EFFECT OF VACUUM TIME, FORMULATION, AND NANOPARTICLES ON PROPERTIES OF SURFACE-DENSIFIED WOOD PRODUCTS

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Abstract. Surface-densified wood products were prepared with only a short vacuum impregnation process instead of the traditional time-consuming pressurizing stage. The top layer of engineered wood flooring planks was successfully impregnated with low-viscosity 1,6 hexanediol dimethacrylate and trimethylolpropane trimethacrylate as well as layered silicate nanoparticles by vacuum impregnation of 30 s to 10 min. Treating tests involved two species, maple and oak, and Brinell surface hardness, impact resistance, and abrasion resistance of the treated wood specimens were measured. Brinell surface hardness increased from 5.05-15.42 MPa for maple, the greatest improvement of 205% being obtained with a 30-s vacuum. For oak, Brinell surface hardness increased from 5.25-11.05 MPa with a 60-s vacuum, an improvement of 108%. Impact resistance was based on measurements of indentation diameters and depths in falling ball tests. Decreases in indentation diameters from 4.96-2.84 mm and indentation depths from 0.172-0.034 mm were observed for maple treated with nanoparticle-containing formulations and a 60-s vacuum impregnation, indicating that impact resistance of a one-step, short vacuum impregnation time dramatically improved wood surface hardness. Measurements of abrasion resistance properties of surface-densified specimens were based on specimen weight loss with time following abrasion tests. Weight loss values decreased considerably with treated wood. A factorial experimental design provided information on effects of vacuum time, nanoparticles, and wood species on properties of impregnated wood specimens. Impacts of individual factors and their interactions were analyzed with Statistical Analysis System.

Keywords: Nanoparticles, vacuum process, surface densification, Brinell surface hardness, abrasion resistance, impact resistance.

INTRODUCTION

Specific wood applications require specific wood treatments. Chemical impregnation of wood to enhance specific wood properties, such as dimensional stability, hardness, and abrasion resistance, has been performed for decades (Moore et al 1983; Rowell 1984, 1991; Schneider 1994, 2001; Singh et al 1999; Ayer et al 2003). Adoption of this technology has, however, been limited because of large-volume chemical consumption and low process productivity. Traditional vacuum/pressure chemical impregnation requires a minimum of 15 min and possibly up to several hours of vacuum to remove air from wood followed by pressure treatment also of 15 min up to several hours to help the chemical penetrate into the wood structure. The chemical retention (CR) needed to improve dimensional stability of pine by acetylation can exceed 200 wt% (Brelid 2002). Surface hardness gains in aspen, maple, and oak specimens through polymethylmethacrylate impregnation required CR levels of 110,

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77, and 43 wt%, respectively (Beal et al 1973). In all cases, costs have been unreasonably large.

In conventional impregnation, a long vacuum/pressure time is needed for chemicals to penetrate the wood structure. Applying vacuum removes air from wood cells and the break of the vacuum lets chemicals penetrate deep into the wood. With this research, we aimed to decrease the cost of this process by limiting treatment to the wood surface, where hardness, impact resistance, and abrasion resistance are most critical, in the face layers of engineered wood flooring. This involved accelerating the impregnation process by shortening vacuum time and removing the pressurizing process, thus lowering CR and improving wood surface properties. This could strategically turn the conventional discontinuous impregnation process into an industrially viable surface densification process.

Our previous work (Cai et al 2007a, 2007b, 2008) proved that nanoparticles can penetrate into wood cell walls with the vacuum/pressure impregnation process and significantly improve mechanical/physical properties. Adding only 1% nanoparticles combined with a low-viscosity chemical as a transport medium was sufficient to achieve significant improvements. Combining nanoparticles and a melamine–urea–formaldehyde (MUF) resin led to superior surface hardness, abrasion resistance, and modulus of elasticity as well as dramatically improved moisture resistance and dimensional stability.

