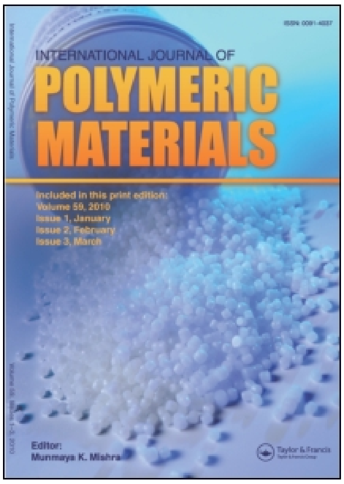

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Thermal Degradation of Wood Fillers at the Melt-Processing Temperatures of Wood-Plastic Composites: Effects on Wood Mechanical Properties and Production of Voiatiles

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Thermal Degradation of Wood Fillers at the Melt-Processing Temperatures of Wood-Plastic Composites: Effects on Wood Mechanical Properties and Production of Volatiles

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The objective of this research was to clarify the effect of wood thermolysis during melt processing on the properties of wood-plastic composites. Oven-dried sugar pine wood strips were subjected to thermal degradation in a stirred molten metal bath in the temperature range 220°C to 260°C. Exposure times ranged from 4096 to 4 minutes. The bath and wood strips were kept free of oxygen. Degraded wood specimens and undegraded ones (used as controls) were tested for bending modulus and strength, toughness, and weight loss. Toughness was most affected by the degradative treatment, followed by bending strength and then bending modulus. Apparent Arrhenius parameters for the thermal degradation process were determined from rates of property loss, and times required to produce various relative property losses were calculated. Losses in wood mechanical properties during a single composite extrusion probably would not significantly alter composite properties, but multiple melt processing steps could be deleterious. Possibly more important are volatile degradation products which could be sufficient to create problems in air pollution, in the melt processing and mechanical behavior of composites.

KEY WORDS Thermal degradation, wood flour, composite, extrusion, mechanical properties, melt processing

INTRODUCTION

For many years, polymeric materials have been modified by using fillers to produce composite materials with improved characteristics and wider application than the unfilled polymers. Inorganic fillers such as mica, fiberglass, talc, clay, etc. have been widely used.[1] Environmental considerations and the increasing costs of inorganic fillers have been incentives to their substitution by wood-based fillers (e.g., wood flour, cellulose fibers), yielding composites with the additional advantage of low density relative to inorganic-filled systems.

However, during the several minutes required for melt processing of these composites at temperatures as high as 250°C, the wood-based particles or fibers can undergo sufficient thermolysis to alter their mechanical properties and surface composition. These changes may have consequences—positive or negative—for the mechanical behavior of the resultant composites. Myers *et al.*,[2] for example, report several consequences of extruding a wood flour-polypropylene composite between 190°C and 250°C—marked darkening of the composite, decrease in polarity of the wood particle surface, small changes in composite strength, and loss in impact resistance. Moreover, they found that some of these effects were increased when small amounts of maleated propylene additive were present. Another undesirable result of wood filler thermolysis during melt processing is the evolution of gaseous products. This can have serious consequences in terms of environmental pollution, interference with melt processing, and reduction in mechanical properties of the solid composite product due to porosity.

Several investigators have studied the kinetics of wood thermal degradation at elevated temperatures and the effects of moisture content and temperature on the mechanical properties of wood.[3-6] The thermal degradation of dry wood has been characterized as an apparent first-order kinetic process although the actual chemical reaction is very complex.[4] However, little or no data have been reported in the temperature range encountered in melt processing wood-filled composites (190°C to 260°C).

We wished to clarify the effect of wood thermolysis on both the mechanical properties of wood flour (or fiber)-plastic composites and the evolution of gaseous products. Therefore, we studied the changes occurring in weight and in selected mechanical properties of wood strips as a result of exposure to 220, 240, and 260°C for periods of 4096 minutes (2.85 days) to 4 minutes. We chose sugar pine (P. lambertiana) for the study because the current major melt-processed wood-filled plastic composite employs pine flour as the filler. Moreover, the wood strips were exposed to these temperatures after drying and in the absence of air to conform more closely to composite processing conditions. This paper presents the results and compares them with earlier findings at lower temperatures.[4]

EXPERIMENTAL

Wood Specimen Preparation

Two sugar pine flat-sawn boards were selected for straightness and uniformity of grain. Each board was cut into rectangular specimens 101.6 mm long, 16 mm wide and 2.54 mm thick. Holes, 3.2 mm in diameter, were drilled in each specimen at 6.4 mm from both ends to facilitate loading onto sample racks for thermal degradation. Specimens were cut and distributed randomly among the temperatures and exposure times as indicated in Figure 1. At each aging condition of temperature and time, five replicate specimens were aged for each of the mechanical properties.

