An Innovative Wood-Fiber Composite Incorporating Nonwoven Textile Technologies

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Abstract

This article is the first to describe a process of manufacturing engineered wood composites that combine two nonwoven textile technologies: bicomponent fiber and needle punching. Hardwood fiber was blended with 10 percent urea formaldehyde and formed into mats. The mats were sandwiched with polypropylene/polyester bicomponent fibers and then needle punched. Needle punching was done by means of barbed needles that oscillated in a vertical direction with regard to the surface of the fiber mat. The barbed needles mechanically interlaced the bicomponent web to the wood-fiber mat and pulled some of the polymer fibers through the thickness direction of the mat. During hot pressing, the polypropylene sheath of the bicomponent fiber flowed, bonded with adjacent wood fibers, and coalesced with the sheath of the adjacent bicomponent fibers. The mats were pressed until the urea formaldehyde was fully cured. Bending and tensile properties of the needle-punched wood composite were assessed and compared with medium-density fiberboard (MDF). An average increase in storage modulus of 40 percent was observed for the 640-kg/m^3 panels and 48 percent for the 550-kg/m^3 panels. A mean longitudinal tensile modulus of 923 MPa was measured for the laminate panels. This is an improvement in tensile modulus of elasticity of almost 34 percent over the wood-fiber core material.

Medium-density fiberboard (MDF) is a wood-based composite that draws on the usage of wood fibers rather than particles or veneers to produce board or sheet products (Guess et al. 2003). It is typically made as a board-type product, replacing solid wood and particleboard in furniture manufacture, cabinetmaking, joinery, craft work, and flooring. Its use as a structural product has, however, been limited by unacceptable weathering properties, particularly thickness swell as a result of moisture fluctuation.

Needle punching is a nonwoven textile technology that could be applied to wood-fiber products to improve their properties. The process is done by means of barbed needles that repeatedly penetrate or punch into the fiber web in the direction vertical to the wide surface of the web (Mrstina and Fejgl 1990). This results in the reorientation of the fibers from the horizontal to the vertical plane. The vertical structure of the fabric consists of tufts of fiber pulled down through the web by the needles, while the horizontal structure consists of fibers following curved paths around these tufts (Lennox-Kerr 1972). This reorientation of some fibers in the vertical plane, the presence of fibers in both planes, and the entanglement of fibers produce a coherent structure with a three-dimensional character and improved mechanical properties (Mrstina and Fejgl 1990).

Technology has evolved for combining wood fiber and flour with plastics to make panel and molded products. Polypropylene and polyethylene are most commonly used because of cost, ease of processing, and relative compatibility with wood fibers. According to Pirvu et al. (2004), fiber-reinforced composites are found in a wide range of applications because of their high strength and stiffness. Recent studies have shown that fiber-reinforced wood-based materials show great promise as structural components in applications like bridge decking and beams. Attempts have

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also been made to incorporate stronger polymer fibers into a wood product, but these have been limited by problems associated with wood-fiber and polymer adhesion (Youngquist et al. 1992, Park and Seo 1993, Gillahm et al. 2000). Fibers from polymer blends have been increasingly used to modify the physical properties of fabrics. Bicomponent fibers are formed by extruding two polymers from the same spinneret with both polymers contained within the same filament. The main objective of producing bicomponent fibers is to exploit capabilities not existing in either polymer alone. Bicomponent fibers are commonly classified by their fiber cross-section structures as side-by-side, sheath-core, islands-in-the-sea and segmented-pie cross-section types. Sheath-core bicomponent fibers are those fibers where one of the components (core) is fully surrounded by the second component (sheath). These fibers are widely used as bonding fibers in the nonwoven industry. The sheath of the fiber is of a lower melting point than the core, and so at elevated temperature, the sheath melts, creating bonding points with adjacent fibers.

This research focused on polypropylene/polyester sheath-core bicomponent fibers used in the nonwoven textile industry and investigated the feasibility of producing a needle-punched laminate sandwich structure with the bicomponent fiber on the surfaces and resinated wood fiber in the core. The composite material thus created was then compared with MDF in terms of longitudinal elasticity and bending modulus.

