HEMP FIBER REINFORCED SHEET MOLDING COMPOUNDS FOR AUTOMOTIVE APPLICATIONS

Ellen C. Lee, Cynthia M. Flanigan, Kelly A. Williams, Deborah F. Mielewski, Daniel Q. Houston

Ford Motor Company, Dearborn, MI 48124

Abstract

Natural fibers have been steadily gaining interest for use as a mechanical reinforcement material in place of fiberglass for thermoplastic and thermoset composites. In addition to their lower cost and lower density, natural fibers are a renewable material and are less energy intensive to produce (grow) than glass fibers. In the current study, hemp fiber reinforced SMCs (sheet molding compounds) were prepared and compared to conventionally reinforced glass SMC for cost, density, and mechanical properties. Continuous hemp fiber (in the form of twine), non-woven hemp mats, fiberglass, and hybrids (fiberglass/continuous hemp twine mixture) were examined. Several commercial resins were screened for compatibility to the various fiber formulations and the effect of added compression during the compounding process was studied. In addition to mechanical performance, moisture uptake measurements were performed for the hemp and glass fiber reinforced materials. Selected SMC composites were evaluated against typical desired properties for automotive applications. Results show that certain formulations are currently close to target values. Next steps for additional optimization of composite formulation, fiber dispersion, fiber compatibility, and moisture resistance will be discussed.

Introduction

The use of natural fibers as a mechanical reinforcement material in place of fiberglass for thermoplastic and thermoset composites has many advantages. In addition to their lower cost and lower density, natural fibers are a renewable material and are less energy intensive to produce (grow) than glass fibers. Furthermore, glass fibers are abrasive to tooling (increasing maintenance costs) and can cause irritation and discomfort to operators, two additional benefits that natural fibers may provide. The reduction in fiber density, and thus composite density, is especially favorable for automotive applications, where vehicle weight and fuel economy are often concerns. Previous work by two of the authors [1] also indicates that in some cases the substitution of natural fibers for glass fibers can also lead to improved material damping characteristics. The damping behavior of composite materials for automotive applications is an extremely important factor in overall vehicle NVH (noise, vibration, and harshness) performance.

Hemp fibers are an ideal choice for composite reinforcement for many reasons. Hemp (C*annibis sativa L*) is a fast growing plant that requires no pesticides or fertilizers, and thrives in the climate that is found in Ontario, Canada, a location that is geographically favorable to the automotive industry. In addition, the bast (or stalk) fibers from the hemp plant have among the highest mechanical properties (e.g., tensile strength and modulus) of many natural fiber types.

In the current study, we have examined the use of hemp fibers in 2 forms – continuous, twisted twines and non-woven mats – to replace either all or a portion of the fiberglass in vinyl ester and polyester based SMC (sheet molding compound) formulations. Several commercially available SMC resins were screened for fiber-resin compatibility and overall performance. Novel processing methods were examined for their effectiveness in improving moisture resistance and mechanical performance of the composites. A custom chopper was successfully used for continuous distribution of hemp, glass, and a hybrid mixture of fibers to the compounding line. Finally, mechanical properties, moisture absorption, and density of 4 composites were evaluated and compared against existing glass SMC specifications for various automotive applications.

Materials

Fiber Types and Forms

Hemp fiber was used for composite reinforcement as a comparison to fiberglass. All hemp fibers in the current study were either in the form of non-woven mats or continuous twine. Hemp mats contained 15 weight % polyester binder and had an overall mat density of 55 g/ft^2 (600 gsm). The mats were needle punched at a density of 30 – 35 $punches/cm^2$ in order to hold the fibers together for ease of handling. Unwaxed hemp twine had a construction of six twisted, continuous strands, each strand itself twisted. Chopped glass fibers were used for the baseline, control group material. Both glass fibers and hemp twine were chopped to 1" (2.54 cm) length on a custom fiber chopper developed in conjunction with Brenner International (Newark, OH).

All hemp fibers were oven dried at 80 ºC for at least 12 hr prior to batch or continuous processing in order to eliminate moisture.