In this work, specimens of two different species, maple and oak, were impregnated with low-viscosity1,6 hexanediol dimethacrylate (HDDA) and trimethylolpropane trimethacrylate (TMPTA) using a single vacuum process and a range of vacuum times. Layered silicate nanoparticles (Claytone®APA; Southern Clay Products, Gonzales, TX) were mixed with a low-viscosity HDDA/TMPTA formulation for impregnating specimens. Our previous work (Cai and Blanchet 2010) investigated effects of such a short vacuum impregnation process on CR, penetration, and resin distribution. In this study, we investigated effects of different vacuum times (30 s, 60 s, 5 min, and 10 min) and addition of nanoparticles into formulations on Brinell surface hardness, abrasion resistance, and impact resistance properties of impregnated wood specimens. A full factorial experimental design was used to analyze impact of wood species, vacuum process time, and nanoparticles on resulting wood properties. Impacts of individual factors and their interactions were analyzed with Statistical Analysis System (SAS).

The objective of this work was therefore to investigate the feasibility of creating surface-densified wood products with a simple fabrication process and at a lower cost, because limiting chemical penetration to the product surface achieves good balance between performance and cost, particularly with respect to flooring. More specifically, our objectives were to shorten the impregnation process by eliminating the pressure step and decreasing resin retention, thus considerably improving the economics of wood impregnation. Success with this approach could strategically replace conventional slow impregnation with a more efficient, industrial densification process yielding high value-added wood products for use in exterior and interior applications such as wood flooring, doors and windows, siding, deck, furniture, cabinets, etc.

METHODS AND MATERIALS

Materials and Impregnation Process

Wood materials used in this study consisted of maple (*Acer saccharum March.*) and oak (*Quercus rubra L.*). The nanoparticles were Claytone®APA supplied by Southern Clay Products, Inc. As transportation medium for the nanoparticles, we selected HDDA and TMPTA resins in a 75/25 ratio. The specimens, 4-mm-thick engineered wood flooring components, were placed in a container and vacuumed to 25 mm Hg. Vacuum was maintained for various amounts of time. When the valve was closed, a known amount of resin was flushed into the system until all specimens were covered with chemicals. Vacuum was released, and specimens were removed from the cylinder. The residue of chemicals on the wood surface was wiped off. Details on this impregnation process with different vacuum times were described in previous work (Cai and Blanchet 2010). The HDDA/TMPTA resin mix with or without nanoparticles was polymerized in the wood by electron beam radiation without any catalyst.

Brinell Surface Hardness

Brinell surface hardness was measured as per European Standard EN 1534 (European Standard 2000) using Alliance RT/50 systems from MTS Systems Corporation (Eden Prairie, MN). The hardness modulus was calculated as the slope of load vs indentation within the 20-60% indentation range. Three points were tested for each specimen, and at least nine specimens were tested for each combination.

Impact Resistance

The falling ball impact resistance test measures the ability of impregnated wood to resist impact of a free-falling large steel ball when dropped on the specimen face from a specific height. The test followed ASTM D 2794-93 (ASTM 1999). The falling-ball equipment is shown in Fig 1. Because of electromagnets, the ball can be placed at different heights, low (76 mm), medium (229 mm), and high (457 mm), to evaluate impact resistance of impregnated wood boards. For each impact, indentation diameter and depth were examined and measured.

Taber Abrasion Resistance

Taber abrasion resistance of treated and untreated specimens was estimated according to ASTM D-4060-95 (ASTM 2001), which involves mounting an abrasive wheel over the specimens and rotating it for a specified number of cycles, ie 100, 300, and 500 cycles. Specimen weight losses were determined and compared. Weight loss (WL) after Taber abrasion was calculated with Eq 1:

Figure 1. Impact resistance apparatus.

$$WL = \frac{W_0 - W_1}{W_0} \times 100 \qquad (1)$$

where WL is weight loss percentage, W_0 is mass of specimen before Taber abrasion, and W_1 is mass of specimen after Taber abrasion.

