Feasibility and Manufacturing Considerations of Hemp Textile Fabric

Utilized in Pre-Impregnated Composites

by

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ABSTRACT

This study investigates the fabrication and mechanical properties of semi-continuous, hemp fiber reinforced thermoset composites. This research determines if off-the-shelf refined woven hemp fabric is suitable as composite reinforcement using resin pre-impregnated method. Industrial hemp was chosen for its low cost, low resource input as a crop, supply chain from raw product to refined textile and biodegradability potential. Detail is placed on specimen fabrication considerations. Lab testing of tension and compression is conducted and optimization considerations are examined. The resulting composite is limited in mechanical properties as tested. This research shows it is possible to use woven hemp reinforcement in pre-impregnated processed composites, but optimization in mechanical properties is required to make the process commercially practical outside niche markets.

DEDICATION

The following is in honor of and inspired by the innumerable mentors throughout my existence. Unequivocally, the genuine scholars endowed with an unyielding clarity of potential in human endeavor and wonderment. The un-jaded and untainted. The passionate educationalists that grasp unbound creativity as a sacred virtue rather than a nuisance. For those that do not superficially discard creation by inaction, but permeate its authenticity by living humbly for the awareness that anything, anything is irrefutably possible. By this understanding, the pervasive obstructions of judgment, pretentiousness and bureaucracy grow weak and concede. That human hindrance breads discontent in the vivid mind and motivates to oppose indifference. Creativity does not wean or waver. It cannot be calmed or repressed. It is far too insidious to be disillusioned by the likes of the timid and ineffectual, the cowering and the coy. Honored mentors, yours do not fear failure. Yours do not tremble, recoil or tolerate apathy. As you have made me, it is my debt and honor to make others of the same understanding. Reverence and admiration to you and the corner stones of my existence, brothers Erik and Ivan, and our mother and father, Barbara and Ivan Sr.

ACKNOWLEDGMENTS

As with any self funded project, reliance upon others is a jagged avenue. Not without tumult, it is an exercise in patience and intrinsic motivation. It is essential that one must believe in the significance of an aspiration, but more importantly, surround themselves with others willing to share that conviction and selflessly contribute to it. This study is entirely the result of sacrifices by others. My endless appreciation is offered to my committee, Dr. Russ Biekert, Trian Georgeau, Dan Ruffner, supporters Andy Estes of Desert Rat Aviation, Gary & Nick Patz of Patz Materials and Technologies, Lawrence Serbin of Hemp Traders, Dan Welch of Phoenix Technology Works Inc. and research scientist Kuang Liu and research assistant Joel Johnston. Without my family and these individuals, this wouldn't have been possible. Thank you all.

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INTRODUCTION

Natural fibers such as hemp have been used for thousands of years for their high strength and multiuse characteristics (Herer, 2010). Since the advent of engineered materials in composites, natural fibers have for the most part been left in the past as reinforcements. This is due to the higher performance characteristics of materials such as carbon and aramid. Natural fibers have more comparable properties to glass in high volume applications (ASM International, 2001). In structural applications where high strength and light weight are absolutely necessary, engineered fibers have no natural equivalent. These applications are generally the cutting edge of composite technology in aerospace, astrospace and high end sporting equipment. Archetypes like aircraft, yachts, exotic cars and rockets, are driven by performance alone where issues like material cost and sustainability have little bearing.

In an effort to lower production cost and provide more consistent results in finished products, processes like resin transfer molding (RTM) and prepreging have become standard in component production (Dorworth, Gardiner, Mellema, 2009). These advanced methods of composite production offer faster means of fabrication with reliable repeatability in finished part mechanical properties. Though they are developed for traditional reinforcement, natural fiber composites could benefit of the prepreg technique.

For the general consumer market, composites are still considered higher end. The automotive industry has for years relied on plastics as a lower cost, lower weight alternative to metals in non-structural components. As the push for better fuel economy in vehicles continues, lighter, stronger and less costly materials have to be developed. In this and many other markets, consumer demand for more environmentally responsible products has risen.

Statement of Purpose

Compared to traditional raw materials, hemp is less costly to produce and more environmentally sustainable than its performance driven counterparts. The purpose of this research is to determine if hemp, a natural organic fiber is a suitable replacement for composite reinforcement using the prepreg method. This study is a preliminary investigation into the potential shortcomings in processing and performance of semi-continuous hemp fiber reinforced thermoset composites. Mechanical properties were tested in a lab setting.

