NATURAL FIBERS – A NOVEL APPROACH TO REINFORCING AUTOMOTIVE COMPOSITES

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ABSTRACT

As petroleum prices continue to increase, the automotive industry has ramped up efforts to reduce vehicle weight through the introduction of natural fiber reinforcement in thermoplastic and thermoset composites. In addition to their lower density, natural fibers are low cost, 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 (increased 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.

In the current study, we have examined the use of hemp fibers in two 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. Hemp fibers were chosen, among other reasons, because of their high mechanical properties (e.g., tensile strength and modulus) as well as their availability and geographic location (Ontario, Canada). Several commercially available SMC resins were screened for fiber-resin compatibility and overall performance. 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 four composites were evaluated and compared against existing glass SMC specifications for various automotive applications.

MATERIALS

Hemp fiber was the primary reinforcement evaluated in this study, in either non-woven mats or as a continuous twine. Mats were obtained from Flexform Technologies (Elkhart, IN) and contained 15 weight % polyester binder and had an overall mat density of 55 g/ft^2. 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 was obtained from Ecolution (Santa Cruz, CA) and had a construction of six twisted, continuous strands, each strand itself twisted. Chopped glass fibers (Vetrotex from Saint-Gobain, Valley Forge, PA, and supplied by Ashland Specialty Chemical Company in Dublin, OH) were used for the baseline, control group material. Both glass fibers and hemp twine were chopped to 1" 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 hours prior to batch or continuous processing in order to eliminate moisture.

Mat Processing

Natural fiber nonwoven mats can be processed in two ways, drylaid or wetlaid. Both methods are able to produce blends of various natural fibers as well as hybrid mats with different combinations of glass, natural fibers, and/or carbon. Hybrids and blends provide the opportunity to tailor the properties to meet specific application requirements such as stiffness, surface appearance, or modulus.

The drylaid process for nonwoven mats can consist of either carding or airlaying. Carding (Figure 1a) is a mechanical drylaid process which starts with the opening of the fiber bales. The carding line separates and opens the fiber bundles and aligns or randomizes the individual fibers. The carding technology converts the loose fibers into a uniform, cohesive web that is then transported to the next processing step (i.e. the addition of a binder, drying, and rolling). In airlaying (Figure 1b), short fibers are fed into an air stream and are then transferred to a moving belt or perforated drum, where they form a randomly oriented web. Compared with carded webs, airlaid webs have a lower density, a better softness and an absence of laminar structure. In addition, airlaid webs offer greater versatility in the types of fibers and fiber blends that can be used. Both methods allow for the addition of a thermoplastic binder, typically polypropylene. The hemp mats provided for this study were carded and needled (no binder was needed as they were held together by the needle punches). Carding offered the opportunity to use longer fibers, increasing the potential for improved mechanicals.

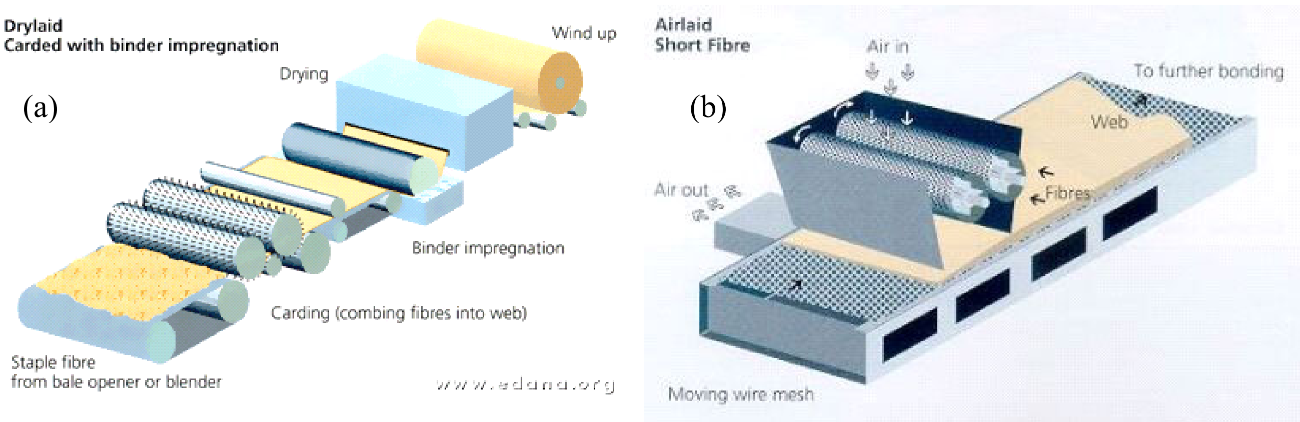

Figure 1. (a) carding process. (b) airlaid process.

