MOISTURE SORPTION AND SWELLING OF WOOD–POLYMER COMPOSITES

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ABSTRACT

Changing moisture content in wood can result in dimensional changes that create problems in some circumstances. The swelling of wood by moisture is not reduced by treating the wood with monomers, resins, or polymers unless these substances penetrate the cell walls. In this study maple, red oak, and southern pine specimens were saturated with acrylic and methacrylic monomers in an effort to penetrate the cell walls with monomers. The volumes of the saturated specimens were measured after each of three soak cycles. The swelling resulting from soaking the specimens in monomers was measured. Soaking at 105 C in certain monomers resulted in a range of swelling from 2 to 21% depending on the specific monomer and species of wood. Other monomers generally did not penetrate the cell walls sufficiently to result in swelling of the wood. After the final soak period, a free radical initiator was added and the monomers were polymerized in the wood to make wood–polymer composites. The moisture content and volumetric swelling of the wood–polymer composites at 90% relative humidity were measured. The wood–polymer composites were swelled by moisture at a slower rate than was just wood, but many wood–polymer composites eventually swelled as much as did untreated wood. Some polymers were hygroscopic, which increased the moisture content and volumetric swelling of the wood–polymer composite specimens at 90% relative humidity.

Keywords: Monomer, polymer, wood–polymer composites, maple, red oak, southern pine, dimensional stability, swelling, acrylate, methacrylate.

INTRODUCTION

Wood is a hygroscopic material that can sorb water as a liquid or as vapor from its surroundings. The sorbed moisture can exist in wood as liquid or vapor in all cavities and as water bound chemically within cell walls. Moisture in the cell walls affects all wood properties, but moisture in voids affects only weight. The amount of moisture held in cell walls varies according to the particular piece of wood and is a function of both the relative humidity and temperature of the surrounding air. The fiber saturation point is the point at which cell walls are completely saturated and the cell cavities are empty. Wood is subject to dimensional changes when its moisture content fluctuates below the fiber saturation point. These dimensional changes are anisotropic, with the greatest change in the tangential direction and the least change in the longitudinal direction. Dimensional changes in wood caused by changing moisture content can result in shape changes, checking, warping, honeycombing, collapse, and raised grain on the surface. The moisture in wood also affects decay resistance, gluing, finishing, and mechanical, thermal, and acoustic properties. Research efforts have resulted in several methods to improve the dimensional stability of wood, the most effective being the reaction of wood with specific chemicals such as acetic anhydride (Rowell 1982;

Stamm and Tarkow 1947; Tarkow et al. 1946), which bulk the cell wall or cross-link with it. These reactions also decrease the hygroscopicity of wood by decreasing the number of hydroxyl groups. Another method to improve dimensional stability is to use nonbonded resins that reside in and bulk the cell walls (Meyer 1984; Stamm and Seborg 1936, 1938).

One way wood–polymer composites (WPC) are made is by saturating wood with monomers followed by *in situ* polymerization of the monomers. Many monomers used to make WPC do not penetrate the cell walls and do not completely fill the voids after polymerization, leaving voids in the wood because of shrinkage of the polymer. Solvents can be used to help swell wood and aid the penetration of monomers into cell walls, resulting in moderately high dimensional stability. Methanol has been used to swell the wood; after methanol treatment, the wood is then heated, evaporating all but a minimum amount of solvent in the wood prior to impregnation with methyl methacrylate (MMA) (Furuya and Taniguchi 1972). Dimensional stability of 70% has been determined by vapor saturation. Acetone, pyridine, dimethyl-formamide (DMF), dimethyl sulfoxide, ethylenediamine, and diethylamine have been used as preswelling agents displaced by either MMA, hydroxyethyl methacrylate (HEMA), or glycidyl methacrylate (GMA) followed by *in situ* polymerization to give improved dimensional stability of wood (Kawakami and Taneda 1977). The use of monomers such as HEMA and GMA in combination with MMA has been shown to improve the dimensional stability of WPC compared with WPC made using only MMA. The degree of cross-linking between the wood and the copolymer contributed to the dimensional stability of the WPC (Fujimura et al. 1990). The use of the polar monomers HEMA and GMA improved dimensional stability of the WPC and improved adhesion of polymer to the inner surface of the cell wall (Kawakami et al. 1981).

