

# Improvements of Fiberboard Properties Through Fiber Activation and Subsequent Copolymerization with Vinyl Monomer

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## SYNOPSIS

High-temperature refined thermomechanical pulp (MDF fiber) was dried, extracted with neutral organic solvent, and reacted with three types of electrophilic reagents (glycidyl methacrylate, maleic anhydride, and succinic anhydride). The adducts formed were further reacted in a hot press with a vinyl monomer in the presence of a free-radical initiator (benzoyl peroxide). Well-conformed boards were produced by the process. Modified boards showed significant improvement in thickness swelling as well as in strength properties compared to control phenol-formaldehyde boards. Glycidyl methacrylate modified/methyl methacrylate boards were the most stable toward the wet- and dry-exposure cycles, whereas succinic anhydride/methyl methacrylate boards showed the lowest water absorption.

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## INTRODUCTION

Various works have been done on the chemical modification of solid wood, and it has been reviewed extensively by Rowell<sup>1</sup> and Banks.<sup>2</sup> The success of the modification on solid wood, especially in improving the dimensional stability, enables the technique to be applied on wood composites. More recently, interest has developed in the use of a di- or polyfunctional reagent so that the product is left attached to the cell wall surface.<sup>3-5</sup> The attached functional groups are then used in secondary reactions. These secondary reactions could provide greater variations and choice of the desired properties, whether by copolymerization to give stable covalent bonding or to provide better physical bonding or entanglements. The purpose of this work was to chemically modify wood fiber so that the dimensional stability of the product would be that of the thermoplastics. This would allow the development of wood composites with the desired properties

incorporated by the thermoplastics and also so that they could be molded or extruded.

## MATERIALS AND METHODS

Thermomechanical pulp (TMP) fiber refined at high temperature for medium-density fiberboard (MDF) production was acquired from the Caber-board Co. in Stirling, Scotland. The fiber was extracted with a 1 : 1 : 4 part mixture of acetone: ethanol:toluene to remove organic soluble material. After extraction, the solvent was drained from the fiber and the residual solvent was removed by evaporation at ambient temperature and then finally by heating at 105°C in an oven for several hours. The fiber was then reacted at 90°C in batches of around 30 g with an approximately threefold excess (based on the estimated hydroxyl content of wood fiber<sup>6</sup>) of three reagents, glycidyl methacrylate (GMA), maleic anhydride (MAL), and succinic anhydride (SUC) (concentration of 0.72M) diluted 9 : 1 v : v with pyridine as the swelling agent/base catalyst. The reagents were selected to produce wood fiber adducts with and without active double bonds and

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to assess the reactivity of these adducts toward copolymerization with a free-radical active monomer (methyl methacrylate). To minimize the risk of free-radical reaction at the unsaturated ends of the molecules, the reactions were carried out in the dark and in an inert atmosphere (argon gas) and in the presence of a free-radical inhibitor (hydroquinone). Reaction time was adjusted to produce adducts with approximately 10, 15, and 20 wt % gain (WPG).

After reaction, the modified wood fiber was separated from the liquid reagents by filtration, washed with acetone, and refluxed with excess fresh acetone for about 2 h to ensure removal of the solvent, the unreacted reagent, and any homopolymers formed during the reaction.

The modified fiber samples were then treated with methyl methacrylate (MMA) monomer. The fibrous samples were hand-mixed into a "dough" with an equal mass of MMA containing about 6% benzoyl peroxide as the free-radical initiator. The doughs were laid as mats between aluminum foil-covered platens and heated under pressure at 70°C for about 1 h and then for a further 20 min at 120°C. The

edges of each board produced were cut off to dispose of the unhomogeneous sections.

For control boards, TMP fiber was extracted and dried the same way as for the modified board. The fiber was mixed with phenol-formaldehyde (PF) resin (in dry form) without any prior chemical modification. Two levels of PF resin loading were applied: 10% (PF10) and 55% (PF55) (% of the dry weight of the fibers). The amount of fibers used was varied depending on the amount of PF used in order to obtain the desired density of 0.7–0.8 g/cm<sup>3</sup>. The purpose of using 55% of PF was to compare the properties of the board with monomer-blended boards where the actual amount of the binder was about the same. Most conventional medium-density fiberboards (MDF) contain about 10% PF. Table I shows a summary of boards produced and the chemicals used in producing them.