Scope

As with any relatively untested material, non-structural parts are the most logical initial intended use, until optimized, tested and certified for a given application. The mechanical properties of hemp can be assumed as less than engineered materials. With this, one can derive it is safer to avoid the intent of structural applications, at least in the interim.

More and more industries are integrating composite materials. Sporting goods, construction, automotive and marine industries are the intended benefactor of this study, as less stringent standards on material need to be met.

Industries like aviation employ composite materials often, however, they are heavily regulated with regard to structural fidelity, processing and material traceability. This is the case for certified, manufacturer built aircraft. Experimental aircraft, a separate classification by Federal Aviation Administration (FAA) standards, does not adhere to such high standards, leaving room for new materials to be developed and implemented. It is important to realize that the builders of experimental aircraft should understand the limits and nature of a given material and that they are responsible for testing to determine the level of its use. This study is intended to be a starting point in the possibility of use in non-structural applications.

General Theory

Fiber composite reinforcements break down into two categories, continuous and non-continuous fibers. In a simplified telling, non-continuous are generally glass fibers (fiberglass) and are most commonly used in boat manufacturing (Mazumdar, 2002). Traditionally, short cut strands of fiber are wet out with resin and cured. Continuous fiber is coated in resin and cured in a similar process as fiberglass, however, the long woven strands transfer load more efficiently than non-continuous.

Most natural fibers are generally short. Among them, coconut husk has been used for centuries for its tough fibers. In today's market, it is well suited as a common material for environmentally friendly doormats but not much for composite reinforcement (www.williamkempf.com). From known history to the advent of nylon, hemp made up at least 70% of cordage, rope, twine, canvas, ship sails and cloth (Herer, 2010). Flax, jute and sisal were also used and still utilized in the production of natural based twine. Though considered in this study, they are again short and not as well refined.

The best readily available, refined natural fiber suitable for composites is hemp. Raw bark fibers are generally five to ten feet in length. These long strands are refined into shorter individual fibers and twisted together to make yarn. The yarn used in textiles is continuous, however, since the yarn is made of shorter discontinuous fibers, the term semi-continuous is used.

Hemp has proven its utility historically. It has favorable cost and sustainability attributes for markets showing increasing demand for environmentally friendly goods. Given its higher degree of refinement as a natural material, it lends itself to be applied to advanced composite manufacturing techniques. This research examines that possibility.

CHAPTER 2

LITERATURE REVIEW

Natural fibers have limited testing in a lab setting. Most papers are based on raw or unrefined fibers. Comparatively, there is very little mechanical property information on the refined material compared to metals or even traditional composite reinforcements. Moreover, much research has been conducted outside of journals and academia as proprietary information or that of hobbyist projects making details much harder to attain. General industry and historical information is available.

Industry

Hemp and other natural materials have been used in industry in conceptual designs and some production. The following are some notable examples of successful uses in consumer and even high end products.

On August 14, 1941, automaker Henry Ford unveiled an automobile with outer bodywork comprised of short strand hemp and flax among other natural materials. It was Ford's intention to create sustainable processes and materials. His ideas have, in some circles, regained popularity. (http://hempcar.org/ford.shtml)

Among the more recent developments, 2007 brought the advent of semi-continuous fiber hemp into surfboard manufacturing by Chad "Kainanu" Jackson. With his line of boards he coined the term "fibergrassing" (www.hempsurfboards.com/)

In 2008, sports car maker Lotus reveled the Eco Elise. This auto used short strand hemp in its body panels. Curb weight is more than 22Kg. (50Lbs.) lighter than that of the standard version of Elise. (http://www.lotuscars.com/engineering/en/eco-elise)

Flexform Technologies, a U.S. based innovator, has been providing formed short fiber panels to the automotive industry since 1999. These bio-composite parts are found in vehicles by GM, Ford, Mercedes Benz, Nissan and Honda. Products for commercial aerospace are showing promise as the technology is already in use in the manufacture of certified private aircraft. (http://www.flexformtech.com/Auto/Applications/)

Most recently, in a press release by U.K. based Amber Composites, announcements were made for a commercially available, woven flax based prepreg material. This product was developed with Composites Evolution, a supplier of sustainable materials. The material offers the performance characteristics of glass fibers with lower weight and the convenience of prepreg layup processing. (http://www.ambercomposites.com/news)

Academic

In an overview of academic research, examination of hemp and other natural fibers have taken place on raw type fibers. One of the benefits of hemp is that it is more developed as a textile. In woven form, it is more comparative with respect to manufacturability to traditional reinforcement; however, characterization of the raw fiber and process methods was necessary in determining the constraints of hemp utilized in pre-impregnated composites.

