MODELLING DIRECT CURRENT RESISTIVITY OF WOOD POLYMER COMPOSITES

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(Received November 1988)

ABSTRACT

Resistivity of wood and treated wood decreased with increasing MC and increasing polymer loading. A rule of mixtures model using decreasing resistivities of polymer and wood with increase in MC agreed reasonably with experimental results.

Keywords: Wood polymer composite, WPC, resistivity, geometrical model, rule of mixtures model.

INTRODUCTION

The study of mechanical, physical, and chemical properties of wood-polymer composites (WPC) provides understanding of the combined effects of polymer and wood on the properties of the composite. One of these physical properties is resistance to the flow of direct current (DC) electricity. Resistance is affected by amounts of polymer and wood in the WPC and by the moisture content of the composite (Siau et al. 1968; Adur and Nigam 1978).

The objectives of this study were to investigate the electrical resistance of a WPC called WSTIWOOD™[2] at several moisture contents, to compare WSTIWOOD™ to other wood-polymer composites, and to investigate the applicability of two models in predicting resistivity at various loadings and moisture contents. WSTIWOOD™ is a recently developed WPC that is being tested for application in knife handles, gunstocks, billiard cues, swagger sticks, hockey sticks, and other high value products.

BACKGROUND

Hiruma (1915) and Hasselblatt (1926) found that there is a linear relationship between the logarithm of wood resistivity and moisture content, with the resistivity decreasing as moisture content increases. This was confirmed by experiments performed on wood by Stamm (1927) and by Curtis (1915) and Kujirai and Akahira (1923) for fibrous materials. Hasselblatt (1926) suggested that this relationship would continue up to the fiber saturation point (FSP) and the resis-

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[2] Trade Mark, owned by Wood Polymer Composite Processes Limited of Fredericton, New Brunswick. The WSTIWOOD formulation is proprietary information.

Wood and Fiber Science, 21(4), 1989, pp. 411–419

tance would not change appreciably above FSP. In the linear region between 8% and 18%, moisture content can be expressed as (Stamm 1929):

$$r = 10^{(c - A\,MC)} \quad [1]$$

where r is the resistivity, MC is the moisture content, and A and C are constants. As cited in Kollmann and Côté (1968), Stamm (1929) obtained values from experimental data of 0.2 and 11.5 for A and C, respectively, whereas Nussar (1938) obtained values of 0.32 for A and 13.25 for C. Polymer resistivity change with moisture content can also be described by Equation [1] (Saums and Pendleton 1973).

Weatherwax and Stamm (1945) investigated the effect of moisture on Impreg and Compreg samples. Impreg is a resin-treated wood and Compreg is a resin-treated compressed wood. Impreg and Compreg samples showed an increase in resistivity compared to untreated samples when resistivity was plotted against relative humidity. The samples were 10 times more resistive at 30% RH and 100 to 1,000 times more resistive at 90% RH than untreated wood.

Siau et al. (1968) obtained resistivity values for untreated wood and for wood treated with polystyrene (PS) or polymethyl methacrylate (PMMA). Their experiments showed that there was an increase in resistivity (under vacuum-dry condition) of 5.6% and 1.7% for Wood-PS and Wood-PMMA, respectively, compared to the untreated wood. The samples were then tested after reaching equilibrium at 40 C and 53% relative humidity, and showed an increase of 12.6% and 5.3% for Wood-PS and Wood-PMMA, respectively, compared to untreated wood. For each sample, there was a decrease in resistivity with increase in moisture content.

Adur and Nigam (1978) conducted a study of the electrical properties of radiation-cured wood-polymer composites using Indian timbers impregnated with either styrene co-acrylonitrile or styrene cross-linked unsaturated polyester. The authors found that an increase in polymer loading increased the resistivity both in the oven-dry and after 24-h water soaking. They noted a logarithmic decrease in resistivity as water content increased for treated and untreated wood.

All of the above-mentioned work on resistivity of wood-polymer composites was with monomers which swelled cell walls to some degree.

RESISTIVITY THEORY

Siau et al. (1968) developed a model for WPC resistivity based on wood cell geometry. This will be identified as Siau's model and is illustrated in Fig. 1. The model permits resistivity prediction based on resistivities of individual constituents of the wood-polymer composite, namely the cell-wall material and the polymer. The wood cell width is considered unit length, and a and b are the interior dimensions for the void space and cell cavity, respectively. The equation from the model developed by Siau et al. (1968) is:

$$r_c = (1 - b)r_w + \frac{(b - a)r_w r_p}{(1 - b)r_p + br_w} + \frac{ar_w r_p}{(1 - b)r_p + (b - a)r_w} \quad [2]$$

The terms r_c, r_p and r_w refer to the resistivity of the wood-polymer composite, the polymer, and the cell-wall material, respectively. The air space included in the lumen is considered to have infinite resistivity.