Three rectangular samples of dimensions approximately 9.0 × 1.5 × 0.50 cm (length × width × thickness) were cut from each board to be used for the static bending test, water absorption, and thickness swelling. All test samples were of the same

**Table I** Types of Samples, Materials Used, and Fiber Loading

Types of Samples	Materials Used	Fiber Loading
Unmodified/PF 10%	Extracted fibers, phenol-formaldehyde	45 g of extracted fibers
Unmodified/PF 55%	Extracted fibers, phenol-formaldehyde	22.5 g of extracted fibers
Unmodified/MMA	Extracted fibers, MMA, benzoyl peroxide	32 g of extracted fibers
10 WPG GMA/MMA	10 WPG GMA-modified fibers, MMA, benzoyl peroxide	35.2 g of 10 WPG GMA-modified fibers
15 WPG GMA/MMA	15 WPG GMA-modified fibers, MMA, benzoyl peroxide	36.8 g of 15 WPG GMA-modified fibers
20 WPG GMA/MMA	20 WPG GMA-modified fibers, MMA, benzoyl peroxide	38.4 g of 20 WPG GMA-modified fibers
10 WPG MAL/MMA	10 WPG maleic anhydride-modified fibers, MMA, benzoyl peroxide	35.2 g of 10 WPG maleic anhydride-modified fibers
15 WPG MAL/MMA	15 WPG maleic anhydride-modified fibers, MMA, benzoyl peroxide	36.8 g of 15 WPG maleic anhydride-modified fibers
20 WPG MAL/MMA	20 WPG maleic anhydride-modified fibers, MMA, benzoyl peroxide	38.4 g of 20 WPG maleic anhydride-modified fibers
10 WPG SUC/MMA	10 WPG succinic anhydride-modified fibers, MMA, benzoyl peroxide	35.2 g of 10 WPG succinic anhydride-modified fibers
15 WPG SUC/MMA	15 WPG succinic anhydride-modified fibers, MMA, benzoyl peroxide	36.8 g of 15 WPG succinic anhydride-modified fibers
20 WPG SUC/MMA	20 WPG succinic anhydride-modified fibers, MMA, benzoyl peroxide	38.4 g of 20 WPG succinic anhydride-modified fibers

Initially, the wood fiber-to-MMA ratio was 1 : 1 weight to weight, i.e., in the case of unmodified/MMA board, 32 g of extracted fiber + 32 g of MMA. Since evaporation occurred during hot-pressing, only 17.6 g remained, which was about 55%. As for the chemically modified boards, evaporation of MMA occurred at the same extent as that of the unmodified/MMA board. For a 10 WPG chemically modified board, 32 g of extracted fiber was first reacted with a chemical until a loading of 10% was achieved or when 35.2 g of modified fiber was produced (weighed after washing and drying, see text).

density range (0.70–0.80 g/cm<sup>3</sup>). All test samples were conditioned at 20 ± 2°C and 65 ± 5% relative humidity until constant mass was achieved, before being tested.

Test samples were subjected to soak and dry cycles. The conditioned samples were weighed and the dimensions were measured, followed by mechanical testing to measure initial properties (MOE initial). The samples were then immersed in cold water for 24 h. On removal, the samples were allowed to drain for a few minutes, then surface-dried with absorbent paper, and the mass and dimensions of each sample were measured. The samples were then dried in an oven at 75°C overnight (approximately 16 h) and reconditioned (at 65% relative humidity and 20°C). After the samples were conditioned, the weight and dimensions were measured followed by mechanical testing to measure MOE (after cycle 1). These procedures were repeated through to the sixth cycle. Initial MOR was measured from the conditioned sample (without any wetting), whereas the final MOR was measured from conditioned samples after subjecting them to six cycles of soak and dry. For the thermal analysis, all board samples were ground and extracted with acetone under reflux for 8 h before being analyzed by thermal analysis to wash out homopolymers and free reagents that did not attach to the wood fiber.

The modulus of rupture (MOR) was measured as follows:

$$\text{MOR} = \frac{3 \times W \times L}{2 \times b \times d^2}$$

where  $W$  is the ultimate failure load;  $L$ , the span between centers of support;  $b$ , the mean width of the sample; and  $d$ , the mean thickness of the sample.

The modulus of elasticity (MOE) was measured as follows:

$$\text{MOE} = \frac{L^3 \times \Delta W}{4 \times b \times d^3 \times \Delta S}$$

where  $L$  is the span between the centers of supports;  $\Delta W$ , the increment in load;  $b$ , the mean width of the sample;  $d$ , the mean thickness; and  $\Delta S$ , the increment in deflection corresponding to  $W$ .

## RESULTS AND DISCUSSION

### Thickness Swelling and Water Absorption

Dimensional changes occurring during the water soak and dry cycles are presented in Table II. The data of Table II show an interesting effect: All types of modified/MMA-bonded boards show significantly lower irreversible swelling than that of the control PF boards (55 and 10% PF). The swelling of the modified boards ranges from –1.9 to 7.8%, whereas for the control board, PF 55% and PF 10%, the

**Table II Thickness Swelling**

Types of Sample	Reversible (%)	Irreversible (%)	Total (%)
Unmodified/PF 10%	12.3 (7.4)	153 (6.2)	165.3 (13.5)
Unmodified/PF 55%	11.9 (0.7)	51.4 (6.8)	63.3 (7.2)
Unmodified/MMA	9.1 (0.1)	7.3 (1.0)	16.4 (0.9)
10 WPG GMA/MMA	9.3 (2.9)	0.7 (4.3)	10.0 (2.1)
15 WPG GMA/MMA	10.8 (0.5)	–1.9 (1.6)	8.9 (1.4)
20 WPG GMA/MMA	8.0 (2.3)	0.5 (1.9)	8.5 (4.0)
10 WPG MAL/MMA	5.9 (0.4)	1.2 (0.6)	7.1 (0.1)
15 WPG MAL/MMA	5.5 (0.2)	2.1 (0.3)	7.6 (0.4)
20 WPG MAL/MMA	7.7 (1.5)	7.8 (0.6)	15.5 (2.1)
10 WPG SUC/MMA	3.5 (0.4)	2.1 (0.2)	5.6 (0.6)
15 WPG SUC/MMA	3.4 (0.2)	1.2 (0.4)	4.6 (0.6)
20 WPG SUC/MMA	3.1 (0.3)	1.6 (0.4)	4.7 (0.1)