Research has been centered in the area of natural based composites by the Affordable Composites from Renewable Sources (ACRES) group at the University of Delaware. Investigating not only natural fiber reinforcements but developing plant oil based rigid polymers as a matrix. By using RTM processed flax and hemp, focus was placed on sizing chemistry and matrix / fiber interface. The brittle nature of the fibers was exposed, however, the general mechanical properties were shown to have promise (Williams, Wool, 2000).

Impact resistance is low among common natural fiber composites. Studies on hemp show relatively weak resistance when using sheet-molding-compound (SMC) method (Müssig, Schmehl, Von Buttlar, Schönfeld, Arndt, 2006). This was determined in the manufacture and testing of hemp based body panels for busses. A separate study was performed on a hybrid of fiberglass and plant fibers. Varying ratios of glass to natural fiber were subjected to impacts. The results showed that impact resistance properties could be manipulated by hybriding reinforcement (Santulli, 2007).

A conceptual design of a pressure vessel was created in 2003. A practical application based on the awareness of sustainability, a vessel was produced by means of filament winding process. It was intended as a substitute to higher priced imported materials. By using locally available products, jute and natural rubber latex were the chosen materials. Feasibility was examined in the Vietnamese market and showed it to be competitive, economical and improved sustainability (Rijswijk, Koussios, Bergsma, 2003).

Thermo degradation of hemp and other natural fibers were studied. Among the fibers tested, it was found that hemp withstood the highest range of temperature, up to 105°C (221°F). This study also examined fiber modification, where various surface treatments were applied and the resulting composite was tested. Bleaching was found to slightly increase tensile strength (Sgriccia, 2008). There were similar findings on fiber treatment increasing tensile strength and thermo degradation temperatures in hemp / polyethylene composites (Aghedo, 2007).

A related study was conducted with thermo-mechanical testing in 2009. With raw hemp fibers in a thermoplastic matrix, layers were created using film stacking method and cured at 180°C (356°F) using a heated press. Samples were subjected to tension until failure. It was found that the mechanical properties were lower than the reviewed literature. By a closer look at the microstructure, inconsistencies in diameter were found along the length of fiber. It was not clear if the higher temperature augmented the inconsistencies (Placet, 2009).

McGill University's Steven Phillips constructed and tested six prototype ukuleles made with flax fiber in 2009. By utilizing a closed mold with a pressure bladder and hand lay-up method, results of mechanical testing indicated the material and production method met criteria for use in production of musical instruments (Phillips, 2009).

Testing Overview

The appropriate testing methods were reviewed. The standard for testing composites in this research is set by the American Society of Testing and

Materials (ASTM). Among the myriad of tests used to analyze material properties, the most applicable were tensile and compression at zero degree fiber orientation, ASTM D3039 and ASTM D3410 respectively. Both tests were specifically designed for polymer matrix composite materials. (www.astm.org)

These studies identify key properties of hemp. They illustrate successful use of various advanced manufacturing techniques like sheet molding, RTM, filament winding and closed mold technology. They examine thermoset, thermoplastic and bio based matrices. They identify the affects of heat and fiber treatment as well as mixing dissimilar fibers to improve impact resistance. The properties studied in the above research exhibit hemps high potential for use in prepreg processing.

CHAPTER 3

METHODOLOGY

Hemp was chosen as the ideal reinforcement for several reasons. It is highly renewable and low-input. Industrial hemp as a crop grows rapidly. It has been harvested after as little as 72 days to maximize fiber quality (Bennett, Snell, Wright, 2006). As a crop, it is more sustainable to produce on large and small scales with little fertilizer consumption and provides natural weed control in fields (Bennett, Snell, Wright, 2006).

