Mechanical Performance of Hemp Fiber Polypropylene Composites at Different Operating Temperatures

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ABSTRACT: In order to quantify the effect of temperature on the mechanical properties of hemp fiber polypropylene composites, formulations containing 25% and 40% (by weight) hemp fiber were produced and tested at three representative temperatures of 256, 296, and 336 K. Flexural, tensile, and impact tests, as well as dynamic mechanical analysis, were performed and the reduction in mechanical properties were evaluated. Impact resistance was independent of temperature, whereas flexural and tensile properties were strongly affected. The highest reductions were observed in stiffness (modulus) values and flexural properties were reduced to a higher degree. The reductions in mechanical properties were well explained by a simple quadratic curve-fitting procedure applied to experimental data. Dynamic mechanical analysis revealed no change in glass transition temperature when the fiber content was increased but the composite material had better temperature resistance at higher fiber content. The results of the present study will be helpful in determining the end-use application of these composite materials.

KEY WORDS: composites, mechanical properties, temperature, hemp fiber, polypropylene.

INTRODUCTION

THE TERM WOOD-PLASTIC composites (WPCs) refers to a relatively new class of engineered materials comprised mainly of a lignocellulosic (wood) component and a plastic component [1,2]. The most commonly used thermoplastics are polyethylene

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(PE), polyvinyl chloride (PVC), and polypropylene (PP), whereas frequently used lignocellulosic materials include pine, maple, oak [1,2], hemp [3–5], and other agro-based materials.

Early applications of these materials were confined to non-structural, non-load bearing applications where the materials were not subject to extreme environmental conditions. However, wood-plastic composites are becoming a viable alternative to traditional civil engineering building materials in select structurally demanding capacities where extreme conditions can occur [6]. These composites have been recognized as potential choices for use in many light-structural applications during the past two decades. Recently, more structurally demanding applications have been recognized. The main obstacle to utilizing these materials as structural members is the general lack of performance data in extreme conditions [6]. Research investigating environmental influences (e.g., service temperature) on mechanical performance with the goal of assigning structural design values is lacking.

Both main components of natural fiber-plastic composites exhibit time and temperature dependent behavior, mainly due to their viscoelastic nature [7]. Previous work by Pooler [8] and Kobbe [9] illustrated different behavior over a practical in-service range of temperatures for HDPE and polypropylene formulations, respectively. Due to the temperature dependent performance of polyolefins, further investigation of the wood-plastic composite material should be conducted in order to quantify changes in the mechanical performance due to change in temperature. Schildmeyer [6] investigated temperature and time dependent behaviors of a pine-polypropylene composite. This work examines the effect of operating temperature on the mechanical performance of polypropylene-hemp composite formulations. Static tensile and flexural tests, impact bending, and dynamic mechanical analysis were employed to monitor changes in mechanical performance due to temperature.

EXPERIMENTAL

The Composite Materials

Hemp fiber-polypropylene composite specimens were sampled from injection-molded specimens containing 25 or 40% (by weight) hemp fibers. The composite materials had been prepared from polypropylene homopolymer with a melt flow index of 35 g/10 min (230°C, 2.16 kg) and a density of 0.90 g/cm^3, and hemp fibers averaging 1 mm in length mixed in a thermokinetic mixer. In addition to the main components, 1 and 2% maleic anhydride polypropylene (MAPP) was also used as compatibilizer in formulations containing 25 and 40% hemp fiber, respectively.

Specimens for DMA testing were cut out of the impact specimens using a table saw. They were further machined down to a nominal thickness of 2 mm using a knee-type Bridgeport vertical milling machine. Each side of the specimen was machined to produce a balanced DMA specimen at the desired thickness. The final specimen dimensions were $52 \times 8 \times 2$ mm.