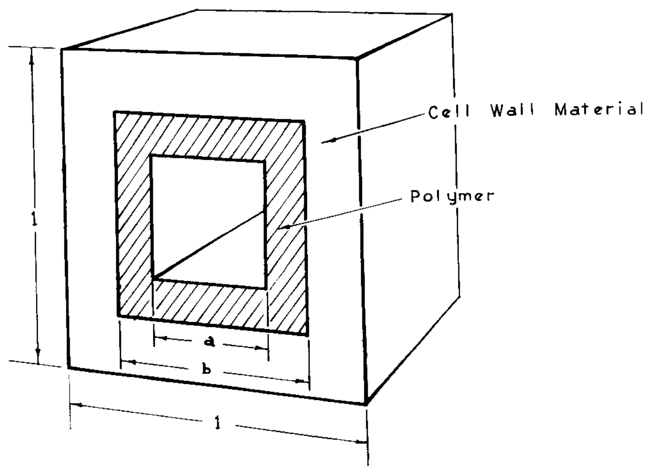

FIG. 1. Cell of a wood polymer composite after Siau et al. 1968.

Another model based upon the rule of mixtures can be used to predict the resistivity of WPC, knowing the properties and relative quantities of materials in the composite.

EXPERIMENTAL METHOD

Yellow birch (*Betula alleghaniensis* Britton) and sugar maple (*Acer saccharum* Marsh.) were impregnated with a vinyl-type monomer and heat was applied to polymerize the monomer in the wood. The treatment was performed by Wood Polymer Composite Processes Limited of Fredericton, New Brunswick. Samples containing a moderate loading and others containing a heavy loading were produced. One radial sample and one tangential sample from each composite was made for each loading of wood-polymer composite, totalling four moderate-load samples and four full-load samples. Radial and tangential untreated sugar maple and yellow birch samples were prepared, giving a total of four control samples. Table 1 gives treated and untreated weight and percent loading for each of the samples. The samples were cut to the size of the electrode surface, 5 cm × 5 cm, such that the current would flow in either radial or tangential direction.

The electrical resistance measurements of each specimen were made using a General Radio Co. Megohmmeter (Type 1862-A) capable of measuring to two tera-ohms (10^{12} ohms). The output voltage of the megohmmeter was 500 volts, which is necessary to overcome the Evershed effect (Davidson 1958). Lin (1965, 1967) reported that a voltage gradient above 200 volts per centimeter was needed to obtain constant measurements for large resistivities (10^{10} ohm-cm and above). The sample thickness for this study, 0.7 cm to 1.0 cm, provided a voltage gradient of approximately 500 volts per centimeter. To reduce possible fluctuations in the line voltage of the building, a constant voltage transformer (Powerstat Variable Autotransformer, The Superior Electric Co.) was used to provide a constant 115 volts to the ohmmeter. The electrodes were made of brass plates (5 cm × 5 cm) with soft lead faces that would conform to the specimen's surface (Stamm 1927).

Stamm (1927) found that electrode contact pressure can affect resistance read-

TABLE 1. *Percent loading of samples.*

Sample[a]	Untreated O.D. weight (grams)	Treated O.D. weight (grams)	Percent loading[b] (%)
MR-M	68.91	83.81	21.62
MT-M	85.95	106.05	23.39
YR-M	58.52	76.89	31.39
YT-M	56.32	74.92	33.03
MR-F	18.91	27.27	44.21
MT-F	60.59	87.36	44.18
YR-F	66.08	103.66	56.87
YT-F	37.89	58.39	54.10

[a] M and Y refer to sugar maple (M) and yellow birch (Y) samples; R and T refer to radial (R) or tangential (T) surface where the electrodes are placed; -M and -F refer to moderate-load (M) and full-load (F) samples.

[b] Percent Loading Calculation:

$$\frac{\text{Treated O.D. Weight} - \text{Untreated O.D. Weight}}{\text{Untreated O.D. Weight}} \times 100\%.$$

ings. Preliminary work established that 81 kPa gave low, reproducable contact resistance. Weights were used to obtain that pressure in this work. A 1.2-mm-thick piece of plastic was used to separate the bottom brass electrode from the metal stand. Resistance between each electrode and the rest of the equipment was infinite, indicating that there was no stray current.