The fiber is refined into yarn. It is then woven into fabric just as the majority of other textiles. This process can take place using existing textile equipment with little, if any, adjustment or modification. The most opportune aspect is that hemp has an already well-developed worldwide supply chain from raw to refined material.

Reinforcement

Being that the available woven hemp textiles were not intended for composites, some careful consideration went into material choice. The yarns that make up the weaves are spun tightly. This leads to an uneven resin wet out. The cylindrical shape of the yarn does not allow the matrix to consistently penetrate to the fibers on the inside of the yarns. Additionally, the potential for moisture absorption under this condition can safely be assumed. To minimize this problem, the material would need a smaller diameter yarn.

The available weaves also presented problems, as they are apparel and upholstery based. Fabric styles typically found at arts and crafts retailers, tightly woven linens, muslins and canvas are garment type fabrics and not ideal for use as composites. A plain weave was the only sufficient option.

As the reviewed literature indicated, a prior bleaching of the material could be advantageous. It is common among textile suppliers to offer pre-bleached materials for apparel manufacturers to aid in dyeing. The process referred to as half-bleach, lightens the dark brown color of hemp to a crisp white color using hydrogen peroxide. Lighter weight hemp fabrics, generally fewer than five ounces per yard, usually undergo this process.

Since the majority of this material is manufactured in China and typical uses do not require certifications, very little information is available on traceability. There is currently no quality control or testing done at the factory that would assure consistent product properties for any uses beyond that of apparel and upholstery. To minimize this issue, all samples in this study were produced from the same run of material; however, this variable will have to be considered in future study. Specifications of the material chosen for this study are seen on Table 1.

Table 1: Chosen Reinforcement Specifications

Item Number	CT-L4
Fabric Blend	100% Hemp
Weight	5.3 Ounce Per yard
Weave	Plain 54 x 54 threads per square inch (TPI)
Yarn	24 Numeral metric (Nm)
Processes	Half bleached

Figure 1: CT-L4 Hemp Fabric

Matrix

The matrix, just as the reinforcement, required careful consideration, however, the advantage was availability. Prepreg epoxy resin systems were originally designed for use in composites. It was not a matter of retrofitting a material for a process, as it was for the reinforcement. Cure temperature was the main driving factor. A lower temperature was better as per reviewed literature, to maintain the strength properties of the fiber. The lowest cure temperature resin available was 83°C (180°F). The next issue was compatibility with the natural fibers. Patz Materials and Technology provided a toughened prepreg epoxy resin system. Testing was conducted to assure matrix / fiber compatibility. This was necessary as the exact chemical formula for their matrix is proprietary and confidential. There were no assumptions made. The matrix properties are displayed in Table 2.

Table 2: Matrix Properties for Compatibility Testing

Item Number	PMT F-1
Process	Sheet film
Weight	75 Grams per square meter (gsm)

Preliminary Testing

Testing for compatibility used the film stacking technique with sheets of uncured resin manually placed onto the reinforcement. Sheet film of PMT F-1 epoxy resin was provided. Six pieces of CT-L4 weave were cut at roughly 50mm (2") in width and 100mm (4") in length at 0°. The sheet film was placed between the layers under vacuum pressure and cured at the specified temperature and cycle seen in Table 3. The resulting sample indicated the fiber required at least twice the volume of matrix. A new sample was produced doubling the film amount between the layers. This sample was favorable. The adhesion of the layers was satisfactory and there was no visual indication of negative reaction between the matrix and fiber. The PMT F-1 was, at this level, compatible. A panel was manufactured with properties displayed in Table 3 for use in mechanical testing in tension and compression.

Table 3: Properties of Mechanical Testing Panel

Material	CT-L4 pre-impregnated with PMT F-1 epoxy resin
Cure time	4 hour @ 83°C (180°F)
Vacuum Pressure	- 22.0 Pounds per Square Inch (PSI)
Layup	Six layers @ 0°
Average thickness	1.905mm (0.075 in)
Length x Width	330mm x 330mm (13"x13")
Fiber volume fraction	49.4%

