.4-15.8
Tensile Strength(GPa)	1.1	0.46-0.533	0.568-0.64	0.69

TABLE 2.2. Chemical composition of natural fibres (Williams and Wool 2000).

Chemicals	Flax (%)	Hemp (%)	Kenaf (%)
Cellulose	78.5	68.1	60.7
Hemicellulose	9.2	15.1	20.3
Lignin	8.5	10.6	11
Extractives	2.3	3.6	3.2
Ash	1.5	2.6	4.7

2.3 Water absorption

Due to the natural fibres nature, they are hydrophilic. Hence, they are highly sensitive to water absorption. Their poor hygrothermal resistance compared to synthetic fibre-reinforced plastics or engineering thermoplastics restricts their use in many structural as well as outdoor applications (Panthapulakkal and Sain, 2007).

Natural fibres are susceptible to environmental degrading because their structure consists of cellulose, hemicellulose, lignin, and pectin. The absorption of moisture can reduce fibre-matrix interaction, lead to poor stress transfer efficiencies, and result in the reduction of mechanical and dimensional properties (Deng et al. 2011). In addition, the swelling of fibres can lead to micro-cracking of the filaments and degrade its mechanical properties. The swelling of fibres is found to be directional with the maximum swelling occurring in the lateral direction and minimum in the longitudinal direction. The amorphous part of native cellulose, with all hydroxyl groups accessible to water, contributes more to swelling than the crystalline part, where only the surfaces are available (Shahzad et al. 2011). For this reason, moisture absorption in natural fibre composites must be overcome by treating these fibres with suitable chemicals to decrease the hydroxyl group in the fibres.

2.4 Surface Treatment of natural fibres

Studies have been done to modify the natural fibre interface. It has been proven in studies that, by modifying the fibres, water absorption and deterioration of fibres decrease. Natural fibres are naturally cooperative to modification as they bear hydroxyl groups in their cellulose and lignin. The use of fibre modifications like mercerization, isocyanate treatment, acrylation, latex coating, permanganate treatment, acetylation, silane treatment and peroxide treatment with various coupling agents and other chemicals, can improve fibre strength and fibre-matrix adhesion in biocomposites because of the hydroxyl groups amending with the chemicals (after Li, 2007).

2.5 Mechanical properties of composites

The mechanical properties of a natural fibre-reinforced composite depend on many parameters, such as fibre strength, modulus, fibre length and orientation. A strong fibre-matrix interface bond is critical for high mechanical properties of composites. A good interfacial bond is required for effective stress transfer from the matrix to the fibre whereby maximum utilization of the fibre strength in the composite is achieved (Karnani et al. 1997).

3.0 MATERIALS AND METHOD

The materials used for this study were industrial hemp fibre mat, earth plaster, 100% Tung oil, oriented strand board (OSB) and medium density polyurethane foam.

3.1 Specimen Type and Preparation

3.1.1 Hemp Mat and Core Foam

The mat was manufactured from hemp bast fibre using a needle punch process. Figure 3.1 illustrates the hemp mat used for this research. The mat has an area-based weight of 750 gr/m^2 with a nominal thickness of 5 mm. The hemp mat panels used in this study were fabricated at the Alternative Village at the University of Manitoba. Medium-density polyurethane foam was used for the core that had a 30% soy-based component. The natural adhesive property

of the foam was used to create the bond with the hemp mat. Coatings were applied only after fabrication of the panels.

3.1.2 Untreated Hemp panels

These specimens were prepared without any surface treatment to provide baseline values for comparison to the specimens with Tung oil and clay treatments.

3.1.3 Tung oil surface treatment

100% natural Tung oil was used for all specimens. The oil was applied in two coats to one surface of each moisture test specimen. The Tung oil was applied using a 50 mm angular paintbrush. A 24-hour time interval was provided between coats. Based on the average specimen weight prior to treatment and after, 0.13 g/cm^2 of tung oil was applied. The flexural specimens were coated on both faces using the same average amount of tung oil per side. When dry, the impregnated fibres formed a hard layer.

3.1.4 Earth plaster surface treatment

The earth plaster applied to the specimens contained 45.1% sand, 35.3% silt, and 19.6% clay based on primary particle analysis. The liquid limit was 0.307 while the plastic limit was 0.123. These values are in keeping with the type of material used for cob construction and plasters (Saxton, 1995). The soil was ground and mixed with water using a ratio of 4:1 dry plaster mix to water. The plaster was applied using a trowel. Based on the average weight prior to treatment and after there was 0.54 g·cm^{-2} coating applied. Figure 3.2 shows the end result of the surface treatment.

