FLEXURAL PROPERTIES AND ORTHOTROPIC SWELLING BEHAVIOR OF BAGASSE/THERMOPLASTIC COMPOSITES

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The flexural properties of commercial bagasse-filled polyethylene (PE) and polypropylene (PP) composites were determined as a function of strain rate at room temperature. The applied strain rates were 1.5 $\times 10^{-4}$, 3.75$\times 10^{-4}$, 7.5$\times 10^{-4}$, and 1.5$\times 10^{-3}$ s^{-1}. The flexural modulus tended to increase linearly for the two types of composites with the logarithm of strain rate. The bending strength of polypropylene composite also behaved in a similar manner, but the polyethylene composite exhibited different behavior in which the MOR values of polyethylene composite didn't alter appreciably as a function of strain rate. The flexural response of a polypropylene-based composite was found to exhibit higher dependency on strain rate than a polyethylene-based composite. Water absorption of both composites followed the kinetics of a Fickian diffusion process. Water absorption and dimensional instability of PE-based composites were lower than those of PP-based composites. The highest swelling took place in the thickness of the samples, followed by the width and length, respectively.

Keywords: Strain rate; Composite; Bagasse; Orthotropic swelling; Water absorption; Flexural properties

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INTRODUCTION

Bagasse is one of the most important nonwood lignocellulosic raw materials in Iran. During the last few decades, much effort has been devoted to increasing the utilization of bagasse. However, large quantities of this raw material are still left unused or burnt. A relatively simple possibility is to use bagasse as reinforcing filler for thermoplastics. Bagasse-based thermoplastic composites can replace wood in applications such as furniture and interior panels (Monteiro et al. 1998). These products are targeted for use in flexural applications, thus the ability to accurately determine the flexural properties is of critical importance if the products are to compete as a structural material (Brandt and Fridley 2003).

The strain rate affects the flexural properties of solid wood (Gerhards and Link 1986) and the yield stress of plastics (Hobeika and Strobl 2000). An understanding of strain rate dependence on mechanical behavior of composite materials is important for encouraging their wide use in engineering and structural applications. Strain rate has a complicated and dramatic effect on materials properties because the energy expended during plastic deformation is largely dissipated as heat (Sarang and Misra 2004).

A problem associated with using natural fibers in composites is their high moisture absorption and dimensional instability (swelling). Swelling of fibers can lead to micro-cracking of the composite and degradation of mechanical properties (Stamboulis et al. 2000). Although there has been considerable research devoted to the thickness swelling of natural fiber thermoplastic composites, there are few reports about length and width swelling. Tajvidi et al. (2009) investigated the physical and mechanical properties of a highly filled old corrugated container (OCC) fiber/polyethylene composite. They showed that the maximum thickness swelling, width swelling, and length swelling were 14, 5, and 1.5%, respectively. Cheng and Wang (2009) investigated the long-term drying behavior, dimension, and weight changes due to moisture cycling in an extruded wood-polypropylene composite. They found that the expansion of the material was orthotropic in character and non-recoverable. Orthotropic swelling has considerable importance in service.

There has been considerable research conducted on the flexural properties of bagasse/thermoplastic composites (Ismail et al. 2009; Luz et al. 2007; Nourbakhsh and Kouhpayehzadeh 2009; Ramaraj 2007; Talavera et al. 2007; Youssef et al. 2008; Zabihzadeh et al. 2009), and the strain rate dependence of mechanical properties for a wide variety of polymers and composites (Cady et al. 2006; Jacob et al. 2004; Smith 1958). However, there are few reports about the effect of strain rate on the flexural properties of natural fiber/thermoplastic composites. Dastoorian and Tajvidi (2008) investigated influence of strain rate on the flexural properties of a wood flour/HDPE composite and reported that the flexural modulus was strain rate dependent and the sensitivity of *MOE* was more than that of *MOR* to strain rate. In addition, there are no experimental data about the orthotropic swelling behavior of bagasse-based composites. The objective of this study is to evaluate the influence of plastic type and strain rate on the flexural properties of commercial bagasse/thermoplastic composites. Long-term water absorption and orthotropic swelling behavior of the composites were also analyzed.