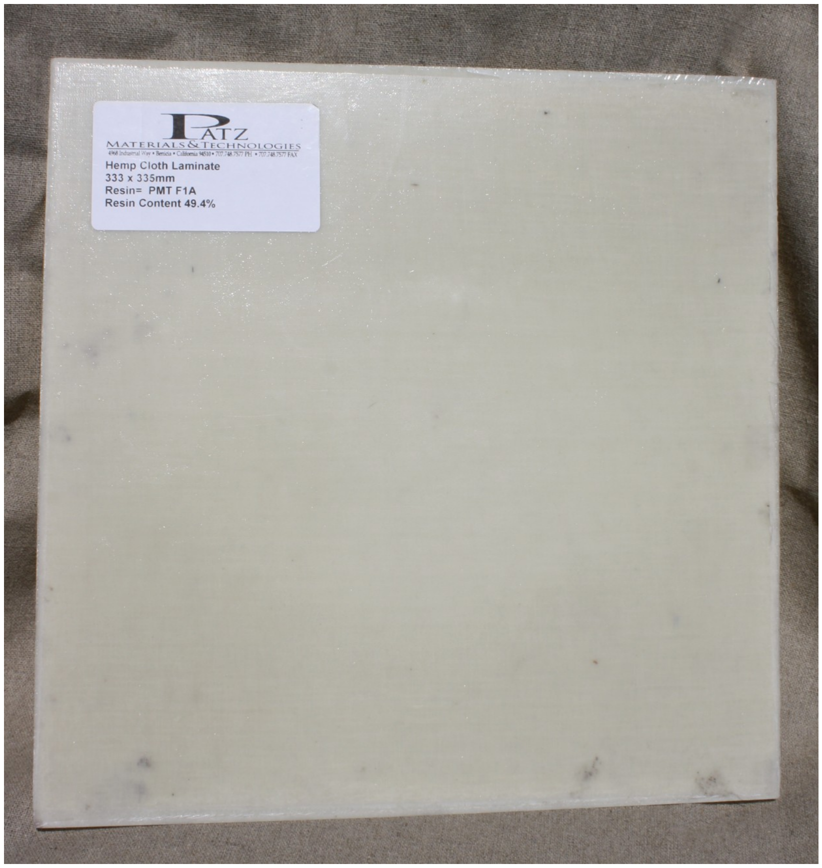

Figure 2: Mechanical Testing Panel

Tensile Testing

Following the ASTM D3039 standard, six samples were cut from the panel with the geometry found in Figure 2. Gripping surface geometry is found in Table 4 and detailed in dark gray shading in Figure 3. Testing was conducted on a MTS biaxial torsion machine (Figure 4) with samples labeled T1 though T6 seen in Table 4. Tabbing was not necessary due to the consistent failure area. Aramis digital image correlation system (version 6.02-6) was used in testing on samples for a more accurate measure of failure strain.

Table 4: Tensile Test Setup

Sample labels	T1, T2, T3, T4, T5, T6
Testing condition	Room temperature
Tabbing	None
Sample geometry	25.4mm x 304.8mm x 1.905mm (1” x 12” x .075”)
Gripping surface	25.4mm x 57.15mm (1” x 2.25”)
Gripping pressure	2100 Lbs
Sample T6 Test	Load to 90% of failure, unload, load to failure
Sample T6 load rate	166 Pounds per minute