Before the degradative treatment, the specimens were dried under vacuum (75

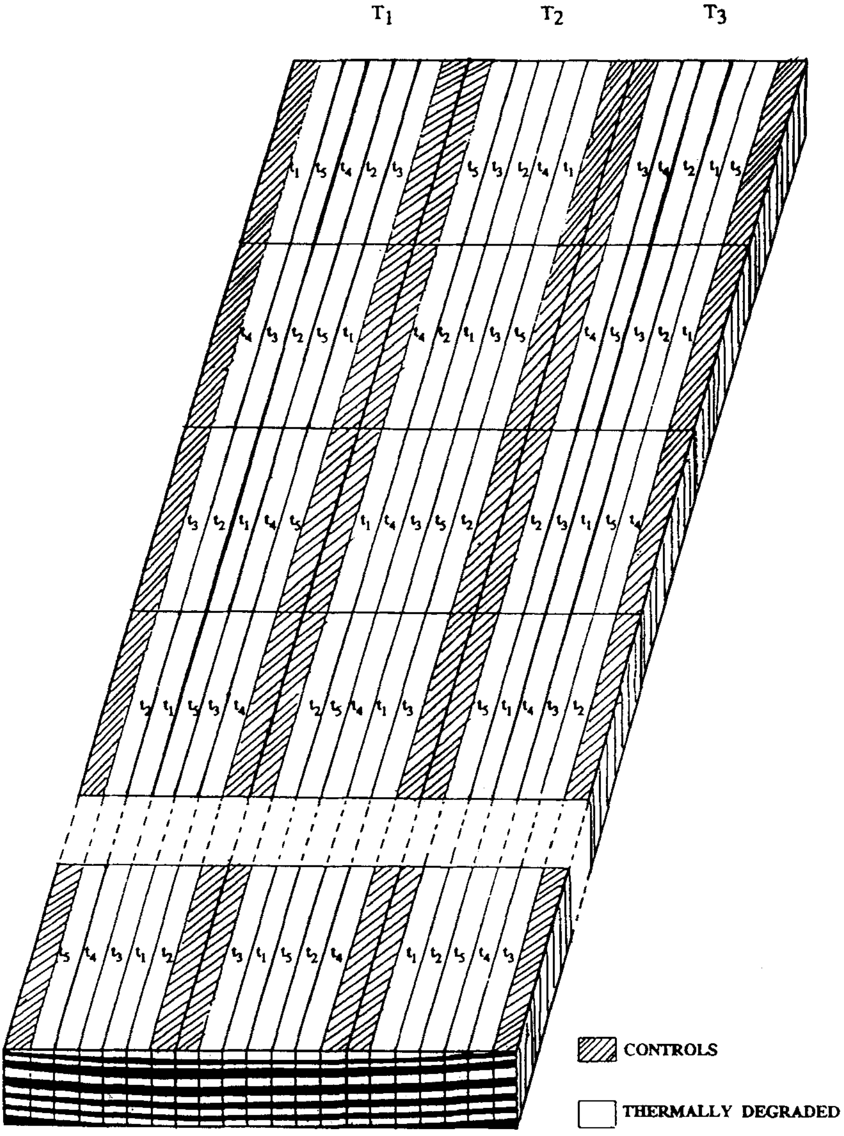

FIGURE 1 Sketch of the board showing specimen orientation and selection pattern of specimens (*T* is temperature; *t* is time).

mmHg) at 60°C for 1 hr and immediately stored in sealed plastic bags. When cool, their weight and size (width and thickness) were measured individually.

Thermal Degradation Process

The thermal degradation of wood specimens was carried out in a molten metal bath measuring 279 mm long, 152 mm wide, and 178 mm deep. The molten metal was a Bi/Sn/Pb alloy (11.2% Bi, 44.4% Sn, 44.4% Pb) with an approximate melting

TABLE I

Average residual weights of wood specimens after degradation

T(°C)	TIME (min)	RESIDUAL WEIGHT (%)[a]	STANDARD DEVIATION[a]	RESIDUAL WEIGHT (%)[b]	STANDARD DEVIATION[b]
220	64	95.45	0.73	96.38	0.66
220	128	95.37	2.11	95.34	0.79
220	256	91.76	0.65	93.43	0.47
220	512	92.28	0.19	91.40	2.01
220	1024	87.50	1.07	86.88	0.67
220	2048	82.36	0.61	-	-
220	4096	75.03	0.56	-	-
240	16	-	-	96.43	0.24
240	32	93.67	0.95	94.98	0.83
240	64	91.78	0.58	92.64	0.29
240	128	90.52	0.33	88.75	0.30
240	256	86.95	0.65	85.10	0.34
240	512	82.51	1.70	80.23	0.62
240	1024	75.12	1.26	-	-
260	4	94.45	0.79	95.08	0.52
260	8	90.98	3.91	93.60	0.38
260	16	94.42	0.35	91.52	0.42
260	32	92.32	1.66	89.25	0.28
260	64	87.06	0.35	85.36	3.63
260	128	81.97	0.44	-	-
260	256	77.10	1.60	-	-

a. From specimens used for bending tests.

b. From specimens used for toughness.

point of 160°C. Two stirrers ensured thorough mixing. To keep the bath and the specimens free of oxygen, a stream of CO_2 continuously flowed over the surface of the molten alloy, and the bath was provided with a sliding cover. The temperature of the bath was reproduced and controlled to ±0.1°C.

Each set of 5 dried specimens was threaded onto two stainless steel (SS) wires, using SS washers to separate the specimens. The set was then fastened by the wires to a SS rack, which was quickly submerged into the molten metal and clamped in place. At the end of the degradation time, the rack of specimens was quickly removed from the bath and placed for 1 hr in a wood box which was purged with carbon dioxide. The specimens were again dried at 60°C under vacuum and their weight, size and mechanical properties determined. (In initial testing, the specimens

TABLE II

Average residual modulus of rupture of wood specimens after degradation

T(°C)	TIME (min)	RESIDUAL MOR (%)	STANDARD DEVIATION
220	64	90.53	2.67
220	128	90.00	2.62
220	256	85.77	3.67
220	512	75.52	4.79
220	1024	62.68	7.78
220	2048	59.15	3.45
220	4096	46.35	5.17
240	32	94.03	3.48
240	64	89.96	1.12
240	128	82.17	2.41
240	256	75.81	3.82
240	512	67.30	2.29
240	1024	61.45	3.11
240	2048	41.47	3.47
260	4	96.76	2.60
260	8	92.94	4.83
260	16	77.99	3.59
260	32	74.57	3.21
260	64	69.78	3.06
260	128	62.34	2.91
260	256	48.33	1.50

were equilibrated to 23°C and 50 percent relative humidity instead of drying them prior to measuring weights and properties. However, the thermal exposures led to changes in moisture uptake at equilibrium conditions, which altered weight and properties and complicated the interpretation.)

The times required for the center of a specimen to reach the bath temperature after submersion and then to cool after removal were estimated using a sandwich of two specimens bonded together with phenol-formaldehyde adhesive and having a fine thermocouple in the bondline. The bondline of this double-thickness specimen came within one degree of the bath temperature (240°C) in approximately two minutes. In two minutes after removal from the bath the bondline fell to 60°C. Assuming heat transport to be proportional to thickness squared leads to a time of less than one minute for the center of individual specimens to effectively achieve bath temperature and to a shorter time after removal to fall to a temperature low enough that significant degradation should not occur.

