The Utilization of Industrial Hemp as a Structural Material

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The need for alternative materials within the construction industry is increasing as more projects are undertaken. Various alternatives are being researched and applied to projects with the purpose of reducing construction waste. However, substitutes are needed especially when it comes to structural materials. Industrial hemp is a fast-growing fibrous plant that can be made into a variety of goods and has properties that give it a high enough strength to be fabricated into various robust products. Hemp is known to take up less land area, requires less water, is a resource that does not need to be mined out of the ground and is carbon negative. There is research and application of various products made of hemp but there are few for structural purposes. The purpose of this paper is to explore all the applications of hemp that have been researched and to analyze an experiment that tested structural hemp-based beams that can act as a substitute for various engineered wood products. Two beams, one made of hemp hurds and the other made of hemp fibers were fabricated and tested to see if hemp is a viable structural material. The hemp fiber-based beam proved to have more promising results.

Key Words: Industrial Hemp, Material, Resource, Structural, Construction

Introduction

The construction industry is one of the major drivers of the U.S. economy and is essential to maintaining society’s infrastructure. The rapid development that has occurred due to the rise in population within industrialized society has put a strain on many of the finite resources upon which the construction industry relies. As these resources become scarce, prices will rise; resulting in the stagnation of many other industries that rely on buildings and other infrastructure. Change and innovation are the only ways in which the construction industry will be able to solve the current issue of resource scarcity. Many professionals within the industry are finding ways to reduce waste, promote cooperation among the different trades, utilize modern technology to resolve issues before they occur and seek alternative materials to use in place of those that are currently being used.

The most important factor in preserving the finite resources, such as steel and limestone, is to find alternative materials that can be recycled or replenished at a fast rate. One example of a material that can be replenished at a fast rate with relatively few resources such as water and land area is industrial hemp. The plant was deemed illegal to cultivate for several decades due to being related to another strain called Cannabis Sativa but, unlike its close cousin, hemp only has a “THC content of 0.3%” (Pollock, 2019). It was legalized in most U.S. states due to the recent acceptance of marijuana and
contains many desirable properties for a variety of manufactured goods. “Hemp can grow up to four
metres high in three months without the use of pesticides and herbicides, and hemp production is
expanding rapidly throughout the world” (Durrant, 2020). Not only is hemp able to be replenished at a
fast rate, but it also absorbs carbon at a high rate. “A hectare of hemp absorbs 4 times more CO2
during its lifetime than the same tree forest area” (Pollock, 2019). The same volume of hemp will
grow faster, use less water, less land area, and will absorb more carbon compared to lumber-
producing trees.

The renewability of industrial hemp has attracted many to take advantage of the plant to manufacture
several goods. It is of lower cost and easier to process than conventional non-food crops such as
cotton and timber. The fibrous nature that hemp possesses makes it a desirable crop to be
manufactured into several types of goods including rope, paper, and textiles. Various types of hemp
can also be processed into different kinds of foods such as hemp hearts and an alternative to milk.
This crop has a long history of being used by mankind for beneficial gain, but the stigma it carries
from the 20th century needs to be overcome. While hemp has been proven to work for various
industries that produce manufactured goods, its recent legalization needs to be taken advantage of
within the construction industry.

**Literature Review**

The legalization and increasing acceptance of industrial hemp can open many avenues for innovation
within the construction industry. There are some examples of hemp being used as a construction
material throughout human history despite the industry that surrounds hemp in modern times being
very young. “Hemp’s useful building properties have been recognized for thousands of years. A 6th
century bridge abutment in France was recently found to have been made with hemp-filled mortar”
(Pollock, 2019). Just like how the Romans integrated additives such as fly ash into concrete to increase
the strength, hemp has been used as a form of aggregate within concrete during the medieval times.
More recent innovations have been made as the plant is becoming more accepted throughout modern
society. The wide range of products that hemp can be transformed into have been recognized by many
industries, including construction. There are no widespread applications of hemp within construction,
but some research and application of industrial hemp has been conducted. One of the first innovations
involving hemp that was developed is known as hempcrete. “The product developed in the early
1990’s in France is a combination of lime and Hemp hurds which are the short, low value fibers of the
plant” (Peev, 2012, p.22). The development of hempcrete has been applied to construction in a variety
of ways, much like how concrete can be formed into various shapes.