Experimental Design and Data Analyses

Table 1 shows the factorial design used in this study. Factors considered were species (maple and oak), formulation with nanoparticles and without nanoparticles, and vacuum process time (30 s, 60 s, 5 min, and 10 min). This led to 16 combinations with 9 replications for each combination.

Effect of wood species, nanoparticles in the formulations, and vacuum time on Brinell surface hardness, abrasion resistance, and impact resistance were analyzed with SAS software. Analysis of variance (ANOVA) of Brinell surface hardness was performed at nine levels (eight levels of treatment and one control). Analysis of Duncan groups was conducted for Brinell hardness. ANOVA of impact resistance of both

Table 1. Factorial experimental design used in this study.

Specimen code	Wood species	Nanoparticles in HDDA/TMPTA	Impregnation vacuum time
M-NN-30s	Maple	No	30 s
M-NN-60s			60 s
M-NN-5min			5 min
M-NN-10min			10 min
M-WN-30s		Yes	30 s
M-WN-60s			60 s
M-WN-5min			5 min
M-WN-10min			10 min
O-NN-30s	Oak	No	30 s
O-NN-60s			60 s
O-NN-5min			5 min
O-NN-10min			10 min
O-WN-30s		Yes	30 s
O-WN-60s			60 s
O-WN-5min			5 min
O-WN-10min			10 min

HDDA, 1,6 hexanediol dimethacrylate; TMPTA, trimethylolpropane trimethacrylate.

indentation diameters and depths at different impact strengths on maple and oak was performed at 16 levels. Analysis of Duncan groups was also conducted for abrasion resistance.

RESULTS AND DISCUSSION

Brinell Surface Hardness

Brinell surface hardness results for treated maple and oak and their controls are shown in Figs 2 and 3, respectively. Duncan groupings of surface hardness are indicated with different letters. As a rule, results assigned the same letter belong in the same group, and there were no significant differences in the group.

With maple, all specimens treated with formulations involving either HDDA/TMPTA resins alone or combinations of resin and nanoparticles at different vacuum times (30 s, 60 s, 5 min, or 10 min) performed significantly better in Brinell surface hardness compared with untreated specimens. The greatest improvement in Brinell surface hardness was shown by HDDA/TMPTA formulation at vacuum times of 30 and 60 s, where surface hardness was improved from 5.05 MPa (Duncan group D) to 15.42 MPa (Duncan group A) and 15.29 MPa (Duncan group A), respectively. This amounts to a three-

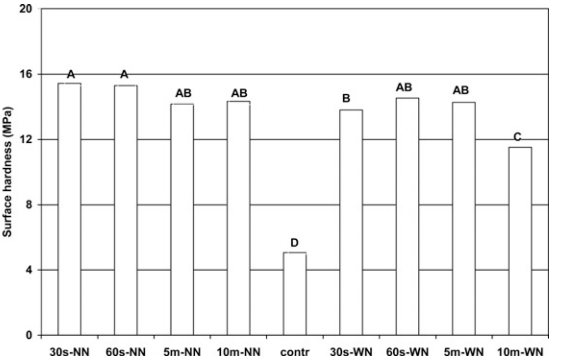

Figure 2. Brinell surface hardness of untreated maple control and maple treated with neat resin or resin/nanoparticles across a range of vacuum times (WN, formulation with nanoparticles; NN, formulation without nanoparticles).