Mechanical Testing

Mechanical tests were performed at three different temperatures (256, 296, and 336 K). Static flexural tests were performed according to ASTM D-790-07 specification [10]. Nominal specimen dimensions were $130 \times 8 \times 3.2$ mm. A span of 100 mm was used, which

gave a span/depth ratio of at least 30. An Instron testing machine Model 4486 equipped with a 10-kN load cell was used and the cross-head speed was 8 mm/min. MOR (modulus of rupture = flexural strength) and MOE (apparent flexural modulus) were calculated from the load–deflection curves. Tensile tests were carried out according to ASTM D-638-03 specification on dumbbell-shaped specimens [11]. The tests were performed using the same Instron machine at a cross-head speed of 5 mm/min. Strain was measured in the mid-span of the specimens using an Instron Extensometer mounted on the specimens. Modulus of elasticity (E) and tensile strength (TS) were calculated using the stress–strain curves. Unnotched Izod impact tests were performed using a Santam digital impact tester (Tehran, Iran) according to ASTM D256-06a specification [12].

Dynamic mechanical analysis was performed using a Rheometric Scientific DMTA V analyzer. A dual cantilever mode was selected and the composites were scanned over a temperature range of -60 to $+120^{\circ}$C. Frequency of the oscillations was fixed at 1 Hz and the strain amplitude was 0.1%, which was well within the linear viscoelastic region. The heating rate was 2°C/min for all temperature scan tests. Storage modulus (E'), loss modulus (E''), and mechanical loss factor ($\tan\delta$) were collected during the test and were plotted vs. temperature. The presented curves are the average of three specimens tested under the same testing conditions.

RESULTS AND DISCUSSION

Flexural Properties

Flexural load–deflection curves of both composite materials are presented in Figure 1 where the effect of temperature on mechanical behavior can be observed. As expected, the slopes of the curves become smaller at elevated temperatures, indicating lower stiffness at higher temperatures. Maximum load is also smaller at higher temperatures. Polypropylene is a semi-crystalline thermoplastic polymer whose glass transition (T_g) is around 273 K (0°C) [13]. Therefore among the three temperatures used in the study, only the one at 256 K is below glass transition temperature. Below T_g, the polymer is in a glassy state which brings about the highest stiffness and strength. However, it is interesting to mention that the load–deflection curves are non-linear even at low deflections and at low temperatures. The change in the shape of the curves as a result of increasing the temperature does not follow a linear trend either. Therefore, the effect of temperature can be expected to be more pronounced at higher temperatures.

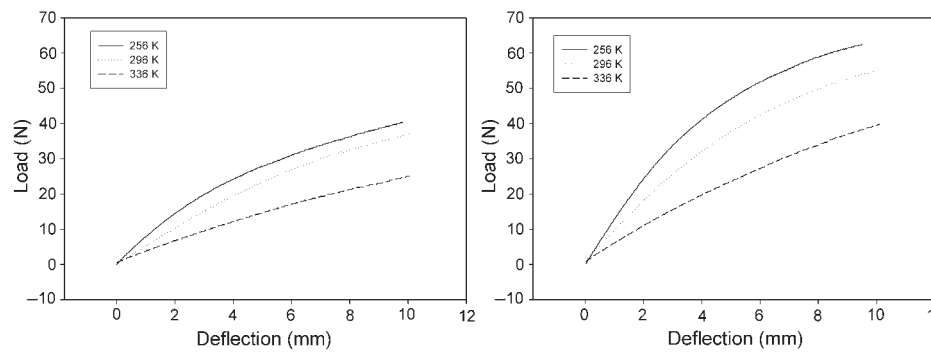

Figure 1. *Flexural load–deflection curves of composites containing 25% (left) and 40% hemp fiber (right).*

Effect of temperature on the flexural strength (MOR) of the composites is presented in Figure 2. Temperature strongly affects MOR, as seen in the reductions in Table 1. Table 1 shows that MOR drops around 7 and 13% at 296 K for the composites containing 25 and 40% hemp fibers, respectively. However, as the temperature is raised to 336 K, the corresponding reductions are 39 and 34%, respectively. This again shows the non-linearity in the effect of temperature on flexural modulus, which is expected considering the load–deflection curves in Figure 1. A simple quadratic function was fitted to the experimental data and R^2 values of unity were obtained, indicating that the effect of temperature on MOR can be quantitatively explained using the obtained equation (Figure 2).