All data are the average of 3. Nos. in parentheses are standard deviations. Reversible swelling =  $[(t_w - t_e)/t_0] \times 100$ . Irreversible swelling (springback) =  $[(t_e - t_0)/t_0] \times 100$ . Total swelling = reversible swelling + irreversible swelling.  $t_0$  = initial thickness of the sample (conditioned);  $t_w$  = thickness of wetted sample; and  $t_e$  = thickness of the sample after soaking and reconditioned at 65% relative humidity and 20°C.

swellings are about 51.4% and 153%, respectively. Even the unmodified/MMA-bonded boards show lower swelling than that of the control PF boards, of about 7.3%. Generally, all GMA-modified/MMA-bonded boards show lower irreversible swelling than that of other modified boards. Hence, it appears that either the process applied allows stress relief as the board is forming or the forces holding the fibers into the formed shape are sufficient to resist any stress-relaxation tendency. It is likely that both effects may play a part in dimensional stability. The process may introduce a degree of thermoplasticity into the fiber that will encourage stress relaxation during board formation, and the attached groups may allow bonding between the fiber and the matrix, whether through chemical bonding or just physical entanglements. Banks et al.<sup>7</sup> indicated that there was some chemical reactions between the terminal double bond of GMA with the MMA monomer, whereas MA showed lower activity compared to GMA toward reaction with MMA.

Modification with GMA does not improve the reversible swelling of the boards compared with the unmodified/MMA bonded boards and the controls. However, SUC-modified/MMA-bonded and MAL-modified/MMA-bonded boards show a significantly lower magnitude of swelling than that of the unmodified/MMA-bonded boards and the controls. Since the reversible swelling relates to the hygroscopicity of the sample,<sup>8</sup> this suggests that SUC- and MAL-modified samples are able to prevent water from entering the fibers more effectively than can the other samples. Several factors may be involved in explaining the differences in the relative effectiveness of the three treatments. GMA is a rather larger molecule (molecular weight of 142) than either MAL and SUC (molecular weights of 98 and 100, respectively). Hence, the cell wall preactivation during modification may be more effective with the two anhydrides. Being unsaturated, the MAL molecule is "stiffer" than is SUC, so that, although these two reagents are of quite similar molecular weight, cell wall preactivation by MAL may be somewhat inhibited by its increased stiffness. Alongside these steric factors, there are differences in functionality. The two anhydrides produce free carboxylic acid groups in the adduct, whereas the glycidyl reagent gives rise to free hydroxyl. All three differences (size, stiffness, and functionality) may play a role in determining the effectiveness in dimensional stability treatment.

The results of total swelling, which is the summation of irreversible and reversible swelling, show that all modified/MMA-bonded and unmodified/

MMA-bonded boards display significantly lower swelling than that of the control boards (PF 10% and 55%). Among the modified samples, succinic-modified boards show the lowest total swelling of all. This is contributed by their lower irreversible and reversible swelling. Though GMA-modified boards show virtually no permanent swelling, their higher total swelling is dominantly contributed by their poor reversible swelling.

Results of water absorption are presented in Table III. All modified/MMA-bonded and unmodified/MMA-bonded boards show significantly lower water absorptions compared with the control boards. The SUC-modified boards show the lowest absorption of all the modified boards. This probably is due to the same factors that explained the reversible swelling.

### Results of Modulus of Rupture (MOR) and Modulus of Elasticity (MOE)

MOR results are presented in Table IV. Each result is an average of 3, and the standard deviation ranges from 8 to 10% of the mean. All modified boards show a significant increase in MOR compared with the controls. The similar results (no significant difference statistically) of the initial MOR for the GMA-modified/MMA-bonded and SUC-modified/MMA-bonded boards suggest that the strength of the bonding formed in these two types of boards are comparable. Modification of wood strips with SUC caused greater degradation than that of the ones modified with GMA.<sup>9</sup> This greater degradation

**Table III Results of Water Absorption**

Types of Sample	Water Absorption (%)
Unmodified/PF 10%	255.3 (12.3)
Unmodified/PF 55%	92.9 (12.0)
Unmodified/MMA	28.9 (3.8)
10 WPG GMA/MMA	26.6 (3.4)
15 WPG GMA/MMA	38.8 (3.8)
20 WPG GMA/MMA	42.7 (4.2)
10 WPG MAL/MMA	29.9 (5.0)
15 WPG MAL/MMA	25.8 (2.6)
20 WPG MAL/MMA	39.9 (10.1)
10 WPG SUC/MMA	12.7 (1.7)
15 WPG SUC/MMA	16.5 (2.6)
20 WPG SUC/MMA	16.1 (2.4)

All data are the average of 3. Nos. in parentheses are standard deviations. Water absorption =  $[(M_2 - M_1)/M_1] \times 100$ .  $M_2$  = mass of the sample after immersion (g);  $M_1$  = mass of the sample before immersion (g).

