EFFECT OF LOAD RATE ON FLEXURAL PROPERTIES OF WOOD-PLASTIC COMPOSITES

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ABSTRACT

With the increase in wood-plastic composite (WPC) products in the commercial marketplace, it is important that the material properties of WPC products are accurately determined. Many of these products are targeted for use in flexural applications; thus the ability to accurately determine the flexural properties is of critical importance if WPC products are to compete as a structural material. Third-point bending tests were conducted on selected WPC formulations at rates ranging from 4.6 mm/min to 254 mm/min and flexural properties were determined. It was found that rate-of-load effects were present for both modulus of rupture and modulus of elasticity over certain ranges of load rate values. Specifically, significant decreases in flexural properties were observed for load rates slower than 62.5 mm/min.

Keywords: Rate of loading, bending, strength, stiffness, wood fiber and plastic composites.

INTRODUCTION

New wood-plastic composites (WPC) products are entering the marketplace at an increasing rate. Many of the applications being considered for WPC components involve flexural loading, making an accurate determination of the flexural properties of WPCs very important. Currently, no consensus standards exist for determining the flexural properties of WPCs. However, standards do exist for evaluating the flexural properties of solid wood, traditional wood composites, and plastic products. These standards are similar in some aspects, but contain significant differences in specifying the rate-of-load application. Discretion of the WPC producers must be exercised to determine which of the existing standards, and thus which load rate, should be used. It has been documented that the rate-of-load application affects the flexural properties of solid wood (Gerhards and Link 1986; Spencer 1979), and that changes in strain rate affect the yield stress of plastics (Hobeika and Strobl 2000). It is, however, unknown whether rate-of-load effects exist in WPCs, and if present, the magnitude of the effects is unknown. It

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was the intent of this experimental research investigation to determine the influence of the rate-of-load application on the flexural response of wood-plastic composites.

BACKGROUND

The standard for determining the flexural properties of structural-sized wood members was created in 1924 when ASTM D198 was first published. The standard recommends that a load rate should be chosen to achieve failure in about 10 min with a minimum of 6 min and a maximum of 20 min. A constant rate of outer-fiber strain equal to 0.001 mm/mm/min is suggested as being sufficient to produce failure within the required timeframe (ASTM 1998).

Similar standards exist for evaluating the flexural properties of plastic products. ASTM D6109 (1997a) is a standard test method for determining the flexural properties of unreinforced and reinforced plastic lumber of rectangular or square cross sections. The standard specifies that it is a test method for evaluating plastic lumber as a product, but is not a material property test method (ASTM 1997a). Two methods are presented, one for products used in the flatwise, weak, or "plank" orientation, and one for products used in the edgewise, strong, or "joist" orientation. The method for edgewise testing specifies that the load rate must be based on a constant rate of outer-fiber strain. A range of 0.002 to 0.003 mm/mm/min is specified for the rate of outer-fiber strain to be used to calculate the rate of crosshead motion. The equation supplied for use in calculating the rate of crosshead motion is given in Eq. (1):

$$R = \frac{0.185ZL^2}{d} \qquad (1)$$

where R is the rate of crosshead motion, Z is the rate of outer-fiber strain, L is the support span, and d is the specimen depth. Note that consistent units must be used with all equations presented.

Another standard for determining the flexural properties of plastic products is ASTM D790 (1997b), a standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. Again, two methods are presented, one for materials that break at comparatively small deflections, and one for materials that undergo large deflections during testing. The first method specifies a load rate based on the outer-fiber strain rate of 0.01 mm/mm/min. The standard provides an equation to calculate the rate of crosshead motion and is given in Eq. (2):

$$R = \frac{ZL^2}{6d} \qquad (2)$$

where all parameters are as defined previously.

Haiar (2000) recommended test procedures for determining material properties of both polyvinyl chloride (PVC) and high-density polyethylene (HDPE) wood-plastic composite formulations. To establish flexural properties, Haiar recommended that the method, apparatus, and procedures outlined in ASTM D198 (1998) be followed with two modifications: the load rate is to be taken from ASTM D790, (1997b) and the span shall be determined from the ratio of length to radius of gyration. The load rate modification was made to account for potential creep effects that may be present at slower rates, and the span modification was made to allow for hollow or nonrectangular sections.

The stress-strain relationship of WPCs is typically nonlinear, creating difficulties in accurately determining the modulus of elasticity. Hermanson et al. (1998) explored the use of a four-parameter hyperbolic tangent constitutive relationship previously shown to fit the load-displacement relationship of WPCs. They found that a simplified two-parameter variation of the model still provided an accurate representation of WPC behavior. In terms of the stress-strain relationship, the simplified equation has the form:

$$\sigma = c_1 \mathrm{Tanh}(c_2 \varepsilon) \qquad (3)$$

where σ is stress, Tanh is the hyperbolic tangent function, ε is the strain, and c_1 and c_2 are