Materials and Methods

Sweetgum (*Liquidambar styraciflua*) fibers and urea formaldehyde resin were obtained from DYNEA, Moncure, North Carolina. The resin mixture and resin/fiber ratios were calculated by means of the blending spreadsheet used by DYNEA in their in-house testing procedures. Fiber moisture content was established by oven drying. Initial separation and blending of the wood fiber with the urea formaldehyde was done in a rotary drum blender. After consultation with researchers at DYNEA, a 10 percent resin blend was used to generate target board densities of 550 and 640 kg/m^3.

Fiber separation and randomization was accomplished by means of a rotary hammer mill with a cyclone attachment. The cyclone attachment deposited fibers into a 0.61 by 0.30-m forming box. When all the fiber had been put into the forming box, the mat was manually precompressed. Depending on the target thickness of the board, the average height of the mat was 100 to 250 mm. To reduce the mat height and densify the mat, the mat was cold pressed to approximately 20 to 100 mm. This allowed for easy handling and insertion into the hot press. Initially, the panels were consolidated using a steam-heated press. Later experiments were conducted using an electrically heated press. The press temperature was approximately 177°C. Panels were pressed for 3 minutes at a minimum pressure of 68 MPa based on recommendations of the resin supplier.

Internal bond (IB) strength is a widely accepted industry standard to determine board integrity of the composite z-direction bonding. IB strength tests were conducted on 50 by 50-mm MDF samples to ensure that the panel met industry requirements. A thermoplastic resin was applied to the surfaces of the samples, and heated aluminum testing fixtures were adhered. The testing fixtures were carefully aligned with the grip grooves on both surfaces kept parallel. Samples were tested to failure in an MTS testing machine in accordance with ASTM D1037 (ASTM International 2006). The boards manufactured during this research had an IB strength of 0.83 MPa (±0.2 MPa), which compared favorably with the results obtained by Xing et al. (2007), who listed IB values of between 0.67 and 1.2 MPa. The American National Standards Institute lists a minimum IB strength of 0.6 MPa for MDF (National Particleboard Association 1994).

Initial experimentation involved determining whether the needle-punching process can successfully be applied to a wood-fiber mat. It was quickly determined that wood fiber is too short to needle punch. A longer carrier fiber was needed in order to ensure the integrity of the fiber mat during the process and for adequate fiber entanglement. The polypropylene/PET bicomponent fiber used in the study was obtained from Fiber Innovation Technologies (http://www.fitfibers.com, accessed December 22, 2009). The average fiber length was 38 mm, with an average linear density of 3 denier (±0.3 denier). Average fiber crimp was 11.0 percent (±1.5%). The sheath melt temperature was listed as 165°C. A thermal scan was conducted on the raw fiber by means of a TA Q100 differential scanning calorimeter.

The bicomponent fiber arrived in bale form and was opened, carded, and crosslapped to form fiber webs with a basis weight of 140 g/m^2 in the laboratories of the Nonwoven Cooperative Research Center at North Carolina State University (NCSU). Carding is a web-forming process in which the fibers are opened and parallelized by means of rotating cylinders. The resultant bicomponent fiber web's basis weight was too low ($<$10 g/m^2) for its intended purpose, and it was decided to crosslap the material. A low crosslapping angle (5 degrees) was used in order to maintain fiber orientation in the final product. A fiber orientation distribution analysis was conducted using the fast Fourier transform on backscattered light images of the nonwoven taken by a light microscope (Kim 2004).

Two panel products were considered for this research. The first consisted of wood/polymer-fiber blend. This idea was discarded after initial attempts failed to obtain a homogeneous blend in the rotary drum blending.