Wet laid technology has recently been investigated for the development of nonwoven glass and natural fiber hybrid mats. These experiments are ongoing. Wet-laid technology originated in the paper industry and has since been modified to form non-woven mats that can be used as reinforcements for plastics, insulation, roofing/shingles, as well as textiles (bedding, clothing). In the wetlay process (Figure 2), the fibers are suspended in water where they are dispersed and separated. A traveling screen filters off the water, resulting in a fibrous web, which can then be dried and bonded.

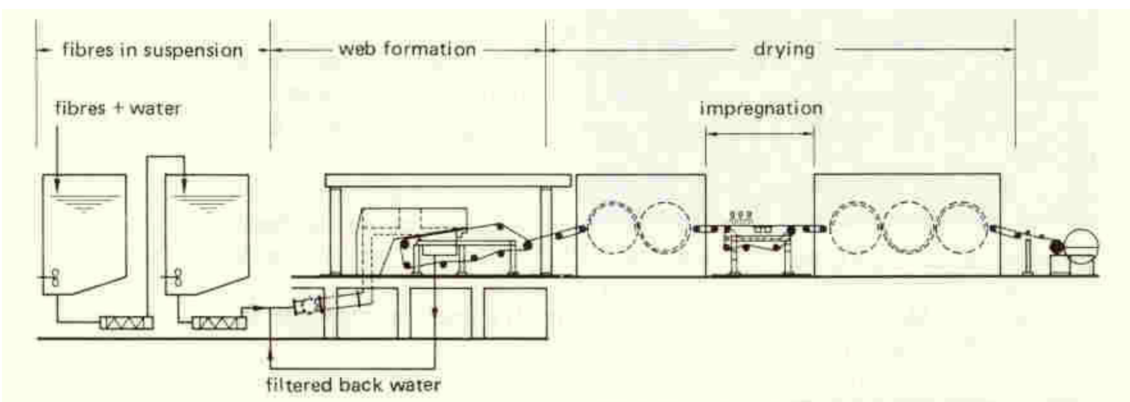

Figure 2: wetlaid process

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 (Figure 3).

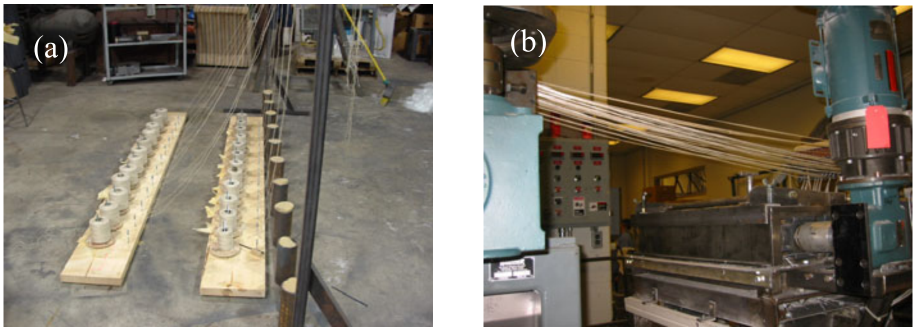

Figure 3. (a) Hemp twine spools on doff racks to feed into custom fiber chopper. (b) Hemp twine feeding into chopper.

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. This process is patent pending.

Resin Types

Several vinyl ester and polyester based resins were examined to compare compatibility with fibers, composite mechanical properties, and moisture absorption. The resins screened in the current study were: Arotech 2000 (denoted as A2000), Envirez 1807 (a soy-based resin, denoted as Soy), Aropol 7440 (denoted as A7440), Aropol 914 (denoted as A914), and Aropol 8014 (denoted as A8014). All resins are commercially available grades from Ashland Specialty Chemical Company. Arotech 2002 (denoted as A2002), a resin system with the same formulation as A2000 with the addition of a low profile additive in the resin blend. Resin dilutions and viscosities are shown in Tables 1.

Resin	Initial % NV	Resin:Styrene Dilution Ratio	Final Viscosity (cP)
A2000	61.1	5:1	173
Soy	69.8	5:2	61
A7440	50.0	1:0	140
A914	77.4	5:3	25
A8014	75.3	2:1	42

Table 1: Resin dilutions and viscosities for batch compression processing method.