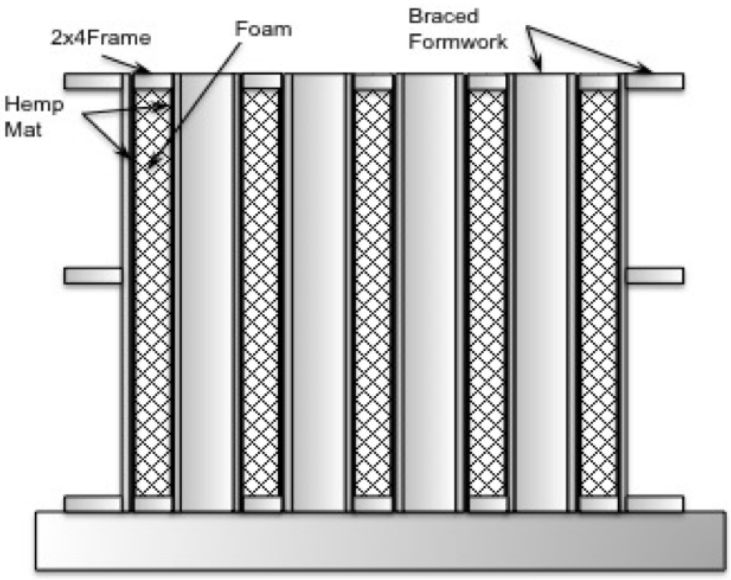
3.1.5 Flexural Test Specimens

Panels measuring 1220mm × 2440 mm panels were fabricated at the Alternative Village. Forms were constructed using plywood and dimensional lumber as shown in Figure 3.3. The hemp mat was attached to the plywood form using staples. The plywood was incorporated into a dimensional lumber

FIGURE 3.1. Chopped strand hemp mat.

FIGURE 3.2. Earth plaster treated hemp fibre specimens.

FIGURE 3.3. Panel formwork.



framework and stiffened to resist the expansion forces created from the foam as it cured. A two-pound polyurethane foam was injected into the formwork and allowed to cure. The specimens used for the absorption tests and flexural specimens with coatings were cut from these full panels. Additional forms were made in the same manner to produce panels with overall dimensions of 300 mm × 1220 mm. These flexural specimens were tested with loads transverse to the 300 mm dimension. Flexural specimens with earth plaster and Tung oil were cut from the larger panels. These specimens were 150 mm wide × 472 mm long by 85 mm thick.

3.2 Methods

3.2.1 Water Absorption Specimens

The hemp mat specimens were tested in conditions of 17 ± 2°C with a relative humidity of 52 ± 5% at the Alternative Village. A total of 24 specimens were cut from larger panels. Each specimen was 300 mm × 150 mm.

Water absorption experiments were conducted using the European Standard, CEN (2003) DIN EN ISO 15148 - Hygrothermal Performance of Building Materials and Products: Determination of Water Absorption Coefficient by Partial Immersion and ASTM D570-98.

3.2.2 Water absorption experiment procedure

Each specimen was placed in a container with water that immersed only the hemp mat cover. The weight of the water in each container was recorded. Spacers were used as support and elevated the specimen in order to achieve the desired immersion depth. Figure 3.4 shows the test setup containers prior to specimen immersion.

The initial weight of each specimen was measured to 0.001 grams using a scale and recorded prior to testing. A stopwatch was started when the treated surface came in contact with the water. The specimens were then left immersed in water for each specified time interval. When a specimen reached the desired time interval, it was removed from the water, shaken to remove surface water, and held over the water tray for 2 seconds. The weight was recorded. This procedure was repeated for time intervals of 30 seconds, 1, 2, 5, and 10 minutes, and 24 hours. Figure 3.5 shows the specimens in the test setup.

FIGURE 3.4. Water containers with spacers.

FIGURE 3.5. Untreated hemp fibre immersed in water.

3.2.3 Flexural experiment procedure

A series of flexural tests were conducted on dry specimens that had not been subjected to any moisture testing. The specimens tested were made using the following components: Polyurethane (PUR) foam, hemp mat, 11 mm OSB skins on foam core, and hemp mat with earth plaster and Tung-oil coatings.