The second involved the manufacture of a simple sandwich panel with the bicomponent-fiber web on the surfaces, and wood fiber in the core. Adhesion between the polymer and wood fiber was found to be lower than desired, and it was determined that the additional mechanical interlocking achieved by needle punching was needed in order to ensure panel integrity. The needle loom used was a James Hunter Machine Co. pilot scale loom. Needles were obtained from Foster Needle, illustrations of which can be found at http://www.engr.utk.edu/mse/pages/Textiles/Needle%20Punched%20Nonwovens.htm (accessed December 22, 2009).

Sample beams with dimensions of 12.5 by 50 mm were cut with a table saw from the different panels made in this study. These beams were tested in a TA Q800 dynamic mechanical analyzer (DMA) with a double cantilever testing jig. A first set of samples were cut with the fiber alignment along the longitudinal axis (L) of the beams, and a second set was cut with fibers aligned perpendicular to the longitudinal axis (C). Samples were conditioned to 9 percent moisture content for 10 days. Sample dimensions were carefully measured, and the samples were weighed. Three samples per panel falling within 3 percent of the target densities were selected for testing. A set strain of 0.5

percent was applied to the samples at a frequency of 1 Hz, and the storage modulus was measured. The temperature in the chamber was kept constant at 26°C. MDF panels were prepared and tested in conjunction with the laminate panels for comparison purposes.

Tensile tests were conducted on the composites to determine the modulus of elasticity (MOE) along the longitudinal fiber direction. It was decided to limit the tests conducted in this section to the 2.3-mm panels with a board density of 640 kg/m^3 because of the comparatively large differences observed in bending modulus between the 2.3-mm wood-bicomponent panels and the MDF control in the DMA. Furthermore, the sample dimensions were limited by the length of the panels produced to 200 by 18 by 2.3 mm. Samples were cut with a fiber orientation of the bicomponent sheets along the longitudinal axis of the beams. Strain gages were attached to the sample using epoxy adhesive. Once the epoxy resin has cured, the sample was preloaded in the MTS at 2.5 mm/min until a load of 8.9 N was reached, after which the test proceeded at 1.25 mm/min. The tests were stopped when a reading of at least 600 microstrains was reached on the longitudinal component of the strain gauge. A total of 15 MDF and bicomponent samples were tested. Similarly, tensile tests were conducted on the wood-fiber cores, and the resultant longitudinal MOE was compared with those obtained from the wood-fiber/bicomponent-fiber composite.

Results and Discussion

After initial experimentation, a needle-punched composite laminate panel with a nonwoven web used in conjunction with resinated wood fiber was investigated. Initial experiments to investigate the feasibility of the research method were conducted using polyester webs (PET) obtained from the Nonwoven Cooperative Research Center at NCSU. The webs used had basis weights of 60 and 100 g/m^2, respectively. Because of inadequate bonding between the wood fiber and the PET, it was decided to switch to a polypropylene/PET bicomponent fiber. Figure 1 illustrates the results obtained from the fiber orientation distribution analyses conducted on the bicomponent-fiber web. It can be seen that the web displays a higher degree of orientation with regard to the machine direction. The slight bimodal distribution is the result of crosslapping after the web is carded. This is in agreement with a fiber orientation analyses conducted by Rawal (2006) on webs produced with a 5-degree crosslapping angle. This allowed control over the fiber orientation in the polymer webs when the bicomponent-fiber webs were sandwiched with the wood-fiber mats.

The biggest issue considered was to obtain the thickest possible final panel thickness at the desired panel density while still adhering to the limitations of the needle-punching process. The needle loom used had a throat height of approximately 30 mm. Initial runs on the loom with approximately 7,475-g/m^2 wood-fiber webs prepressed to less than 30 mm resulted in an excessive amount of needle breakage. In order to optimize the needle design and mat thickness, the needle types were changed and tested on wood-fiber mats with basis weights of 4,485, 2,990, 1,495, 748, and 500 g/m^2, respectively. A conical blade, 9-barb needle (F 20 9-20-3B) with a triangular cross section proved to be the most successful.