TABLE III

Average residual modulus of elasticity of wood specimens after thermal degradation

T(°C)	TIME (min)	RESIDUAL MOE (%)	STANDARD DEVIATION*
220	64	97.10	3.76
220	128	96.32	3.29
220	256	94.01	3.31
220	512	79.58	5.04
220	1024	71.29	6.10
220	2048	73.53	5.42
220	4096	64.20	7.86
240	32	97.35	6.47
240	64	95.05	3.77
240	128	92.44	3.38
240	256	80.50	4.54
240	512	81.67	4.01
240	1024	71.58	2.62
240	2048	61.72	3.34
260	4	99.15	4.10
260	8	97.23	4.83
260	16	86.26	3.90
260	32	84.32	3.58
260	64	78.10	3.86
260	128	72.70	3.74
260	256	66.32	4.11

Several trials were also performed to establish the appropriate temperatures and times to produce an approximately 5 to 50 percent range of property losses. The shortest exposure time was set at four minutes. The following conditions were finally selected for three-point bending tests. Because the rates of loss in impact energy were higher, the longest times were not used for that property. Assuming the heat-up and cool-down times approximately cancelled one another, no corrections were made to any of the exposure times.

220°C for 64, 128, 256, 512, 1024, 2048 and 4096 minutes.

240°C for 16, 32, 64, 128, 256, 512 and 1024 minutes.

260°C for 4, 8, 16, 32, 64, 128, 256 minutes.

TABLE IV

Average residual toughness of wood specimens after degradation

T(°C)	TIME (min)	RESIDUAL TOUGHNESS (%)	STANDARD DEVIATION
220	64	93.81	2.04
220	128	89.71	3.47
220	256	78.41	3.80
220	512	70.27	9.73
220	1024	60.88	8.56
240	16	84.92	18.74
240	32	82.17	5.34
240	64	75.45	4.22
240	128	70.71	9.70
240	256	60.26	6.03
240	512	54.67	8.56
260	4	84.99	7.22
260	8	80.74	5.19
260	16	76.43	5.19
260	32	64.12	5.51
260	64	53.54	8.95

Testing

As noted, five specimens were randomly selected for each degradation condition and property. Forty-two control specimens were similarly selected and subjected to the same ambient drying and storage treatment as the degradation specimens. Property values are therefore the mean of forty-two measurements for the undegraded wood and five measurements for each aging condition. Static bending tests (three-point bending) were conducted on a universal testing machine (AMETEK Riehle) using a support span of 51 mm and a crosshead rate of 1.7 mm/min. Three-point bending maximum strength (modulus of rupture) and modulus (modulus of elasticity) were measured in conformance with ASTM D 1037-78.[7] Impact bending tests were conducted in a Forest Products Laboratory type toughness machine according to ASTM D 143-83[8]; the unnotched specimens were struck on the 16 mm × 102 mm face at the center of the length. Weight loss during thermal degradation was determined from specimen weights before and after exposure.

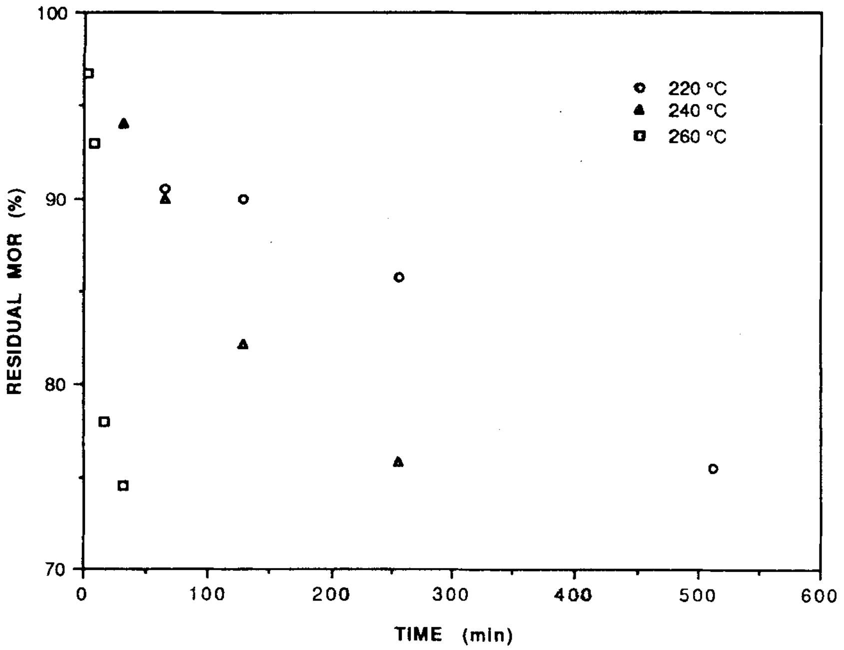

FIGURE 2 Relationship of wood residual bending modulus of rupture (MOR) to exposure time.

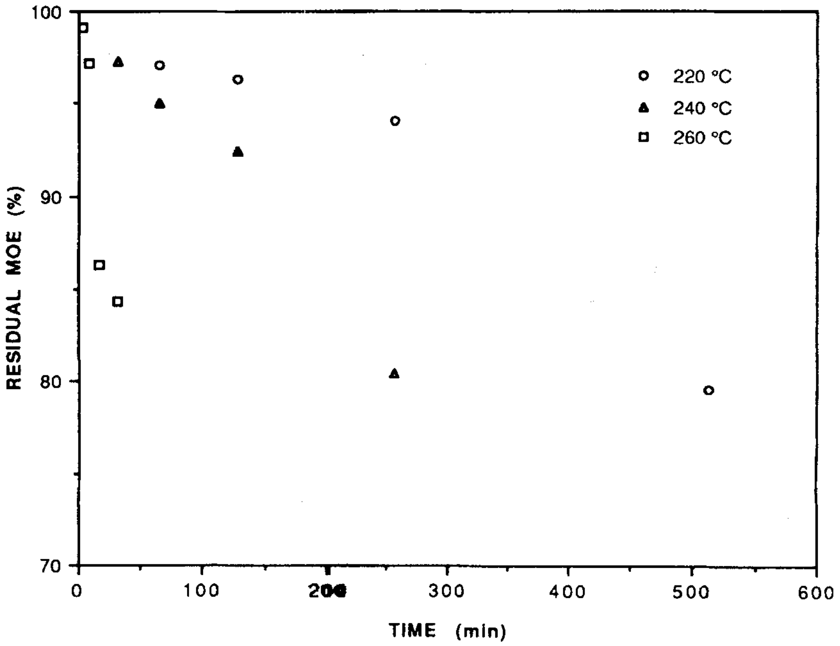

FIGURE 3 Relationship of wood residual bending modulus of elasticity (MOE) to exposure time.