Figure 3.6 illustrates the test setup for the flexural specimens. The load-deformation relationship was recorded using a computer data acquisition system and analyzed (Fig.3.7). Specimens with coatings were dried and conditioned at 24 ± 2°C and a relative humidity of 32 ± 5% for 7 days prior to load testing.

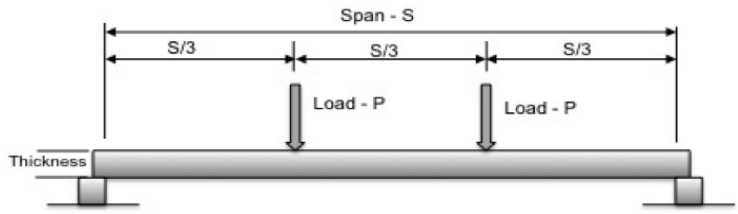


FIGURE 3.6. Flexural Test Setup.

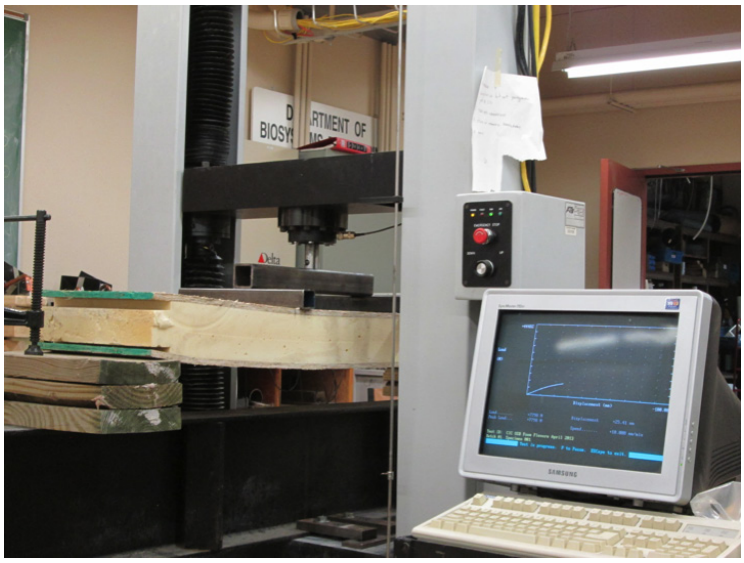


FIGURE 3.7. OSB specimen in ATS series 1410 computer controlled universal testing machine.

4.0 RESULTS AND DISCUSSION

4.1 Characterizing Water Absorption

When a material allows liquid moisture to enter its structure, contact with liquid water will gradually increase its weight. The increase in test specimen weight tends to increase linearly before it approaches the saturation point (Kumaran, 1999). The slope of the linear portion of this variation is called the water absorption coefficient $-A_w$ (Trechsel, 2001). This parameter was used for specimen comparison.

$$A_w = \frac{(M_t - M_i)}{A\sqrt{t}} \tag{1}$$

where:

M_t = weight of specimen after time "t"
M_i = initial weight of specimen
A = contact area of the liquid
t = time

In addition to the water absorption coefficient (A_w), an approach defined in ASTM D-570 was used to characterize the percentage change in weight resulting from immersion (ASTM, 2010). This approach is defined as follows.

$$\%\ \text{Weight Change} = \frac{\text{Wet weight} - \text{Conditioned weight}}{\text{Conditioned weight}} \times 100 \tag{2}$$

where:

Wet weight = Weight after immersion
Conditioned weight = Initial weight of specimen

4.2 Specimen Comparison – Water Absorption

Figure 4.1 illustrates the average water uptake behaviour of the specimens for the first 10-minute time period. The increase in weight per unit area is greater for the untreated hemp

as compared to the tung oil specimens. This implies a greater absorption coefficient A_w for the untreated hemp mat as indicated in Figure 4.1.

Based on the plot it appears that the earth-plaster coating is essentially a sacrificial layer. Within the first minute there is an average weight loss of 19.4% as the earth layer is loosened and dissolves in the water (Fig.4.2). Given this behaviour, the use of A_w to characterize the plaster performance is considered less appropriate in this situation.

The water absorption coefficient A_w was determined for the untreated and Tung oil specimens as shown in Fig. 4.1. By comparison the average gain for the untreated hemp is 47.9% while the Tung oil is 6.9% for the first minute. The Tung oil treatment provides a markedly improved performance compared to untreated hemp.