Panels were differentiated according to punching depth. For the first panel type, the carded web was placed on top of

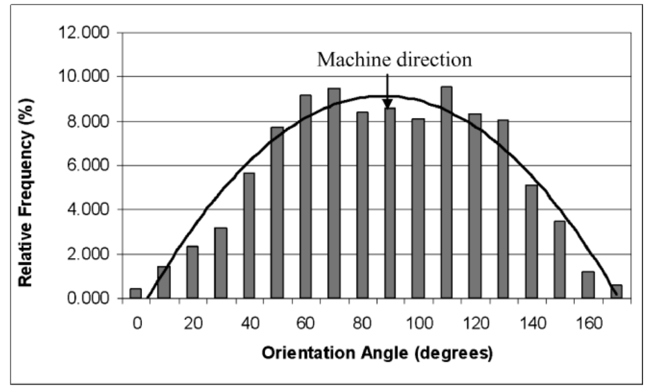

Figure 1.—Fiber orientation distribution of the polypropylene/polyester bicomponent nonwoven fiber web used as reinforcement of a wood-fiber composite.

1,495-g/m^2 wood fiber and needle punched. This provided adequate bonding for the surface laminate. Two of these needle-punched webs were then used to sandwich resinated wood fiber before consolidation in the press. The final panel thickness for this configuration was 6.9 mm. In the second panel type, a 1,495-g/m^2 wood-fiber web was needle punched in conjunction with a bicomponent web. Two needle-punched mats were placed on top of each other with the wood fiber facing the center. The final panel thickness after consolidation in the press was 4.6 mm. The third was a sandwich panel containing a 1,495-g/m^2 wood-fiber web punched all the way through with bicomponent fiber placed on both sides of the wood-fiber mat. The panels were punched from both sides and had a final thickness after pressing of 2.3 mm.

The fiber alignment in the bicomponent webs were carefully noted and controlled during the formation of the panels with both surfaces of the panels having the same fiber alignment. Ten panels of each type were made at target densities of 550 and 640 kg/m^3. For the 550-kg/m^3 panels, 1,285-g/m^2 wood-fiber webs were used. Figure 2 illustrates an unpressed and pressed sandwich panel with bicomponent fiber on the surfaces.

To further investigate the interaction between the bicomponent and wood fibers, samples were prepared for imaging on a scanning electron microscope. The samples were vacuum dried prior to being sputter coated with gold. Figure 3 shows a bicomponent-fiber tuft pulled from one surface through the wood-fiber core, illustrating the action of the needles during punching. Figure 4 illustrates the interface between the surface reinforcement and the wood core. A wood fiber can be observed at the center of the scan, with a bicomponent fiber adjacent to it.

The melting point of the polypropylene sheath was observed at 165°C in the DSC scan and that of the polyester core at 250°C, which is in agreement with results published by Perry and Green (1997). This indicates that the polypropylene sheath will melt and fuse with the wood at the press temperature of 177°C, while the polyester core will remain intact during pressing. A total of three samples were tested.

Figure 5 illustrates the results obtained for the storage modulus of the 550-kg/ m^3 panels with the DMA. The mean storage modulus of all three MDF panel thicknesses were 392 MPa (coefficient of variation [CV] = 2.8%), while *t*