**Table IV Results of MOR**

Types of Sample	Initial MOR (MOR × 10 <sup>2</sup> MPa)	Final MOR (MOR × 10 <sup>2</sup> MPa)	MOR Loss (%)
Unmodified/PF 10%	0.6 (0.1)	0.1 (0.01)	86.7
Unmodified/PF 55%	1.4 (0.3)	0.3 (0.1)	75.7
Unmodified/MMA	2.6 (0.2)	1.2 (0.1)	51.7
10 WPG GMA/MMA	4.0 (0.1)	2.5 (0.2)	37.1
15 WPG GMA/MMA	4.0 (0.2)	3.2 (0.04)	19.7
20 WPG GMA/MMA	3.3 (0.1)	2.8 (0.2)	18.4
10 WPG MAL/MMA	5.0 (0.3)	2.7 (0.6)	45.9
15 WPG MAL/MMA	3.4 (0.4)	1.8 (0.2)	46.9
20 WPG MAL/MMA	3.7 (0.3)	1.3 (0.5)	65.1
10 WPG SUC/MMA	4.0 (0.2)	2.6 (0.3)	34.8
15 WPG SUC/MMA	3.4 (0.1)	2.3 (0.2)	34.0
20 WPG SUC/MMA	3.7 (0.1)	2.4 (0.2)	33.1

All data are the average of 3. Nos. in parentheses are standard deviations.

probably results in the exposing of larger surfaces for the bonding of MMA within the fibers. These larger surfaces together with the incorporation of an  $-\text{O}-\text{C}-\text{C}-\text{C}-\text{C}(\text{OH})=\text{O}$  long alkyl chain seems to lead to effective bonding with the binder (PMMA) at all levels of modification. Since chemical interaction between the monomer (MMA) and the succinate ester group is unlikely (there is no unsaturated carbon for addition to occur),<sup>7</sup> the data suggest that physical bonding through effective wetting and hydrogen/van der Waal bonding is sufficient to give high initial strength at all three levels of modification.

The picture is different after soak/dry cycles. Here, the proportion of strength retained is generally greater for the boards prepared from GMA-modified fibers. These data are in line with the idea of covalent bonding between matrix and fiber. Banks et al.<sup>7</sup> showed indications that GMA reacted with MMA, through the double bond of the former. Where covalent bonds formed, it seems likely that they will show greater resistance to attack by water than will simple physical bonds. Hence, although physical bonding seems adequate to give satisfactory dry MOR, an element of covalent bonding appears to improve resistance to wet exposure. MAL-modified

**Table V Results of MOE**

Types of Samples	Initial MOE (MOR × 10 <sup>2</sup> MPa)	Final MOE (MOR × 10 <sup>2</sup> MPa)	MOE Loss (%)
Unmodified/PF 10%	32.3 (1.2)	0.4 (0.1)	98.8
Unmodified/PF 55%	65.7 (3.7)	9.4 (0.9)	85.7
Unmodified/MMA	218.0 (0.2)	69.2 (0.8)	68.3
10 WPG GMA/MMA	292.0 (0.2)	189.4 (16.9)	35.1
15 WPG GMA/MMA	240.0 (0.1)	224.2 (12.5)	7.1
20 WPG GMA/MMA	240.0 (0.1)	163.9 (9.2)	31.7
10 WPG MAL/MMA	296.0 (16.4)	211.0 (21.2)	28.7
15 WPG MAL/MMA	275.0 (5.0)	188.0 (6.7)	31.6
20 WPG MAL/MMA	266.0 (43.8)	92.3 (3.8)	65.3
10 WPG SUC/MMA	309.0 (14.7)	236.0 (7.6)	23.6
15 WPG SUC/MMA	311.0 (6.4)	241.0 (4.8)	22.5
20 WPG SUC/MMA	312.0 (10.7)	252.0 (12.4)	19.2

All data are the average of 3. Nos. in parentheses are standard deviations.

boards show greater loss in strength compared with GMA and SUC-modified boards. This might be as a result of greater permanent damage (irreversible swelling), especially at 20 WPG level, and also of the low activity of MAL toward MMA as indicated by Banks et al.,<sup>7</sup> where the extent of reaction between MAL-modified fiber and MMA seemed to be less compared with GMA-modified fiber.