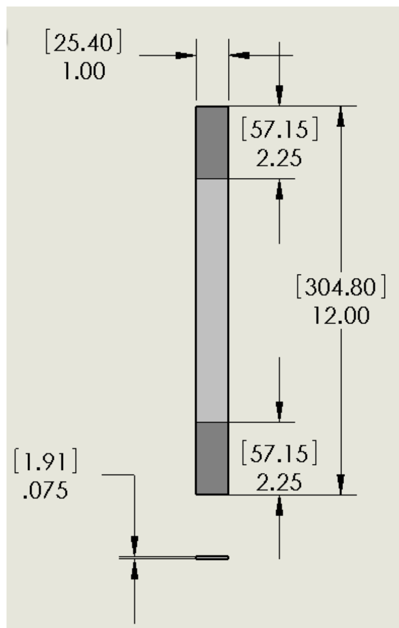

Figure 3: Tensile Sample Geometry T1-T6

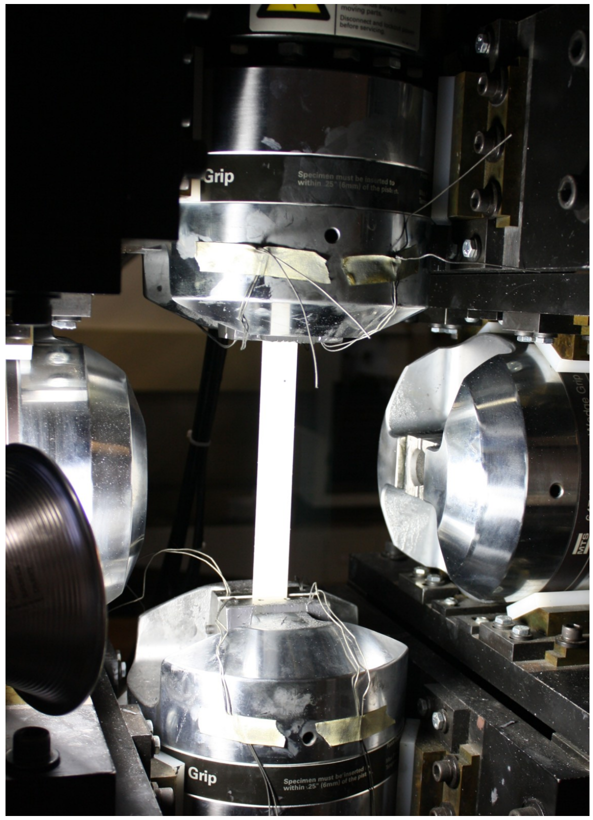

Figure 4: Tensile Sample in Machine

With successful results of samples T1 through T5, the last sample was loaded to roughly 90% of the average failure of the previous five tests. T6 was brought back down to zero load then reloaded to failure.

Compression Testing

Three sets of sample geometry were cut from the panel. Given the difficult nature of compression testing per the ASTM D3410 standard, it was unclear which geometry and clamping method would achieve the best result with samples of 1.905mm (.075”) thickness. Sample geometry and clamping surface details are found in Figures 5,6 and 7. Testing was conducted with Instron model #5985 (Figure 8) and MTS Bionix (Figure 10) universal testing machines. Details of test setup are found in Table 5. Aramis digital image correlation system (version 6.02-6) was again used for a more accurate measure of failure strain.

Table 5:Compresion Test Setup

Samples labels	C1, C2, C3, C4, C5
Testing Condition	Room temperature
Tabbing	None
Sample geometries	
C1	5.4mm x 127mm 1.905mm (1" x 5" x .075")
C2, C3, C4	5.4mm x 105.41mm 1.905mm (1" x 4.150" x .075")
C5	5.4mm x 57.15mm x 1.905mm (1" x 2.25" x .075")
Clamp style	
C1, C2, C3, C4	Wedge (Procedure B)
C5	Hydraulic
Gripping surfaces	
C1, C2, C3, C4	25.4mm x 50.8mm (1" x 2.25")
C5	25.4mm x 25.4mm (1" x 1")
Feed Rate	0.0635mm Per Minute / 0.025 Inches per minute (IPM)