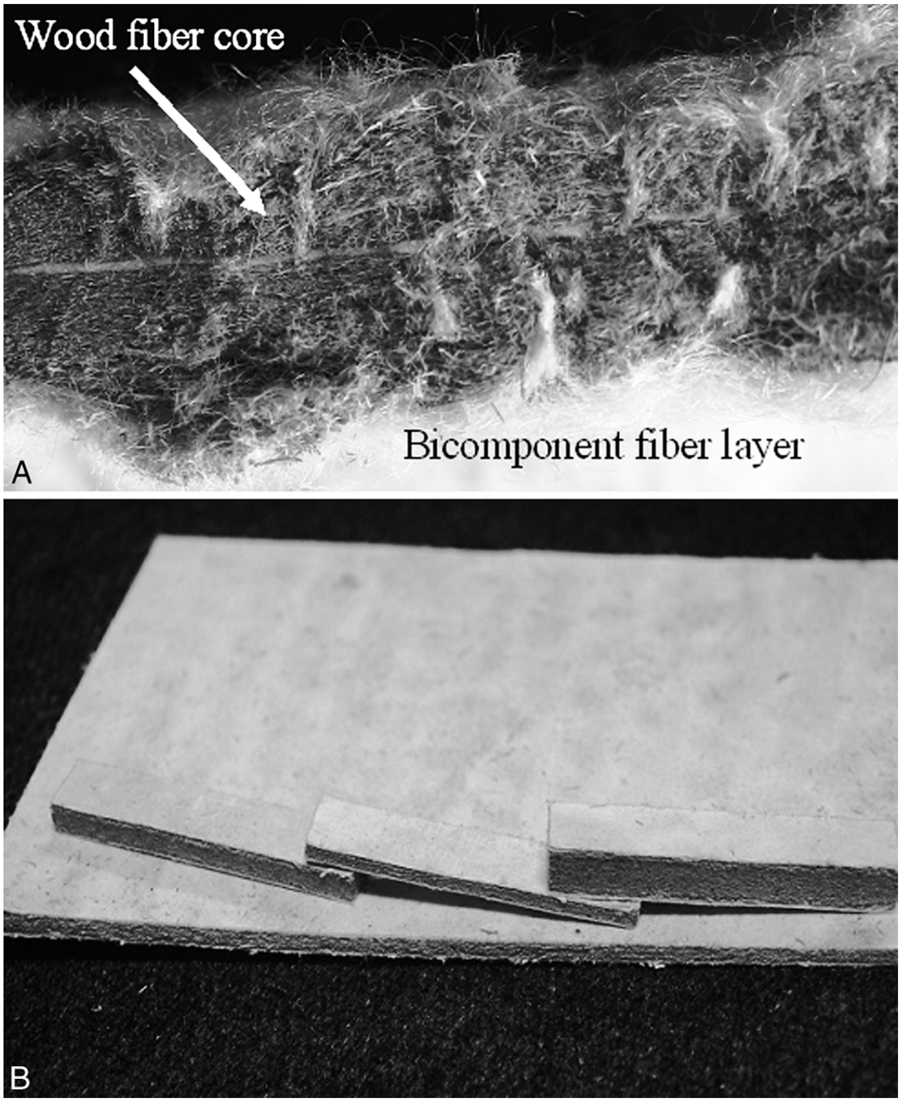

Figure 2.—(A) Unconsolidated 4.3-mm half-punched wood-bicomponent-fiber panel and (B) consolidated wood-bicomponent-fiber panels manufactured for this research.

tests conducted comparing the storage modulus of the composite panel at different thicknesses with the corresponding MDF control panels found no significant differences in storage modulus (P values < 0.05; highest P value $= 0.0011$). The mean storage modulus of the 2.3-mm punched-through wood-bicomponent-fiber laminate panel with the bicomponent fibers aligned along the longitudinal axis was found to be 563 MPa (CV = 5.2%), while the storage modulus for the 4.6-mm half-punched and 6.9-mm surface-punched panels were 489 (CV = 5.1%) and 501 (CV = 4.5%) MPA, respectively. All three values were significantly higher than the MDF of the respective thicknesses. The storage modulus obtained from the 2.3-mm samples were, however, 11 percent higher than that obtained from the 4.6- and 6.9-mm samples. This can be attributed to the fact that the bicomponent-fiber sheet is stiffer than MDF and has a greater influence on the overall stiffness of the thinner panels.

The storage modulus calculated when the bicomponent fibers were aligned perpendicular to the longitudinal axis of the beams was found to be higher than that obtained from the longitudinally aligned fibers. Similar trends were observed with the cross-directional fibers, with the 2.3-mm panels having a significantly higher storage modulus than the 4.6- and 6.9-mm panels. The storage moduli for the 2.3-, 4.6-, and 6.9-mm panels were 683 (CV = 5.8%), 581 (CV = 8%), and 589 (CV = 4.5%) MPa, respectively. Further investigation is needed to determine why the longitudinal modulus is lower than the cross-directional modulus. One reason might be that the crimp in the fiber is actually causing a perpendicular shift in the fiber alignment.