PROCESSING

Batch Processing

Batch compounding was used to screen various resin formulations (Table 1) for moisture resistance and fiber resin compatibility, i.e. mechanical properties. Batch press experiments were performed on hemp mats cut into 12" x 12" panels. A single panel was laid down on a sheet of aluminum foil. One of various resin paste formulations (Table 1) was manually poured onto the mat and sandwiched by a second mat. All resin systems were prepared to reduce 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 for 120 seconds. The saturated mats were then molded in compression molding (with no maturation) at 300 ºF and 75 tons. 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 (Figures 4a-c). The process is described in previous publications.[2,3] Resin paste formulations, A2000, A2002, and soy, are equivalent to commercial formulations. 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. Additional compression was added, via a nip roller, after the fibers and resin paste were mated. This is further detailed in previous publications[10]. Fibers in mat form were fed continuously onto the resin paste layer from a large roll (Figure 4a), while continuous fibers (both hemp twine and glass rovings) were distributed onto the resin automatically by the custom chopper (Figures 4b and c) 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 hours prior to compression molding at 300 °F and 75 tons.

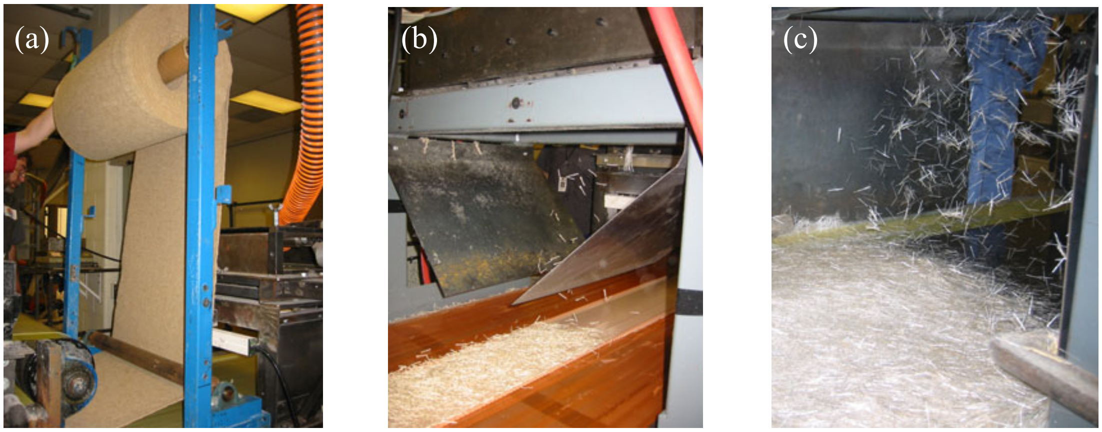

Figure 4. Continuous SMC compounding line utilizing: (a) non-woven hemp mat; (b) chopped hemp twine; and (c) hybrid mixture of chopped hemp twine and glass.

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 and ASTM D3410 compression specimens, such that mechanical performance could also be evaluated after moisture conditioning. The short term moisture absorption tests were performed per ISO 62, 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 hours for the short term test and up to 168 hours 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), and notched Izod impact (ASTM D256, Method A).

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 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 hours prior to testing to eliminate moisture from the polishing process. Compressive tests were performed on an MTS 810 load frame with a 5000-lb load cell and a 5.0-inch 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 diameter load nose in three-point bend geometry. Notched Izod impact tests were performed on a Model TMI 43-02-03 Monitor/Impact machine with a 10-lb pendulum. Notches were cut into the specimens with a Model TMI 22-05 Notching Cutter.

RESULTS

Effect of Resin

Five commercially available resins (Table 1) were screened for hemp fiber compatibility, composite mechanical properties, and moisture absorption. Figure 5 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 the A2000, A7440, and Soy resins 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 which may be a contributing factor.

Figure 6 shows the compression strength, tensile strength, and tensile modulus of the hemp mat SMC composites processed with the batch press method. Again, 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. The plot shows that the overall top performing resins for the hemp mat composite are A2000, A7440, and Soy. Due to limited resources, along with a goal of environmentally friendly materials, A2000 and Soy resins were chosen for further investigation and optimization. A2002 resin was also used during this study and is essentially the same system as A2000 with additional low profile additives (LPA) that can enhance the surface smoothness of the finished composite.