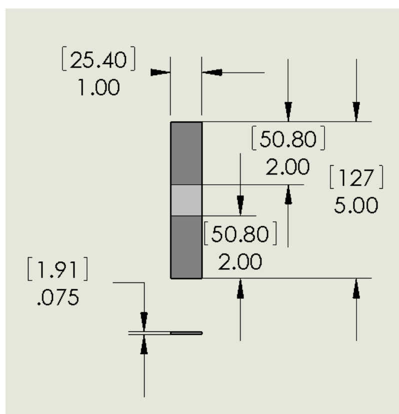

Figure 5: Compression Sample Geometry C1

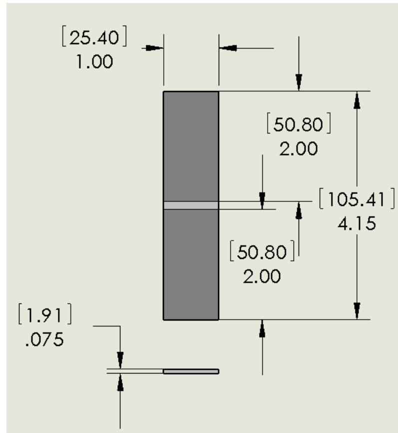

Figure 6: Compression Sample Geometry C2 – C4

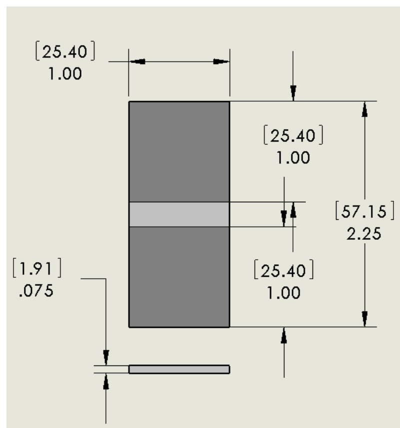

Figure 7: Compression Sample Geometry C5

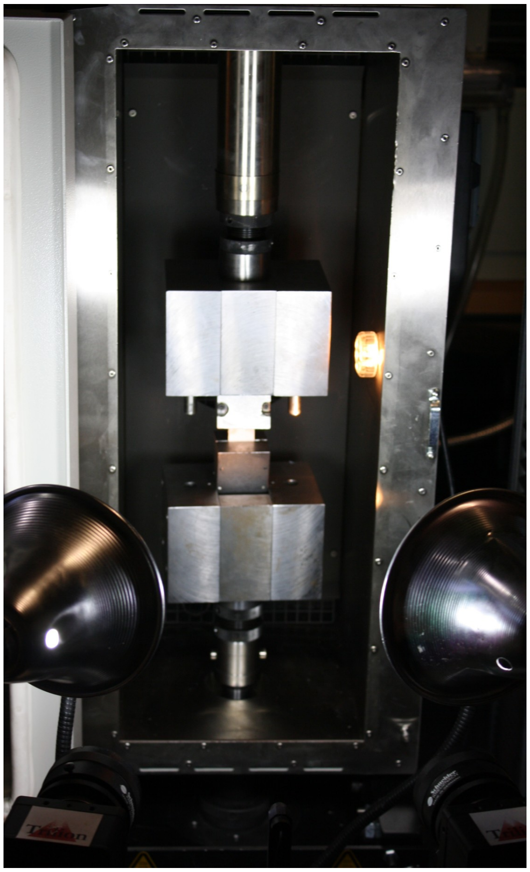

Figure 8: Compression Sample C1 Being Loaded Into Fixture

Figure 9: Compression Sample C2 in Fixture

Figure 10: Compression Sample C5 Hydraulic Clamping

Fiber Volume Fraction

Thermal and chemical methods for determining resin content could not be used on these samples. The hemp material degrades at lower temperatures than the matrix, so it cannot be burned off; likewise, the hemp is not as resistant to chemical matrix removal as carbon or glass fibers. Both methods destroy the hemp reinforcement. The fiber volume fraction was determined by pre-weighing the material before the panel was manufactured.

The methods set forth are based on the compromise between properties found in reviewed literature and the available material. Confirming matrix and fiber compatibility with preliminary testing enabled a panel to be manufactured and tested.

CHAPTER 4

DATA ANALYSIS

Tensile Testing Results

All samples failed in a consistent manner, as seen in Table 6 and 7, at or near the middle. Results for T1 through T5 had a range of 20.3 Kg (44.8 Lbs). T6 was loaded to 294.8 Kg (650 Lbs). When reloaded, it failed curiously at 362.5 Kg (799.1 Lbs). This was 22.2 Kg (49 Lbs.) higher than the failure of the highest sample in the T1 through T5 group.

Table 6: Tensile Testing Results T1 – T5

Sample	Failure Mode	Cross Sectional Area	Failure Stress (ksi)	Failure Strain %	Stiffness (ksi)	Poisson's Ratio
T1	LGM	0.07878	9.514	2.32	9.112	0.178
T2	LGM	0.0804	8.857	-	-	-
T3	LGM	0.07448	9.444	1.89	8.812	0.192
T4	LGM	0.0808	8.804	-	-	-
T5	LGM	0.0808	8.909	2.32	9.390	0.186

Table 7: Tensile Testing Results T6

Sample	Failure Mode	Cross Sectional area	Failure Stress (ksi)	Failure Strain %	Stiffness (ksi)	Poisson's Ratio
T6	LGM	0.07722	10.597	2.88	8.571	0.1845

Compression Testing Results

Achieving a consistent result proved to be a challenge. Of all the specimens tested, C2 was only sample that failed in a way that provided reliable data as seen in Table 8. The samples were too weak at 1.905mm (.075") thickness, to fail in a manner that displayed the true strength of the material.