The objectives of this research were to (1) identify monomers that swell and penetrate the cell wall without the use of solvents, (2) measure the extent of swelling as a result of soaking in individual monomers, (3) polymerize the monomer in the wood, and (4) measure the volumetric swelling and moisture content of the WPC at 90% relative humidity (RH).

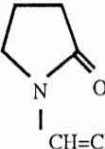## MATERIALS AND METHODS

Monomers

Monomers selected for this study were acrylates and methacrylates, which can be polymerized using the thermal polymerization initiator 2,2'-azobis-(2-ethylbutyronitrile). All monomers were used as received without further purification or removal of inhibitors added by the manufacturers. Monomers used and their structures are listed in Table 1. For the purpose of this study, we classified monomers into two categories based on whether the monomers could swell wood. The first group of monomers, those that cannot swell wood because they have a large molecular structure or because they do not strongly hydrogen bond, include polyethylene glycol (600) dimethacrylate (PEG600DMA), and polyethylene glycol (400) diacrylate (PEG400DA), which have a larger molecular structure, and hexanediol diacrylate (HDDA), hexanediol dimethacrylate (HDDMA), and MMA, which do not strongly hydrogen-bond. The second group of monomers, those that have low molecular weight and those that can participate in hydrogen bonding so they can penetrate cell walls and cause swelling of the wood, include 1-vinyl 2-pyrrolidinone (VP), HEA, HEMA, hydroxypropyl acrylate (HPA), hydroxypropyl methacrylate (HPMA), GMA, and polyethyleneglycol monomethacrylate (PEGMA).

Wood specimens

Maple (*Acer saccharum*), northern red oak (*Quercus rubra*), and southern pine (*Pinus* sp.) woods were used. The wood was cut into specimens 2.5 by 2.5 by 0.6 cm (radial by tangential by longitudinal). Growth rings were oriented parallel to one side of each specimen to minimize distortion during shrinking and swelling.

TABLE 1. *Monomers used to prepare specimens.*

Monomer	Name	Structure	Molecular weight
PEG600DMA	Polyethylene glycol (600) di-methacrylate	$H_2C=C(CH_3)CO_2(CH_2CH_2O)_{12}CH_2CH_2OCC(CH_3)=CH_2$	726
PEG400DA	Polyethylene glycol (400) di-acrylate	$H_2C=CHCO_2(CH_2CH_2O)_7CH_2CH_2OCCH=CH_2$	478
PEGMA	Polyethylene glycol mono-methacrylate	$H_2C=C(CH_3)CO_2(CH_2O)_6H$	366
HDDMA	1,6 hexanediol dimethyacrylate	$H_2C=C(CH_3)CO_2(CH_2)_6O_2CC(CH_3)=CH_2$	254
HDDA	1,6 hexanediol diacrylate	$H_2C=CHCO_2(CH_2)_6O_2CCH=CH_2$	226
HPMA	Hydroxypropyl methacrylate	$H_2C=C(CH_3)CO_2CH_2CH(OH)CH_3$	144
GMA	Glycidyl methacrylate	$H_2C=C(CH_3)CO_2CH_2\overset{O}{\overset{\displaystyle\wedge}{CH\text{-}CH_2}}$	142
HEMA	Hydroxyethyl methacrylate	$H_2C=C(CH_3)CO_2CH_2CH_2OH$	130
HPA	Hydroxyepropyl acrylate	$H_2C=CHCO_2CH_2CH(OH)CH_3$	130
HEA	Hydroxyethyl acrylate	$H_2C=CHCO_2CH_2CH_2OH$	116
VP	1-vinyl 2-pyrrolidinone	[pyrrolidinone ring structure with N–CH=CH$_2$ and C=O]	111
MMA	Methyl methacrylate	$H_2C=C(CH_3)CO_2CH_3$	100

The specimens were oven-dried overnight at 105 C, then measured in the radial, tangential, and longitudinal directions, and weighed. The oven-dry volumes were then calculated.