![Figure 1: Hempcrete](Source: Architect Magazine (Courtesy of Flickr Commercial Commons))
Although hempcrete and concrete share the properties that provide workability, there are some key differences between the two materials. Unlike concrete, hempcrete is not able to be utilized in any structural system, the load bearing capabilities of hempcrete are not enough to support any loads that buildings may encounter. “Hempcrete is only about fifteen percent as dense as concrete, and cured hempcrete blocks will actually float in water. Because of this, hempcrete must be used with a frame that supports vertical load, like wooden stud framing” (Pollock, 2019). There are properties of hempcrete that allow it to be used for nonstructural applications within buildings.

One of the most significant uses of hempcrete is that it can be used as an alternative to conventional insulation between and around studs. The material can be casted in place as walls and slabs, or precast as blocks that can be stacked due to the material being lightweight and versatile. “The significant portion of trapped air in hempcrete makes it a good insulation. It’s relatively breathable, but a good insulator for both heat and noise” (Pollock, 2019). Aside from its ability to insulate, it can be used as an alternative for plaster and stucco depending on how much water is added. The various uses that hempcrete offers has not yet been utilized on a mass scale within the construction industry, but there are some buildings that have been constructed with the material.

Hempcrete is one of the composites that have been created out of industrial hemp that shows real promise as a construction material that can be used in the future. While most is nonstructural and used as insulation, there is an alternative that can bear the weight of a structure in place of concrete masonry units. “The Super SSR Block exhibits a compressive strength of more than 5,800 psi, which compares favorably to the range of 1740 psi to 3045 psi typical from CMUs. Additionally, the product is an excellent insulator and is highly fire-resistant with over a one-hour rating” (Brownell, 2018). They are only meant to be used in place of masonry construction, so only structural elements such as columns, walls, opening with lintels, and shear walls. “The combination of hemp and lime has obviously excellent performance as a construction material. However, the lime in hempcrete is considered the weak point of the mixture from (an) environmental point of view” (Peev, 2012, p.25). The issue with hempcrete is the lime binder is a finite resource that requires vast amounts of energy to be mined out. There are drawbacks to hempcrete, but it does show promise for a multitude of uses.

There are other construction materials that have been derived from hemp, but none are as well-known as hempcrete. There is hemp fiberboard (Peev, 2012, p.30), which is where short hemp fibers are pressed together to create a substitute for oriented strand board (OSB). Another promising material is hemp insulation batts (Peev, 2012, p.29) used to replace less sustainable fiberglass batts and are safer
for laborers to install. The other use for hemp that has been researched is a composite utilizing recycled plastics infused with hemp fibers to create an alternative decking material to treated wood (Lu, Korman, 2012). Hemp fibers were infused with recycled high-density polyethylene and was tested to a maximum tensile strength of 60.2 MPa (8,731 psi) and shows promising usage as composite decking for future homes (Lu, Korman, 2012).

Many construction materials have been derived from industrial hemp, ranging from load bearing blocks that replace concrete masonry units to insulation which replaces the unsustainable fiberglass batts that are typically used in residential units. Many of these developments are not load bearing, including most of the hempcrete that has been developed and used, but there are many breakthroughs for insulation and other construction materials. The structural blocks that have been created can be used as a replacement for walls and columns that undergo compression, but when it comes to beams that undergo tensile and bending forces, there is little to no research. There is yet to be a possible hemp-based alternative for suspended beams to be used in future construction projects.

Methodology

The objectives of the research project are as follows:

• Fabricate two hemp-based load bearing beams using two different types of fibers that can take shear and bending stress.
• Determine which hemp-based beam would take a greater load.
• Compare the hemp-based beams to conventional materials that are currently used in the same applications.
• Ascertain if the use of hemp to create an alternative engineered wood product is feasible.