Resin Types

Six vinyl ester and polyester based resins were examined to compare compatibility with fibers, composite mechanical properties, and moisture absorption. All resins, denoted in this study as A – F, are commercially available grades. Resin dilutions and viscosities are shown in Table I.

Table I: Resin dilutions and viscosities for batch compression processing method.

Resin	Initial % NV	Resin : Styrene Dilution Ratio	Final Viscosity (cP)
A	61.1	5:1	173
B	69.8	5:2	61
C	50.0	1:0	140
D	77.4	5:3	25
E	75.3	2:1	42
F	75.3	2:1	42

Processing

Batch Processing

Batch compounding was used to assess the effect of added compression on the permeation of resin paste into the natural fiber mats. Batch press experiments were performed on hemp mats cut into 12" x 12" (30.5 cm x 30.5 cm) panels. A single panel was laid down on a sheet of aluminum foil. One of various resin paste formulations was manually poured onto the mat and sandwiched by a second mat. All resin systems were prepared to reduced viscosities by diluting to 50% non-volatile level (NV) with styrene. Additionally, $CaCO_3$ fillers were omitted. Both of these variations to the formulations were introduced to lower the viscosity and further enhance resin penetration through the natural fibers. The mat-resin-mat sandwich was wrapped in aluminum foil and compressed to 1000 psi (7 MPa) for 120 s. The saturated mats were then molded in compression molding (with no maturation) at 300 ºF (150 ºC) and 75 tons (7 MPa). All hemp mat composites had a nominal fiber loading of 45 weight-%.

Continuous Compounding

Continuous compounding was performed on a 24"-wide, laboratory scale Model 600 Series SMC compounding line from Brenner International. Hemp mat, hemp twine, glass roving, and hemp twine/chopped glass hybrids were all compounded continuously. The process is described in previous publications [2,3]. Only resin pastes A, B, and F were used in continuous compounding. Resin paste formulations were prepared without additional styrene dilution, but including $CaCO_3$ filler (see Table III for resin paste formulations). This resin paste formulation is equivalent to commercial formulations for automotive applications. A first layer of resin paste was doctor bladed onto a carrier film, fiber materials were delivered atop the resin paste, and a second layer of resin paste was doctor bladed onto a second film before sandwiching the fiber materials. The resin-fiber-resin sandwich next traveled through several compaction rollers and exited at the end of the line. An additional nip roller was used for supplementary compression in some cases. Fibers in mat form were fed continuously onto the resin paste layer from a large roll, while continuous fibers (both hemp twine and glass rovings) were distributed onto the resin automatically by the custom chopper described earlier [2,3]. Nominal fiber loadings were 40 – 45 weight-% for all of the SMC composite formulations. Compounded materials were allowed to maturate for 24 – 72 hr prior to compression molding at 300 °F (150 ºC) and 75 tons (7 MPa).

Testing

Moisture Absorption

The moisture absorption performance of the various composites was assessed in both short-term and long-term tests. The long-term tests were performed on ASTM D638 tensile specimens [4] and ASTM D3410 compression specimens [5], such that mechanical performance could also be evaluated after moisture conditioning. The short-term moisture absorption tests were performed per ISO 62 [6], for comparison against existing Ford specifications. For ISO testing, specimens were cut from molded panels to 50 mm x 50 mm dimensions. All specimen thicknesses were predetermined by the composite panel thickness. Both short-term and long-term moisture samples were immersed in water at ambient temperature: 24 hr for the short-term test and up to 168 hr for the long-term test. Initial and final weights were measured to determine water uptake. Because the percentage of water uptake is dependent on the density of the composite material, the final moisture content can also be expressed in mass of water per unit surface area.

Mechanical Properties

A battery of mechanical tests was performed on the glass, hemp, and hybrid SMC composites. These included: tensile (ASTM D638, 5 mm/min, which is technically equivalent to ISO R 527), compressive (ASTM D3410), flexural (ISO 178, 2 mm/min [7]), and notched Izod impact (ASTM D256, Method A [8]).