Treatment of specimens with monomers

Duplicate specimens of each species were placed in a container within a vacuum chamber. The chamber and specimens were degassed under reduced pressure (0.7 to 1.3 kPa) for 30 min, and the vacuum maintained as sufficient monomer was delivered into the container to cover the specimens. The vacuum was maintained for an additional 15 min to remove air from the monomer. The vacuum was then released and the chamber returned to atmospheric conditions. The specimens in the monomers were put in closed containers and put progressively through three soak cycles: (1) 4 days at 20 C, (2) 24 h at 60 C, (3) 24 h at 105 C. Dimensions were measured and volumes calculated after each soak period. After the last soak period, the polymerization initiator 2,2'-azobis-(2-ethylbutyronitrile) was added to the monomers, and the specimens were kept in the monomer an additional 7 days at 20 C to permit the initiator to permeate the monomer and specimens. The specimens were removed from the monomers and wiped to remove excess monomer. The monomers were then polymerized by placing the specimens between aluminum platens in a press for 15 min at 105 C. The pressure applied was just sufficient to hold the platens firmly against the specimens. After polymerization, the specimens were oven-dried and weighed, and the dimensions were measured. The percentage of polymer loading (PL) and percentage of swelling were calculated for the resulting WPC specimens, based on the original oven-dry weights and volumes. The extent of polymerization of the monomers in the wood was not determined.

Volumetric swelling and moisture content

The WPC specimens and untreated control specimens were conditioned in a humidity chamber at 27 C and 30% relative humidity

TABLE 2. *Polymer loading by species.*

Monomer	Polymer loading (%)		
	Maple	Red oak	Southern pine
HEMA	101.0	96.1	113.6
HEA	98.1	97.0	108.6
HPA	86.7	80.1	93.9
GMA	85.5	85.5	86.4
VP	84.3	81.7	91.4
HPMA	78.5	65.6	86.9
PEGMA	71.6	68.0	87.4
PEG400DA	67.5	63.9	91.4
HDDA	60.1	48.5	76.2
PEG600DMA	57.4	51.4	82.9
HDDMA	57.1	44.5	75.2
MMA	49.6	40.9	40.7
Average	74.8	68.6	86.2

TABLE 3. *Volumetric swelling of maple by monomers.*

Monomer	Volumetric swelling (%)[1]			
	20 C	60 C	105 C	Poly-merized (%)
VP	1.9	14.8	20.4	15.6
HEA	13.9	16.4	19.4	13.4
HEMA	1.4	6.5	16.8	17.7
HPA	1.0	4.4	15.8	13.1
GMA	1.2	2.2	12.5	8.2
HPMA	0.0	0.2	11.7	8.8
PEGMA	0.2	0.6	9.3	10.0
MMA	1.4	3.9	6.1	5.7
HDDA	0.0	0.2	2.8	−1.2
PEG400DA	0.2	0.2	1.5	4.4
PEG600DMA	0.2	0.0	0.8	1.4
HDDMA	0.0	0.1	0.6	0.9

[1] Soak time at 20 C was 4 days; at 60 C, 24 h; and at 105 C, 24 h.

(RH) for 7 days. The conditioned specimens were weighed, dimensions measured, and volumes calculated. The specimens were then placed in a humidity chamber at 27 C and 90% RH. Specimens were weighed and measured after 2, 4, 6, and 24 h, and 2, 3, 4, and 7 days. The percentage of volumetric swelling based on the treated oven-dry volumes was calculated for each specimen. The percentage of moisture content of each specimen was calculated based on the oven-dry untreated weight.

RESULTS

Swelling of wood soaked in monomers

Swelling at 20 C. — All three species of wood specimens swelled when soaked in HEA: maple 13.9%, red oak 9.2%, and southern pine 4.0% (Tables 3 to 5). The results showed little or no swelling from soaking in the other monomers at 20 C.

Swelling at 60 C. — The greatest swelling at 60 C resulted from soaking specimens in HEA; maple, red oak, and southern pine had 16.4, 12.0, and 13.0% swelling, respectively. Soaking maple, red oak, and southern pine in VP resulted in swelling of 14.8, 11.9, and 2.4%, respectively. In HEMA, maple swelled 6.6%, but red oak and southern pine showed less than 1% swelling. The swelling of maple in HPA and MMA was 4.4 and 3.9%, respectively. The

remaining monomers did not result in more than 2% swelling of any specimen (Tables 3 to 5).