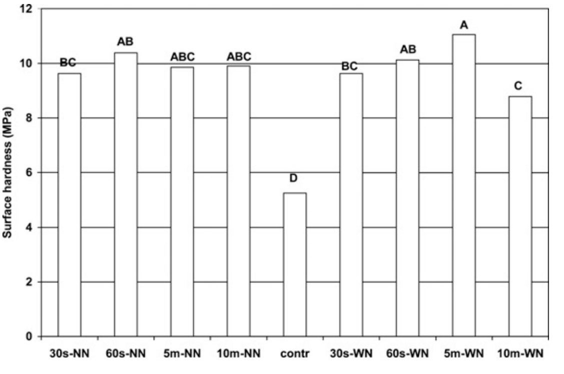

Figure 3. Brinell surface hardness of untreated oak control and oak treated with neat resin or resin/nanoparticles across a range of vacuum times (WN, formulation with nanoparticles; NN, formulation without nanoparticles).

fold improvement compared with untreated maple. Surface hardness improvements ranged from 125.5-202.4% for maple planks when impregnated through the one-step vacuum process with vacuum times from 30 s to 10 min. Such surface hardness improvements are similar to those obtained in previous work with conventional vacuum/pressure (15 min/15 min) impregnation of aspen with a formulation of MUF and nanoparticles, where aspen surface hardness increased from 1.09-3.25 MPa (Cai et al 2007b). Comparison of surface hardness results from conventional vacuum/pressure and one-step vacuum impregnation indicates that a high-quality surface-densified product can be obtained without the time-consuming pressurizing step characterizing the traditional vacuum/pressure impregnation process.

Surface hardness of oak impregnated with HDDA/TMPTA resins and with or without nanoparticles with different vacuum times also exceeded that of untreated oak, increasing from 5.25 MPa (Duncan group D) for control specimens to a minimum 8.78 MPa (Duncan group C) and a maximum 11.05 MPa (Duncan group A), ie 65.7-108.5% improvements. The greatest improvement was observed with a formulation combining HDDA/TMPTA and nanoparticles and a vacuum impregnation time of 5 min (Fig 3).

Effects of dependent variables and their interactions on Brinell surface hardness were statistically analyzed for maple and oak impregnated by the one-step vacuum process. Statistical analysis revealed a significant effect of vacuum time and nanoparticle addition in the formulation on Brinell surface hardness at the 0.01 probability level (Table 2) for maple. Maple impregnated with a neat formulation showed greater Brinell surface hardness than did samples treated with formulations containing nanoparticles (Fig 2). This could be attributed to greater CR of the neat formulation-treated maple compared with samples treated with nanoparticle-containing formulations (Cai and Blanchet 2010). The lower CR of samples treated with nanoparticle-containing formulations may be attributed to accumulation of nanoparticles in pores located near the surface, which limited resin penetration into the specimen centers (Cai et al 2007a, 2007b).

Table 2. Effect of dependent variables on Brinell surface hardness of impregnated maple and oak.[a]

Source	Degree of freedom	F value	Pr > F
Maple			
Nanoparticles	1	13.84	0.0003**
Vacuum process time	3	6.55	0.0003**
Nanoparticles × vacuum time	3	3.32	0.0211
Oak			
Nanoparticles	1	0.03	0.8577
Vacuum process time	3	3.04	0.0302
Nanoparticles × vacuum time	3	2.61	0.0529

[a] ** Significant at 0.01 probability level.

For oak, the effect of nanoparticles and vacuum process time on Brinell surface hardness did not prove significant. Effect of interaction between the two factors (nanoparticles and vacuum time) on Brinell surface hardness was not significant for maple or oak. This could be ascribed to the different anatomical structures of maple and oak. Both maple and oak are porous, but maple is diffuse porous and oak is ring porous. A diffuse porous species offers a better response to penetration of nanoparticles and resin formulations, hence better impregnability and superior mechanical performance.

Impact Resistance

Table 3 presents results of the ANOVA for the impact resistance properties of maple and oak surface densified by means of a short vacuum process and formulations with or without nanoparticles. Indentation diameters and depths of the specimens being tested at low, medium, and high heights such as measured and analyzed by SAS software showed a significant effect of surface densification on impact resistance at the 0.01 probability level.