Tensile specimens were sectioned on a diamond blade band saw and milled using a high speed router. Fine filing was used on the milled edges to reduce potential stress risers. Tensile tests were performed on an Instron 3300 Model load frame with a 10-kN load cell and 2-inch (50 mm) extensometers.

Compressive, flexural, and Izod test specimens were cut from molded panels with a diamond blade band saw and the rough edges were wet polished on a grinding wheel on 320 grit polishing paper. Specimens were then oven dried at 60 ºC for 2 hr prior to testing to eliminate moisture from the polishing process. Compressive tests were performed on an MTS 810 load frame with a 5000-lb (2270 kg) load cell and a 5.0-inch (12.7 cm) stroke cartridge. A custom Ford Motor Company version of the standard IITRI lock-down compression fixture was used for testing [9].

Flexural tests were performed on an Instron 3300 Model load frame with a 10-kN load cell, a 40-mm span, and a 0.5-inch (1.25 mm) diameter load nose in 3-point bend geometry.

Notched Izod impact tests were performed on a Model TMI 43-02-03 Monitor/Impact machine with a 10-lb (4.5 kg) pendulum. Notches were cut into the specimens with a Model TMI 22-05 Notching Cutter.

Results

Effect of Resin

Six commercially available resins (Table I) were screened for hemp fiber compatibility, composite mechanical properties, and moisture absorption. Figure 1a shows a plot of the weight percent of moisture uptake in the hemp mat SMC formulations (produced via the batch press method) as a function of water immersion time. A comparison of the resin systems reveals that SMCs formulated with resins A, B, and C absorb the least amount of water over the duration of the test. All of the hemp mat SMC formulations shown here absorb significantly more moisture than is currently acceptable for any automotive application. It is important to note, however, that the formulations from the batch press method have been diluted by additional styrene and do not contain $CaCO_3$ filler. From a previous study, it was shown that hemp mat SMC compounded in resin A without $CaCO_3$ filler absorbed significantly more moisture in water immersion tests than similar composites compounded with the 25 parts filler (see Figure 1b). The formulations shown here are consequently poorer in moisture resistance than a commercial formulation.

Figure 2 shows the compressive strength of the hemp mat SMC composites processed with the batch press method, both prior to and after conditioning in water for 168 hr. Because of the high level of styrene dilution and the absence of $CaCO_3$ filler, the mechanical properties are not indicative of potential commercial composites, but rather are comparative relative to one another. Figure 2 shows that there is a significant reduction in the compressive properties after water immersion, indicating that the significant moisture absorption has a deleterious effect on the mechanical performance. Similar results were found for the tensile modulus and strength. The overall top performing resins for the hemp mat formulations are A, B, and C. Due to limited resources, resins A and B were chosen for further investigation and optimization.