Values to be collected, calculated, and analyzed:

• P- Point-load at midspan of the beams (lbs)
• V- Shear force (lbs)
• M- Bending moment (ft-lbs)
• Fb- Bending stress (psi)
• Fv- Shear Stress (psi)
• E- Modulus of elasticity (psi)

The methodology of the following research project was about gathering quantitative data via empirical means for the purpose of comparing values to one another and to several control values.

The purpose of the experiment that was undertaken was to place two fabricated beams into a machine that applied a point load at each of their midspans. The process leading up to the testing of the specimens involved designing and building the formwork, fabricating the hemp-based specimens, and correctly sizing them to proper dimensions for post-testing calculations. The values that were derived from the collected data are indications of what is analyzed when designing a load bearing structural beam and are of various magnitudes. The two beams that were fabricated and tested are each made of different types of hemp fibers along with epoxy to act as a binding agent. The first beam was fabricated with short rigid fibers known as hemp hurds while the second was made of long thin hemp fibers. The prediction for the outcome of the experiment was the beam made of the long thin fibers would prove to be better suited for use as a structural beam.
Project Background

Before the testing of the hemp-based beams could occur, the beams needed to be fabricated and sized to the proper dimensions. The dimensions of both beams were planned to have a cross-sectional area of 4x6 (nominal) and a length of 3 feet. There were various steps that had to be completed to fabricate beams and make them suitable for the load testing.

Step 1: Formwork

The first step for the fabrication of the beams was the creation of formwork. The chosen design included the application of pressure from all sides to achieve the highest density possible. This was achieved by using bolts and clamps to apply pressure on the sides, a lid to keep the curing beam from expanding, and bricks placed on the top of the form for additional pressure.

The forms were constructed out of:
- One 3-foot long 2x4 for the bottom
- Two 4-foot long 2x12s for the side pieces
- Two 1-foot long 2x4s for the ends
- One 3-foot long 2x4 with two handles to act as the lid
- Two sets of 2 bolts that can be adjusted that lock the side pieces together for added pressure
- Plastic sheeting lining the interior of the form for easy removal
- Cooking spray used as form release
- Duct tape was used to seal all joints to make sure that little to none of the binding agent would leak out, compromising the beams.

Step 2: Pouring the Hemp-Based Beams

Once the forms were constructed, the beams needed to be fabricated and cured. The binding agent used to hold the fibers together was a clear coat epoxy brand, Pro Glas, that is commonly used for boat repair and surfboard fabrication. According to the Pro Glas technical data sheet, Pro Glas Epoxy has a modulus of elasticity of 440,000 psi, and a bending strength of 13,534 psi (Fiberlay Inc): more than enough strength for all intents and purposes.
A series of trials were conducted to figure out how much epoxy was needed to coat the hemp fibers. Three bread pans were filled to the top with half hemp fibers and half hemp hurds. The volume of the first pan was filled 33% of the way up followed by pouring in the hemp fibers, but the sample failed because there was too little epoxy to evenly coat all the fibers. The second pan was poured in alternating layers with 66% of the volume being epoxy; it turned out that the layered pour was effective, but too much epoxy was used as most of it spilled out when the lid was pressed down. The final trial involved pouring 3 alternating layers with 50% of the volume being epoxy and it worked the best. Excess epoxy still poured out the top; resulting in most of the sample being comprised of hemp fibers, but it still coated all the fibers without being as wasteful.

It was determined that the beams would be poured in three layers to ensure the full saturation of the fibers with the epoxy binder. The amount of epoxy that was used per beam was 1.5 gallons, which took up 50% of the volume of the beam prior to any excess that spilled out the top of the forms. The amount of hemp to use was determined by filling the forms up to a line that was drawn 5.5 inches from the bottom, followed by pressing down the lid and seeing if more hemp could be added in until it was not possible to press down the lid anymore. Once the layers were all poured, the lid of the form was pressed down on top to squeeze out any excess epoxy and provide the correct dimension of the beam to the extent possible. The side bolts were tightened, clamps were added, and bricks were put on top to apply pressure during the curing process. To the maximum extent possible, the same method was used for both beams.