Effect of temperature on the flexural modulus (MOE) of the composites along with the predictive equations is presented in Figure 3. MOE is also strongly affected by temperature and its reduction is much larger as compared with that of MOR. Table 1 shows that MOE drops around 40 and 32% at 296 K for the composites containing 25 and 40% hemp fibers, respectively. As the temperature is raised to 336 K, the corresponding reductions are 61 and 57%, respectively. The reduction in MOE is larger for the composite, containing 25% fiber content as they have a higher plastic fraction which is inherently more sensitive to temperature than natural fibers due to higher viscoelasticity [13].

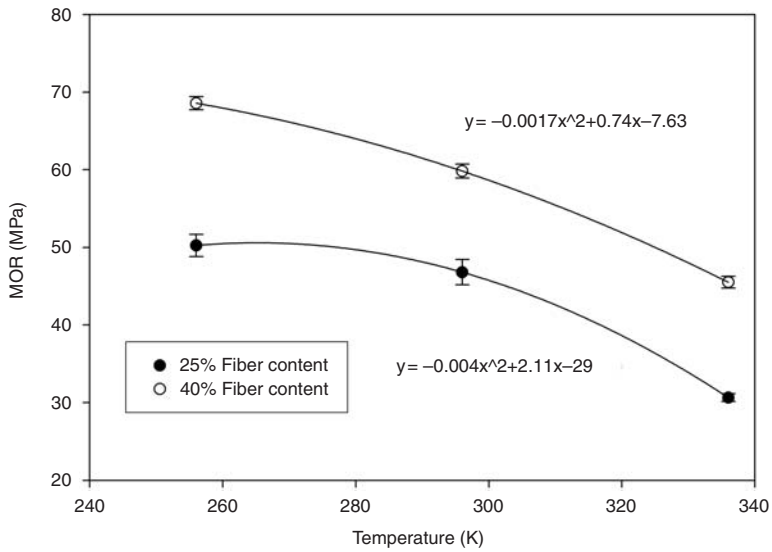

Figure 2. *Effect of temperature on the MOR of the composites.*

Table 1. Percent reduction in mechanical properties at elevated temperatures in comparison with the properties at 256 K.

Fiber content (%)	Temperature (K)	MOR	MOE	Tensile strength	Tensile modulus
25	296	6.85	39.63	7.41	27.90
	336	39.00	61.01	25.35	43.34
40	296	12.75	32.17	13.59	29.16
	336	33.63	56.74	26.49	51.75

Tensile Properties

Tensile stress–strain curves for both composites containing 25 and 40% hemp fiber at the three studied temperatures are presented in Figure 4. A similar behavior to that of flexural load–deflection curves can be seen in the greater impact of the highest temperature (336 K) on stress–strain behavior. At higher temperatures, elongation at break (strain) is also higher for both composites of 25 and 40% hemp fiber. The 40% fiber content composites also have lower elongation values as compared with those containing 25% hemp fibers at all temperatures due to higher stiffness.

Figure 5 exhibits the effect of temperature on the tensile strength of the composite formulations. Tensile strength drops around 7 and 14% at 296 K for the composites containing 25 and 40% hemp fibers, respectively, which are very close to the reduction values of MOR (flexural strength). When the temperature is raised to 336 K, the