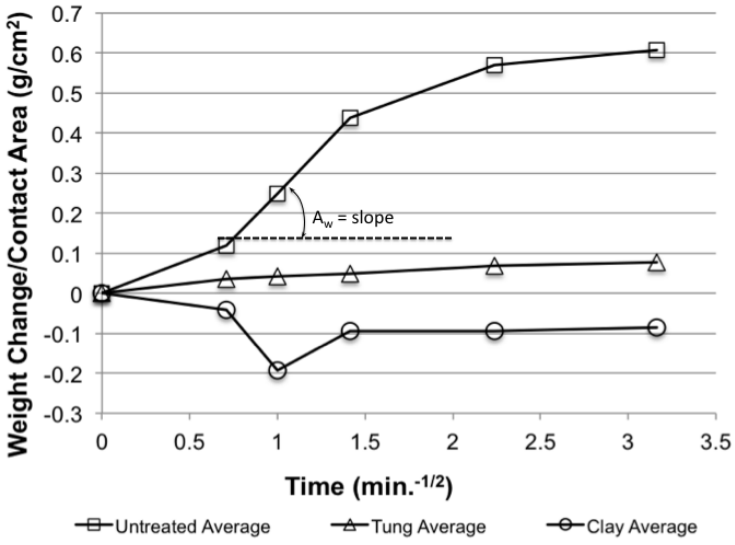


FIGURE 4.1. Water Absorption Behaviour of Specimens for first 10 minutes 24 hours.

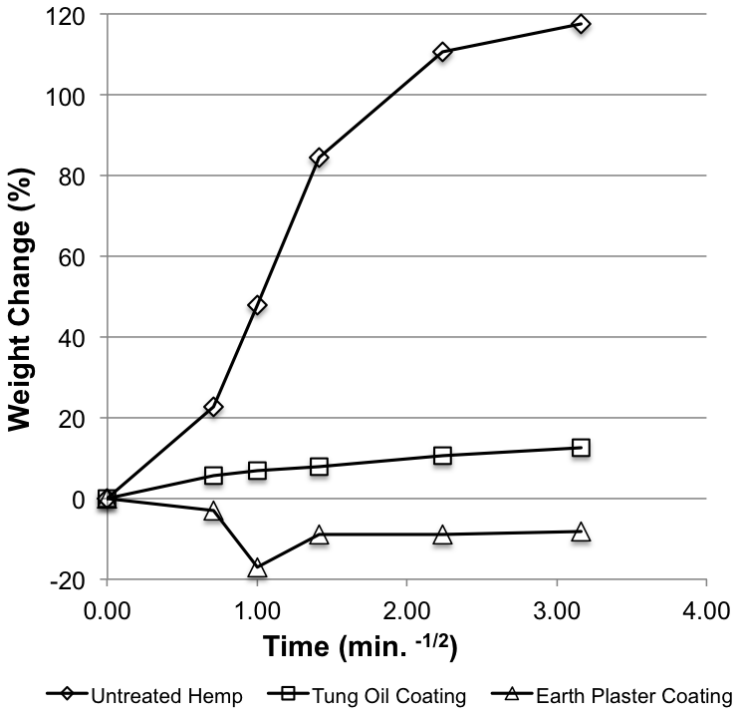


FIGURE 4.2. Weight Change as Percent of Conditioned Weight for first 10 Minutes.

The values in Table 4.1 indicate that the Tung-oil treatment significantly reduces A_w when compared to untreated hemp mat. While the coefficients of variation for both specimens were greater than anticipated, they are considered to be acceptable given the clear difference in A_w and also based on comments in Trechsel and Bomberg (2009) and others that comment on the variation with this particular parameter.

Figure 4.3 contains plots for the entire 24-hour period. The Tung treated specimen gradually gains water over the this time frame although it is still well below the untreated hemp. As mentioned previously, the earth-plaster specimens lose the majority of their coating in the first few minutes of immersion. What is interesting is that the untreated and earth-plaster coated specimen exhibit similar performance after the 10-minute mark based on a comparison of the slope of the water uptake versus time line. The average weight loss for the earth plaster specimens was 66.97%. It appears that the remaining 33.03% of the earth-impregnated hemp does retard the uptake of water. It is not clear why there is a decrease in the untreated hemp, but this could be attributed to loose particles dislodging from the mat and going into solution.