TABLE 1. *Formulation materials and percentages.*

Formulation	% Flour	Wood flower type	% Plastic	Plastic type	Additives
PVC	50	Ponderosa Pine (AWF #4020)	50	PVC Compound (Georgia Gulf) (3014 nat 00)	None
HDPE 8	58	Maple (AWF #4010)	31	HDPE (Equistar) (LB 0100 00)	8% Ceramic Talc (Suzqrite) 3% Processing Aides
HDPE 67.5	67.5	Maple (AWF #4010)	32.5	HDPE (Equistar) (LB 0100 00)	None
HDPE 67.5 w/MAPE	67.5	Maple (AWF #4010)	30.95	HDPE (Equistar) (LB 0100 00)	1.55% MAPE (AlliedSignal) (575A1)

constants determined through a least-squares method. Hermanson et al. (1998) also found that Eq. (4) could be used to estimate the initial modulus of elasticity:

$$E = c_1 c_2 \tag{4}$$

where E is the modulus of elasticity, and all other parameters are as defined previously. It was determined that Eq. (4) overpredicts a linear estimate by 5–10% at a prescribed 1% strain.

Very little documentation exists detailing research conducted to investigate the effect of rate-of-load application on the flexural properties of WPC products. Thus, experimental research is necessary to determine if rate-of-load effects exist for WPC products and to evaluate the two standards currently being used to determine the flexural properties of WPC products.

MATERIALS

Four wood-plastic composite formulations were selected for evaluation. The first formulations was produced with polyvinyl chloride (PVC), and the remaining three were produced with high-density polyethylene (HDPE). The HDPE 8 formulation contained the following processing aides: 2% zinc stearate (Ferro Chemicals Synpro DLG-20B) and 1% EBS wax (GE Specialty). Another of the HDPE formulations contained an ethylene-maleic anhydride polymer (MAPE), which is a commercially available coupling agent added to strengthen the bond at the interface between the polyethylene and wood fibers. Table 1 lists the material composition of each formulation and gives the percentage used by weight.

All materials were dry blended in a 1.2-m-diameter drum mixer in 20-kg batches. The dry mixture was then loaded into the hopper, a conical counter-rotating twin screw extruder (Cincinnati-Milacron E55); and a two-box cross section was extruded using a stranding die (Laver 1996) and was then cut into 2.44-m (8-ft) lengths. Process temperatures are provided in Table 2. Figure 1 illustrates the two-box cross section, and Table 3 summarizes the

TABLE 2. *Extrusion process temperatures.*

Formulation	Process temperature (°C)				
	Barrel	Screw	Die zone 1	Die zone 2	Die zone 3
PVC	168	140	174	174	160
HDPE 8	163	163	171	171	171
HDPE 67.5	163	163	163	171	143
HDPE 67.5 w/MAPE	163	163	163	171	143

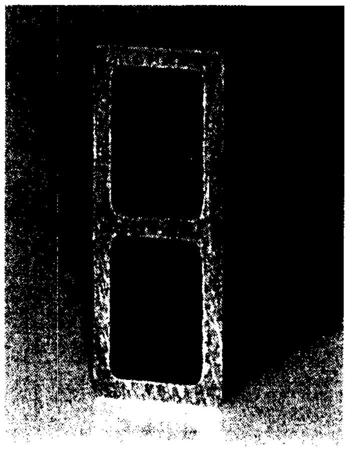

FIG. 1. Two-box cross section.

nominal section dimensions and selected properties.

TABLE 3. *Two-box section dimensions and properties.*

Property	Value
Depth	89 mm
Width	36 mm
Wall Thickness	5 m
Cross-Sectional Area	1,290 mm^2
Moment of Inertia (Strong Axis)	1.05×10^6 mm^4

LOAD RATE TESTS

Five specimens from each formulation were weighed to the nearest milligram on a digital scale, and cross-sectional dimensions were measured to the nearest 0.025 mm with digital calipers. Procedures outlined by Haiar (2000) for determining strong-axis modulus of rupture (MOR) for structural wood-plastic composite beams were followed. The test method specifies that ASTM D198 (1998), a standard test method for determining properties of structural lumber, be followed with two exceptions: load rate and span length. Haiar recommended that the load rate be calculated according to ASTM D790 (1997d), a standard test method for determining flexural properties of unreinforced and reinforced plastics. The standard species that the load be applied such that the rate of strain in the outer fiber is 0.01 mm/mm/min. Based on nominal section dimensions, this corresponded to a load rate of 62.5 mm/min. This "standard" load rate and the other rates selected are listed in Table 4 along with the corresponding outer-fiber strain rate.

Haiar (2000) recommended that the ratio of support span length to radius of gyration be used to determine the test span; however, a span consistent with that used in static bending tests performed as part of the load-duration research (see Brandt 2001) of 1.83 m was used. Similarly, the load was applied at third points, or 610 mm from the end reactions to be consistent with the previous work. Lateral bracing was provided along the span to ensure that lateral-torsional buckling effects were negligible.

Five specimens from each formulation were ramp loaded to failure at the rates listed in Table 4 using a computer-controlled screw-driven 146 N Instron 4400R testing machine. Temperature and relative humidity were monitored during testing and were found to fluctuate between 21°C and 23°C and 40 to 50% RH. A spreader beam was used to evenly distribute the single point load of the crosshead into two point loads applied to the specimen. Center span displacement was measured using a linear position transducer accurate to ± 1.27 mm. A computerized data acquisition system recorded load-displacement data, maximum load, and time-to-failure for each specimen. The test setup is shown in Fig. 2.