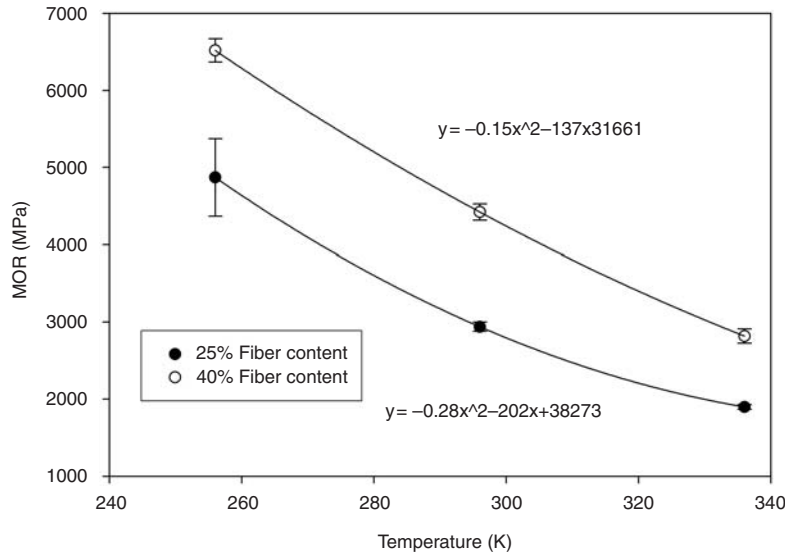

Figure 3. *Effect of temperature on the MOE of the composites.*

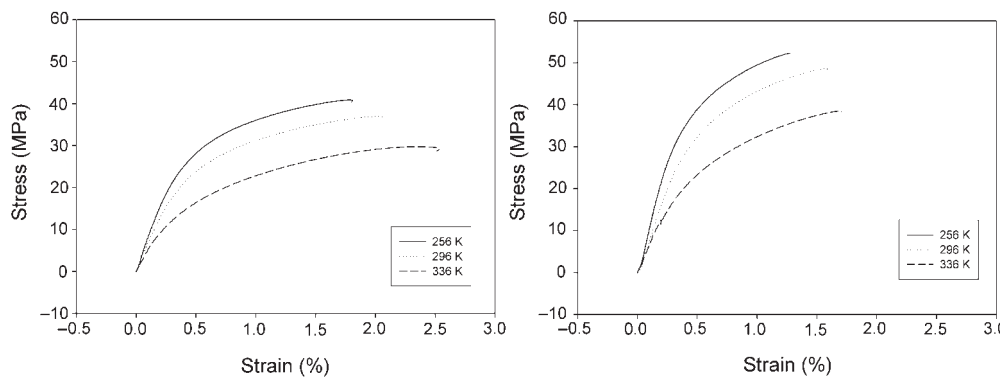

Figure 4. *Tensile stress–strain curves of composites containing 25% (left) and 40% hemp fiber (right).*

corresponding reductions are 25 and 26%, respectively, which shows tensile strength is less affected by temperature compared with its flexural counterpart. The simple quadratic functions fitted to the experimental data again yielded R^2 values of unity, indicating that the effect of temperature on MOR can be quantitatively explained using a quadratic equation.

Effect of temperature on the tensile modulus of the composite formulations is presented in Figure 6. The predictive equations are also presented, which have very