Based on these data specimens with the Tung oil treatment, the water uptake is 5.3% of the untreated hemp. It is not clear what mechanism is responsible for this effect but it assumed that some of the oil is absorbed by the hemp fibres which increases their resistance to water uptake. Also oil that is adsorbed between the fibres is filling in some of the void space between the fibres resulting in reduced porosity. This behaviour is similar to Wang's postulation for flax fibre that intermolecular fibre-matrix bonding is increased, which decreased water aborption in the hemp (Wang, 2004).

TABLE 4.1. Summary Statistics of water absorption samples.

Sample treatments	Average A_w ($g \cdot cm^{-2}s^{-0.5}$)	Standard Deviation	Coefficient of variation (%)
Untreated	0.450	0.118	26.3
Tung oil treated	0.024	0.008	34.5

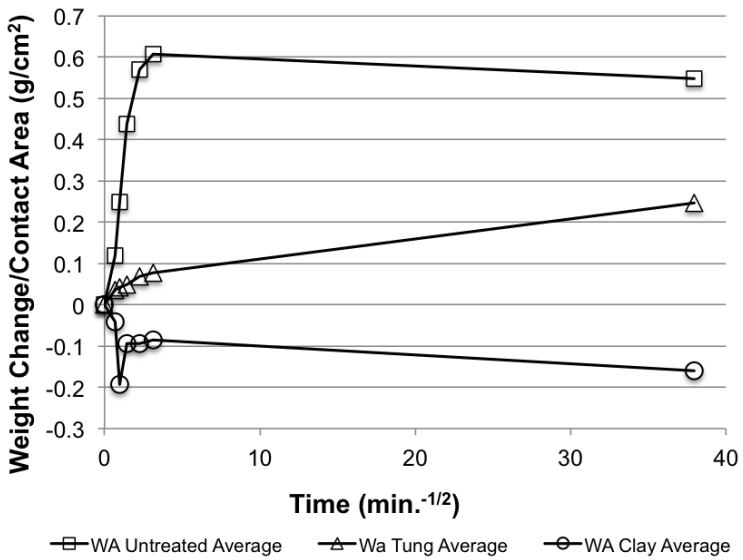


FIGURE 4.3. Water absorption comparison for 24 hours.

If the intent of coating the hemp mat is to reduce water uptake for a short period of time such as that of a rainfall event, then both the Tung oil and earth plaster provide resistance. Although tests were not conducted on the drying rate of the specimens, it is postulated that the Tung oil would be a solution having repeatability. The earth plaster is more of a sacrificial layer that would have to be reapplied, or modified with a stabilizer to lessen degradation. While the use of earth-plaster is not the best choice for resistance of directly applied water, its use on an interior surface would provide for moisture buffering for indoor areas.

4.3 Flexural Tests

Tests were conducted using specimens that had not been subjected to water immersion to investigate the effect of surface preparation on flexural performance. A set of six flexural tests was conducted on two specimen sizes. The samples coated with either earth plaster or tung oil were 150 mm wide, 85mm thick by 472 mm long. A second series of tests was done on specimens 300 mm wide by 1220 mm in length with a nominal thickness of 108 mm to investigate the flexural performance of the core foam without any skins and with hemp-mat and OSB skins.

A set of tests was conducted on specimens with no coating to obtain a baseline. The typical failure mode was pulling apart of the hemp matrix followed by a split in the foam core on the tension side of the specimen.

4.3.1 Coated Flexural Specimens

Figure 4.4 illustrates the typical failure mode for the earth plaster coated specimens. The core of the panel crushed under the load points on the compression face. As the load increased, the hemp mat fibres separated within the matrix on the tension side of the flexural specimen. This resulted in a tension crack to form in the foam core as seen in the figure. Inspection of all the specimens indicated there was no bond separation between the hemp mat and the foam core. Once the confining effect of the hemp mat was lost, failure was immediate given the lower tensile strength of the foam core.

The Tung-oil treated specimens did not exhibit any of the crackling sounds as did the other specimen types. The hemp mat on all of the specimens remained intact with no separation of the hemp mat matrix. The test was stopped after the specimens deformed excessively as shown in Fig. 4.5. The Tung-oil coating appears to have improved the fibre-matrix tensile resistance and increased the initial stiffness of the specimens. Figure 4.6 presents a comparison of the three specimens

FIGURE 4.4. Flexural earth plaster hemp specimen.