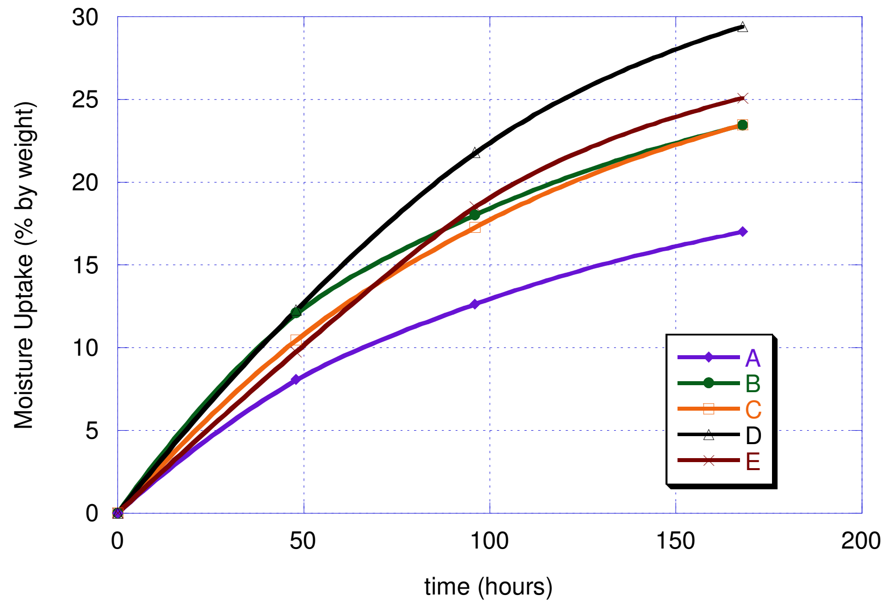

Figure 1a. Moisture uptake of hemp mat SMC composites of different resin formulations produced by the batch press method. Specimens immersed in water at RT for up to 168 hr.

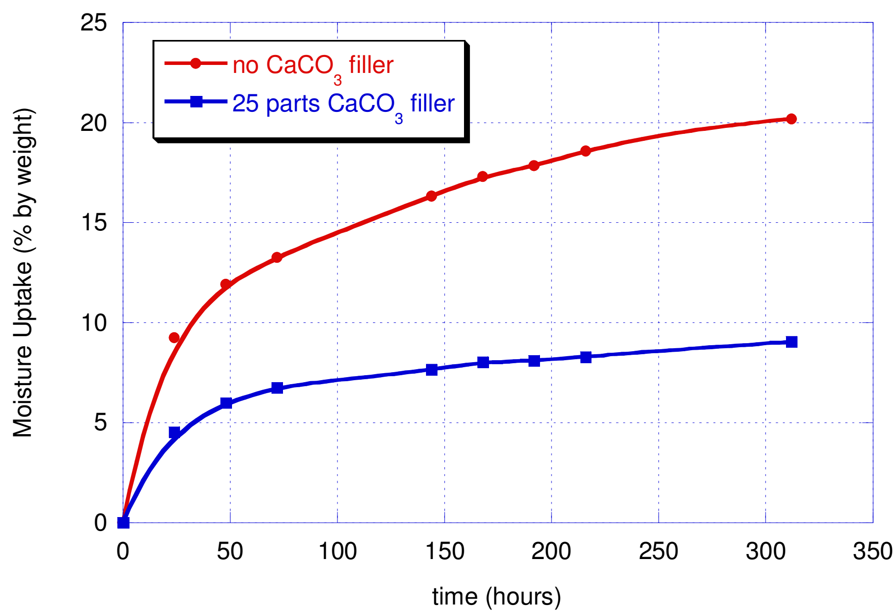

Figure 1b. Moisture absorption of hemp mat/resin A SMC composites during RT water immersion. Samples shown here were produced by the conventional continuous compounding method (without additional compression).