EXPERIMENTAL

Materials

Two kinds of commercial extruded bagasse/thermoplastic composites from a manufacturer (Dez Choob-Plastic Company, Khozestan, Iran) were used for this study. The polypropylene-based composite was made with 30% polypropylene powder with a density of 0.90 g/cm^3 and the melt flow index of 16 g/10min, 68% bagasse (50-mesh depithed bagasse flour), and 2% maleic anhydride grafted polypropylene (PP-g-MAH) from kimiya Javid Sepahah Co., Iran, with the melt flow index of 40 g/10min by weight. The polyethylene-based composite was made with 30% polyethylene powder with a density of 0.95 g/cm^3 and the melt flow index of 4 g/10min, 68% bagasse flour, and 2% maleic anhydride grafted polyethylene (PE-g-MAH) from kimiya Javid Sepahah Co., Iran, with the melt flow index of 1 g/10min by weight. The composites are produced for pallet applications.

Flexural Properties

Specimens for three-point flexural test were cut according to ASTM-D790-00 specification. The flexural tests were carried out using an IMAL Ib 600 universal testing machine at strain rates of 1.5 $\times 10^{-4}$, 3.75×10^{-4}, 7.5×10^{-4}, and 1.5×10^{-3} s^{-1}. Nominal specimen dimensions were 100×13×4.8 mm^3. Test specimens were placed in a conditioning chamber at 23°C ± 3°C and 50% ± 5% relative humidity for 72 hours. The modulus of rupture (*MOR*) and flexural modulus (*MOE*) were calculated. Five specimens were tested, and the average values are reported.

Water Absorption and Orthotropic Swelling Tests

Five specimens (Length×Width×Thickness=25×12.5×4.8 mm^3) of each composite were dried in an oven for 24 h at 105±2°C. The dried specimens were weighed with a precision of 0.001 g and their length, width, and thickness were measured with a precision of 0.001 mm. Then they were placed in distilled water at room temperature for 864 h. At predetermined time intervals, the specimens were removed from the distilled water, the surface water was wiped off using blotting paper, and their wet mass, length, width, and thickness were determined. Water absorption and orthotropic swelling were calculated using the following formulas,

$$M(\%) = (m_t - m_o) / m_o \times 100 \quad (1)$$

where m_o and m_t denote the oven-dry weight and weight after time t, respectively, and

$$S(\%) = (D_t - D_o) / D_o \times 100 \quad (2)$$

where D_o and D_t denote the oven-dry dimension and dimension after time t, respectively.

Statistics Method

Duncan's multiple range tests for pair-wise comparison were used to test the effect of various strain rate on the modulus of rupture (*MOR*) and flexural modulus (*MOE*) of the composites using SPSS (SPSS Inc). Values of $P<0.05$ were considered significant.

RESULTS AND DISCUSSION

Flexural Behavior

The average and standard deviation values of flexural properties of PE and PP composites as a function of strain rate are summarized in Table 1.

The influence of the strain rate on flexural modulus of the PP and PE composites is presented in Fig 1. It was found that the flexural modulus strongly depends on the applied strain rate. The modulus increases from ~4033 MPa and 2541 MPa at 1.5 $\times 10^{-4}$ s^{-1} to 5186 MPa and 3050 MPa at 1.5 $\times 10^{-3}$ s^{-1} for PP and PE-based composites, respectively. This increase can be attributed to the viscoelastic nature of both bagasse and polymer matrix. Increasing the strain rate leads to higher moduli. This is in correspondence with reducing the relaxation time by polymer chains (Ward and Hadley 1993). Brandt and Fridley (2003) found that as the rate-of-load increases, the effect of viscous flow of the wood-plastic composite is decreased; thus the increase in *MOE* values was expected.

Table1. Flexural Properties of Bagasse-based Thermoplastic Composites

Composites	Flexural properties	Strain rate (s^{-1})			
		1.5×10^{-4}	3.75×10^{-4}	7.5×10^{-4}	1.5×10^{-3}
Bagasse/PP composite	*MOE* (MPa)	4033.31 (349.25)	4566.63 (162.46)	4836.47 (147.63)	5186.46 (115.20)
	MOR(MPa)	50.87 (3.27)	56.26 (1.12)	57.52 (2.11)	60.29 (2.53)
Bagasse/PE composite	*MOE* (MPa)	2540.72 (149.98)	2644.42 (102.83)	2855.59 (78.10)	3049.96 (199.26)
	MOR(MPa)	37.51 (1.48)	38.99 (1.73)	38.19 (1.60)	39.08 (2.01)

Values in parentheses are standard deviation.