RESULTS

The objective of this research was to evaluate the effects of load rate on flexural properties, specifically the MOR and modulus of elasticity (MOE). Deflection at failure was

TABLE 4. *Load rates tested and corresponding strain rates.*

Rate-of-load application mm/min	Rate-of-strain in outer fiber mm/mm/min
4.6	0.0007
62.5	0.01
254	0.04

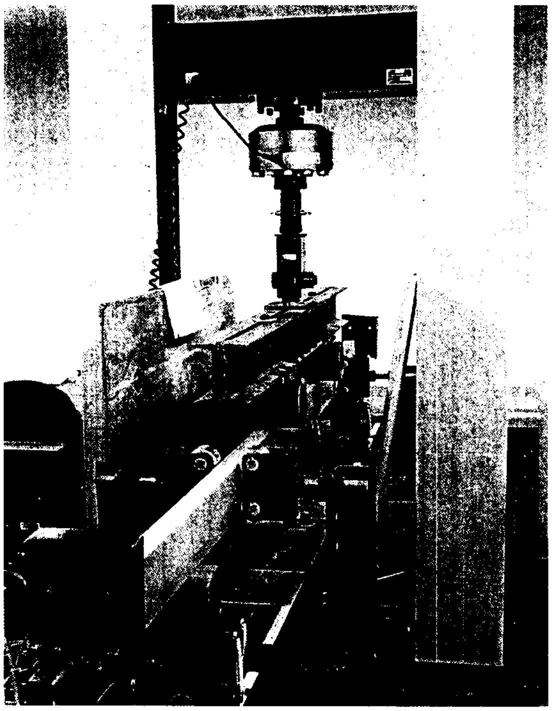

FIG. 2. Load-rate test setup.

TABLE 5. *Modulus of rupture values.*

Formulation	Modulus of rupture (MPa)		
	4.6 mm/min	62.5 mm/min	254 mm/min
PVC	42.55	48.29	47.48
HDPE 8	14.56	16.88	17.68
HDPE 67.5	18.15	21.13	21.04
HDPE 67.5 w/MAPE	27.63	32.03	33.23

also monitored and recorded. A load versus displacement curve was generated for each specimen tested. Figures 3 through 6 illustrate a typical load-displacement curve for each formulation at the "standard" 62.5 mm/min rate of loading. Examination of Figs. 3 through 6 reveals that the PVC and HDPE 67.5 w/ MAPE formulations exhibited less ductility than the HDPE 8 and HDPE 67.5 formulations.

Using the load at failure data, MOR values were calculated for each specimen. The average MOR values at each rate of loading are presented in Table 5 and in Fig. 7. From a visual inspection, it appears that MOR increased with the increase in rate-of-load ap-

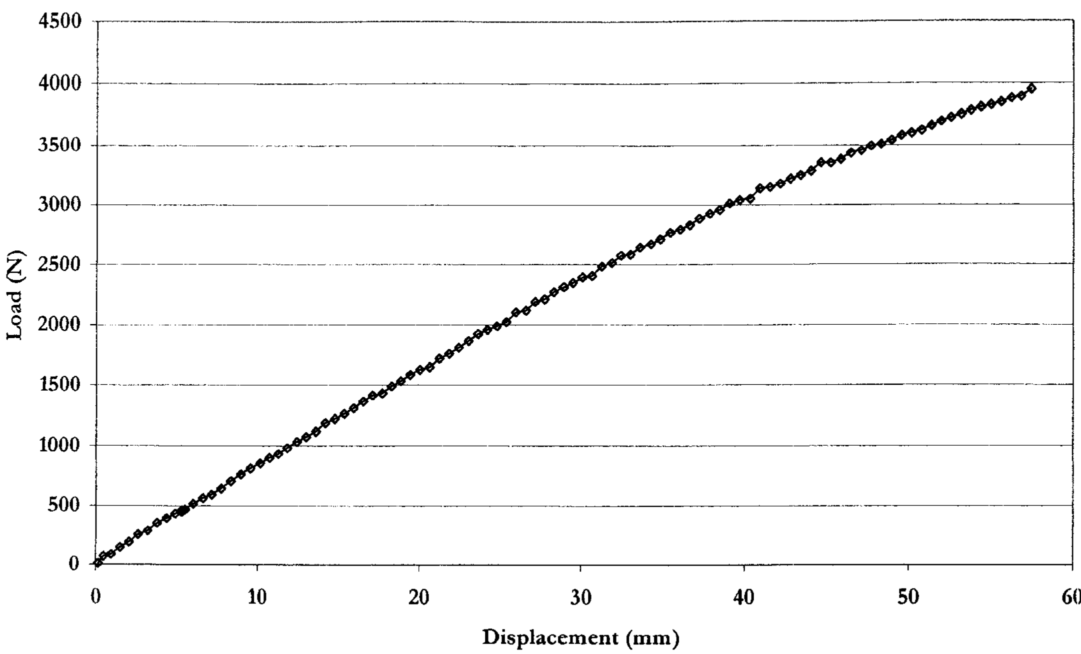

FIG. 3. Load versus Displacement for PVC at 62.5 mm/min.