TABLE V

Apparent Arrhenius parameters

Property	Residual value	"Best visual fit" Intercept	"Best visual fit" Slope	"Two first order" Intercept	"Two first order" Slope
Weight	0.95	-20.49	11154	-14.95	8548
	0.85	-13.64	8272	-11.37	7319
	0.75	-9.91	6656	-11.12	7319
Bending strength	0.95	-11.18	6331	-15.14	8518
	0.85	-12.35	7233	-14.64	8518
	0.75	-14.11	8364	-14.39	8518
	0.65	-12.55	7765	-11.74	7551
	0.55	-12.19	7653	-11.60	7551
Bending modulus	0.95	-13.55	7704	-16.42	9310
	0.85	-12.60	7517	-10.09	6596
	0.75	-11.40	7098	-9.84	6596
	0.65	-10.47	6861	-9.67	6596
Toughness	0.95	-20.74	10856	-17.58	9544
	0.85	-18.71	10311	-17.08	9544
	0.75	-16.16	9246	-14.98	8901
	0.65	-15.23	8927	-14.81	8901

a. For equations: $\log t_r = A + B/T$; t_r = time (min) to attain residual value.

RESULTS AND DISCUSSION

Data Analysis

Although it is possible to analyze the property values directly, the results are much less variable when expressed as a percentage of the initial (undegraded) property value, that is, as the "relative residual property" value. These values are listed in Tables I to IV, and we illustrate the general behavior at early times in Figures 2 and 3. The figures show data for only the shortest four points in order to clarify the behavior on the region of primary interest here.

Two procedures were examined for analyzing the relative residual properties, and we have termed these the "two first-order kinetic" and the "best visual fit" procedures. The two "first-order kinetic" procedures arose from the observation that when the data were plotted as first-order reactions, i.e., as log (relative residual property) versus time, the degradation appeared to follow two successive first-order processes. The linear regression slopes from the two straight lines were thus

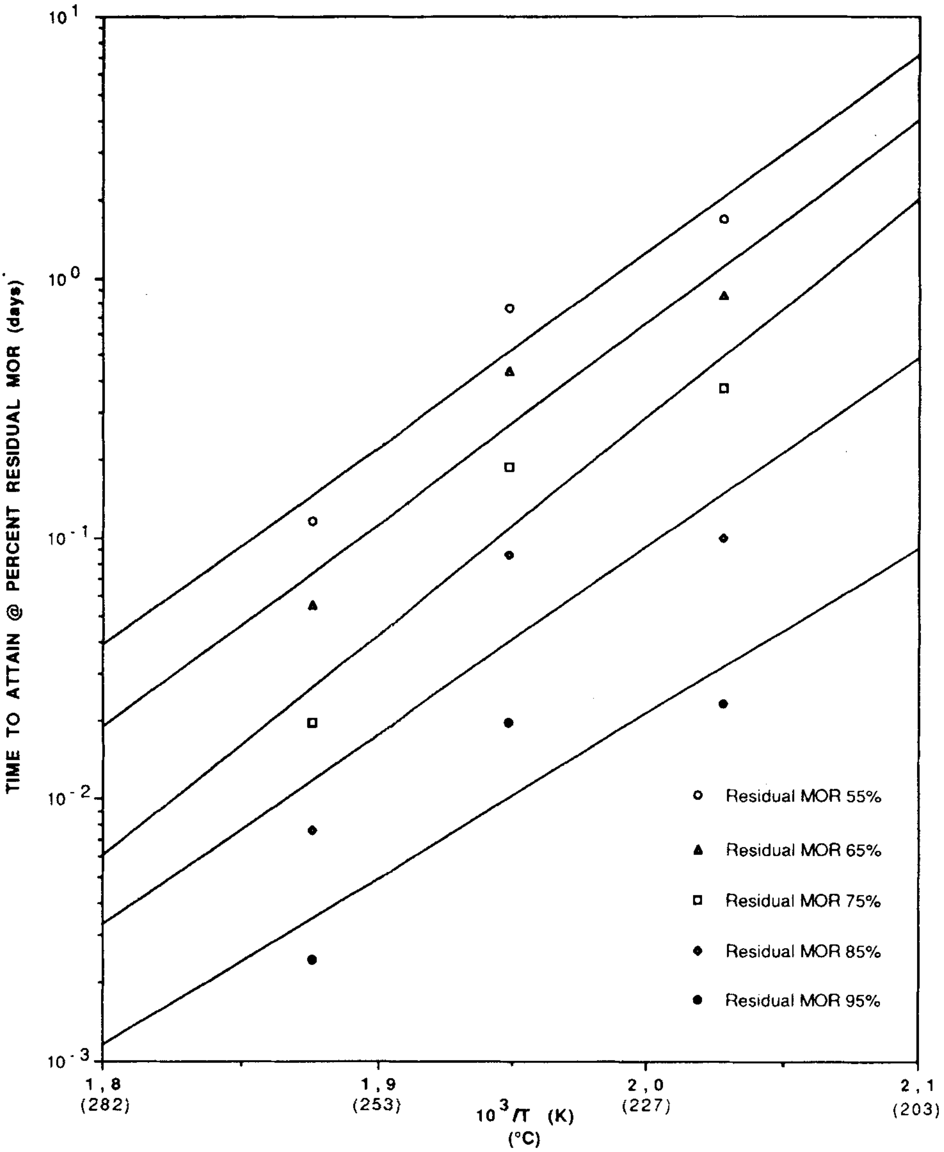

FIGURE 4 Relationship of time for wood specimens to attain various residual bending modulus of rupture (MOR) to reciprocal of absolute temperature.

treated as apparent first-order rate constants and their logarithms subsequently plotted against reciprocal temperature to obtain apparent Arrhenius parameters. The "best visual fit" curve procedure followed that of previous investigators.[4] Here, smooth curves were first drawn through the data in Figures 2 and 3, and the values of exposure time were read off the curves at relative residual property values of 0.95, 0.90, etc. Those times were considered as inverse measures of property degradation rates whose temperature dependence followed the Arrhenius equation.