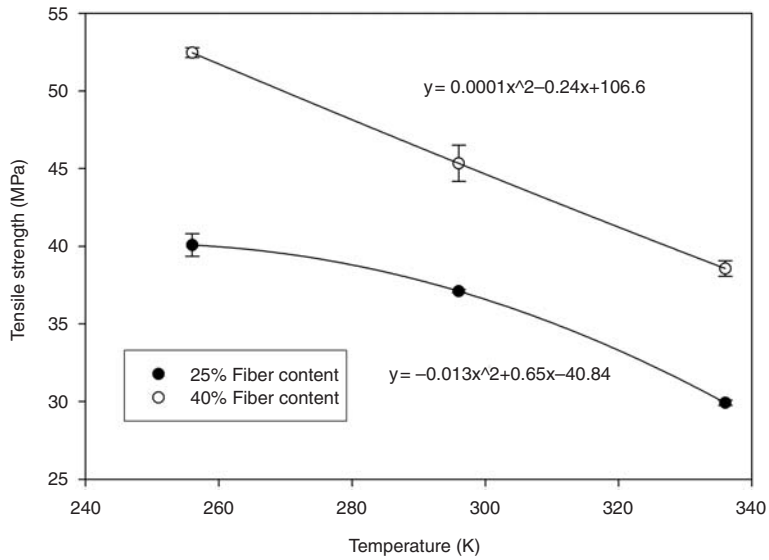

Figure 5. *Effect of temperature on the tensile strength of the composites.*

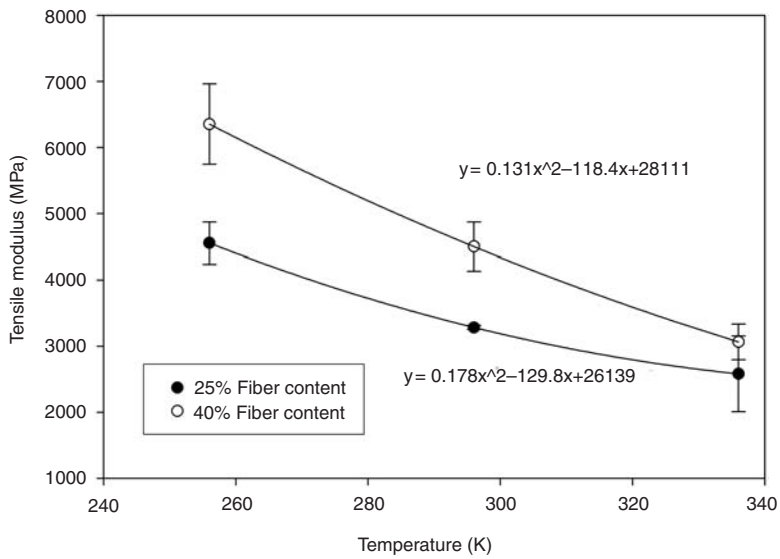

Figure 6. *Effect of temperature on the tensile modulus of the composites.*

good fits ($R^2 = 1$). Tensile modulus is more adversely affected by temperature compared with tensile strength. As seen in Table 1, at 296 K tensile modulus drops almost the same for composites containing 25 and 40% hemp fibers (around 25 and 26%, respectively). At 336 K, the corresponding reductions are 43 and 51%, respectively. Unlike flexural strength, the reduction in tensile strength is larger for the composite containing 40% fibers.

Generally it was found that the effect of temperature was the highest for stiffness of the composites (both flexural and tensile) as compared with that of strength values. This is mainly because of the fact that stiffness of the composite is directly related to the stiffness of the constituents which heavily depend on temperature. Strength values are mainly governed by interfacial adhesion which is less influenced by temperature.

Impact Resistance

Unlike other mechanical properties, the unnotched impact resistance of the composite formulations is independent of temperature (Figure 7). Also, the impact resistances of the composites containing 25 and 40% hemp fiber are very close to each other. The unnotched impact resistance describes the resistance of the material to crack initiation. Incorporation of wood or other natural fibers into high-impact plastics such as polypropylene drastically reduces the impact strength by providing micro-gaps at the surface of the specimens acting as notches or crack propagation sites [14]. Only a small amount of fiber can reduce impact energy to a considerable level whereas further addition of fiber content will no longer be effective. This explains why both composite formulations have similar impact strengths. It seems that although temperature reduces the stiffness of the composite material, which could eventually lead to higher impact resistance due to viscoelasticity effects, it has no influence on impact resistance.

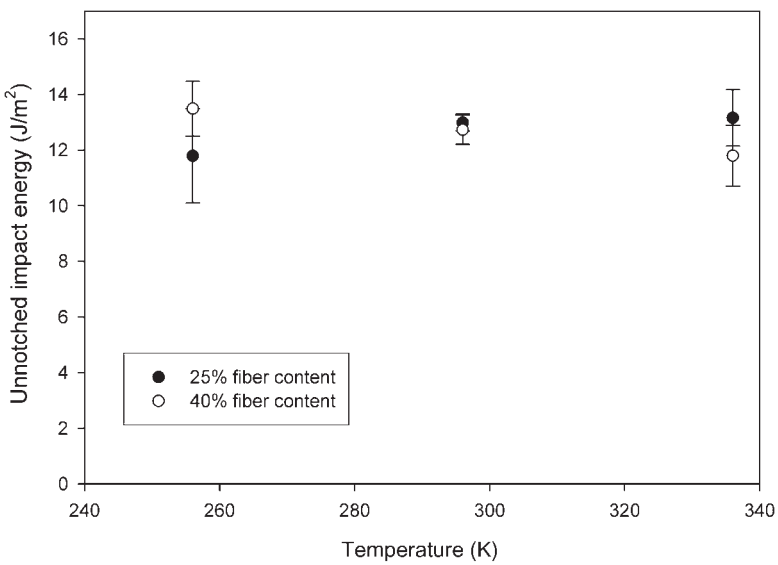

Figure 7. *Effect of temperature on the tensile modulus of the composites.*

Dynamic Mechanical Properties

Changes in the storage modulus of the formulations due to the increase in temperature are presented in Figure 8 along with the curves depicting the modulus retention term, which is calculated by dividing the storage modulus at any given temperature by its initial value at the lowest temperature (highest stiffness). As clearly seen, the composite material containing 40% hemp fibers has higher storage modulus values all over the studied temperature range. The sharp drop at around 275 K is the glass transition, which is almost the same for both composite formulations. The modulus retention term shows how much of the stiffness is retained at any given temperature. As seen, below glass transition