FIG. 4. Load versus Displacement for HDPE 8 at 62.5 mm/min.

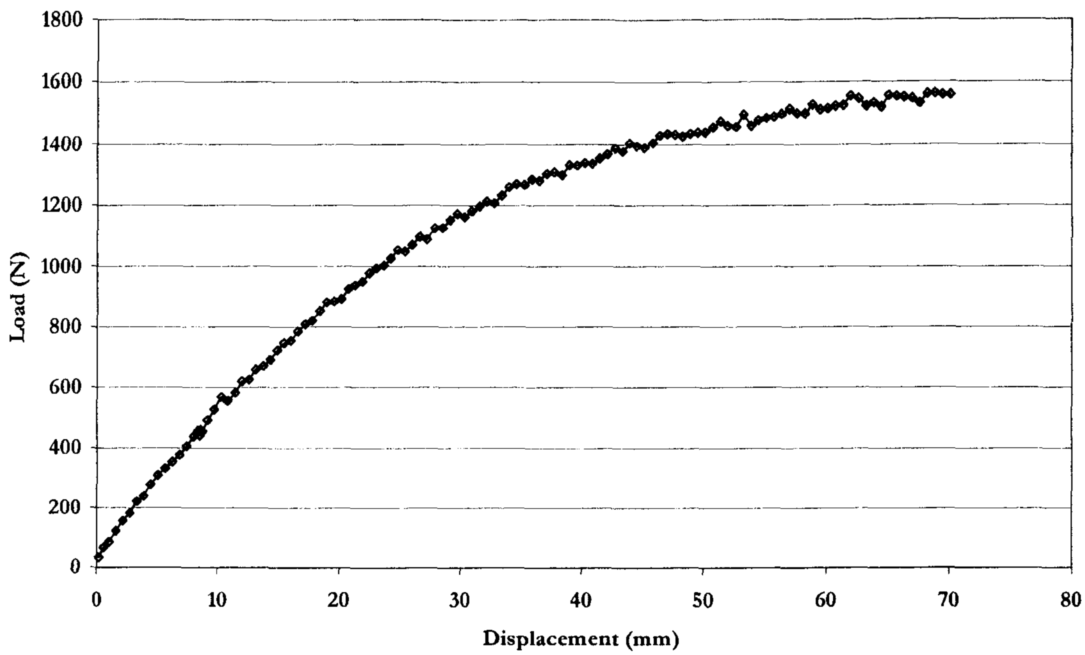

FIG. 5. Load versus Displacement for HDPE 67.5 at 62.5 mm/min.

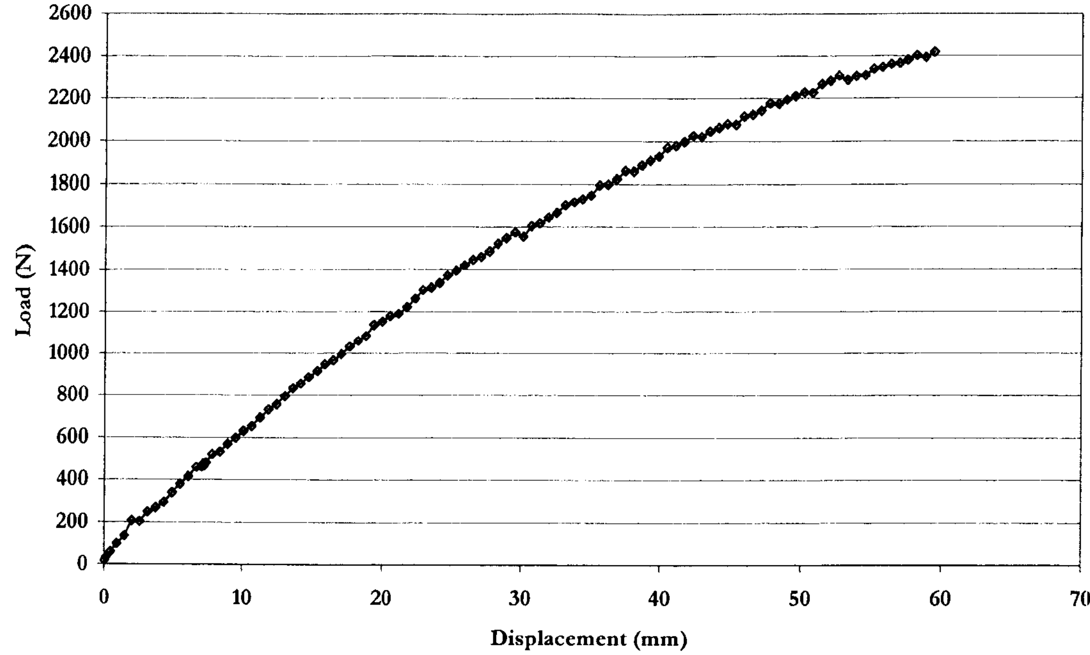

FIG. 6. Load versus Displacement for HDPE 67.5 w/MAPE at 62.5 mm/min.