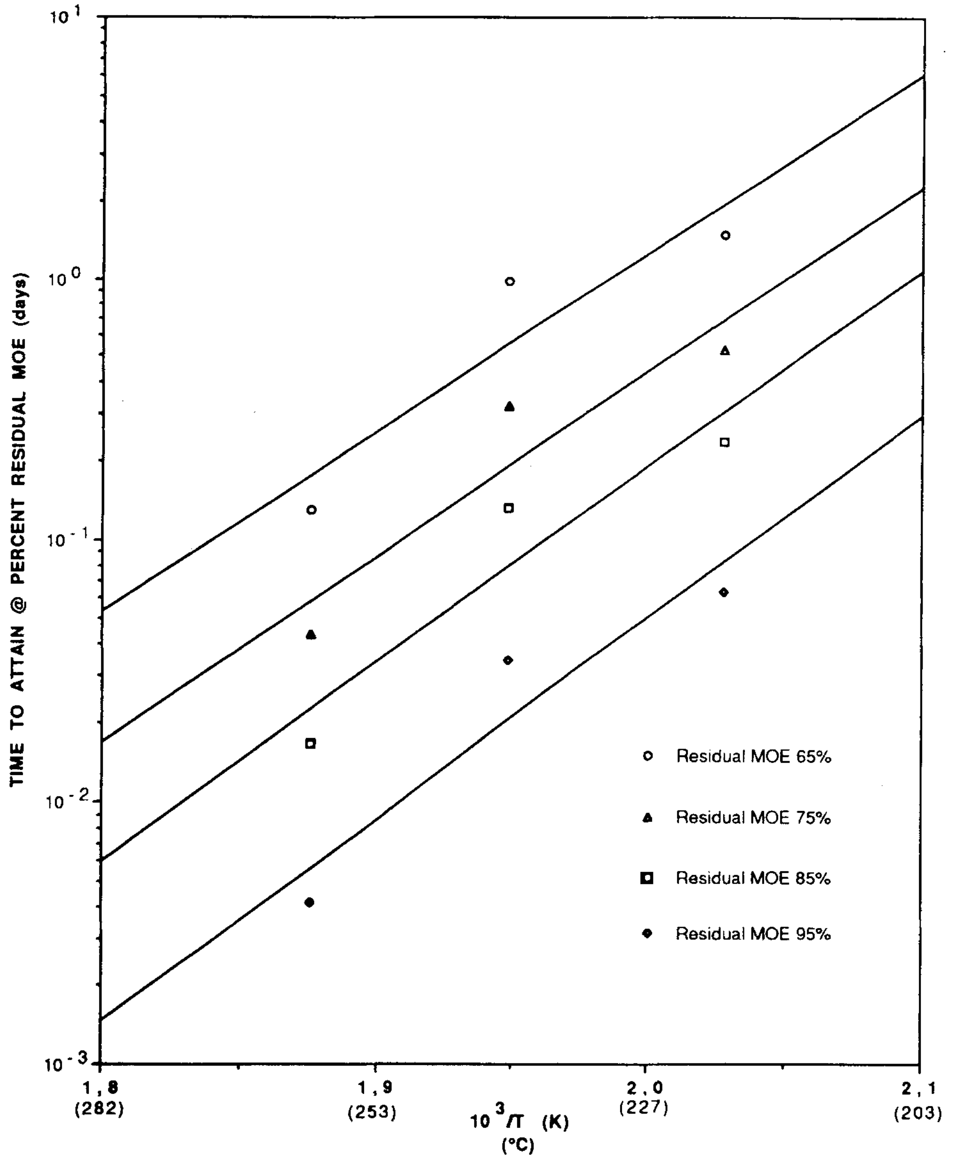

FIGURE 5 Relationship of time for wood specimens to attain various residual bending modulus of elasticity (MOE) to reciprocal of absolute temperature.

The apparent Arrhenius parameters from the two procedures were not always in agreement (Table V), and neither procedure produced equations that reproduced the observed degradation data generally better than the other. We attribute the disagreement between the two procedures to several factors: (1) the inadequacy of the "two first-order kinetic" assumption, (2) the difficulty in choosing which of the data points in a given curve belonged to each of the two supposed kinetic processes, and (3) data scatter due to the unavoidable absorp-