Figures 4 and 5 illustrate indentation diameters and depths of treated maple and control specimens from low, medium, and high impact levels. Indentation diameters decreased from 4.96-2.84 mm, a 42.7% decrease. Indentation depths decreased from 0.172-0.027 mm, an 84.3% decrease, with 60-s vacuum and a formulation containing nanoparticles. Impact resistance improved dramatically when impact strength was low. At the medium impact level, indentation diameters decreased from 6.49-4.10 mm, a 36.8% decrease, and for maple treated with a 30-s vacuum and a formulation without nanoparticles, indentation depths decreased from 0.302-0.059 mm, an 80.5% decrease. At the high impact level, indentation diameters decreased from 7.72-4.62 mm, a 40.2% decrease, for maple treated with a 10-min

Table 3. Analysis of variance of impact resistance of maple and oak.[a]

Source	Degree of freedom	F value	Pr > F
Indentation depth at low impact level (76 mm)			
Model	15	11.77	< 0.0001**
Error	304		
Total	319		
Indentation diameter at low impact level (76 mm)			
Model	15	18.38	< 0.0001**
Error	304		
Total	319		
Indentation depth at medium impact level (229 mm)			
Model	15	22.12	< 0.0001**
Error	304		
Total	319		
Indentation diameter at medium impact level (229 mm)			
Model	15	22.89	< 0.0001**
Error	304		
Total	319		
Indentation depth at high impact level (457 mm)			
Model	15	21.40	< 0.0001**
Error	304		
Total	319		
Indentation diameter at high impact level (457 mm)			
Model	15	30.99	< 0.0001**
Error	304		
Total	319		

[a] ** Significant at 0.01 probability level.

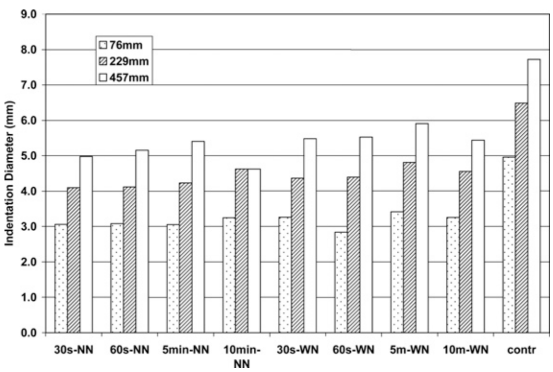

Figure 4. Indentation diameter of maple with low impact level from 76 mm, medium impact level from 229 mm, and high impact level from 457 mm (WN, formulation with nanoparticles; NN, formulation without nanoparticles).

vacuum and a formulation without nanoparticles, whereas indentation depths decreased from 0.462-0.107 mm, a 76.8% decrease, for maple treated with a 60-s vacuum and a formulation without nanoparticles.

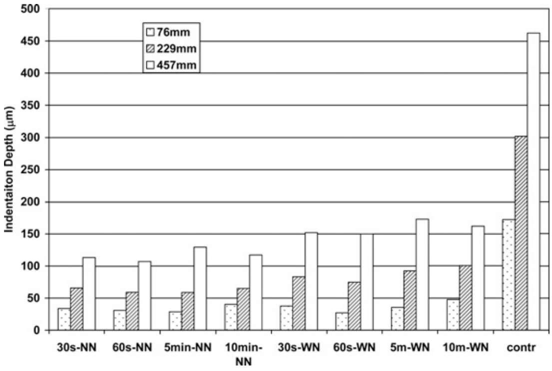

Figure 5. Indentation depths of maple with low impact level from 76 mm, medium impact level from 229 mm, and high impact level from 457 mm (WN, formulation with nanoparticles; NN, formulation without nanoparticles).