**Step 3: Sizing the Beams**

![Figure 4a: First Layer](image1.png) ![Figure 4b: Curing Process](image2.png)

![Figure 5a: Post-Sanding: Hemp Fiber Beam (Darker) Hemp Hurd Beam (Lighter)](image3.png) ![Figure 5b: Finished Beams Prior to Testing](image4.png)
After 48 hours of cure time, the beams were pulled out of their forms and any remaining excess epoxy on the tops of the beams was sanded off using a jigsaw to cut off the bulk of it and a palm sander to get the beams to the desired dimensions. The whole process took approximately 12 hours, and the resulting dimensions were not exact due to human error. While the unrefined fabrication process resulted in the beams not turning out to be exactly 3.5” x 5.5”, the calculations done after the testing were able to correct for that disparity.

**Step 4: Testing the Beams**

![Figure 6a: Hemp Hurd Beam in Machine](image1)

![Figure 6b: Hemp Fiber Beam in Machine](image2)

Each beam was set up in a machine that applied a point load at the midspan and was loaded until failure. The data logged during testing was the point at which each beam failed and the deflection. To determine the proper deflection, a camera was set up to record the loading and deflection at the same time. To enable proper calculations, the video was able to be paused to find the exact deflection at specific load to determine the modulus of elasticity. Overall, testing took around 15 minutes per beam.

### Results and Analysis

The results of the testing were in line with the predicted outcome; the hemp fiber beam proved to be stronger than the hemp hurd beam. Both beams experienced the same type of failure, a sudden fracture that was caused by deflection due to the load applied at the middle span of each beam. A large crack occurred quickly starting at the bottom of the beam and worked its way to the middle of the beam perpendicular to the surface at which the load was applied. Due to the crude fabrication process, some air was entrapped in the epoxy, weakening the overall strength of the beam. The top layer of epoxy in the hemp fiber beam did not have as much air entrapped in it, causing the crack to divert around it. Unlike the herds, the fibers managed to stay intact within the beam while the brittle epoxy fractured.
The data gathered from the testing included the maximum loads (P) that the beams were able to take prior to failure and the deflection with the corresponding loads in order to calculate all the values as accurately as possible. Both hemp-based beams that were tested were compared to control values corresponding to current building materials. Control #1 being Douglas Fir-Larch Grade #1 which is a common species of wood used to frame residential buildings on the west coast of the U.S., and control #2 being a common grade of glue laminated lumber, an engineered wood product that involves bonding smaller members into one large beam that can handle large spans, using Douglas Fir-Larch as the wood material.

**Beam #1: Hemp Hurds**

Beam #1 (Hemp Hurds) had a width of 3.5 inches, a depth of 5.375 inches, and spanned 30 inches when the point load was applied during testing. It was able to take a maximum load of 2,850 lbs prior to failing, a modulus of elasticity (E) that was calculated based off the corresponding load/deflection pair in Figure 8a was 122,560 psi, resulting in a max deflection of 0.289 inches at the point of maximum loading. The bending stress (fb) of the beam resulted in a value of 1,268.3 psi which is higher than the bending stress of the first control only being around 1000 psi (American Wood Council, 2018, p.34). The shear stress (fv) was the lowest of the four members only being 113.6 psi. The results of the first beam were rather low compared to the control values and the values of beam #2, making the hemp hurds a poor choice for use in a structural beam. This was the lighter of the two hemp-based beams having a unit weight of 33.92 lbs/ft³, but control #1 was lighter weighing in at 31 lbs/ft³ (Sierra Pacific Industries, 1956).