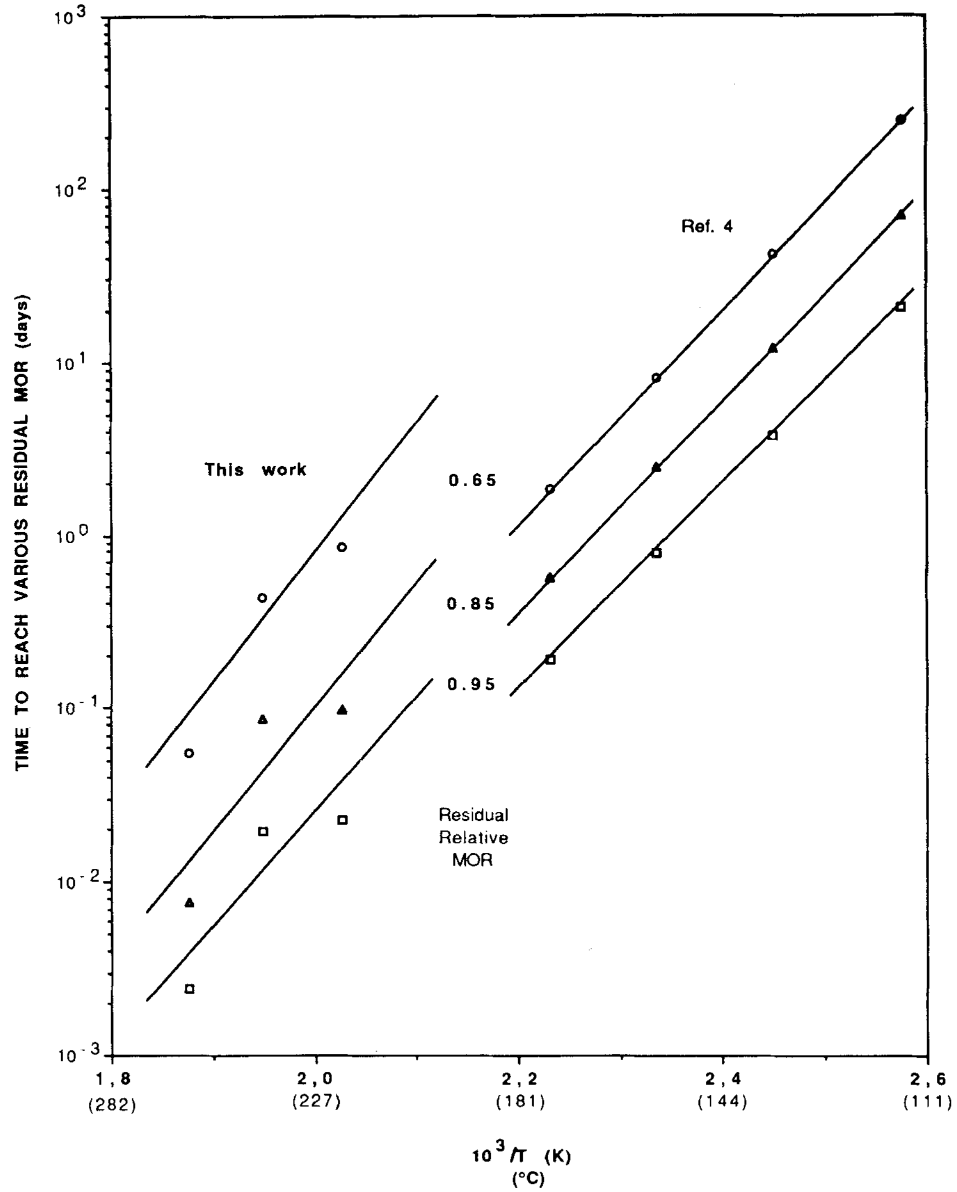

FIGURE 6 Comparison between previous work and the present work.

tion of small, variable quantities of moisture by oven-dried samples before insertion into the bath and by degraded samples before testing. Point (3) is supported by previous studies[3,5]; for example, Mitchell found the mean rate of strength loss to be four times as great for specimens with 12 percent moisture compared to oven-dry specimens,[5] and the significant effect of moisture content on wood mechanical properties is well known.

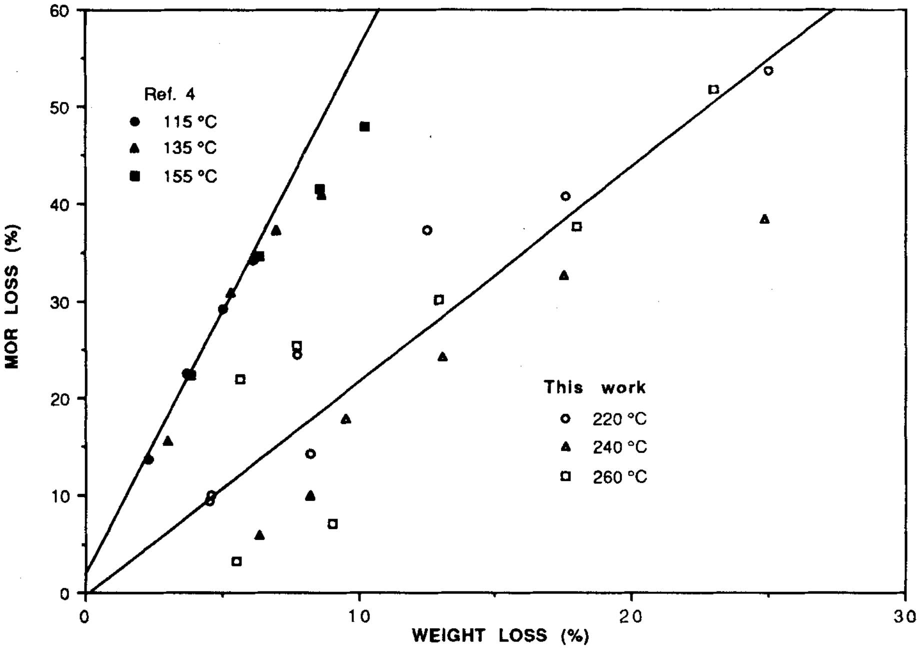

FIGURE 7 Relationship between MOR and weight losses.

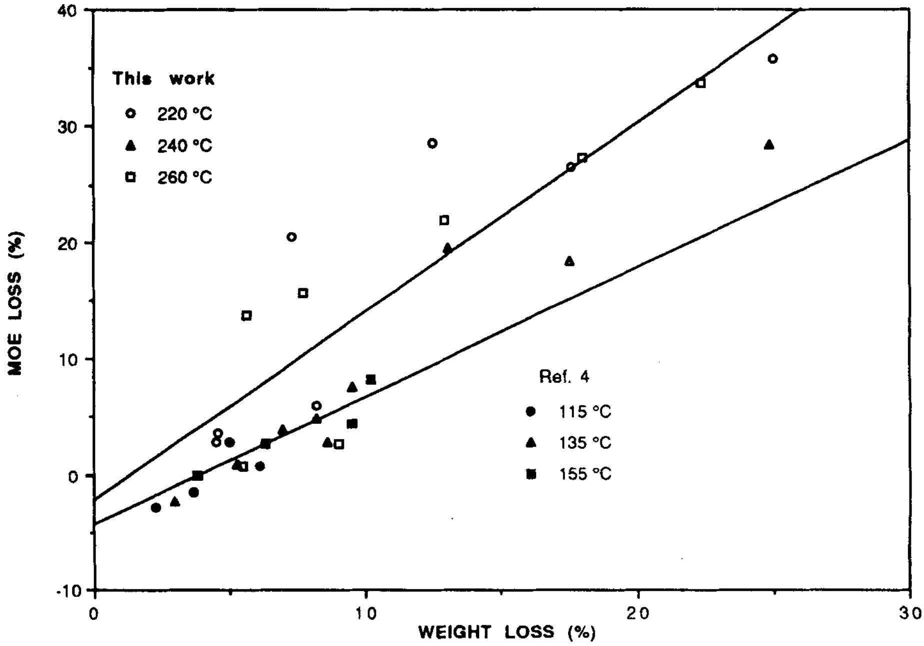

FIGURE 8 Relationship between MOE and weight losses.