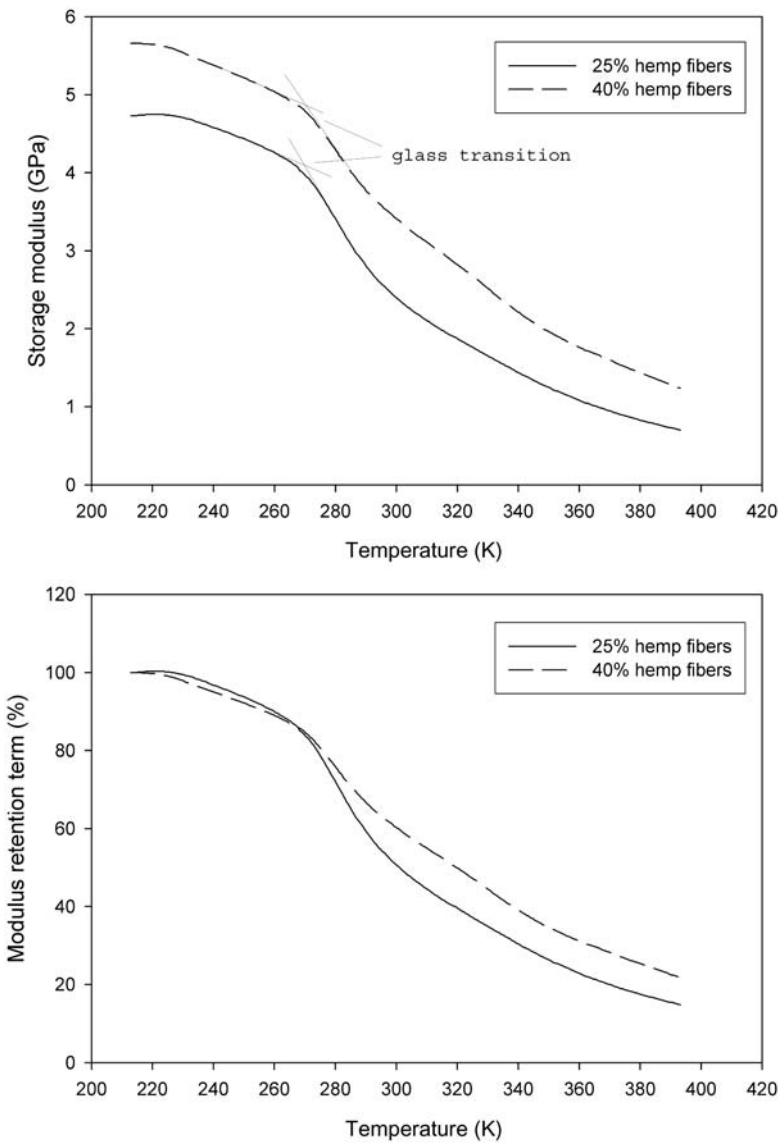

Figure 8. *Storage modulus spectra of the formulations (top) and the modulus retention term (bottom).*

temperature both composite formulations have similar modulus retention term values. However, after this point, the formulation containing 25% hemp fibers starts to lose stiffness to a much higher degree compared with the formulation with 40% hemp fibers. This indicates better mechanical performance of the composite material at elevated temperatures when fiber content is higher.

Polypropylene is a semi-crystalline polymer and the reduction of stiffness beyond glass transition temperature is quite considerable [13,14]. Glass transition temperature can be determined from storage modulus (Figure 8), loss modulus, and tan δ curves (Figure 9) but they would not necessarily give similar values as these curves represent different stages in phase transition. However, Chen and Gardner [15] state that from the mechanical point