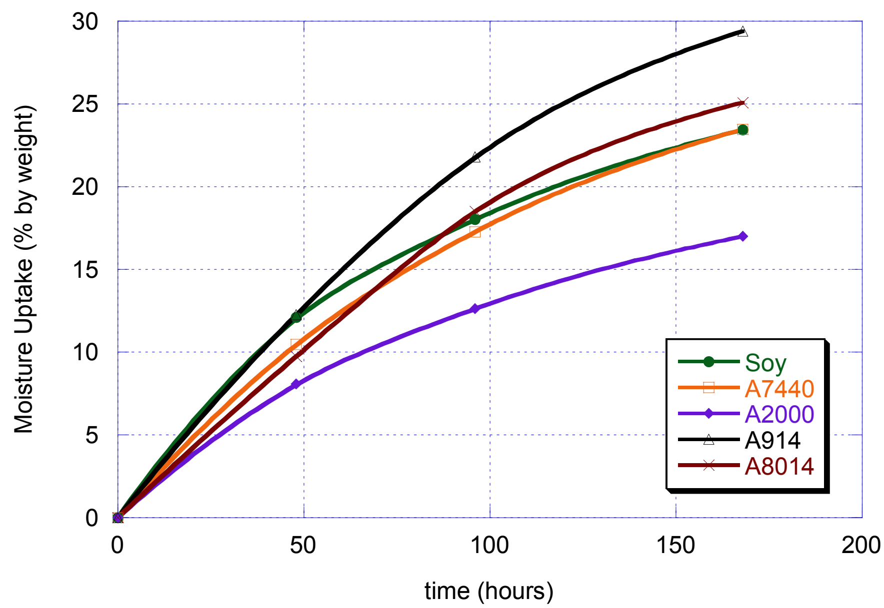

Figure 5. Moisture uptake of hemp mat SMC composites of different resin formulations produced by the batch press method. Specimens immersed in water at RT for up to 168 hours.

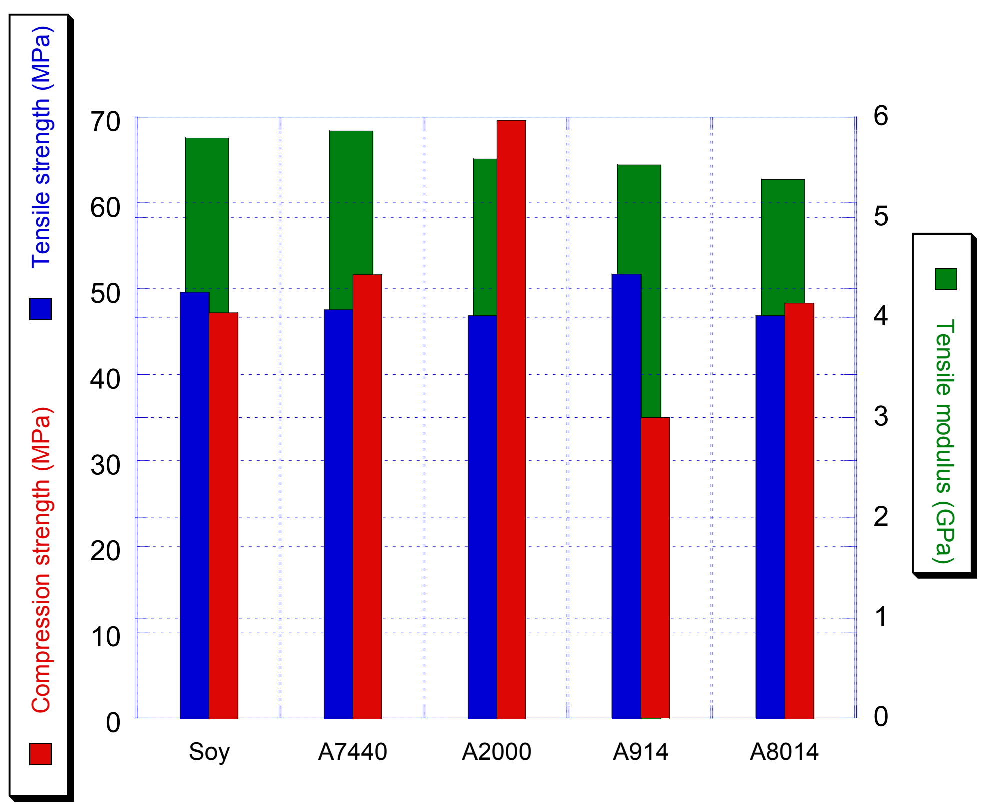

Figure 6. Mechanical properties of hemp mat SMC composites of different resin formulations produced by the batch press method.