Because the "best visual fit" procedure was more straightforward and followed previous work, we ultimately employed it for the data analysis. The resultant apparent Arrhenius plots are illustrated in Figures 4 and 5.

Comparison with Degradation at Lower Temperatures

Millet and Gerhards[4] studied the kinetics of wood degradation at lower temperatures (115°C to 175°C) than those used in this work (220°C to 260°C), and they supplied the Arrhenius parameters for bending strength (MOR), averaged over several species. Figure 6 compares the apparent Arrhenius plots from the two studies for selected values of relative residual MOR. In addition, Figures 7 and 8 show the correlations between the residual properties and residual weight loss data from both studies. We note the following:

In both studies the slopes of the apparent Arrhenius plots in Figure 6 (proportional to apparent activation energies) increased with greater extent of degradation. However, the slopes for the present work were higher than those for the lower temperature study.

Extrapolation of the apparent Arrhenius lines from our higher temperature study to the temperature range of the previous work led to much lower rates of degradation than were actually observed at the lower temperatures. For example, at 180°C and residual relative MOR's of 0.95, 0.85 and 0.65, our extrapolated times were, respectively, 3, 7, and 20 times longer than the extrapolated times from Millet and Gerhards.

Figure 7 shows that more than twice as much MOR was lost for a given weight loss in the previous work as was lost in our work. In contrast, it appears from Figure 8 that a given weight loss led to greater modulus of elasticity (MOE) loss in our work compared to the previous, lower-temperature study.

These differences indicate a distinct change in degradation mechanism between the two experiments. This could be due to different degradation mechanisms in the two temperature regions. It could also result from the fact that our experiments were conducted in a molten metal bath in the absence of oxygen whereas the earlier experiments were conducted in a forced-air oven. Stamm has reported that heating wood specimens in a molten metal bath caused smaller losses in strength than did heating in air.[10]

Property Losses During Melt Processing Times

Weight versus mechanical properties. As noted above, our values of weight loss and property loss were approximately linearly correlated, independently of the three temperatures (Figures 7 and 8). We observed similar results with the data of Millett and Gerhards,[4] although the correlations were different and their data scatter was less, as shown by the following linear regression equations and coefficients. The greater scatter of data about our regression lines perhaps resulted from the greater inherent difficulties in conducting these experiments at higher temperatures in the absence of oxygen and moisture. Existence of the correlations provides further evidence that within each study the degradation mechanism remained constant over the particular temperature range.

Present study:

$$\% \text{ MOR loss} = 0.74 + 2.00x \text{ (\% weight loss)}; r = 0.89$$

$$\% \text{ MOE loss} = -1.55 + 1.46x \text{ (\% weight loss)}; r = 0.85$$

$$\% \text{ impact loss} = 3.41 + 2.52x \text{ (\% weight loss)}; r = 0.94$$

Millet and Gerhards[4]:

$$\% \text{ MOR loss} = 5.94 + 4.30x \text{ (\% weight loss)}; r = 0.98$$

$$\% \text{ MOE loss} = -5.05 + 1.14x \text{ (\% weight loss)}; r = 0.92$$

Magnitude and significance of property losses. Using the apparent Arrhenius parameters derived from the "best visual fit" procedure (Table V), we calculated the times required to produce various relative property losses by exposure to temperatures between 180°C and 260°C (Table VI). At 220°C and above, toughness was the most sensitive to loss among the three mechanical properties, followed by bending strength and then bending modulus. For example, at 260°C toughness fell by 15 percent in 4 minutes, while 17 and 32 minutes were required for strength and modulus, respectively, to fall by 15 percent.

During injection molding, residence times can be 10 minutes or more. Although machine temperatures are not likely to be above 180°C to 200°C, significant shear heating may occur. For simplicity, we restrict ourselves in the following discussion to possible property changes in the extrusion process.

During extrusion of wood fiber-polypropylene composites the materials are subjected to barrel temperatures ranging from approximately 190°C to 250°C, but more commonly from about 190°C to perhaps 230°C. Due to shear heating, however, actual melt temperatures may be as high as 250°C to even 270°C. Residence times vary from perhaps 1 to 4 minutes. Considering the inherent uncertainties in the calculated times for property losses in Table VI, it seems probable that during extrusion we could expect the wood component to lose up to 15 percent of its toughness and 5 percent of its bending strength, but less than 5 percent of its bending stiffness.

What significance might these surprisingly small changes in wood properties have for the properties of the composites produced by the extrusion, assuming no changes in properties for the matrix polymer? We can estimate the effects for modulus by considering equations (1) and (2), which correspond to the upper and lower bounds, respectively, for the modulus of a two-component composite[11]:

$$E_c = v_f E_f + v_m E_m \tag{1}$$

$$1/E_c = v_f/E_f + v_m/E_m \tag{2}$$

where E is modulus, v is volume fraction, and the subscripts c, f, and m refer to composite, filler, and matrix, respectively. For a 50/50 weight ratio of the com-

TABLE VI

Calculated times for property losses

T (°C)	Percent loss	Weight	Bending strength	Bending modulus	Toughness
		Time for percent loss (min)			
180	5	13300	600	2800	3100
	15	41000	4100	9700	11100
	25	60000	22200	18400	17500
200	5	1200	160	540	300
	15	7000	900	1900	1200
	25	14300	3700	4000	2400
220	5	130	45	120	35
	15	1400	210	440	160
	25	3900	710	1000	390
240	5	20	14	30	5
	15	300	60	110	25
	25	1150	150	270	70
260	5	3	5	8	1
	15	75	20	30	4
	25	380	40	80	15

a. From "smoothed loss" parameters in Table 5.

ponents and using representative values of E for wood and polyolefins at ambient temperature, the above-noted 5 percent loss in wood modulus leads to a loss in composite modulus between 0.002 (Equation (2)) and 4.6 percent (Equation (1)).