The samples were placed in an oven at 105 C to obtain the oven-dry (OD) condition. The samples were then weighed to one tenth of a milligram to obtain the OD weight, and their dimensions were measured to one hundredth of a millimeter. The resistance was measured at the OD condition. They were placed over water in desiccators at room temperature (20 C), three per desiccator, and their weights were monitored. As the samples gained moisture, they were removed and placed into separate plastic bags for at least 12 h, allowing the samples to equilibrate. The samples were then removed from the bags and their resistance measured at 20 C. A detailed description of the procedure can be found in Hartley (1988).

RESULTS AND DISCUSSION

Resistivity of the composite versus its MC is plotted in Fig. 2 for untreated, moderate-load, and full-load samples. The maximum variation of all data at a given moisture content and polymer loading was 10% (Hartley 1988), and therefore data for each loading were combined to obtain trends for the diffferent polymer loadings. The small number of samples precluded drawing conclusions about species and grain direction, which may be worthwhile future research. Data could not be taken below seven on the logarithmic resistivity scale because of limitations of the megohmmeter. There was decrease in logarithmic resistivity with an increase in moisture content as expected. However, there was a decrease in resistivity at a given moisture content with increased polymer loading. This decrease is opposite to the expected increasing resistivity with higher polymer loading.

Considering Fig. 2, the control samples followed the same pattern as cited for wood in the literature (Stamm 1964). The behavior of the moderate-load samples appeared to be similar to the control samples, but shifted to the left. The loga-

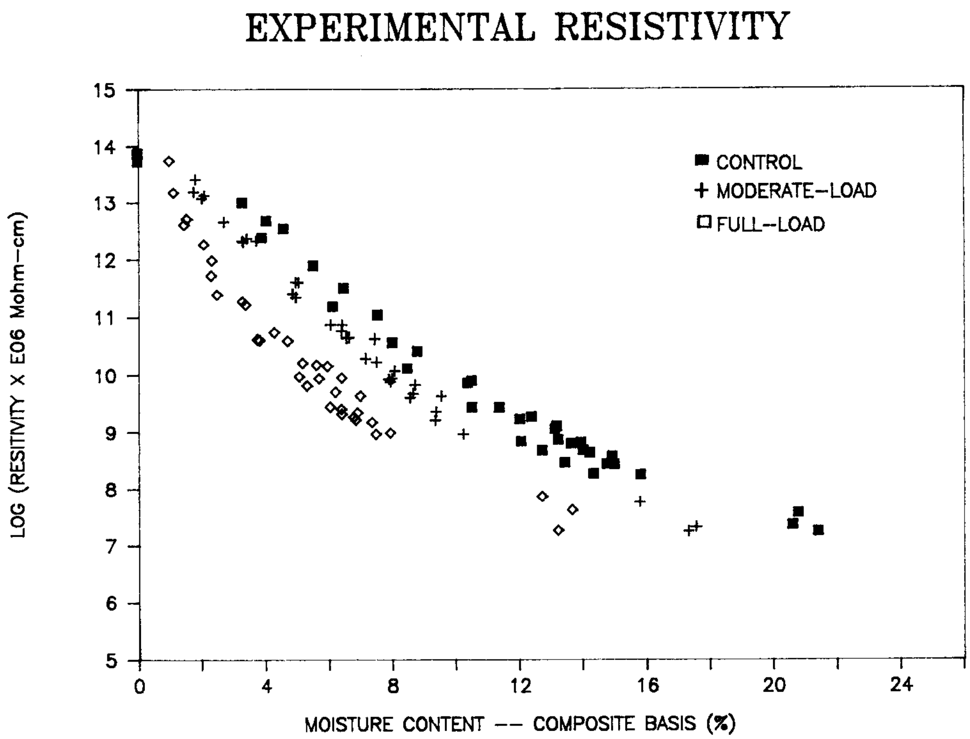

FIG. 2. Resistivity of untreated sugar maple and sugar maple with two levels of polymer loading versus moisture content.

rithmic resistivity of full-load samples versus moisture content (lower curve) decreased more steeply than the control and moderate-load samples, and there does not appear to be any linear region.

Comparing the moderate-load and full-load samples (Fig. 2) with the control samples showed, at a given moisture content, an overall decrease in resistivity with increasing polymer loading. For example, at 4% moisture content, the logarithmic resistivity values were 12.6, 12.0, and 10.75 for the control, moderate-load, and full-load samples, respectively.

THEORETICAL MODEL AND EXPERIMENTAL RESULTS

Siau's model was based on the assumption that the polymer did not enter the cell wall and it was not hygroscopic. The WSTIWOOD® polymer used in this study did not swell the wood and in its bulk state had negligible hygroscopicity, so that the conditions upon which the theory was based appear to hold in this case.