**Figure 7a: Failure of Hemp Hurd Beam**

**Figure 7b: Failure of Hemp Fiber Beam**

<table>
<thead>
<tr>
<th>Description</th>
<th>Load (lbs)</th>
<th>Shear (lbs)</th>
<th>Moment (lb-in)</th>
<th>fv (psi)</th>
<th>fb (psi)</th>
<th>E (psi)</th>
<th>Max Deflection (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam #1 (Hemp Hurds)</td>
<td>2850.0</td>
<td>1425.0</td>
<td>21375.0</td>
<td>113.6</td>
<td>1268.3</td>
<td>122560</td>
<td>0.289</td>
</tr>
<tr>
<td>Beam #2 (Hemp Fibers)</td>
<td>6175.0</td>
<td>3087.5</td>
<td>46312.5</td>
<td>240.6</td>
<td>2624.6</td>
<td>149893</td>
<td>0.478</td>
</tr>
<tr>
<td>Control #1: DF-L #1</td>
<td>2352.8</td>
<td>2310.0</td>
<td>17645.8</td>
<td>180.0</td>
<td>1000.0</td>
<td>1700000</td>
<td>0.016</td>
</tr>
<tr>
<td>Control #2: GLB 20F-V3 DF</td>
<td>5000.0</td>
<td>3312.5</td>
<td>37500.0</td>
<td>265.0</td>
<td>2000.0</td>
<td>1600000</td>
<td>0.031</td>
</tr>
</tbody>
</table>

**Figure 8a: Modulus of Elasticity**

**Figure 8b: Specimen Strength Values**

**Source for Control Values**: American Wood Council, 2018, p.34, p.64

*Beam #1: Hemp Hurds*
Beam #2: Hemp Fibers

Beam #2 (Hemp Fibers) had a width of 3.5 inches, a depth of 5.5 inches, and spanned 30 inches when the point load was applied during testing. It was able to take a maximum load of 6,175 lbs prior to failing, a modulus of elasticity (E) that was calculated based off the corresponding load/deflection pair in Figure 8a was 149,893 psi resulting in a max deflection of 0.478 inches at the point of maximum loading. The bending stress (fb) of the beam resulted in a value of 2,624.6 psi which was the highest value compared to the other specimens. The shear stress (fv) was calculated to be at 240.6 psi, which was the second highest of all the members; only to be beaten by the glulam which had a shear stress value of 265 psi (American Wood Council, 2018, p.64). Overall, this beam put out promising values that bested the first beam and has values that can compete with other engineered wood products. Although, this was the heaviest of all the beams with a unit weight of 46.62 lbs/ft³ since the fibers were able to be packed down to a greater density level compared to the hemp hurds.

Analysis

Within Figure 8b, the shear stress (fv) and bending stress (fb) values that were put out by Beam #2 look promising, especially compared to the values of Beam #1, resulting in the beam comprised of hemp fibers to be the superior specimen. The modulus of elasticity (E) turned out to be significantly lower for the hemp-based beams, residing in the six-figure range, compared to the control values, which were in the seven-figure range. The highest value is placed on the Douglas-Fir-Larch with a value of 1,700,000 psi, then the glulam with a value of 1,600,000 psi (American Wood Council, 2018, p.34, p.64), and the hemp-based beams being in distant last. Based on the way the data turned out, there seems to be a correlation between how homogenous the material is compared to the modulus. The hemp-based beams involved many small fibers being pressed together with an epoxy binder, while the Douglas Fir-Larch, which is the most homogenous material of the four members, had the highest modulus.

<table>
<thead>
<tr>
<th>Description</th>
<th>Width (in)</th>
<th>Depth (in)</th>
<th>I (in^4)</th>
<th>L (in)</th>
<th>P (lbs)</th>
<th>E (psi)</th>
<th>Deflection (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam #1 (Hemp Hurds)</td>
<td>3.5</td>
<td>5.5</td>
<td>48.53</td>
<td>30.0</td>
<td>5000</td>
<td>122560</td>
<td>0.473</td>
</tr>
<tr>
<td>Beam #2 (Hemp Fibers)</td>
<td>3.5</td>
<td>5.5</td>
<td>48.53</td>
<td>30.0</td>
<td>5000</td>
<td>149893</td>
<td>0.387</td>
</tr>
<tr>
<td>Control #1: DF-L #1</td>
<td>3.5</td>
<td>5.5</td>
<td>48.53</td>
<td>30.0</td>
<td>5000</td>
<td>1700000</td>
<td>0.034</td>
</tr>
<tr>
<td>Control #2: GLB 20F-V3 DF</td>
<td>3.5</td>
<td>5.5</td>
<td>48.53</td>
<td>30.0</td>
<td>5000</td>
<td>1600000</td>
<td>0.036</td>
</tr>
</tbody>
</table>