Fiber Chopper

Figure 7, shows an assessment of chopped hemp, chopped glass, and chopped hemp and glass hybrids in the three chosen resin systems: A2000, Soy, and A2002. The hemp/glass hybrid consists of a 50 weight percent of each fiber.

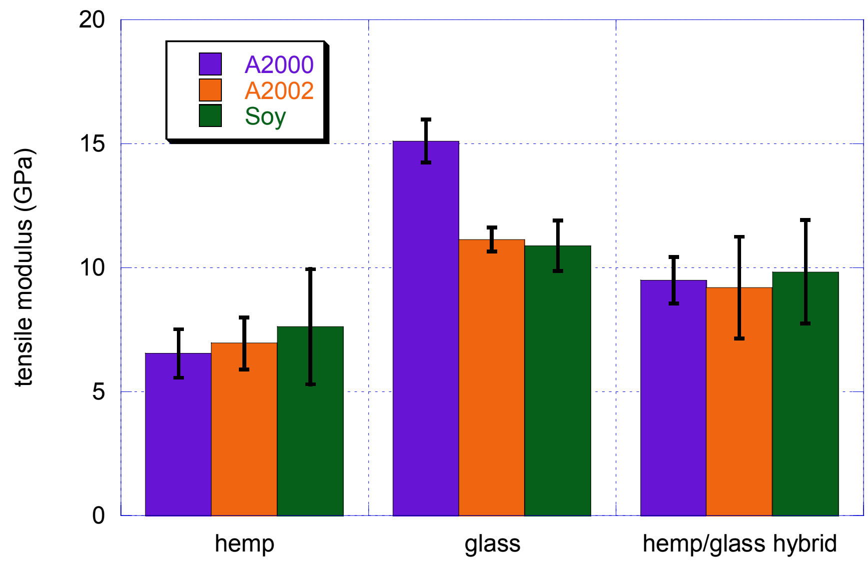

Figure 7a. Tensile modulus of chopped fiber SMC formulations produced by continuous compounding (with no added compression); comparison of resin systems.

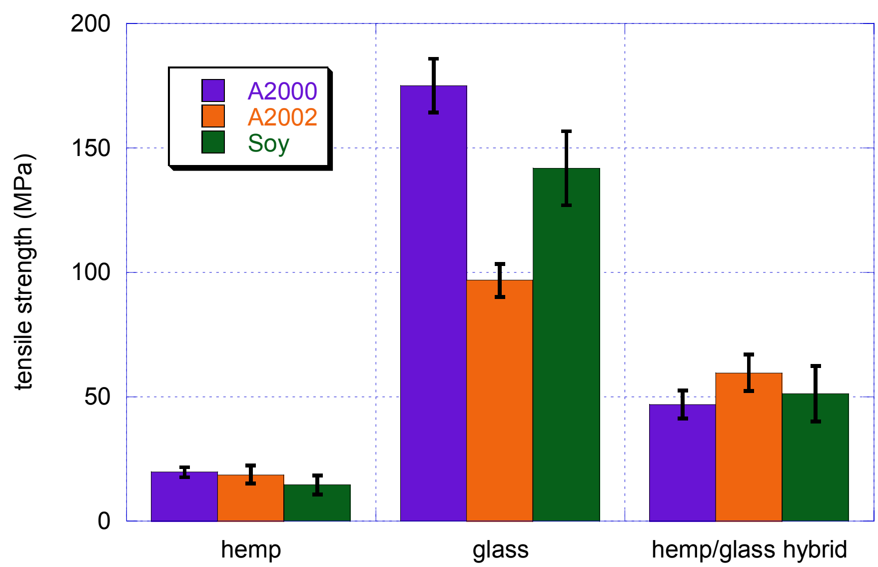

Figure 7b. Tensile strength of chopped fiber SMC formulations produced by continuous compounding (with no added compression); comparison of resin systems.

From the plots in Figure 7, 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. This is attributed to the resin rich areas of the composite, a result of poor dispersion of the hemp fibers throughout the material. Moreover, the hemp twines contain six 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 A2000 is clearly the best resin for the chopped glass system. For the hemp and hybrid materials, however, the resins 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 non-Class A applications were sought and are shown in Table 2. Other, more structural applications will be targeted as the mechanical properties of the natural fiber SMC composites are optimized.

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

Table 2. Potential applications for natural fiber containing SMC composites.