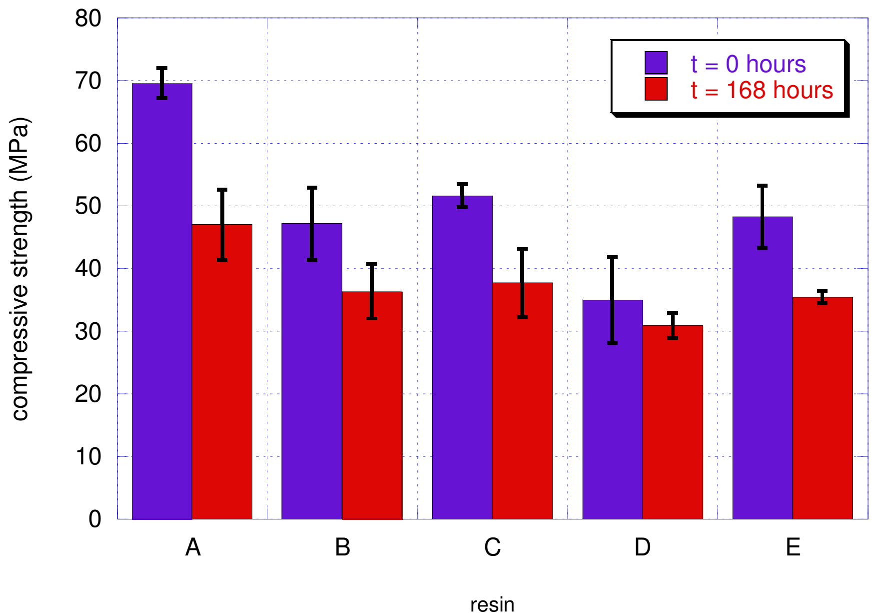

Figure 2. Compression strength of hemp mat SMC composites of different resin formulations, produced by the batch press method; before and after immersion in water at RT.

Effect of Added Compression

A major challenge with compounding hemp fibers in the non-woven mat format is the permeation and wetting of the resin paste throughout the entire hemp fiber mat. Therefore, the effect of additional compression after contacting the fibers with resin paste was studied in a series of batch and continuous compounding experiments. Only non-woven mats were used for this series of experiments. Resins A - E were examined in the batch press method, while only resins A and B were studied with the continuous method.

For the batch experiments, resin viscosities were reduced to enhance wet out further by diluting to 50% NV with styrene. Final resin viscosities are shown in Table I. As described in the processing section, the batch press compounding experiments were performed by sandwiching resin paste between 2 12" x 12" (30.5 cm x 30.5 cm) mats with subsequent compression at 1000 psi (7 MPa) and ambient temperature. After additional compression, all mats and resin formulation combinations were observed to be fully wet out by visual inspection. All resins had a small amount of added carbon black in order to visualize extent of resin penetration. Processed mats were immediately molded in compression at 75 tons (7 MPa) and 300 ºF (150 ºC). Although the mechanical properties could not be directly compared to commercially viable SMC composites, the tensile and compressive properties (Figure 3) do show that wet out of the mats by all resin formulations is improved with the added compression.

A further comparison of moisture absorption in hemp mat/resin A SMCs (in batch press molded versus conventionally processed material) shows that additional compression in the batch process results in a slightly reduced water uptake rate (see Figure 3). Neither of the composites contains $CaCO_3$ filler, but the pressed material does contain added styrene. Due to the dissimilar resin formulations, we caution that the comparison is tenuous.

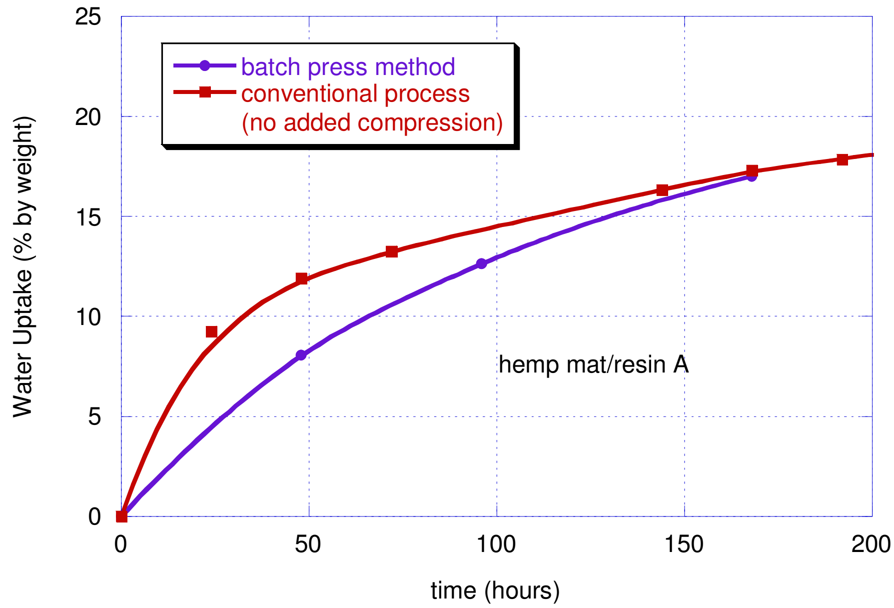

Figure 3. Hemp mat/resin A SMC composites with no $CaCO_3$ filler. The effect of added compression is shown by comparing samples prepared by the batch press method versus conventional compounding.