Figure 8c: Deflection Comparison

Source for Control Values: American Wood Council, 2018, p.34, p.64

To accurately compare the different moduli of elasticity, all the different materials must be extrapolated to have the same dimensions and the same amount of loading to determine how much deflection occurs. When looking at Figure 8c, all four specimens were calculated to have the exact same cross-sectional areas of 3.5 inches by 5.5 inches, resulting in all members having an identical moment of inertia (I) of 48.53 in^4, and point loads (P) of 5,000 lbs. The moduli of elasticity are the only differing values to directly compare the different deflection values of the various materials. The largest deflection occurs from the hemp hurd beam and was 0.473 inches, second place goes to the hemp fiber beam with a deflection of 0.387 inches, third place goes to the glulam beam with a deflection of 0.036 inches, and fourth place goes to Douglas Fir-Larch with a value of 0.034 inches. It takes less force to cause the hemp-based beams to deflect compared to the control specimens. The abnormally low moduli of elasticity can be attributed to the fabrication process of the beams and not...
being able to achieve as high of a density and uniformity as one could with the proper machinery. It is proven that the hemp-fiber beam has the highest bending stress value yet a low modulus; meaning that the beam has a high loading capacity, but it will deflect a good amount prior to failure.

The way both of the hemp-based beams were fabricated was unrefined, as the forms were built out of wood and the pressure applied to the curing beams was performed by hand. The maximum possible density could not be achieved, as during the curing process the wooden forms cracked. Every attempt was made to fabricate both of the beams in the same exact way, but without the use of machines human error was inevitable.

Conclusion and Future Research

Although some of the results look promising, there is still further research that needs to be conducted to create a feasible hemp-based engineered wood product for structural applications. A better way to fabricate the testing specimens needs to be investigated so a greater bond can be achieved to obtain a greater modulus of elasticity. Other binding agents need to be researched that resemble the glue used to bind glulam beams together rather than the epoxy used in the current project. Epoxy is just not feasible when it comes to cost; it is more expensive than glue and two parts have to be mixed together before use. More environmentally friendly glues are readily available while epoxy can outgas.

Further testing needs to be conducted to obtain values for the compressive and tensile stresses, along with tests that involve the placement of strain gauges; this way more values can be obtained to properly assess the practical use of hemp-based beams within a structural system. Effective manufacturing techniques need to be researched to properly fabricate hemp-based beams on a mass scale at a low cost to be in competition with conventional building materials.

The hemp fibers need to be refined before being fabricated into the beam, a possible way would be to weave the fibers into sheets, just like how carbon fiber is, that can be layered and pressed into beams. The layers would be staggered to prevent joints running down the entire depth of the beam. This would result in a more uniform composition compared to the hemp fiber beam used in the experiment. The mechanical press that would need to be used for manufacturing should be fabricated out of steel as it can take more stress than the forms used for the experiment. The last recommendation for future research would be to continue pursuing the long hemp fibers rather than the hemp hurds. The long fibers gave better results and are a promising material for beams. In contrast, the hemp hurds would be better suited for boards and sheathing, like oriented strand-board (OSB). While the project described herein was only a partial success, it proved that the possibility of using hemp as a substitute for structural engineered wood products is worth further investigation.

As research and the adoption of hemp-based products increases, the availability of the material will increase; causing the cost of hemp to decrease making it more practical than it currently is. The construction industry needs to increase the development of sustainable structural materials as the risk of the supply of conventional ones running low in the future will continue to increase. Researchers have shown that the variety of construction materials derived from industrial hemp points to a promising future for their application in the construction industry. While many of these alternative hemp materials are in their infancy, the research and development of these products will promote a much-needed wave of innovation within the construction industry and will be a step in the direction of a more sustainable future.
References