Several of the required material performance properties of four chosen experimental SMC composites were compared against the specifications chosen. The experimental materials chosen included: hemp twine in A2002 resin (denoted as hemp twine/A2002), hemp mat in A2000 resin (denoted as hemp mat/A2000), hemp twine and chopped glass hybrid in A2002 (denoted as chopped hybrid/A2002), and chopped glass in A2000 (denoted as glass/A2000). The chopped glass/A2000 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. After a 24hr water immersion, 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 allowing for a 5.08 weight % gain versus the 2.26 weight % experienced by the twine.

In order to assess the experimental materials against the specifications, the required performance properties were plotted on a radar plot (Figure 9). All properties were normalized by the specification value for ease of comparison. For density and water absorption, the values on the radar plot were calculated by dividing the specification value by the material property value. By preparing the data in this way, a quick glance at the radar plot shows that values >1 are desirable. Figure 9a shows a comparison of the experimental and control SMC materials in relation to a specification for exterior body panel applications. The radar plot shows that the chopped hybrid/A2002 and the control glass/A2000 both pass all performance properties except for the Izod impact strength. The hemp mat and hemp twine materials pass all but the impact and water absorption criteria. Figure 9b shows a comparison to a specification for noise shield applications. In this case, the chopped hybrid and control materials both significantly exceed all specifications and fall close to meeting the requirement for water absorption. Again, the hemp twine and hemp mat materials lack in impact and water absorption performance.

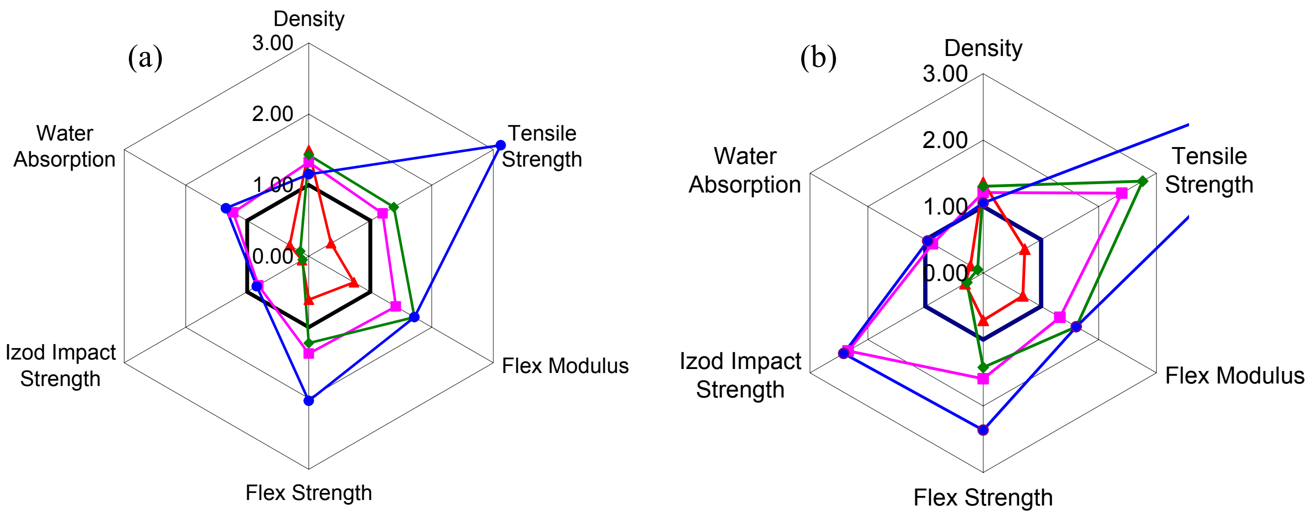

Figure 9. Experimental natural fiber SMC formulations compared against existing Ford specifications. Values shown are normalized to specification values (shown in black). ▲ hemp twine/A2002; ◆ hemp mat/A2000; ■ chopped hybrid/A2002; ● glass/A2000. a) Ford Specification WSS-M3D184-A. b) Ford Specification WSS-M3D170-A2.

CONCLUSIONS

The results of the current study indicate that vinyl ester and polyester based SMC formulations containing natural fiber reinforcement can meet required 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, it can be shown that they perform on par for most properties with conventional glass reinforced SMC.

An evaluation of several commercially available resins showed that the best performance for the hemp reinforced materials was obtained with A2000 and Soy based resins. Furthermore, the Soy resin 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. 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. Further studies are being performed to develop a processing method to obtain a hybrid mixture (hemp and glass fibers) of well dispersed, chopped fibers.

ACKNOWLEDGMENTS

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