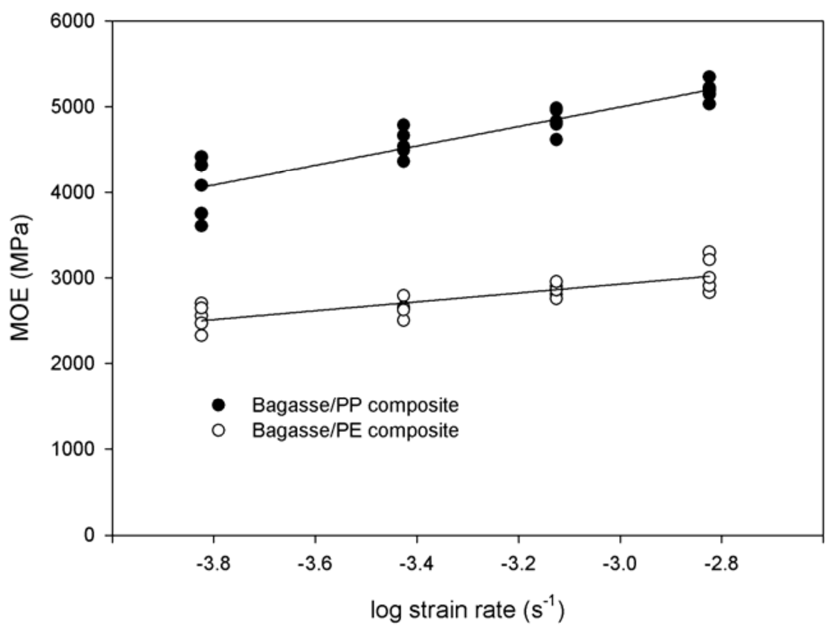

Fig. 1. The effect of strain rate on flexural modulus of bagasse-based composites

The relationship between the logarithm of strain rate and flexural modulus is well described by a linear model, assuming that this would be more realistic.

For bagasse/PP composite,

$$MOE = 8401 + 1135\dot{e} \quad R^2 = 0.82 \tag{3}$$

and for bagasse/PE composite,

$$MOE = 4485 + 519\dot{e} \quad R^2 = 0.68 \tag{4}$$

where *MOE* is flexural modulus and $\dot{e}$ is logarithm of strain rate.

Considering the fact that the bagasse fraction was constant in both composites (68% by weight), the different flexural modulus observed between two kinds of composites can be attributed to the type of the thermoplastic matrices. It can be seen from Fig. 1 that the flexural modulus of the bagasse/PP composite was much higher than that of the bagasse/PE composite over the range of strain rates studied. From the slope of the curves, it can be concluded that the strain rate sensitivity of PP-based composite was more than that of the PE-based composite. Kazemi Najafi et al. (2006) reported that PP (virgin and recycled)/sawdust composites were stronger and stiffer than HDPE (virgin and recycled)/sawdust composites. Statistical analysis showed significant association of flexural modulus with strain rate (P=0.05), and Duncan's multiple range test indicated significantly the lowest flexural modulus corresponded to the lowest strain rate and vice versa for both composites.

Figure 2 shows the influence of the strain rate on flexural strength (*MOR*) of PP and PE-based composites.

The behavior of bagasse/PP composite with strain rate was linear, suggesting that the flexural strength of PP-based composite is also strain-rate sensitive,

$$MOR = 86.15 + 9.06\dot{e} \quad R^2 = 0.69 \tag{5}$$

where *MOR* is representative of flexural strength and $\dot{e}$ is the logarithm of strain rate.

In contrast, the *MOR* values of PE-based composite showed a slight initial rise followed by a little decline. Statistical analysis verified these results, indicating no significant differences between the *MOR* values at different strain rates for PE-based composite (P=0.05). The flexural moduli of bagasse-based thermoplastic composites were more responsive to strain rate in comparison with flexural strengths. This is evident from the higher slope of the linear relationship between *MOE* and the log strain rate as compared with that of the relationship between *MOR* and the log strain rate. These results are attributed to the fact that modulus values which are directly related to relaxation of molecules at longer times will respond more to strain rate (Dastoorian and Tajvidi, 2008).