Buckling repeatedly occurred even on samples with 3.81mm (0.150”) gauge area, see Figure 9. Hydraulic clamping in Figure 10, afforded no distinct advantage on sample C5. The tight geometry presented complications with the aramis system, as the visible area was too small for the optics to capture.

Table 8: Compression Testing Results C1 – C5

Sample	Failure Mode	Cross Sectional area	Failure Stress (ksi)
C1	EGM	0.07867	7.086
C2	TGM	0.07952	12.664
C3	EGM	0.08136	15.516
C4	EGM	0.07848	15.013
C5	EGM	0.06840	15.451

Problems occurred limiting the reliability of the data. The properties that were found are likened to that of wood. Results are slightly higher than Douglas Fur pine. The tests show limited performance of the material in comparison to traditional engineered reinforcement, but it does not negate the use of pre-impregnated hemp processing.

CHAPTER 5

CONCLUSION

This study shows that it is possible to use woven hemp reinforcement in pre-impregnated processed composites, though, the end product is very limited in regard to its mechanical properties as tested. Logic dictates the process is too costly and involved to justify it with low properties. This is not to say that applications do not necessarily exist, but more importantly, it does not mean there is no room for optimization. It is essential to note that the materials used in this experiment were off-the-shelf and never intended for composites. Improvements can be made through optimization in specific areas.

Optimization

The process for manufacturing hemp yarn starts with aligning loose fibers that are then spun to create the yarn. It is in this step that other fibers can be introduced, creating a hybrid yarn at any given mix ratio. Hemp textiles are currently available in varying blends of cotton, silk, flax and other natural and synthetic fibers. Reviewed literature showed flax fibers have higher degree of impact resistance. The addition of flax fibers may improve the properties of the resulting fabric ergo composite. Nearly any ratio of recycled, natural or synthetic fibers can be introduced in this process to tailor fit a given application.

The use of plain weave for the test panel had no negative effect as it was completely flat and drape was of little concern. Real world parts with more complex geometry will encounter unfavorable issues. The current off-the-shelf hemp textiles are woven too tightly to allow for compound curves. This will promote wrinkling, buckling and bridging that will compromise the integrity of the part. Composite style weaves need to be implemented for this material to be practical.

Given the process and feasibility focus of this study, issues like matrix adhesion to fibers and fiber treatment were assumed acceptable by preliminary testing, visual inspection and literature review only. No chemical modifications were made to either the matrix or fiber beyond what was market available. Since the hemp pre-impregnating process has been shown to be feasible under these conditions, more confidence can be placed in research to optimize the matrix / fiber interface.

It is also important to overcome the issue of uneven matrix absorption into the yarns that make up the fabric. This study utilized lighter fabric, with smaller diameter yarn to compensate for this issue. Air voids and dry pockets within the yarns compromise transfer of load from the matrix to the fibers. This will increasingly occur as the diameter of the yarn in the fabric gets larger. As the matrix may not be designed for the more absorbent hemp, problems could occur due to a myriad of concerns like the flow rate, ramp up in the curing cycle or other thermo variables combined with tightly spun yarn. More research and testing could be advantageous in matrix impregnation.

On the part of the hemp textile manufacturer, implementing quality control and product tracability is paramount to become a certified material. Current woven hemp textiles are not intended for composites, but as the material is implemented as a legitimate reinforcement, it will need to meet industry standards. More research most be done to justify the investment to certify this material.

Recyclability and biodegradability have been a major shortcoming of composites. With the increasing implementation of composites in consumer goods and a more environmentally aware consumer, sustainability, from material acquisition through end of use, will become a paramount social responsibility and economic necessity. Hemp and other natural fibers as reinforcement show a high degree of potential for end of use biodegradability and compost. Matched with bio-based matrices, the resulting composite part could lesson the extent of negative environmental and finite resource impact

Industry has shown that natural fibers were successful historically and are still very much relevant in the contemporary age. This material can meet the needs of many industries and do so in a more environmentally sustainable way. This study finds advanced processes like pre-impregnated hemp composites can be implemented, but they require optimization to augment mechanical properties.

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