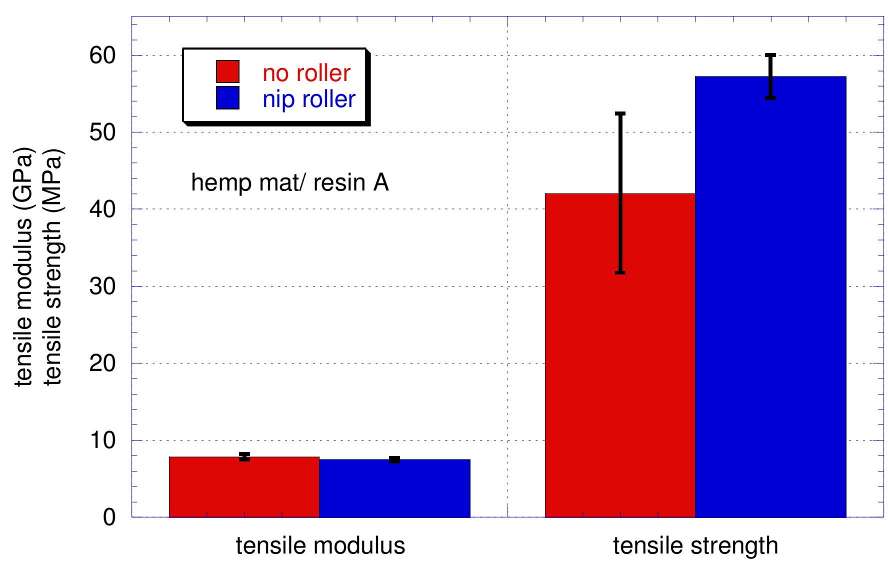

Figure 4. Tensile properties of hemp mat/resin A SMC composites with and without additional compression from nip rollers.

For the continuous experiments, the compounding process was run similarly to the conventional method with the addition of nip rollers to increase the compression by 100 psi (0.7 MPa) at the end of the processing line. Hemp mat SMC was processed with 2 resin systems, A and B, both with and without nip rollers. In this case, the resin pastes were prepared per a commercial formulation. Compounded materials were allowed to maturate for 24-72 hr prior to molding. The effect of additional compression from the nip rollers was assessed both visually and by measurement of mechanical properties. Again, a small amount of carbon black was added to the resin pastes in order to aid visualization. Materials compounded with the nip rollers applied showed better resin penetration through the fiber mat thickness as assessed by visual inspection. Figure 4 also shows that the tensile strength of the hemp mat/resin A SMC was improved by processing with nip rollers, while there was no significant change in the tensile modulus. The significant improvement in the tensile strength indicates better fiber wet out because the interfacial contact between fiber and resin will more significantly affect the strength of the material.

Fiber Chopper

A custom chopper, described in previous publications [2,3], was used to deliver chopped hemp twine, chopped glass, and a hybrid mixture of the fiber types to the compounding line during processing.

This study marks the first time both hemp and glass fibers were intermixed within a chopper and continuously delivered to the compounding process. In addition, both pure hemp and pure glass SMC formulations were processed under the same conditions, allowing for direct comparison. During processing, it was noted that the fiber delivery onto the carrier film displayed slightly uneven transverse distribution. Continued optimization for random fiber distribution and orientation is currently underway for the chopper system.

For the assessment of chopped hemp fibers, resins A, B, and F were chosen. Resin F is essentially the same system as resin A, but with additional low profile additives (LPA) that can enhance the surface smoothness of the finished composite.