The results of storage modulus measurements obtained from the 640-kg/m^3 panels (Fig. 6) were similar to those obtained with the 550-kg/m^3 panels. An overall increase in storage modulus of 10 percent was observed because of the higher panel density. The relative difference between the storage modulus of the laminate panels and MDF was lower in the case of the 640-kg/m^3 panels than for the 550-kg/m^3 panels. This can be attributed to the greater influence of the lower stiffness wood-fiber composite in the 640-kg/m^3 panels. Furthermore, there is an overall increase in the storage moduli with an increase in panel density. This is in

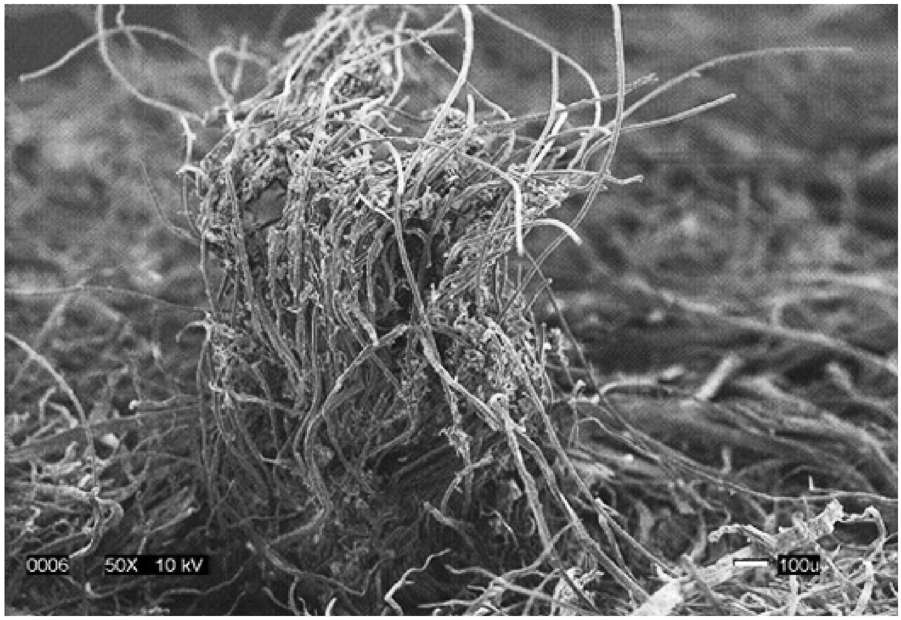

Figure 3.—Fiber tuft protruding from the surface of the wood-fiber core.

agreement with Xu and Suchsland (1998), who found that MOE increases linearly with an increase in panel density.

The composite material also showed an improvement in longitudinal MOE in tension when compared with that obtained from the core. The wood-fiber core material had a mean MOE of 689.13 MPa (CV = 6.5%). Cai (2006) obtained values for MOE in tension for MDF of 2,000 MPa. This large discrepancy between the values obtained during this research and those cited in the literature can be attributed to the long press times used in this study to ensure that the bicomponent-fiber surface reinforcement has adequate time at high temperature to melt the polypropylene sheath. UF resin degrades when it is exposed to high temperature for long periods of time. Furthermore, the blender used during this research was specifically designed to process particleboard, and it is suspected that resin blending during furnish processing was nonuniform. A mean longitudinal modulus of 923 MPa (CV = 2.3%) was measured in the laminate panels. The laminate panel therefore showed an improvement in longitudinal MOE of almost 34 percent. In addition, the panels were delaminated, and the tensile moduli of the constituents were determined. The MOE of the core was measured at 689.13 MPa (CV = 6.5% MPa) with a mean Poisson's ratio of 0.288 (CV = 9%). A mean E_1 of 2,178.2 MPa (CV = 5.4%) was observed for the bicomponent-fiber lamina.