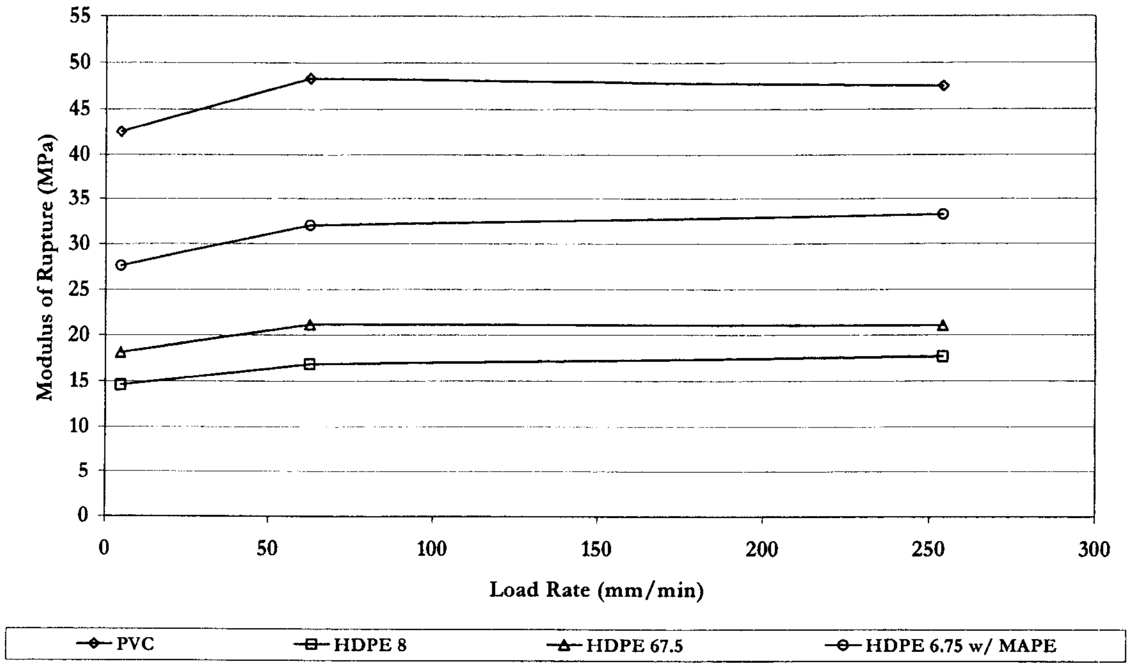

FIG. 7. Rate-of-Load Effect on Modulus of Rupture.

TABLE 6. *t-test results for MOR values.*

Load rate	t statistic	t critical	P-value
PVC			
4.6 mm/min to 62.5 mm/min	7.663	1.860	2.973E-05
62.5 mm/min to 254 mm/min	0.971	1.860	0.180
HDPE 8			
4.6 mm/min to 62.5 mm/min	6.701	1.860	7.628E-05
62.5 mm/min to 254 mm/min	2.418	1.860	0.021
HDPE 67.5			
4.6 mm/min to 62.5 mm/min	9.437	1.860	6.529E-06
62.5 mm/min to 254 mm/min	0.159	1.860	0.439
HDPE 67.5 w/MAPE			
4.6 mm/min to 62.5 mm/min	27.704	1.860	1.555E-09
62.5 mm/min to 254 mm/min	7.622	1.860	3.089E-05

plication from 4.6 to 62.5 mm/min and then remained nearly constant between 62.5 mm/min and 254 mm/min for all four formulations.

To confirm the trends observed for the average values, a one-sided t test was performed at the 0.05 significance level to determine whether statistical differences in mean values exist. Analysis of a separate, larger data set confirmed that the normally distributed data assumption is not violated for any of the formulations. The MOR values from the 62.5 mm/min (ASTM D790) (1997b) load rate were used as the standard to which the MOR values from the 4.6 mm/min and 254 mm/min rates were compared. Table 6 presents the results for each formulation.

The t test results for the modulus of rupture do not fully agree with the visual observations made for the data. The MOR at a load rate slower than the ASTM D790 rate was found to be statistically different from the MOR at the ASTM D790 (1997b) rate for all formulations. The MOR at a load rate faster than the ASTM D790 rate was found to be statistically similar to the MOR at the ASTM D790 rate for the PVC and HDPE 67.5 formulations and statistically different for the HDPE 8 and HDPE 67.5 w/ MAPE formulations.

For the HDPE-based formulations, a trend toward a linear increase in modulus of rupture values with the logarithm of loading rate was observed; however, the same was not true for the PVC formulation. Gerhards and Link (1986) observed a similar trend in strength values of solid sawn lumber. With a limited number of data points collected over a broad range of load rates, it was not possible here to explore the relationship between the two beyond the point of making a note of the potential trend.

Following Hermanson et al. (1998), the method of least squares was used to estimate paramters c_1 and c_2 in Eq. (3), and then the hyperbolic tangent modulus of elasticity was calculated for each specimen using Eq. (4).