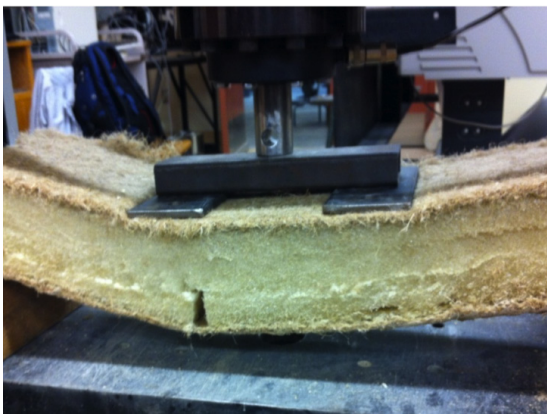


FIGURE 4.5. Deformed Tung-treated hemp panel.

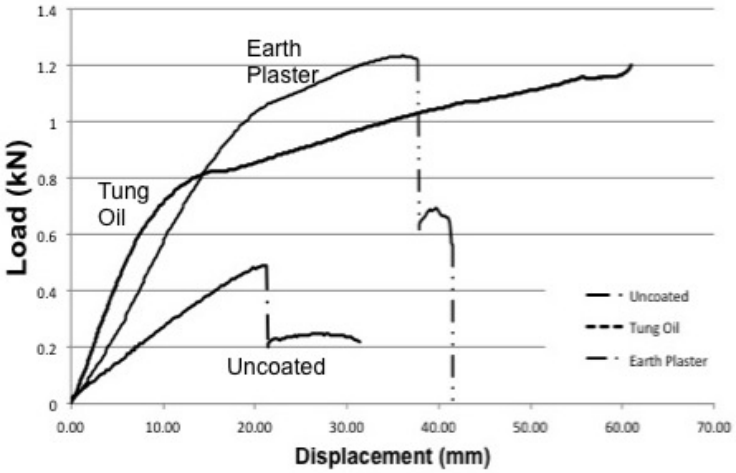


FIGURE 4.6. Example of Load-Displacement Coated Specimens.

flexural behaviour. The tension and brittle failure is evident in the plots for the untreated and earth-plaster coatings. Table 4.2 provides a summary of various properties determined from the flexural test data. The flexural stress was determined using the gross cross section of the panels for moment of inertia calculations. The stress at the extreme fibre was used as a basis of comparison. While the earth plaster specimen is stiffer than the untreated ones, it was anticipated that these specimens would also have greater initial stiffness than the Tung-oil samples. This was not found to be the case for this study. As mentioned previously, the Tung-oil treatment created a hard outer layer on these specimens. It is postulated that while the earth plaster specimens would have a slightly higher moment of inertia with the plaster layer adding to the overall depth, the tensile capacity of earth plaster is low in comparison to the Tung oil specimens. This would provide less tensile resistance, but as evidenced in Table 4.2, the presence of earth within the hemp mat matrix increased initial stiffness by 2.29 times that of untreated hemp mat.

The slope of the second portion of the plaster curve is similar to the untreated specimen. Once the earth plaster was sufficiently cracked flexural resistance is governed by the tensile capacity of the hemp mat. Once exceeded, brittle failure of the foam core occurs shortly after. The Tung oil specimens exhibit approximately 1.83 times more energy absorbing capacity than uncoated ones. While admittedly this increase corresponds to significant geometry change beyond serviceability limits, the ability to dissipate energy may have potential for use in some structural systems.

TABLE 4.2 Comparison of Flexural Behaviour of Coated Specimens

Specimen Type	Max Total Load (N)	Displacement at Max. Load (mm)	Flexural Stress at Max. Load (MPa)	Stiffness[1] (N/mm)	Energy[2] (J)
Uncoated	471	22	0.19	25.4	0.036
Earth Plaster	1243	35	0.52	58.3	0.048
Tung Oil	1296	57	0.54	74.5	0.066

1. Based on the slope of the initial linear portion of load-deformation plot
2. Based on the total area under load-deformation curve