Figures 6 and 7 give indentation diameters and depths for treated and untreated oak at different impact levels. At the low impact level, diameters decreased from 4.98-3.63 mm, a 27.1% decrease, for wood treated with a 60-s vacuum and a formulation without nanoparticles or with a 10-min vacuum and a formulation containing nanoparticles. Indentation depths decreased from 0.145-0.054 mm, a 62.8% decrease, for wood treated with 60-s vacuum and a formulation without nanoparticles. At the medium impact level, indentation diameters decreased from 6.58-4.84 mm, a 26.4% decrease, for wood when treated with a nanoparticle-containing formulation and a 10-min vacuum. Indentation depths decreased from 0.337- 0.140 mm, a 58.5% decrease, for wood treated with formulations containing nanoparticles and a 60-s vacuum. At the high impact level, diameters decreased from 7.60-6.23 mm, a 18.0% decrease, for wood treated with a 30-s vacuum and a formulation without nano particles. Depth decreased from 0.472-0.223 mm, a 52.8% decrease, for wood treated with a 5-min vacuum and a formulation with nanoparticles.

Table 4 shows effects of dependent variables on impact resistance of impregnated maple and oak specimens in terms of indentation depths at different impact levels. Effects of individual factors, eg wood species–vacuum time, proved

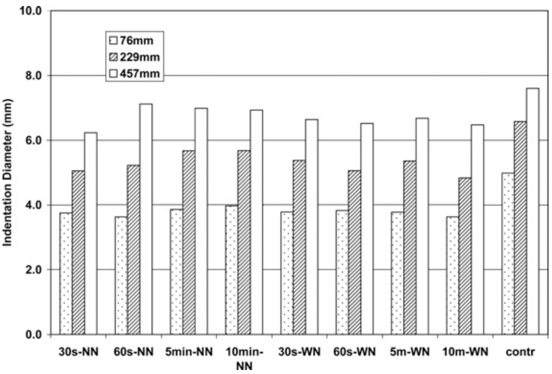

Figure 6. Indentation diameters of oak with low impact level from 76 mm, medium impact level from 229 mm, and high impact level from 457 mm (WN, formulation with nanoparticles; NN, formulation without nanoparticles).

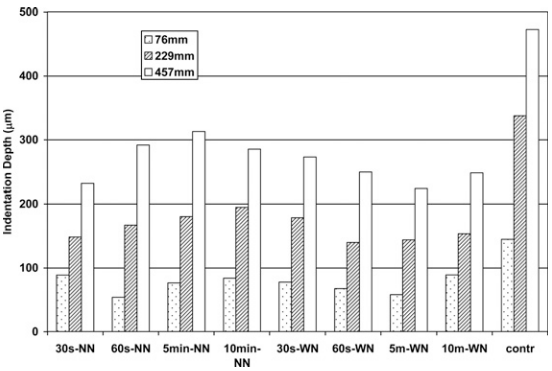

Figure 7. Indentation depths of oak with low impact level from 76 mm, medium impact level from 229 mm, and high impact level from 457 mm (WN, formulation with nanoparticles; NN, formulation without nanoparticles).

significant at the 0.01 probability level for all impact levels. Effect of vacuum process time on indentation depth was significant at the low impact level. At medium and high levels, however, the effect of vacuum time on indentation depth was not significant at the same probability level. The two-factor interaction of wood species–nanoparticles showed no significant effect on indentation depth at the low impact level, but at medium and high impact levels, it was significant at the 0.01 probability level. The effect of the three-factor interaction of wood species–nanoparticles–vacuum time on indentation depth proved significant at the medium impact level. With respect to the weight of F

Table 4. Effect of dependent variables on impact resistance of impregnated maple and oak—Indentation depths from different impact levels.[a]