TABLE 7. *Mean values of constants for hyperbolic tangent relationship.*

Formulation	4.6 mm/min		62.5 mm/min		254 mm/min	
	c_1	c_2	c_1	c_2	c_1	c_2
PVC	60,655	143	74,407	114	76,832	115
HDPE 8	14,400	240	16,920	258	17,961	265
HDPE 67.5	17,726	266	21,128	255	21,606	279
HDPE 67.5 w/MAPE	28,986	188	37,232	168	38,670	181

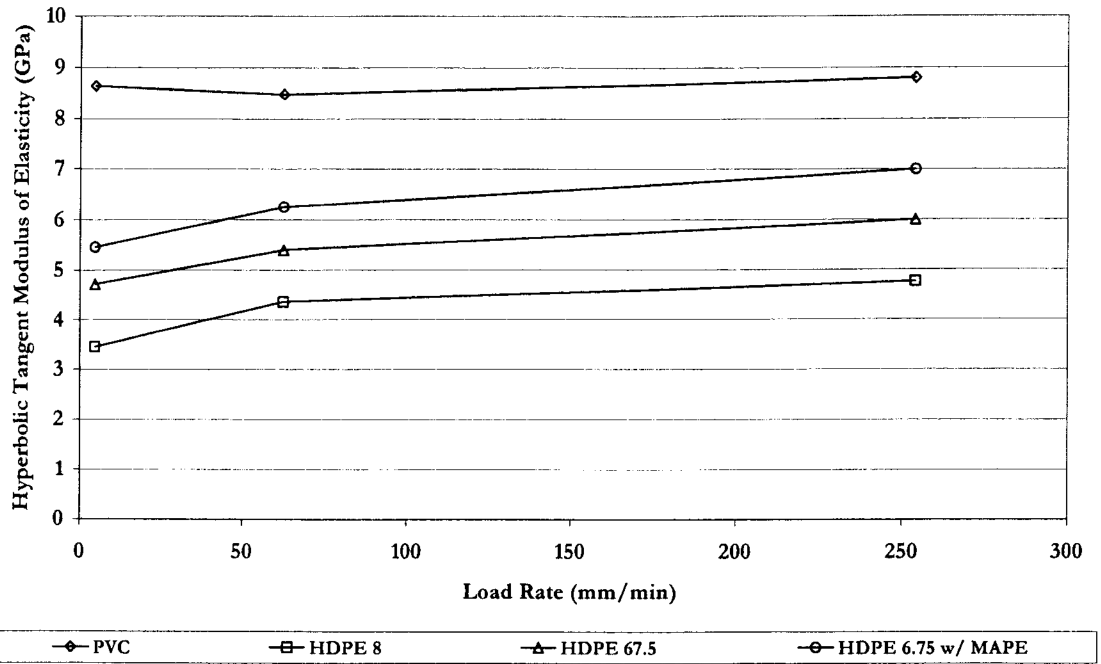

FIG. 8. Rate-of-Load Effect on Hyperbolic Tangent Modulus of Elasticity.

Table 7 contains the mean values of c_1 (kPa) and c_2 (unitless) for each formulation and rate-of-load.

Additionally, an initial tangent modulus of elasticity was calculated for comparison by assuming that the stress-strain relationship was linear in the range from 0–30% of the ultimate stress. Table 8 and Table 9 contain average values for hyperbolic tangent MOE and initial tangent MOE for each specimen, respectively. Figures 8 and 9 present the data in graphical form for convenience. Note that the values in Tables 7 and 8 are both mean values, and that the constants c_1 and c_2 are not perfectly correlated. Therefore, the values in Table 8 cannot be obtained by direct multiplication of the values in Table 7 because the average of the products does not equal the product of the averages for non-perfectly correlated values.

A comparison of the values in Tables 8 and 9 shows that, in general, the initial tangent modulus values are an average of 4.9% higher than those calculated following the method proposed by Hermanson et al. (1998). However, the hyperbolic tangent constitutive relationship is considered to give a more reliable and consistent representation of the behavior of WPC materials. Therefore the hyperbolic tangent MOE will be assumed representative of the material and, from this point forward, any use of the term MOE refers to the hyperbolic tangent MOE.

Figure 9 indicates that MOE values increase with an increase in load rate for all three HDPE-based formulations, and that MOE values for PVC remain nearly constant. Again, a one-sided t test was performed at the 0.05 significance level to determine whether statistical differences in mean values exist. Analysis of a separate, larger data set confirmed that the normally distributed data assumption is not violated for any of the formulations. The MOE values from the 62.5 mm/min (ASTM D790) load rate were used as the standard to which the MOE values from the 4.6 mm/min and 254 mm/min rates were compared. Table 10 presents the results for each formulation. It was found that as the rate-of-load increases, the ef-