Swelling at 105 C. — Soaking the wood specimens at 105 C in VP, HEA, HPA, and HEMA resulted in 15 to 20% swelling of maple and red oak and 20, 17, 12 and 10% swelling of southern pine, respectively (Tables 3 to 5). The remaining monomers resulted in less than 4% swelling of southern pine. For maple and red oak, soaking in PEGMA, HPMA, and GMA resulted in 7 to 12% swelling, and soaking in MMA resulted in about 6% swelling. The re-

TABLE 4. *Volumetric swelling of red oak by monomers.*

Monomer	Volumetric swelling (%)[1]			
	20 C	60 C	105 C	Poly-merized (%)
VP	1.0	11.9	21.1	12.0
HEA	9.2	12.0	19.0	10.3
HEMA	0.4	0.3	14.8	10.7
HPA	0.6	1.7	14.7	11.1
GMA	0.5	0.8	10.9	8.4
HPMA	0.3	0.3	9.5	7.3
PEGMA	0.1	0.5	7.5	8.3
MMA	1.0	2.2	5.4	6.2
HDDA	0.2	0.3	1.4	−1.2
PEG400DA	0.1	0.3	1.3	4.1
PEG600DMA	0.3	0.3	0.8	0.0
HDDMA	0.1	0.1	0.5	−0.1

[1] Soak time at 20 C was 4 days; at 60 C, 24 h; and at 105 C, 24 h.

TABLE 5. *Volumetric swelling of southern pine by monomers.*

Monomer	Volumetric swelling (%)[1]			
	20 C	60 C	105 C	Polymerized (%)
VP	0.3	2.4	20.5	17.2
HEA	4.0	13.0	17.2	12.4
HPA	0.3	0.8	12.4	9.0
HEMA	0.2	0.8	10.5	16.9
PEGMA	0.2	0.6	3.7	9.1
HPMA	0.0	0.2	2.8	2.2
GMA	0.2	0.3	1.9	2.5
MMA	1.3	1.5	1.7	5.5
PEG600DMA	0.2	0.3	0.3	−0.1
HDDA	0.1	0.2	0.2	−0.8
HDDMA	0.0	0.2	0.2	0.7
PEG400DA	0.2	0.4	0.0	4.2

[1] Soak time at 20 C was 4 days; at 60 C, 24 h; and at 105 C, 24 h.

mainder of the monomers (HDDA, HDDMA, PEG400DA, and PEG600DMA) resulted in about 2% swelling for the three species.

Polymer loading

The PL of the WPC specimens varied from 40 to 113% (Table 2). Generally, the monomers with potential for hydrogen bonding resulted in the highest PL. In general order of decreasing PL, the monomers were HEMA, HEA, HPA, GMA, VP, and HPMA. This order changed somewhat depending on the species of wood. Monomers having little or no

potential to hydrogen-bond gave lower PL. In general order of decreasing PL, these monomers were HDDA, HDDMA, and MMA. MMA gave the lowest PL, partially because MMA is more volatile (bp 100 C) than any other monomer used; therefore, some MMA was lost before it polymerized. The PEG400DA and PEG600DMA monomers resulted in low PL probably because of the large size of the molecules. Southern pine gave the highest PL for all monomers used except MMA with an average PL of 86%; maple had the next highest PL for all monomers and an average of 75%; red oak had the lowest PL of the three species for all monomers and an average of 69%. These differences in PL indicate that treatability is species-dependent (Table 2).

Swelling retained after polymerization. —After polymerization, maple and red oak retained most of the swelling caused by soaking in the monomers. In decreasing order of retained volume of specimens, the monomers were VP, HEMA, HPA, HEA, PEGMA, GMA, HPMA, and MMA. In southern pine, monomers in decreasing order of swelling retained after polymerization were VP, HEMA, HEA, PEGMA, HPA, and MMA. As the monomers were polymerized, there was usually a slight decrease or no change in the swollen volume of specimens of all three species. If the swelling was generally retained by specimens, the

TABLE 6. *Volumetric swelling of treated oven-dry maple specimens with time at 90% RH.*