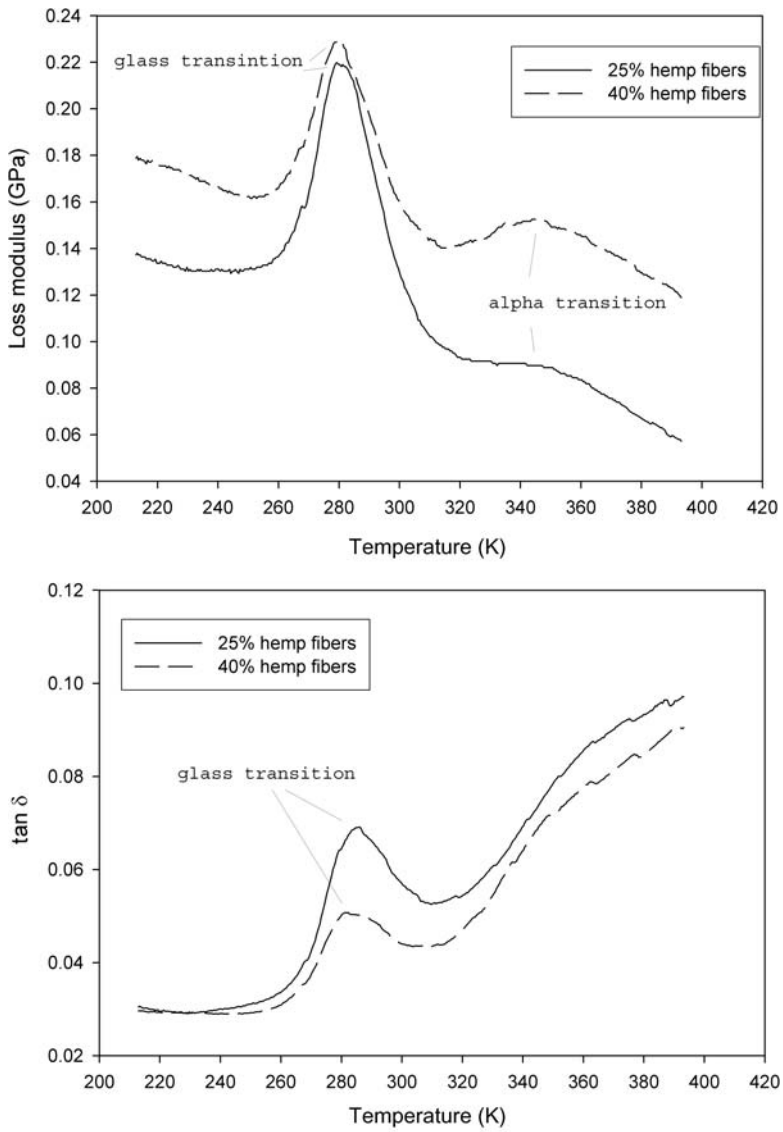

Figure 9. *Loss modulus spectra of the formulations (top) and the mechanical loss factor (tan δ) (bottom).*

of view, the glass transition temperature determined from storage modulus curves should be considered as it relates directly to the stiffness of the material. Nevertheless, the important point is that very little change was observed as to the location of glass transition temperature, indicating that the presence of more hemp fibers did not affect phase transition.

Figure 9 shows that the mechanical loss factors are very similar for both composite formulations before the glass transition temperature. However, the $\tan\delta$ values are remarkably lower for the composite containing 40% hemp fiber after glass transition when the material is in a rubbery status. As far as the study of the viscoelasticity of the materials is concerned, $\tan\delta$ is a better indicator to be considered than storage or loss modulus, as its value is independent of sample geometry [14]. The presence of 15% more hemp fibers has considerably reduced damping, indicating that the composite material is more elastic at higher fiber content, which can explain lower temperature sensitivity as well.

CONCLUSIONS

The effect of operating temperature on the mechanical properties of hemp fiber polypropylene composites was studied in the present research and the following conclusions could be drawn from the results and discussions presented above:

- flexural strength, flexural modulus, tensile strength, and tensile modulus of the composites drop remarkably at higher temperatures;
- the effect of temperature is the highest for stiffness of the composites (both flexural and tensile) compared with that of strength values;
- flexural properties of the composite formulations were influenced by temperature to a higher degree than tensile properties;
- impact strength was found to be independent of temperature;
- the reductions in mechanical properties could be best predicted using a simple quadratic curve-fitting procedure;
- glass transition temperature is the critical temperature beyond which the properties of the composite material will strongly depend on fiber content.

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