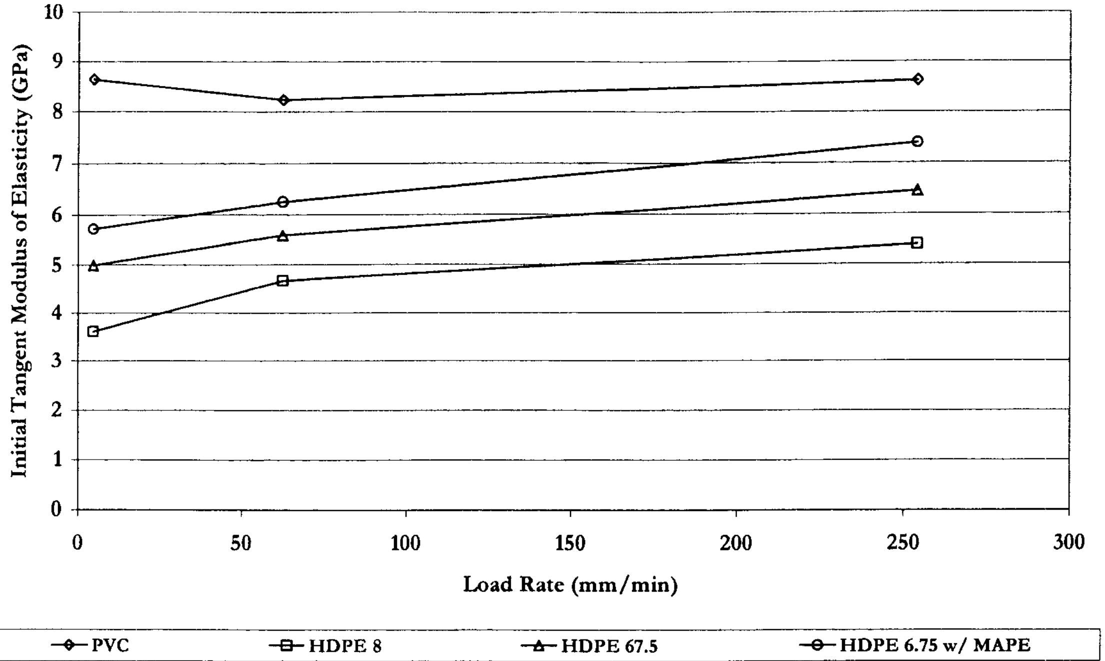

FIG. 9. Rate-of-Load Effect on Initial Tangent Modulus of Elasticity.

fect of viscous flow of the material is decreased; thus the increase in MOE values was expected.

The t test results for the modulus of elasticity confirm the visual observations made for the data for all formulations tested with a few exceptions. The MOE at a load rate slower than the ASTM D790 (1997b) rate was found to be statistically different from the MOE at the ASTM D790 rate for all HDPE formulations, while the MOE was found to be statistically similar for the PVC formulation. The MOE at a load rate faster than the ASTM D790 rate was found to be statistically different than the MOE at the ASTM D790 rate for all formulations.

Finally, deflection at failure was evaluated in a manner similar to that done for MOR and MOE to further investigate the effects of rate-of-load application. Figure 10 illustrates a decreasing trend in deflection as rate-of-load application increases. T test results confirm that a rate-of-load effect is present for deflection at failure values over the 4.6 mm/min to 62.5 mm/min interval for all formulations; a rate-of-load effect is present for deflection at failure values over the 62.5 mm/min to 254 mm/min interval for all formulations except HDPE

TABLE 8. *Hyperbolic tangent modulus of elasticity values.*

Formulation	Hyperbolic tangent modulus of elasticity (GPa) 4.6 mm/min	62.5 mm/min	254 mm/min
PVC	8.84	8.48	8.80
HDPE 8	3.42	4.36	4.76
HDPE 67.5	4.72	5.39	6.00
HDPE 67.5 w/MAPE	5.45	6.25	7.00

TABLE 9. *Initial tangent modulus of elasticity values*

Formulation	Initial tangent modulus of elasticity (GPa) 4.6 mm/min	62.5 mm/min	254 mm/min
PVC	8.92	8.23	8.63
HDPE 8	3.59	4.67	5.39
HDPE 67.5	4.99	5.58	6.45
HDPE 67.5 w/MAPE	5.72	6.25	7.39

TABLE 10. *t-test results for MOE values*

Load rate	t statistic	t critical	*P*-value
PVC			
4.6 mm/min to 62.5 mm/min	1.242	1.860	0.125
62.5 mm/min to 254 mm/min	3.078	1.860	0.008
HDPE 8			
4.6 mm/min to 62.5 mm/min	8.244	1.860	1.758E-05
62.5 mm/min to 254 mm/min	4.372	1.860	0.001
HDPE 67.5			
4.6 mm/min to 62.5 mm/min	7.919	1.860	2.349E-05
62.5 mm/min to 254 mm/min	3.950	1.860	0.002
HDPE 67.5 w/MAPE			
4.6 mm/min to 62.5 mm/min	8.443	1.860	1.478E-05
62.5 mm/min to 254 mm/min	4.669	1.860	8.024E-04

8. Again, it was found that as the rate-of-load increases, the effect of viscous flow of the material is decreased, thus the decrease in deflection at failure was expected.