Monomer	Volumetric swelling (%)								
		Time at 90% RH							
	30% RH	2 h	4 h	6 h	24 h	2 days	3 days	4 days	7 days
PEG600DMA	1.4	1.9	2.2	2.7	6.3	9.6	12.4	13.7	16.1
HEA	0.8	0.9	1.0	1.3	3.3	5.3	7.0	8.6	12.9
PEGMA	1.3	1.7	2.0	2.2	5.1	8.7	9.9	10.9	12.1
Control	1.6	4.3	5.7	6.6	9.0	9.8	10.2	10.7	11.9
HDDA	1.1	1.5	1.7	1.8	3.9	5.1	7.5	8.5	11.2
HPMA	1.1	1.0	1.1	1.3	3.3	5.0	7.1	7.8	11.0
PEG400DA	1.0	1.3	1.7	1.8	3.6	5.1	6.5	7.5	10.8
HDDMA	1.3	1.3	1.4	2.1	4.5	7.5	8.6	9.4	10.7
HEMA	1.0	0.9	0.8	1.2	2.3	3.0	3.7	4.6	9.2
MMA	0.9	1.5	1.9	2.3	6.2	7.9	8.5	8.6	9.1
GMA	0.6	0.6	0.8	0.8	2.1	3.4	5.0	6.1	9.0
HPA	0.3	0.1	0.2	0.2	1.3	1.9	3.4	4.2	8.4
VP	2.0	1.6	1.7	2.1	3.4	3.8	4.1	4.0	4.1

TABLE 7. *Volumetric swelling of treated oven-dry red oak specimens with time at 90% RH.*

| Monomer | 30% RH | Volumetric swelling (%) | | | | | | | |
| | | Time at 90% RH | | | | | | | |
		2 h	4 h	6 h	24 h	2 days	3 days	4 days	7 days
PEG600DMA	1.2	2.1	2.6	3.2	7.9	11.3	13.4	14.5	16.8
HEA	1.0	1.3	1.7	1.8	4.6	8.0	11.3	12.2	14.6
PEGMA	1.2	1.9	2.4	2.6	6.3	9.2	10.6	11.0	13.1
PEG400DA	1.1	1.5	1.7	2.0	4.4	6.2	7.7	8.9	10.9
HPMA	1.3	1.4	1.9	1.7	4.0	5.5	7.7	8.7	10.7
Control	1.6	4.2	5.3	6.1	8.2	9.0	9.4	9.6	10.5
HEMA	1.2	1.4	1.4	1.9	2.6	4.8	5.5	7.7	10.4
HDDA	1.0	1.3	1.4	1.8	4.5	6.8	8.0	8.8	10.2
HDDMA	1.3	1.5	1.7	1.8	4.6	6.9	8.3	8.7	10.0
HPA	1.4	1.1	1.1	1.5	2.6	5.1	6.9	8.2	9.5
MMA	0.7	1.7	2.2	2.8	6.5	7.9	8.3	8.8	9.0
GMA	0.1	0.3	0.1	0.4	1.3	2.6	3.7	5.3	8.9
VP	2.7	2.7	3.2	3.6	6.2	7.9	8.0	8.2	7.7

monomers/polymers bulked the cell walls, preventing shrinkage to the untreated dimensions.

Volumetric swelling of WPC specimens

The rate of swelling of WPC specimens was slow for the first few hours at 90% RH, compared to that of the control specimens (Tables 6 to 8). After 6 h in 90% RH, maple, red oak, and southern pine control specimens swelled 6.6, 6.1, and 7.0%, respectively. In contrast, all maple WPC specimens swelled less than 3%, red oak WPC specimens less than 3.6%, and the southern pine WPC specimens less

than 4.0% during the same period (Tables 6 to 8). The polymers slowed the movement of moisture into the wood, which lowered the rate of swelling compared to that of controls during the first few hours at 90% RH.

After 7 days at 90% RH, many WPC specimens swelled as much as or, for some specimens, more than the control specimens (Tables 6 to 8). Generally, WPC specimens that swelled as a result of soaking in monomers and that had cell walls bulked by polymer showed less swelling in moisture than specimens that did not swell in a monomer. Maple WPC specimens treated with HEMA, MMA, GMA,

TABLE 8. *Volumetric swelling of treated oven-dry southern pine specimens with time at 90% RH.*