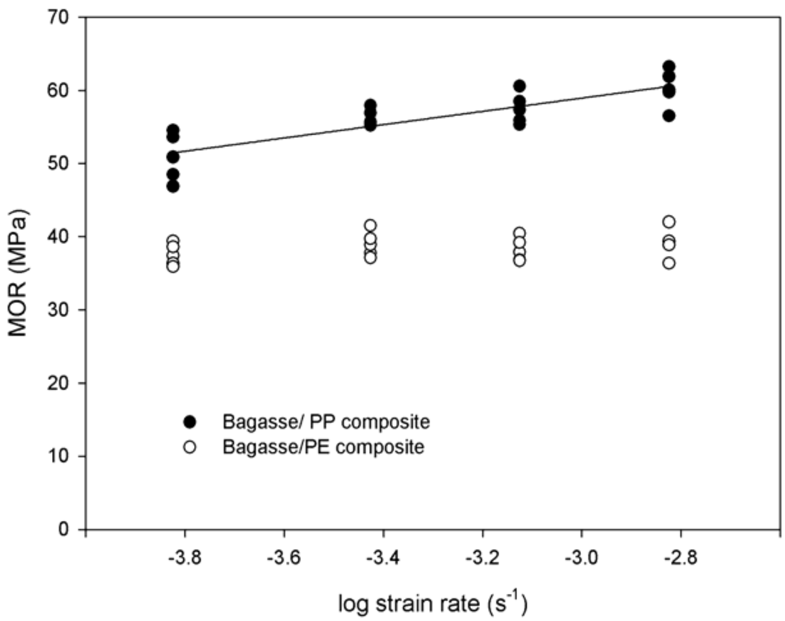

Fig. 2. The effect of strain rate on flexural strength of bagasse-based composites

Long-term Water Absorption

Figure 3 shows the long-term water absorption curves of bagasse-based composites at room temperature, where percentage of water absorbed is plotted against the square root of the immersion time. It can be seen that the water absorption increased with $t^{0.5}$ during the first stages until reaching a certain value, and the water content remained constant, indicating a Fickian mode of diffusion. The diffusion coefficient is the most important parameter of the Fick's model. The water diffusion coefficient of the composites was calculated using the following formula (Yadav et al. 1999),

$$D = \pi \left[\frac{mT}{4M_{\max}} \right]^2 \left[1 + \left(\frac{T}{L} \right) + \left(\frac{T}{W} \right) \right]^2 \qquad (6)$$

where D is the water diffusion coefficient corrected for edge effect; m is the slope of the linear portion of the water content against root time/thickness curve; M_{max} is the equilibrium moisture content; T is the thickness; L is the length; and W is the width.

The hygroscopic properties of PP and PE composites are summarized in Table 2. It can be seen from Table 2 that the water diffusion coefficient and maximum water absorption of the bagasse/PP composite was higher than those of the bagasse/PE composite.

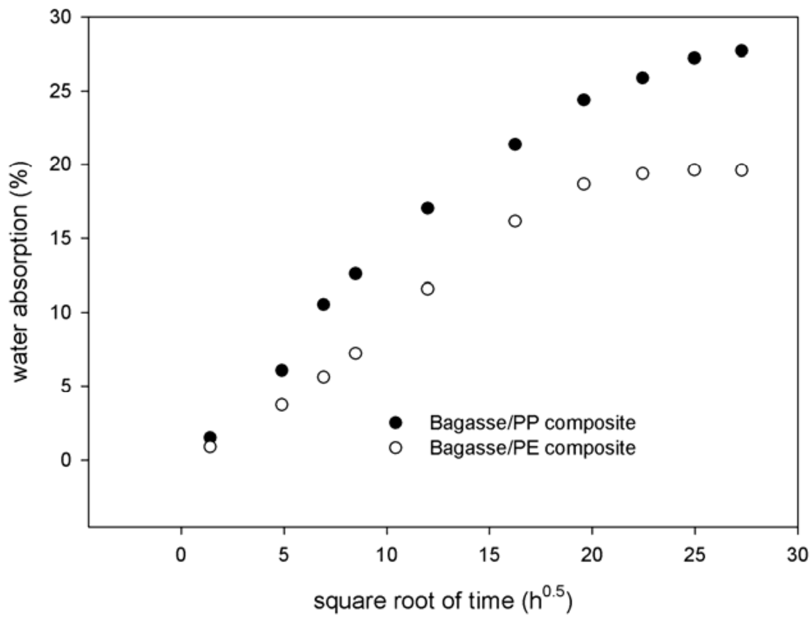

Fig. 3. Water absorption process for bagasse-based composites

Table2. Hygroscopic Properties of Bagasse-based Thermoplastic Composites

Composites	Maximum water absorption (%)	Water diffusion coefficient ($10^{-7}mm^2/s$)	Equilibrium swelling (%)		
			Length	Width	Thickness
Bagasse/PP composite	28.05	14.58	1.61	4.77	12.88
Bagasse/PE composite	19.87	9.11	1.41	4.04	11.79