Table V shows the result of the modulus of elasticity (MOE). Overall, SUC-modified/MMA-

bonded samples show significantly higher initial and final MOE in the dry state than that of MAL-modified/MMA samples at 15 and 20 WPG levels of modification except at 10 WPG. SUC-modified samples also exhibit a higher initial MOE than that of the GMA-modified samples at 15 and 20 WPG and higher final MOE at 10 and 20 WPG modification levels. Thus, this shows that the higher the level of modification the SUC/MMA system gives a stiffer product than that of the MAL/MMA, fol-

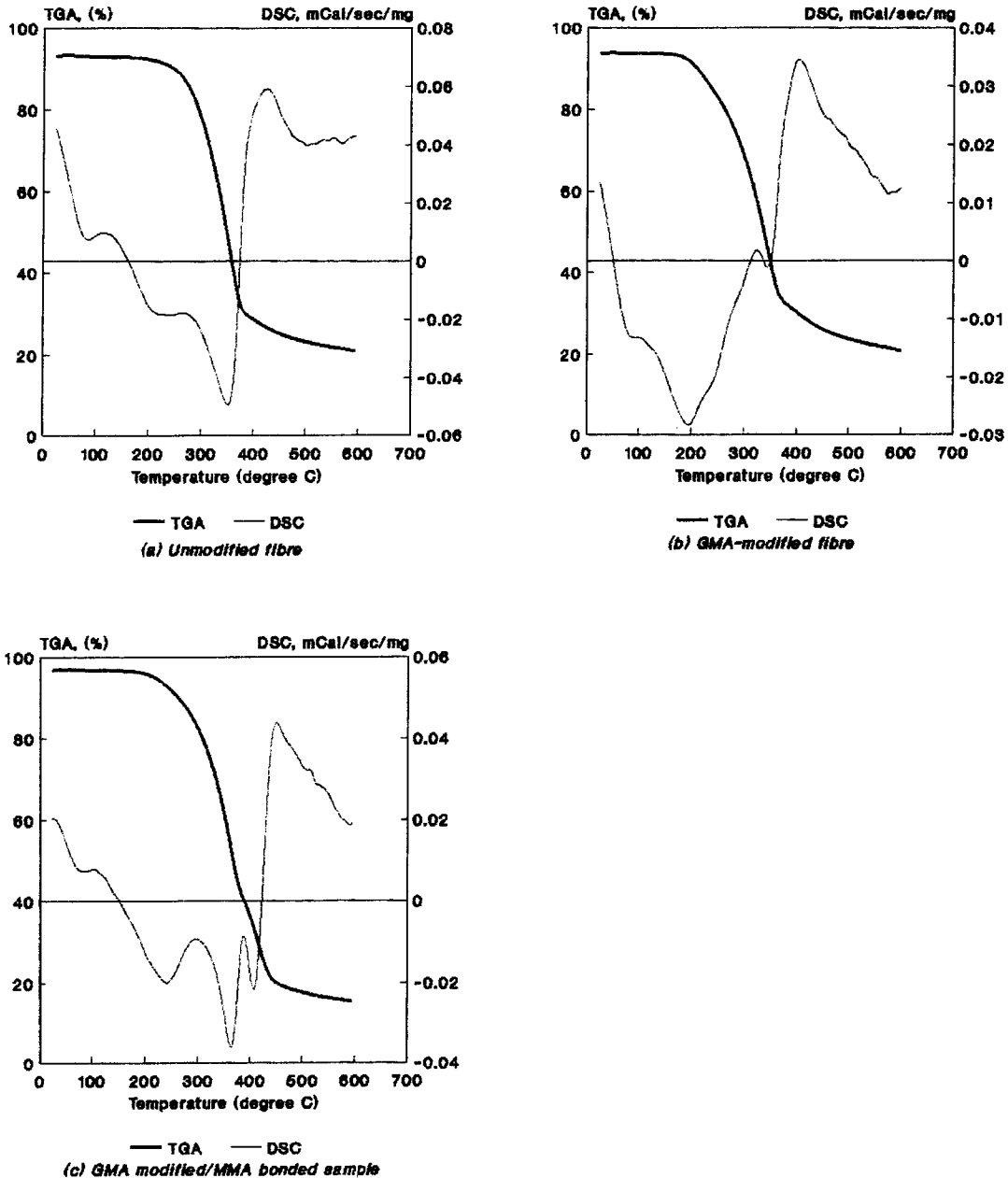
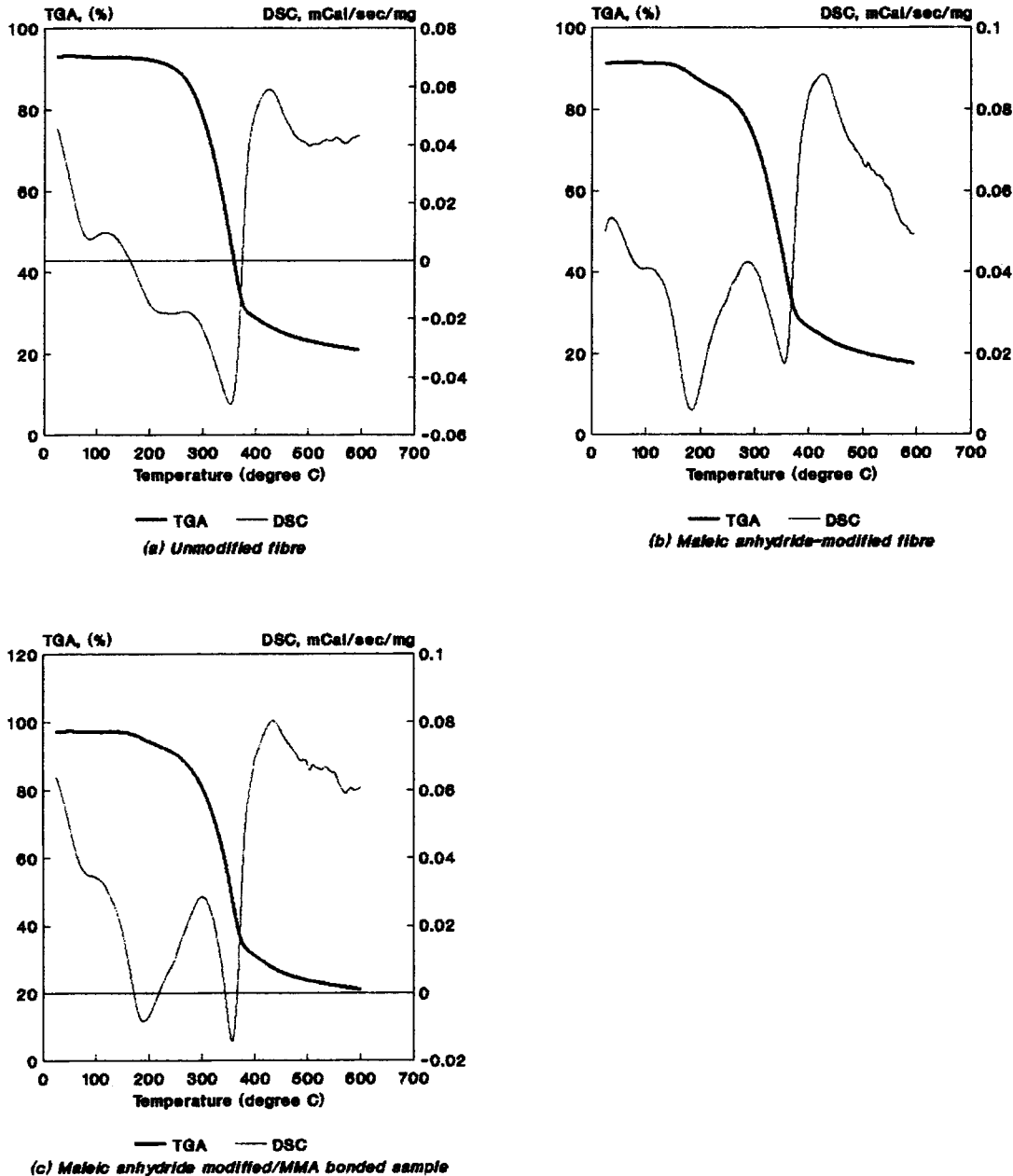