In Siau's model, as the volume of the polymer increased, the volume of the void space decreased. Siau et al. (1968) considered the cell cavity to be square having a cross sectional area of b^2, and the void volume having an area of a^2. The lumen size is assumed constant at the average for a particular species. Therefore, as the polymer loading increased, a was the only dimension that changed.

The resistivity term for wood that appears in Eq. [2], will decrease with an

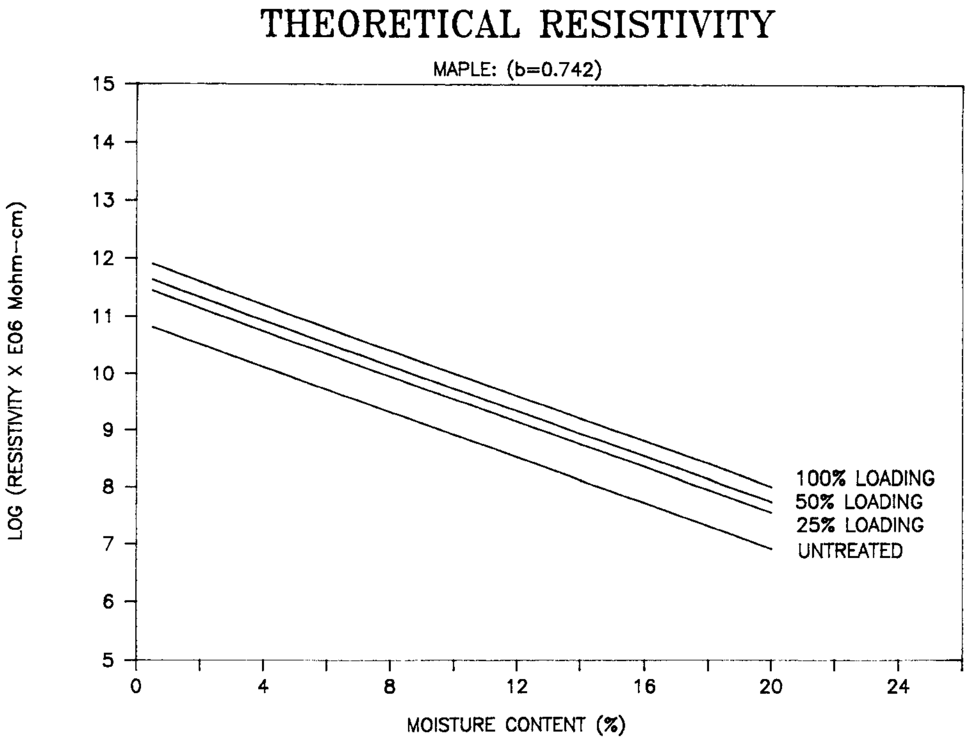

FIG. 3. Geometrical model predictions of change in resistivity with polymer loading and moisture content.

increase in moisture content according to Eq. [1]. Incorporating Eq. [1] into Eq. [2] and setting the constants A and C to be 0.2 and 11.5, respectively, (Stamm 1929), predicts how the resistivity of a wood-polymer composite will be influenced by moisture content. The resistivity of the polymer was assumed to be 10^{18} ohm-cm (Adur and Nigam 1978). With the above assumptions and conditions for sugar maple with b of 0.74 (Hartley 1988), the logarithmic values of resistivity were calculated using Eq. [2], at four polymer loadings (untreated, 25%, 50%, and 100%). The results are given in Fig. 3, which shows a decrease in resistivity with an increase in moisture content and an increase in resistivity with increased polymer loading. The experimental relationships between log resistivity and moisture content (Fig. 2) are similar to the theoretical (Fig. 3) in that resistivity decreases as MC increases. However, the two levels of polymer loading did not influence the resistivity of the composites as predicted by Siau's model.

The resistivity of the composite was found to be experimentally lower than wood (Fig. 2), possibly because the resistivity of the polymer changed with an increase in moisture content. The polymer type used in WSTIWOOD® has resistivity of 10^{13} ohm-cm (personal communication with the manufacturer); therefore, the constant C in Eq. [1] would be 13. There was not much difference between the slopes of the control curve and the two curves of the wood-polymer composite. This suggests that constant A for polymer in Eq. [1] may be similar to wood, about 0.3. Applying Eq. [1] and using these constants for the polymer,