Long-term Orthotropic Swelling

Figures 4 and 5 exhibit the orthotropic swelling curves of the bagasse-based composites. It can be seen that the highest swelling took place in the thickness of the samples, followed by the width and length, respectively, indicating the orthotropic nature of dimensional instability of the bagasse-based composites. Natural fibers swell the most in their thickness direction as a result of the orientation of cellulose microfibrils in the cell wall. Short fibers generally align in the direction of the flow in an extruder, thereby resulting in the difference in swelling in various directions (Tajvidi et al. 2009). Table 2 shows that the equilibrium thickness, width, and length swellings were 1.61, 4.77, and 12.88 for bagasse/PP composite; and 1.41, 4.04, and 11.79 for bagasse/PE composite, respectively. Considering the fact that the natural filler fraction was constant in both composites (68% by weight), the different swelling between the composites can be attributed to the type of the thermoplastic.

In order to develop a model for the orthotropic swelling behavior of the composites, a single two-parameter exponential rise to maximum function was applied to the experimental swelling data. This equation has the form of,

$$y = a\left(1 - e^{-bx}\right) \tag{7}$$

where *Y* is the swelling value, *a* and *b* are constants, and *x* is time.

The nonlinear curve fitting was used to find the constants that provide the best fit between the equation 7 and the experimental data. This algorithm seeks the constants that minimize the sum of the squared differences between the observed and predicted values of the dependent variable, as seen in equation 8,

$$SS = \sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2 \tag{8}$$

where *SS* is the sum of squared difference and y_i and $\hat{y}_i$ are the observed and predicted values of the dependent variable, respectively.

The results of the nonlinear curve fitting are presented in Table 3 for orthotropic swelling. Very good relationships were found, as indicated by the R^2 values.

Table 3. Results of the Nonlinear Curve Fitting for Orthotropic Swelling

Composites	Orthotropic swelling equation		
	Length	Width	Thickness
Bagasse/PP composite	$LS(\%) = 1.48\left(1 - e^{-0.0129t}\right)$ $R^2 = 0.97$	$WS(\%) = 4.56\left(1 - e^{-0.0081t}\right)$ $R^2 = 0.98$	$TS(\%) = 13.10\left(1 - e^{-0.0051t}\right)$ $R^2 = 0.98$
Bagasse/PE composite	$LS(\%) = 1.44\left(1 - e^{-0.0047t}\right)$ $R^2 = 0.99$	$WS(\%) = 4.18\left(1 - e^{-0.0049t}\right)$ $R^2 = 0.99$	$TS(\%) = 11.79\left(1 - e^{-0.0046t}\right)$ $R^2 = 0.98$