Figure 1 Thermal analysis results for unmodified fiber, GMA-modified fiber, and GMA-modified/MMA-bonded sample.

lowed by GMA/MMA systems. However, after undergoing six cycles of soaking and drying, the order changes and SUC-modified samples show the highest MOE followed by the GMA-modified samples and the MAL-modified samples consecutively. The data show that at 15 and 20 WPG levels of modification, the MAL-modified samples lose about 32 and 65% of their initial MOE in the dry state, respectively. These are significantly higher than those exhibited by GMA-modified samples with 7 and 32%

and by SUC-modified samples with 22 and 19%, at 15 and 20 WPG, respectively. Hence, the results indicate that the stiffness of MAL-modified samples is much affected by the cyclic process, as also shown in the MOR data. The greater reduction in stiffness of the MAL-modified samples might be related to the dimensional degradation as shown by their greater permanent damage (irreversible swelling or springback) as the result of soaking and drying cycles (see Thickness Swelling and Water Absorp-



**Figure 2** Thermal analysis results for unmodified fiber, MAL-modified fiber, and MAL-modified/MMA-bonded sample.

tion). It should be noted that 15 WPG GMA-modified samples show the smallest loss in MOE as compared to the rest of the samples. It is clearly shown that all modified and unmodified MMA-bonded samples show significantly higher initial and final MOE than those of the control PF boards.