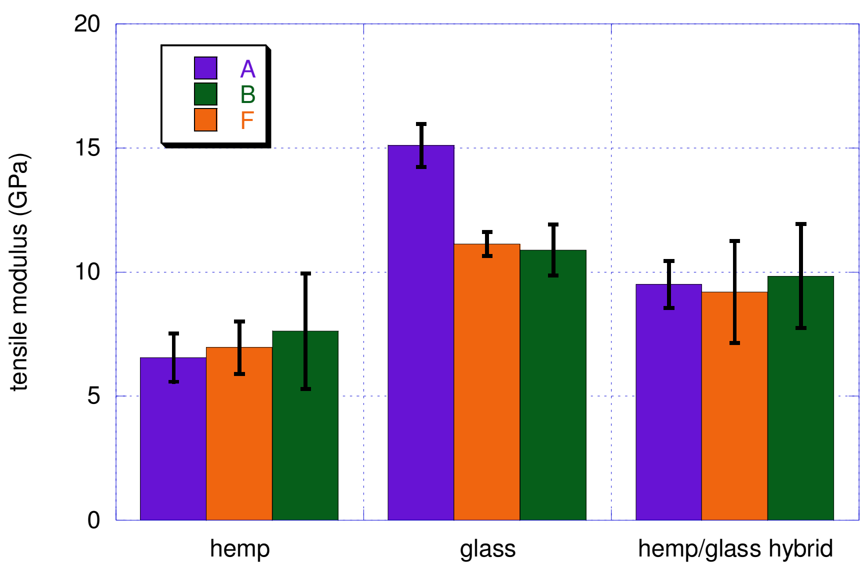

Figure 5. Tensile modulus of chopped fiber SMC formulations produced by continuous compounding (with no added compression); comparison of resin systems.

From the plot in Figure 5, it is apparent that the SMC formulations containing chopped hemp fiber fall significantly short of the properties of the glass fiber SMC, especially in tensile strength (not shown here). This is attributed to the resin rich areas of the composite due to poor dispersion of the hemp fibers throughout the material. Moreover, the hemp twines contain 6 twisted strands that are again twisted together, further exacerbating the dispersion issue. Other types of hemp fiber, including sliver and finer yarns (with less twist) are currently being investigated. The chopped glass SMC composite shows slightly lower tensile properties than a traditional chopped glass material. This can be explained by the uneven transverse distribution of fibers from the chopper, as described earlier. A comparison of the resins shows that resin A is clearly the best resin for the chopped glass system. For the hemp and hybrid materials, however, resins A, B, and F all perform similarly.

Application Testing

The hemp fiber reinforced SMC materials have been initially targeted for specific automotive applications that are not class A or highly structural so as to lessen the performance requirements needed. Due to the stringent requirements for Class A (a measure of surface smoothness for exterior body applications), several potential non-Class A applications were sought (see Table IV). These include such applications as engine sealing covers, heat shields, and noise shields. Other, more structural applications will be targeted as the mechanical properties of the natural fiber SMC composites are optimized.

Table IV: Potential applications for natural fiber containing SMC composites.

Application	Material Description
Engine sealing cover	12.5 mm long glass fiber reinforced epoxy vinyl ester SMC
Heat shield	30% glass fiber reinforced thermosetting pre-preg SMC based on phenolics
Noise shield below engine compartment	30%, 25 mm long glass fiber reinforced unsaturated polyester (UP) SMC
Painted engine cover	Glass fiber reinforced unsaturated polyester (UP) SMC
Engine sealing cover	12.5 mm long glass fiber reinforced epoxy vinyl ester SMC

Mechanical properties of the experimental SMCs were compared against target properties for the potential applications. The experimental materials chosen included: hemp twine in resin F, hemp mat in resin A, hemp twine and chopped glass hybrid in resin F (denoted as chopped hybrid/resin F), and chopped glass in resin A (denoted as glass/resin A). The chopped glass/resin A SMC was compounded with a traditional glass roving cutter, so this material serves as a baseline, control material for evaluation.