To estimate the effect of wood strength loss on composite strength, σ_c we can use equations (3) and (4)[11]:

$$\sigma_c = Kv_f\sigma_f(1 - L_c/2L) + v_m\sigma_m^* \qquad (L > L_c) \tag{3}$$

$$\sigma_c = Kv_f\sigma_f L/2L_c + v_m\sigma_{my} \qquad (L < L_c) \tag{4}$$

where K is a fiber orientation factor ($=3/8$ for random planar), σ_m^* is the stress of the matrix at the failure strain of the fiber, σ_{my} is matrix yield strength, L is fiber length, and L_c is the critical fiber length. For a 5 percent loss in wood

TABLE VII

Some consequences of wood weight loss during melt processing 50/50 wood fiber/thermoplastic composite

Temperature	Weight loss in 4 min[a]	Volume of gas per cc of composite solids at 1 atm[b]		Gas pressure at 25 C if 0.5% voids in composite		Weight of gas per hr at 1000 kg per hr extruder throuhgput
		At exposure temperature	At 25 °C	No gas lost[c]	99% gas lost	
- °C-	- % -	------ cc ------		------- MPa -------		--- kg ---
160	0.006	0.07	0.04	0.8	0.008	0.06
180	0.03	0.37	0.24	5	0.05	0.3
200	0.15	1.9	1.2	24	0.24	1.5
220	0.40	5.4	3.3	67	0.67	4.0
240	1.5	21	12	240	2.4	15
260	4.5	66	37	750	7.5	45

[a] Estimated by linearizing weight loss vs time data and interpolating or extrapolating, as necessary. Values should be regarded as crude estimates, particularly at lower temperatures.

[b] Volume = [weight loss from column 2] × RT/30. Assumes average molecular weight of gas is 30.

[c] E.g., for extrusion at 200°C, the pressure for no gas lost = 1.2 mL × 0.1 MPa/0.005.

strength and random planar orientation, the calculated loss in composite strength is 3.7 percent if L is equal to one half of L_c or 4.1 percent if L is twice L_c.

Unfortunately, impact toughness is far too complicated a phenomenon to permit similar estimates of the effects of wood toughness loss. The 15 percent decrease in wood toughness noted above is qualitatively consistent with the reported decrease in toughness of wood flour-polypropylene composites after extrusion at 250°C.[2] However, the observed loss in polarity of the wood surface from that extrusion very likely contributed significantly to the loss in composite toughness due to its probable consequences for increased wood-polypropylene bonding.[2,9]

From a practical viewpoint these calculated decreases in composite modulus and strength are trivial, and this conclusion is consistent with the observed effects of extrusion temperature (190°C to 250°C) on these properties of wood flour-polypropylene composites.[2] However, the relatively small magnitude of the direct influence of wood degradation on composite properties that results from a single extrusion should not be taken as a green light to employ more extreme exposures during melt processing of these systems. Subjecting the mixtures to additional melt processing (extrusion, injection molding, etc.) for the purposes of further blending, of product manufacture, or of recycling would obviously multiply the effects of wood degradation and surface modification on the composite properties.

Some consequences of weight loss. Weight loss in these experiments results from wood thermolysis and production of volatiles. We noted earlier that if such volatiles were produced in sufficient quantity, they could lead to problems in air pollution during melt processing and to porous composites. To estimate the amounts of gases produced over a wide range of temperature, we extrapolated the raw weight loss data and calculated the quantities listed in Table VII. Although the values given in Table VII must be regarded as only crude estimates, they suffice to provide the rough guidelines we are interested in here. From the values of weight loss during 4 minutes of melt processing a 50/50 composite (column 2), we calculated the volumes of gas per cc of composite (column 3) by assuming a gas average molecular weight of 30. At 260°C, for example, the gas volume would be 66 times greater than the volume of the gas-free composite and at 200°C the volume would still be approximately twice that of the composite. Unless most of that gas can be removed by venting, the molten composite will be moderately to extremely foamed. If as much as 99 percent of the gas could be removed and it were desired to keep the porosity of the solidified composite below 0.5 percent, the melt would need to be solidified under pressure, and the internal gas pressure of the solidified composite might still be as high as 7.5 MPa after melt processing at 260°C. This level of internal pressure is 1/4 to 1/3 the usual measured tensile strength of these systems and could significantly alter the effective strength of large cross section articles. Finally, the last column of Table VII indicates the amounts of gases that might have to be scrubbed from the air at an extruder throughput of 1000 kg per hr—45 kg/hr at 260°C to 1.5 kg/hr at 200°C.

CONCLUSIONS

The major findings/conclusions from this study of wood degradation at the temperatures required for melt processing wood-plastic composites were:

1. Toughness and bending strength were decreased more by the degradative treatment than was bending modulus.
2. Losses in the bending strength and modulus of wood during a single extrusion step probably would have only a marginal effect on the strength and modulus of a wood-plastic composite. Although the wood toughness would be decreased more than the other bending properties, the influence of that toughness loss on the composite toughness is difficult to predict.
3. Additional melt processing steps, such as injection molding and/or processing involved in recycling, might well decrease the wood mechanical properties sufficiently to result in losses in composite mechanical properties that would be practically significant.
4. Changes in wood surface chemistry due to degradation may cause changes in the wood-plastic bonding that could have more influence than the losses in wood mechanical properties on composite behavior.
5. Gas evolution due to wood thermolysis could present serious problems for air pollution, composite density, and composite mechanical properties.

Finally, we re-emphasize two points. First, we have ignored probable changes in the properties of the matrix polymer and the added effects on composite behavior. Second, changes in the properties of both wood filler and polymer matrix will increase strongly with melt processing temperature, and it behooves processors of wood/plastic composites to maintain melt temperatures at a maximum of 200°C.

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