| Monomer | 30% RH | Volumetric swelling (%) | | | | | | | |
| | | Time at 90% RH | | | | | | | |
		2 h	4 h	6 h	24 h	2 days	3 days	4 days	7 days
PEGMA	1.2	1.8	2.2	2.7	7.1	12.0	16.8	20.4	27.6
PEG600DMA	2.1	2.5	2.9	3.5	7.1	9.8	12.3	14.0	18.5
HEMA	0.4	1.1	1.3	0.7	3.1	5.5	8.9	10.7	17.9
HEA	1.4	0.8	0.8	0.8	2.7	5.6	8.0	10.4	17.6
HPMA	0.8	1.0	1.2	1.1	3.7	6.0	8.5	9.9	13.9
HDDA	1.7	2.2	2.6	3.4	7.3	9.7	10.8	11.3	12.6
PEG400DA	1.4	1.8	2.1	2.4	4.9	6.6	8.5	10.3	12.4
HDDMA	1.7	2.3	2.7	3.3	7.5	9.5	10.8	11.1	12.4
GMA	0.9	1.3	1.5	1.6	4.2	6.5	8.3	10.1	11.9
Control	2.0	5.2	6.1	7.0	9.3	10.0	10.7	10.8	11.6
HPA	0.5	0.7	0.8	0.7	1.9	4.0	6.1	7.4	11.0
MMA	1.3	2.6	3.0	4.0	7.6	8.2	8.6	8.5	8.9
VP	1.8	1.6	1.6	2.2	3.0	3.7	3.7	3.7	4.3

TABLE 9. *Moisture of treated maple with time at 90% RH, based on untreated oven-dry weight.*

Monomer	Polymer loading (%)	30% RH	Moisture (%) Time at 90% RH						
			2 h	4 h	24 h	2 days	3 days	4 days	7 days
PEGMA	71.6	3.9	7.2	8.8	18.8	26.5	31.9	35.6	42.5
HEA	98.1	4.4	6.6	7.5	12.4	16.8	21.0	24.7	32.7
PEG600DMA	57.4	4.4	6.8	8.0	16.5	22.4	26.2	28.7	32.5
HPA	86.7	3.8	5.4	6.1	10.0	13.0	15.8	18.4	26.1
PEG400DA	67.5	3.6	5.2	6.1	11.7	15.6	18.5	20.9	26.0
HPMA	78.5	3.6	5.2	5.9	9.9	13.4	16.5	19.2	24.8
VP	84.3	6.3	10.1	11.9	18.8	23.3	24.9	22.7	24.3
HEMA	101.0	3.9	6.1	6.9	10.8	13.2	15.5	17.6	24.1
Control	0.0	4.0	10.1	11.9	16.2	17.6	18.5	19.3	21.0
HDDMA	57.1	3.8	4.7	5.3	10.9	15.0	17.2	18.6	20.7
HDDA	60.1	3.2	3.9	4.4	8.1	11.5	14.0	15.9	19.6
MMA	49.6	3.2	4.9	5.9	13.7	16.5	17.3	17.7	18.0
GMA	85.5	1.5	2.5	2.9	5.8	8.3	10.6	12.7	17.8

HPA, and VP showed less swelling in moisture than did control specimens. Red oak WPC specimens treated with MMA, GMA, and VP swelled less at 90% RH than did the control specimens. Southern pine WPC specimens treated with MMA and VP swelled less than did control specimens. All WPC specimens treated with VP showed the least swelling because the polymer was bulking the wood at near green volume so little additional swelling was possible.

Moisture content of WPC specimens

The moisture content of WPC specimens was calculated from specimen weight at spec-

ified time intervals in 90% RH. The rate of moisture sorption during the first few hours was slower than it was after 24 h in 90% RH. After 7 days at 90% RH, the moisture content calculated on the basis of only the wood in the specimens (untreated oven-dry weight), excluding the weight of polymer, showed that many treated specimens sorbed more moisture than did control specimens (Tables 9 to 11). The monomers/polymers that increased the *moisture sorption of all three species were* PEGMA, PEG600DMA, PEG400DA, HEA, HEMA, HPA, HPMA, and VP. The higher moisture content of the specimens treated with these monomers/polymers was caused by the

TABLE 10. *Moisture of treated red oak with time at 90% RH, based on untreated oven-dry weight.*