Mechanical Properties. A comparison of the tensile and flexural strengths of the experimental materials and the conventional glass SMC reveals that a large disparity still exists between the natural fiber containing composites and glass SMC. This is especially true for the hemp twine SMC. The flexural modulus, on the other hand, is much closer to meeting the performance of the control SMC. Across the board, it appears that the hybrid SMC is the best performer, particularly in terms of Izod impact strength and moisture absorption. In these areas, the hybrid performed just as well as the control SMC. It is noted that both the chopped hybrid and the control glass SMC specimens all displayed hinge breaks on Izod testing, while the hemp twine and hemp mat SMC specimens all displayed complete breaks. The presence of glass fibers was essential both in boosting the Izod impact strength as well as keeping the break type hinged.

Moisture Uptake. Comparing all SMC formulations, the conventional glass fiber reinforced SMC absorbed the least moisture, at 0.52 weight-%. The chopped hybrid SMC also absorbed very little moisture, at 0.57 weight-%. Reinforcement with hemp alone, both in mat and twine forms, caused the composites to absorb a significant amount of moisture. Due to the more uniform dispersion of the mats compared to the twine, more of the fibers are exposed to water, rendering the mat composites more hygroscopic at 5.08 weight-% (versus 2.26 weight-% for the twine).

Conclusions

The results of the current study indicate that vinyl ester and polyester based SMC formulations containing natural fiber reinforcement can meet performance properties for select automotive applications. Although the formulations and processes have not been fully optimized, the mechanical and moisture absorption properties approach acceptable performance ranges. In fact, taking into account the lower density of the hemp reinforced materials, a comparison between specific properties shows that they perform on par for most properties with conventional glass reinforced SMC (see Figure 6).

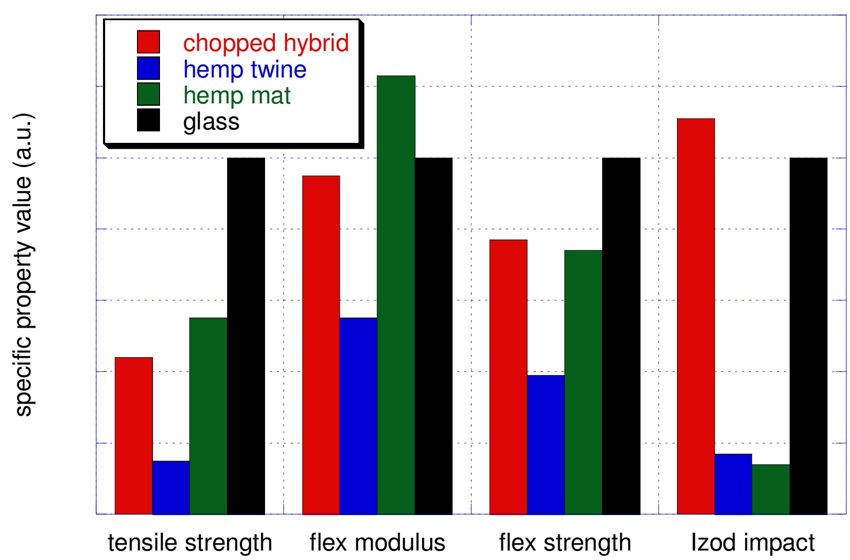

Figure 6. Mechanical properties divided by specific gravity. Data have been normalized to glass SMC control properties. Aside from Izod impact strength, mechanical performance of natural fiber containing materials is not significantly poorer than that of glass SMC.

An evaluation of several commercially available resins showed that the best performance for the hemp reinforced materials was obtained with resins A and B. Furthermore, resin B contains approximately 8% of renewable material itself, giving an additional boost to the environmental theme of natural fiber reinforced SMC.

Moisture absorption continues to be a significant technical issue that needs to be addressed before commercialization of the hemp reinforced SMC can occur. Sizing and compatibilization strategies that may also positively contribute to the moisture resistance are currently under investigation and will be reported in future publications. Hybrid formulations containing glass fibers seem to perform well with respect to moisture. We believe that further enhancement of fiber dispersion throughout a hybrid formulation will result in vast improvements in the mechanical properties while maintaining good moisture resistance. Processing methods to obtain a hybrid mixture (hemp and glass fibers) of well dispersed, chopped fibers are under development at this time.

Acknowledgments

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