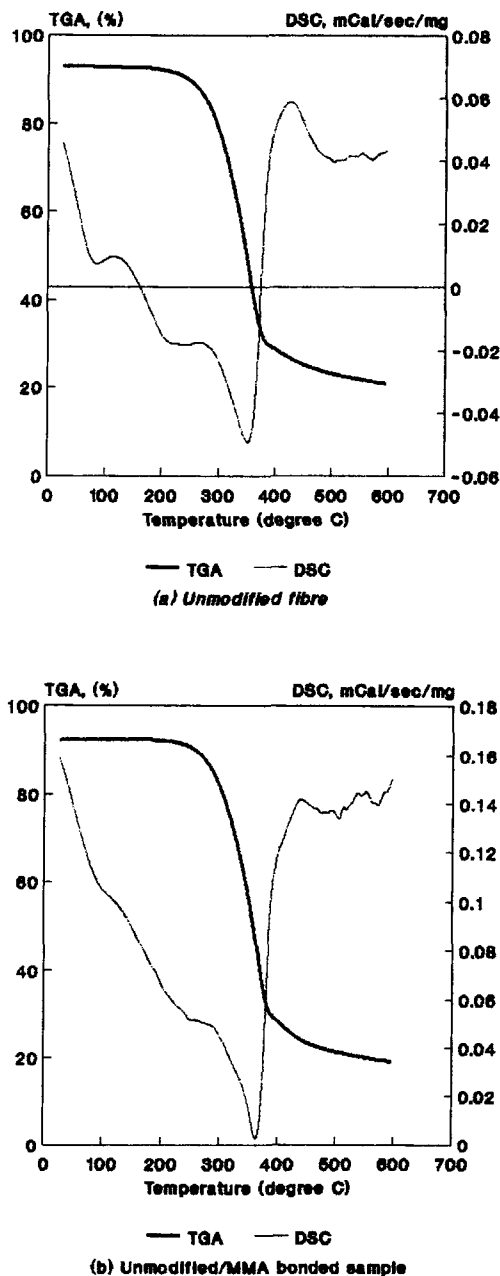
### Results of Thermal Analysis

Figure 1 show the thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) data for the unmodified fibers, GMA-modified fibers, and GMA-modified blended with MMA. From the thermograms, it can be seen that there are obvious changes in the heat input at around 200–300°C and some slight difference in weight decrease for the GMA-modified fiber [Fig. 1(b)] compared with the unmodified fiber [Fig. 1(a)]. In the case of GMA-modified/MMA-bonded sample [Fig. 1(c)], there are obvious changes in the heat input and weight decrease at around 200–300°C, 300–400°C, and 400–500°C, compared with the GMA-modified fiber [Fig. 1(b)]. These results suggest that there is chemical reaction of GMA with the fiber and reaction of the GMA-modified fiber with MMA (GMA-modified/MMA-bonded sample) that changes the thermal behavior of the fibers.<sup>9</sup> The data are consistent with those of the IR spectroscopy results as indicated by Banks et al.,<sup>7</sup> which indicate that GMA (which is attached to wood fiber) reacts with MMA. Collectively, these data suggest strongly that interaction of the wood fiber with glycidyl methacrylate leads to the formation of a chemically modified polymer system and that this modified fiber is chemically linked to the matrix substance (PMMA).

It is obvious from the TGA data that there are differences between the corresponding curves for the MAL-modified fibers [Fig. 2(b)] and that of the unmodified fiber [Fig. 2(a)], at around 200°C. Similarly, the DSC curve of MAL-modified fiber is relatively different in the heat input around 200°C compared to the unmodified fiber, suggesting that MAL reacts with the fiber. The corresponding TGA and DSC curves for the MAL-modified fiber [Fig. 2(b)] and MAL-modified/MMA-bonded sample [Fig. 2(c)] are found to be relatively the same. As indicated by Banks et al.<sup>7</sup> in their FTIR study, the extent of the reaction of the MAL-reacted fiber and MMA seemed to be less than the GMA-reacted fiber and MMA. Since the MAL/MMA sample was exhaustively washed with solvent to remove homopolymers and excess chemicals, the results indicate that, after washing, most of the PMMA homopolymer formed has been washed away. Thus, there