CONCLUSIONS

Through an experimental evaluation of the effect that rate-of-load application has on flexural properties of selected wood-plastic composites, it was determined that rate-of-load effects occur only over certain ranges of load-rate application. A one-sided t test was used to determine if modulus of rupture and modulus of elasticity values were dependent on rate-of-load application. An increase in rate-of-load application, from 4.6 mm/min (approximately one-third the rate specified in ASTM D6109 (1997a)) to 62.5 mm/min (the

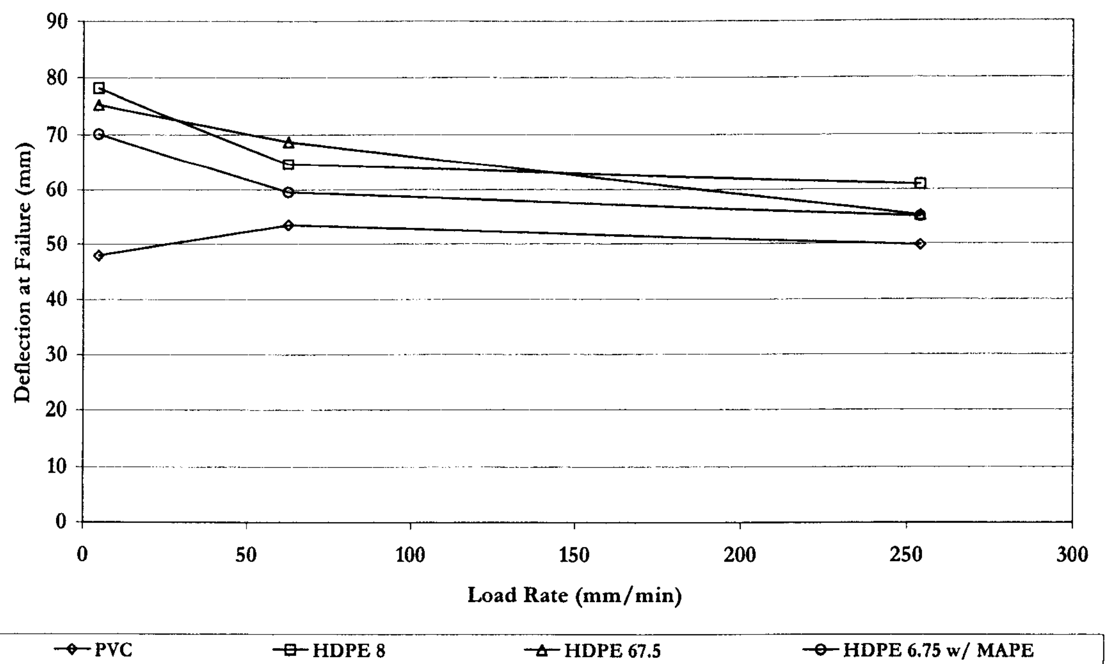

FIG. 10. Rate-of-Load Effect on Deflection at Failure.

rate specified in Procedure A of ASTM D790 (1997b)), resulted in an increase in MOR values for all formulations. Similarly, an increase was noticed in MOE values for all formulations except PVC, for which values remained statistically unchanged. A further increase in rate-of-load application, from 62.5 mm/min to 254 mm/min, resulted in an increase in MOR values for both HDPE 8 and HDPE 67.5 w/ MAPE, while the MOR values for PVC and HDPE 67.5 remained similar. MOE values for all formulations were found to increase over this range of load rates.

It is concluded from the results presented herein that a rate-of-load effect is present in flexural response of WPCs, and that there is a significant difference between the properties obtained from the load rates specified by the two ASTM standards currently used. At approximately one-third the load rate calculated according to ASTM D6109 (1997a), average MOR values were found to be between 13% and 15% lower than at the ASTM D790 (1997b) rate, and average MOE values were between 2% and 23% lower. Without having the exact relationship between load rate and MOR or MOE, it is difficult to determine the magnitude of the difference that would be observed using the ASTM D6109 rate. However, if a linear relationship were assumed, the percent difference would remain at approximately 13% for MOR, and between 2% and 21% for MOE. Consequently, it is quite apparent that the potential for underestimating the flexural properties of WPC products exists.

An examination of load rates above the ASTM D790 rate shows that, at four times the load rate specified in ASTM D790, average MOR values were either constant, or increased by less than 5% depending on the formulation, and average MOE values increased by between 4% and 11%. While a general increase in flexural properties was witnessed at the 254 mm/min load rate, the short duration of the test, 13 seconds on average, makes high-speed data acquisition (5 Hz or greater) necessary in order to collect an adequate amount of data. Thus, it is concluded that flexural tests conducted at the ASTM D790 recommended outer-fiber strain rate of 0.01 mm/mm/min are not only practical in terms of the test equipment required, but also produce representative material properties. The values obtained using this load rate were conservative when compared to those obtained using a higher rate of outer-fiber strain, but not overly conservative as was observed using a lower rate of outer-fiber strain. Furthermore, ASTM D6109, while admittedly not a material property test standard, should not be used for determining the rate of load used in flexural tests of wood-plastic composites, as the outer-fiber strain rates that it recommends results in overly conservative estimates of both modulus of rupture and modulus of elasticity.

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