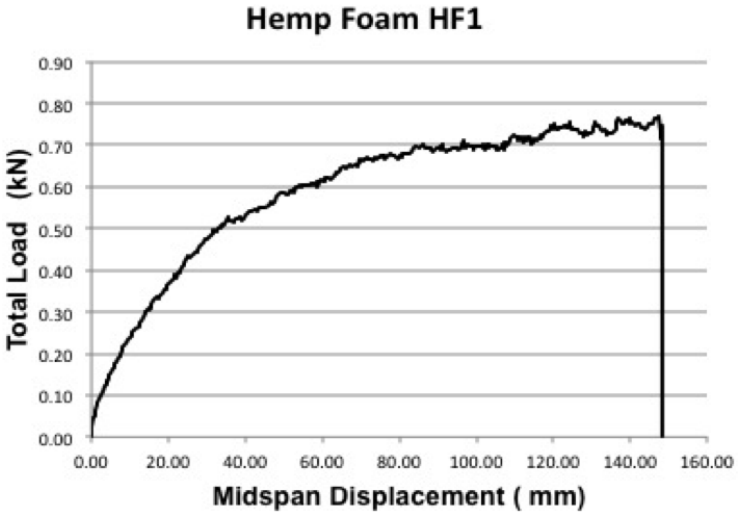


FIGURE 4.7. Typical Load Deformation Curve for Hemp Mat on Foam Core.

TABLE 4.3. Comparison of Average Flexural Behaviour

Specimen Type	Max Total Load (kN)	Δ at Max Load[2] (mm)	Flexural Stress at Max Load (MPa)	Energy[3] (J)
Foam Core	0.74	110.7	0.43	0.21
Hemp Mat[1]	0.86	118.2	0.50	0.22
OSB Skin	11.73	44.6	3.02	0.59

1. No treatment on hemp mat.
2. Midspan deflection at maximum load
3. Based on the total area under load-deformation curve

4.3.2 4-Foot Flexural Tests

A typical load-deformation relationship is shown in Figure 4.7. The typical failure was a result of a separation in the hemp matrix on the tension side of the specimen. Once the mat separated, the foam core split on the tension side at the same location. Examination of all specimens indicated that there was no bond failure between the hemp mat and the foam core.

Table 4.3 provides a summary of test results for the three panel types. The hemp mat covered foam panels showed an average 16.3% increase in flexural capacity when compared to an un-surfaced foam billet. There was an average 6.6% increase in deflection for the hemp mat specimens at maximum load, indicating a slightly better toughness. Failure was sudden after the mat failed in tension as evidenced in the plot contained in Fig. 4.7. The failure mode of the OSB specimens was either a shear failure of the bond between the panel and the foam, or a tensile failure of the OSB skin.

5.0 SUMMARY AND CONCLUSION

5.1 Moisture Performance

The water absorption of untreated and the treated hemp fibres composites were studied. The average water absorption coefficients of the untreated and Tung-oil treated composites were 0.450 g · $cm^{-2}s^{-0.5}$, and 0.024 g · $cm^{-2}s^{-0.5}$ respectively. While the earth plaster provided some

protection reducing absorption it acted more as a sacrificial layer that was dissolved by water immersion. It is clear that the use of a two-coat Tung-oil application substantially restricts water uptake.

5.2 Flexural Performance

The application of a hemp mat bonded to polyurethane foam enhances the flexural performance when compared to uncovered foam billets. The flexural capacity was increased by an average of 16.3% compared to pure foam. Uncoated hemp mat allowed specimens to deform more than uncovered billets. Once the hemp mat separated, tension failure of the foam core was sudden. The 11 mm OSB skin specimens used in this study were approximately 6 times as strong as the hemp mat panels.

Hemp mat flexural specimens coated with earth plaster or Tung-oil were compared with uncoated specimens. The earth plaster and tung oil treatments increased the flexural capacity by 2.73 and 2.84 times respectively based on flexural stress at maximum load. While the increase in strength was similar for both coatings the failure modes were markedly different. Once the earth plaster cracked the hemp mat pulled apart with a sudden brittle tensile failure of the foam core. The Tung-oil specimens deformed over 2.6 times more at maximum load when compared with uncoated specimens. None of the Tung-oil specimens in this study failed due to separation of the bond between the foam core and the hemp mat.

5.3 Overall

The use of hemp mat as a "skin" for polyurethane foam panels appears to have potential. The use of tung oil in this research significantly improves not only the moisture performance but also the flexural performance. It was unexpected that the tung oil application would result in panels that in essence did not fracture, but exhibited the ability to withstand significant deformation. While this deflection was far in excess of acceptable geometry change within a structure, it does indicate the energy-absorbing capacity using this treatment which may have some applications for systems subjected to short term loads.

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