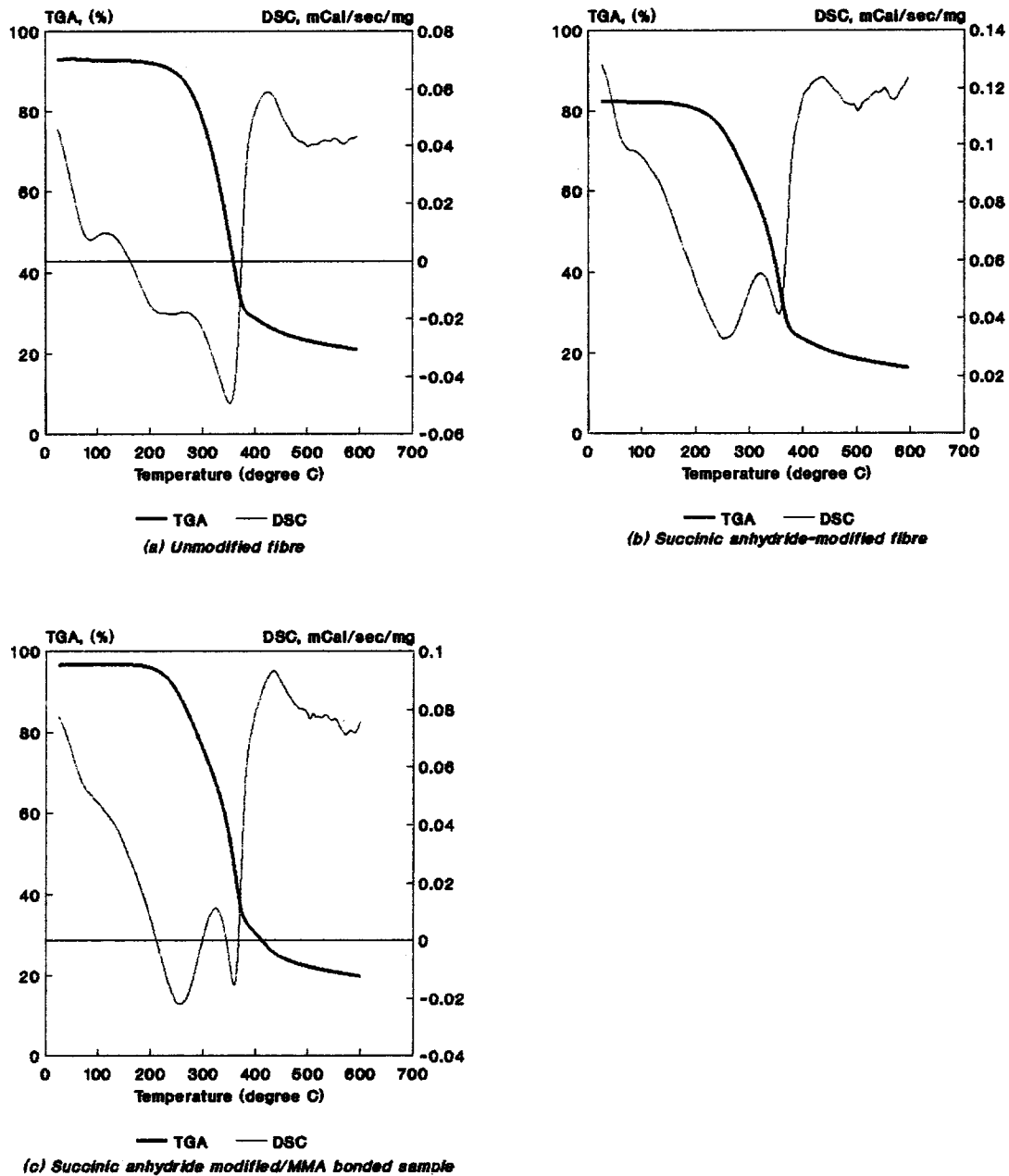
may be a limited chemical reaction between PMMA and the modified and unmodified regions of the fiber (Fig. 3) or just physical interlocking between PMMA and the modified fibers. This could well mean that in the MAL/MMA-bonded boards the physical interlocking predominated the bondings.

The behavior of the SUC-modified fiber [Fig. 4(b)] is also found to be different from that of the unmodified fiber [Fig. 4(a)] at around 200–300°C. This probably corresponds to the thermal degra-



**Figure 3** Thermal analysis results for unmodified fiber and unmodified/MMA-bonded sample.





**Figure 4** Thermal analysis results for unmodified fiber, SUC-modified fiber, and SUC-modified/MMA-bonded sample.

dation of SUC firmly attached to the fiber. The TGA and DSC curves of the SUC-modified fibers [Fig. 4(b)] and SUC/MMA-bonded sample [Fig. 4(c)] are found to be relatively the same. As shown by the IR results,<sup>7</sup> these data suggest that there may be a limited chemical reaction between PMMA and the unmodified region of the fiber (Fig. 3) or just a physical interlocking between PMMA and the modified fibers. This also means, as suggested for the MAL-modified/MMA-bonded samples that the

properties of the SUC-modified/MMA boards are contributed to significantly by the physical interlocking of the synthetic homopolymer (PMMA) and the natural cell wall polymers.

## CONCLUSIONS

The work demonstrates that chemical modification of wood fibers followed by polymerization of vinyl

monomer improve considerably the physical and mechanical properties of the boards compared to the control PF boards. Samples that involve covalent bonding show greater stability toward repeated wet and dry conditions compared to those involve predominantly by physical interlocking or entanglements. With these principles, a simpler process that could provide the same nature of chemical bondings should be a subject of further study.

## ABBREVIATIONS

- Unmodified/PF 10% or UN/PF 10  
Control boards made from oven-dried unmodified fibers blended with 10% PF (% of the dry weight of the fibers)
- Unmodified/PF 55% or UN/PF 55%  
Control boards made from oven-dried unmodified fibers blended with 55% PF (% of the dry weight of the fibers)
- Unmodified/MMA or UN/MMA  
Boards made from unmodified fibers blended with MMA
- GMA-modified/MMA or GMA/MMA  
Boards made from GMA modified fibers (10, 15, and 20 WPG) blended or bonded with MMA
- MAL-modified/MMA or MAL-MMA  
Boards made from maleic anhydride modified

fibers (10, 15, and 20 WPG) blended or bonded with MMA

- SUC-modified/MMA or SUC/MMA  
Boards made from succinic anhydride modified fibers (10, 15, and 20 WPG) blended or bonded with MMA.

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