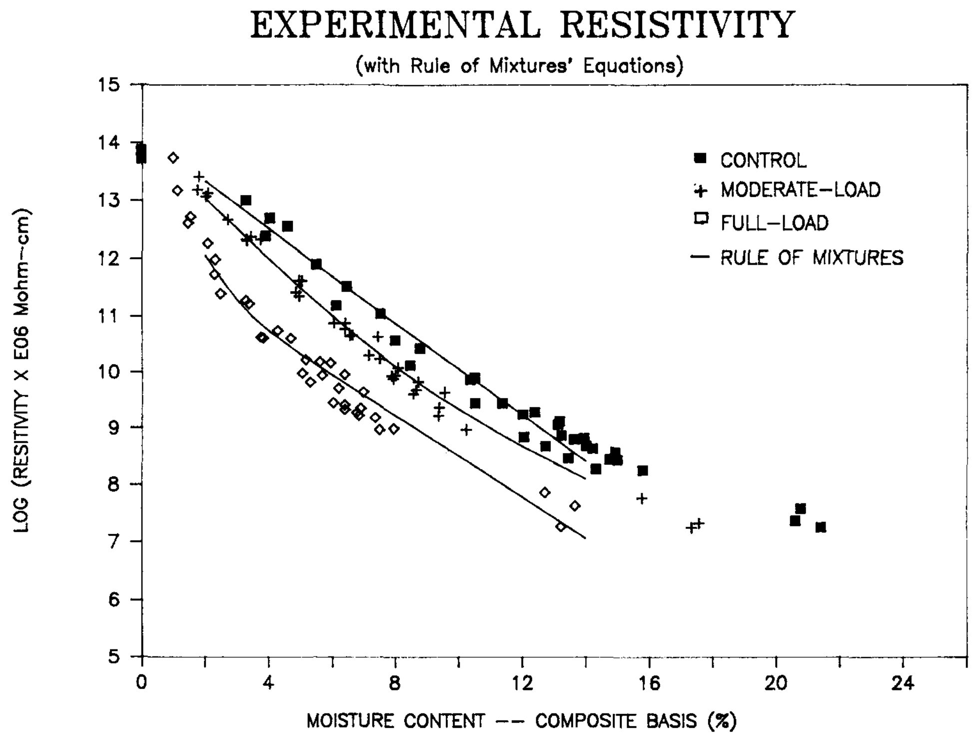

FIG. 4. Rule of mixtures WPC resistivity predictions with changes in polymer loading and moisture content superimposed on experimental results.

Siau's model still predicts an increase in composite resistivity with increased polymer loading. This was contrary to experimental results.

The resistivity of the composite alternatively can be predicted by the rule of mixtures:

$$r_C = V_w r_w + V_p r_p \qquad [3]$$

where V_w and V_p are volume fraction of wood and polymer, respectively, in the composite. To determine the goodness of fit of Eq. [3] to the experimental results, it was necessary to determine the constants A and C for r_w and r_p (Eq. [1]). They may not be the same as for bulk wood or polymer alone because of interactions between the two. For wood alone, the constants C and A were determined from the region between 2% and 14% MC in Fig. 2 to be 14.15 and 0.41, respectively. Then, several iterations were performed for the polymer to determine which constants seemed best to describe the material. Table 2 presents the best-fit constants for control, moderate-load, and full-load curves. Figure 4 was plotted using Eq. [1] to describe the change of resistivity of wood and polymer as a function of moisture content and the constants from Table 2. From Fig. 4, there seems to be good agreement between the rule of mixtures and the experimental results.

The agreement of the rule of mixtures with the experimental results supports the presupposition that wood and polymer were closely associated. Such close association should increase homogeneity and therefore reduce the importance of

TABLE 2. *Constants for rule of mixture equation.*

	Wood			Polymer		
	V_w	A	C	V_p	A	C
Control	1.0	0.41	14.15	—	—	—
Moderate-load	0.79	0.52	14.15	0.21	0.27	12.48
Full-load	0.58	0.99	14.15	0.42	0.36	12.48

macroscopic geometry on the composite bulk properties, such as electrical resistivity. It may also cause changes in properties of one or both components in the composite. In this case if the association decreased the resistivity of the polymer, the resistivity of the composite would decrease. This is one possible explanation of the observed decrease in composite resistivity with increased polymer loading.

CONCLUSIONS

The resistivity of WSTIWOOD® decreased as the moisture content increased. As the polymer loading was increased, the resistivity decreased at a given moisture content. This latter behavior is different from other wood-polymer composites found in the literature and may result from the changes in the polymer in association with the wood.

Siau's geometrical model, together with the resistivity of wood versus moisture content, did not agree well with the experimental data. A rule of mixtures model, which considers the volume fraction of wood and polymer, was shown to be in reasonable agreement.

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