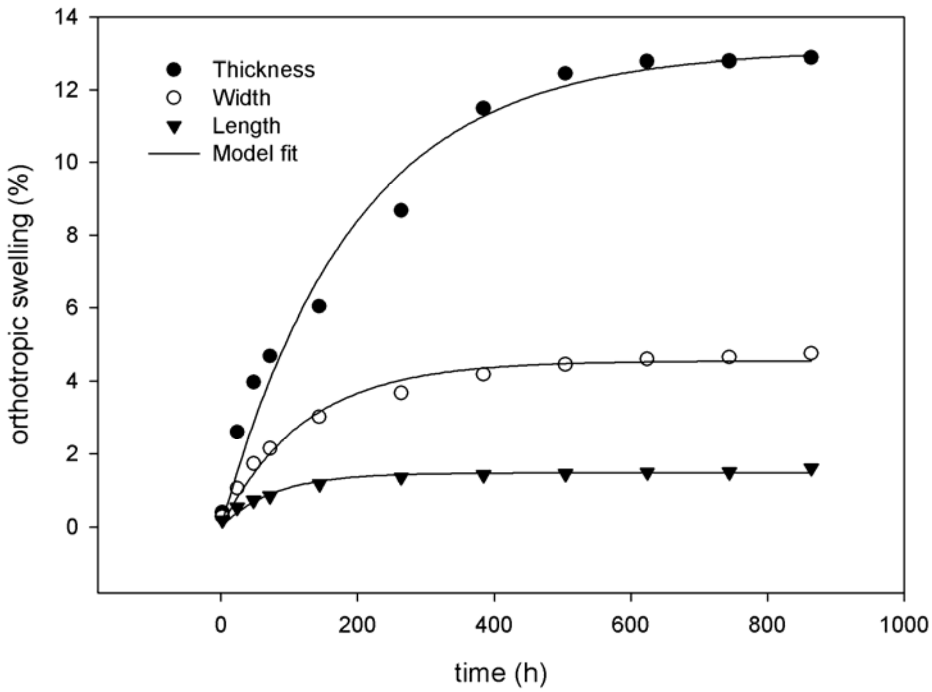

Fig. 4. Orthotropic swelling behavior of bagasse/PP composite

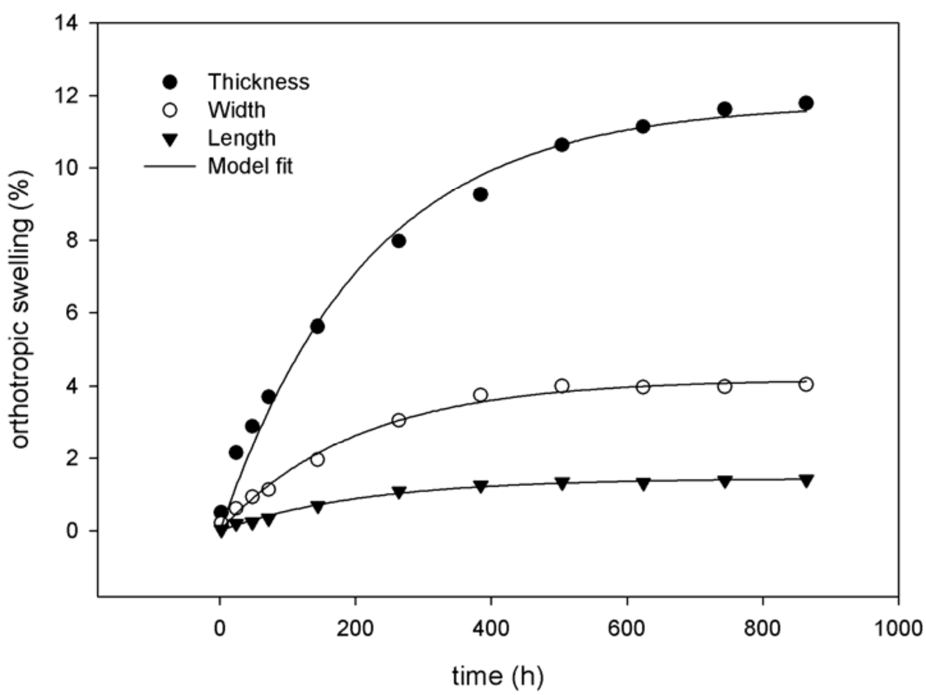

Fig. 5. Orthotropic swelling behavior of bagasse/PE composite

CONCLUSIONS

1. It was found that the flexural modulus of bagasse/thermoplastic composites strongly depended on the applied strain rate. The flexural modulus tended to increase linearly for both composites with the logarithm of strain rate. The flexural strength increased linearly for the PP-based composite with the logarithm of strain rate, but the polyethylene composite exhibited different behavior in which the flexural strength values didn't alter appreciably as a function of strain rate. These findings imply that the flexural properties at only one strain rate are insufficient to describe their behavior in structural applications.
2. The flexural response of polypropylene composite was found to exhibit the higher dependency on strain rate than polyethylene composite.
3. Flexural properties of the PP-based composite were significantly superior to those of the PE-based composite.
4. Dimensional instability of the bagasse-based composites had an orthotropic nature. The highest swelling took place in the thickness of the samples, followed by the width and length, respectively.
5. Water absorption and dimensional instability of the bagasse-based composites were affected by plastic type. Water absorption and dimensional instability of PE-based composites were found to be lower than those of PP-based composites.

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Article submitted: January 16, 2010; Peer review completed: Feb. 11, 2010; Revised version received and accepted: Feb. 13, 2010; Published: Feb. 15, 2010.