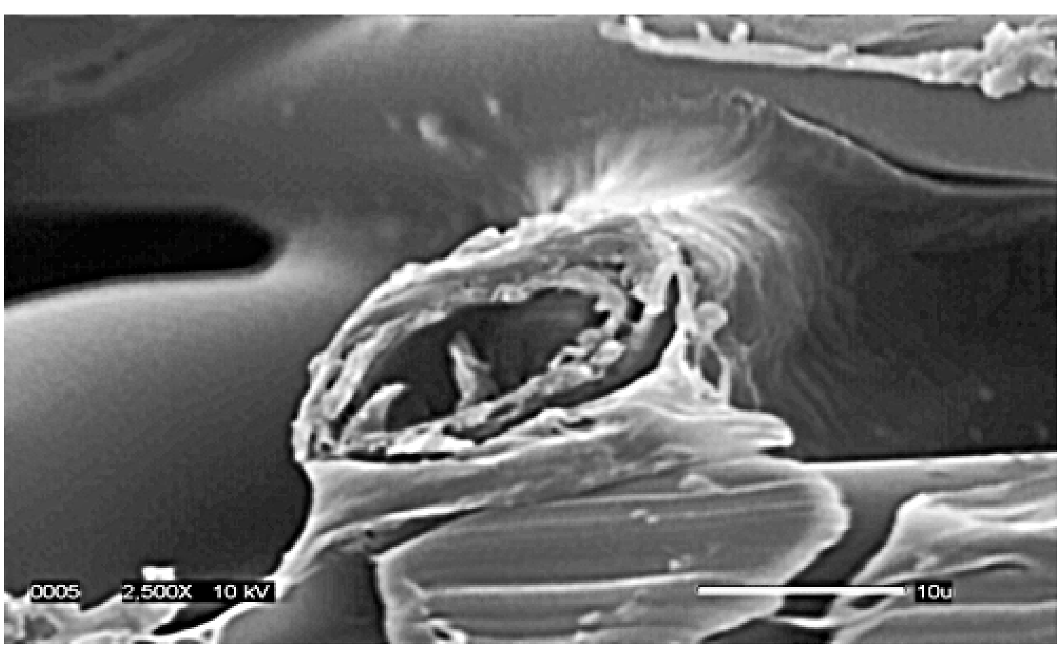

Figure 4.—Scanning electron microscope scan of the composite showing a wood fiber encapsulated in polymer.