Monomer	Polymer loading (%)	30% RH	Moisture (%) Time at 90% RH						
			2 h	4 h	24 h	2 days	3 days	4 days	7 days
PEGMA	68.0	3.6	7.8	9.5	22.0	30.4	35.2	38.5	44.7
HEA	97.0	4.2	7.4	8.7	17.2	24.3	29.7	33.0	37.1
VP	81.7	6.1	11.3	13.5	28.0	33.7	35.2	35.3	34.6
PEG600DMA	51.4	3.9	6.9	8.4	18.7	24.5	27.9	30.2	33.8
HEMA	96.1	4.0	6.5	7.4	13.0	16.7	20.1	22.9	29.2
HPA	80.1	3.7	6.2	7.2	13.5	18.7	23.0	25.7	28.9
PEG400DA	63.9	3.1	5.2	6.0	12.1	16.6	20.1	22.5	26.2
HPMA	65.5	3.4	5.7	6.6	12.1	16.3	19.7	21.9	24.4
Control	0.0	3.9	9.4	11.0	15.6	16.7	17.5	18.3	21.7
GMA	85.5	1.1	2.3	2.7	5.8	8.4	11.0	13.3	18.7
HDDA	48.5	2.9	4.5	5.2	10.1	13.4	15.3	16.5	18.2
HDDMA	44.5	3.1	4.7	5.3	10.2	13.7	15.6	16.6	18.1
MMA	40.9	2.7	5.4	6.5	13.7	15.5	16.1	16.3	16.5

TABLE 11. *Moisture of treated southern pine with time at 90% RH, based on untreated oven-dry weight.*

Monomer	Polymer loading (%)	Moisture (%)							
		30% RH	Time at 90% RH						
			2 h	4 h	24 h	2 days	3 days	4 days	7 days
PEGMA	87.4	4.7	9.2	11.0	23.6	33.2	40.6	45.9	54.1
HEA	108.6	4.7	7.9	8.9	15.8	22.0	27.4	32.1	40.6
PEG600DMA	82.9	5.4	8.6	9.9	18.9	25.2	29.8	33.1	38.9
HEMA	113.6	2.4	4.7	5.4	9.7	13.6	17.5	21.6	32.4
HPA	93.9	4.1	6.7	7.6	13.2	17.6	21.7	25.2	32.2
PEG400DA	91.4	4.4	7.1	8.1	15.3	20.2	23.8	26.7	31.0
HPMA	86.9	3.0	4.9	5.6	9.6	13.2	17.0	20.9	30.0
VP	91.4	7.6	13.5	16.0	22.6	30.2	32.6	30.4	29.3
HDDMA	75.2	4.4	6.1	7.0	14.4	17.7	19.3	20.2	21.5
GMA	86.4	1.5	3.1	3.6	8.0	12.1	15.7	18.4	21.5
HDDA	76.2	4.1	6.0	6.8	13.5	16.9	18.5	19.4	20.9
Control	0.0	4.5	11.0	12.7	16.7	17.8	18.5	19.1	19.9
MMA	40.7	3.8	6.8	7.9	14.8	15.8	16.2	16.6	16.9

polymers themselves sorbing moisture. Because the amount of moisture sorbed is dependent on the surface area of the polymer material, larger solid pieces of polymer sorb less moisture than does polymer milled into granules. Polymer in wood has a greater surface area to sorb moisture than does a piece of solid polymer. Polymers in decreasing order of amount of moisture sorbed when not in wood are PEGMA, PEG600DMA, PEG400DA, HEA, HEMA, HPA, HPMA, MMA, GMA, HDDA, and HDDMA.

After 7 days at 90% RH, some WPC specimens had the same or lower moisture content than did control specimens. The polymers in these specimens did not sorb moisture; they were from the monomers HDDA, HDDMA, and MMA that were not able to hydrogen-bond with water. Specimens treated with GMA had the lowest moisture content because the oxirane ring can react with hydroxyl groups in the wood, reducing the ability of the wood to sorb moisture.

CONCLUSIONS

Certain monomers can swell wood at temperatures above room temperature. These monomers have low molecular weights and molecular structures that facilitate hydrogen-bonding. For wood–polymer composite (WPC) specimens that displayed some volumetric swelling after polymerization, cell-wall bulking had the potential to reduce the moisture-related swelling, but this potential was counteracted by the hygroscopicity of the polymers. This attraction of moisture to the WPC specimens resulted in some swelling that likely would not have occurred had the polymers not been hygroscopic. The hygroscopicity of the polymers can likely be decreased by including a reactant with the monomer that will react during polymerization with the free hydroxyl groups, leaving no unreacted hydroxyl groups in the polymer to attract moisture. Interest is growing in the use of WPC, especially for products that benefit by an increase in hardness and abrasion resistance. Because of this interest, we are continuing research on swelling wood with monomers and bulking cell walls by including a chemical to react with hydroxyl groups during polymerization, thus reducing the hygroscopicity of the polymers.

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