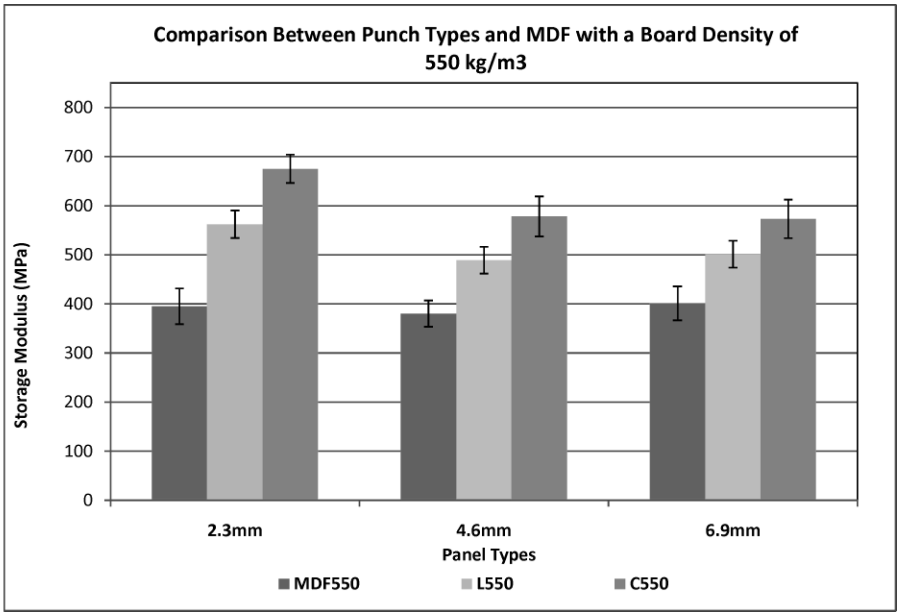

Figure 5.—Storage modulus comparison of MDF with a board density of 550 kg/m^3 (MDF550) and wood-bicomponent-fiber panels with bicomponent-fiber alignment along (L550) and across (C550) the testing beam length and for three punch types (2.3, 4.6, and 6.9 mm).

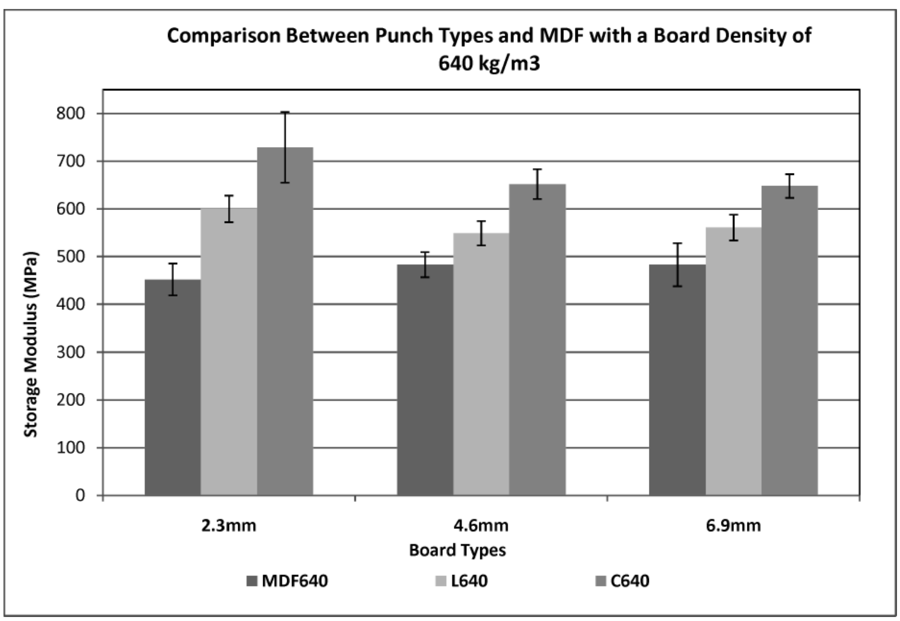

Figure 6.—Storage modulus comparison of MDF with a board density of 640 kg/m^3 (MDF640) and wood-bicomponent-fiber panels with bicomponent-fiber alignment along (L640) and across (C640) the testing beam length and for three punch types (2.3, 4.6, and 6.9 mm).

Conclusion

Attempts have been made by the wood composites industry to blend a high-strength fiber into a wood-fiber panel product with some success. They are, however, limited by the difficulty of obtaining adequate wood-fiber/polymer adhesion. Nonwoven textile technologies such as needle punching and the use of bicomponent fibers could prove to be a viable option for incorporating high-end polymer fibers into an engineered wood-fiber panel. Polypropylene is commonly used to produce wood plastic composites and has been shown to form a weak bond with wood flour. When hot pressing the polypropylene/polyester (PP/PET) bicomponent fiber, the melt temperature of the polyester is not reached. PP, however, melts at approximately 165°C. When incorporated into a wood-fiber product, the PET component will remain intact, while the PP will melt and infuse into the wood fiber. This, along with the fiber rearrangement resulting from needle punching, mechanically bonds the polyester fiber to the wood. The overall stiffness values of the wood-bicomponent-fiber laminate panels were found to be significantly higher than that obtained from MDF.

The needle-punching process shows considerable promise for incorporation in an industrial setting. To overcome the problems of low final product thickness, minor adjustments need to be made to the needle loom machine parameters and the needle design.

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