Source	Degree of freedom	F value	Pr > F
Low impact level (76 mm)			
Wood species	1	140.42	< 0.0001**
Nanoparticles	1	0.01	0.9378
Wood species × nanoparticles	1	0.52	0.4733
Vacuum process time	3	8.21	< 0.0001**
Wood species × vacuum time	3	0.89	0.4491
Nanoparticles × vacuum time	3	0.84	0.4734
Species × nano × vacuum	3	1.95	0.1215
Medium impact level (229 mm)			
Wood species	1	289.85	< 0.0001**
Nanoparticles	1	0.43	0.5103
Wood species × nanoparticles	1	18.22	< 0.0001**
Vacuum process time	3	2.09	0.1015
Wood species × vacuum time	3	0.05	0.9856
Nanoparticles × vacuum time	3	1.76	0.1551
Species × nano × vacuum	3	3.87	0.0097**
High impact level (457 mm)			
Wood species	1	273.76	< 0.0001**
Nanoparticles	1	0.50	0.4809
Wood species × nanoparticles	1	23.61	< 0.0001**
Vacuum process time	3	0.89	0.4457
Wood species × vacuum time	3	0.54	0.6570
Nanoparticles × vacuum time	3	2.90	0.0352
Species × nano × vacuum	3	3.37	0.0188

[a] ** Significant at 0.01 probability level.

values of individual factors, wood species (F = 289.85 at medium impact strength, F = 273.76 at high impact strength), nanoparticles played a key role in determining interaction effect on indentation depth because maple has a diffuse porous structure and oak has a ring porous structure.

In terms of indentation diameters, wood species and vacuum time factors had a significant effect at the 0.01 probability level at low, medium, and high impact levels (Table 5). The effect of nanoparticles on indentation diameters was not significant. The interaction of wood species and vacuum time and that of nanoparticles and vacuum time showed no significant effect on indentation diameter at a low impact level. At medium and high levels, the two-factor interactions of wood species–nanoparticles and nanoparticles–vacuum time showed no significant effect on indentation diameters. For the three-factor interactions of wood species–nanoparticles–vacuum time, the effect on indentation diameters was

Table 5. Effect of dependent variables on impact resistance of impregnated maple and oak—Indentation diameters from different impact levels.[a]

Source	Degree of freedom	F value	Pr > F
Low impact level (76 mm)			
Wood species	1	208.33	< 0.0001**
Nanoparticles	1	0.82	0.3660
Wood species × nanoparticles	1	0.03	0.8689
Vacuum process time	3	6.93	0.0002**
Wood species × vacuum time	3	3.64	0.0131
Nanoparticles × vacuum time	3	3.10	0.0271
Species × nano × vacuum	3	8.49	< 0.0001**
Medium impact level (229 mm)			
Wood species	1	255.33	< 0.0001**
Nanoparticles	1	0.02	0.8913
Wood species × nanoparticles	1	21.80	< 0.0001**
Vacuum process time	3	7.92	< 0.0001**
Wood species × vacuum time	3	1.88	0.1337
Nanoparticles × vacuum time	3	8.63	< 0.0001**
Species × nano × vacuum	3	3.65	0.0130
High impact level (457 mm)			
Wood species	1	396.0	< 0.0001**
Nanoparticles	1	0.99	0.3197
Wood species × nanoparticles	1	22.38	< 0.0001**
Vacuum process time	3	6.97	0.0002**
Wood species × vacuum time	3	1.13	0.3368
Nanoparticles × vacuum time	3	4.87	0.0025**
Species × nano × vacuum	3	2.19	0.0898

[a] ** Significant at 0.01 probability level.

significant at the 0.01 probability level at the low impact level only. In these two- or three-factor interactions, the F value of wood species played a key role because of its substantive weight (F = 255.33 at medium impact level, F = 396.0 at high impact level). This may be caused by the different anatomical structures of maple and oak. Nanoparticles proved more effective with the diffuse porous structure of maple than with ring porous oak, which explains the greater gains in impact resistance observed with maple compared with oak. Vacuum time was also a key factor related to the diffuse porous or ring porous structure of the wood.

Taber Abrasion Resistance

Taber abrasion resistance or wear resistance of treated and untreated maple and oak was expressed as weight loss percentage after Taber abrasion rotation testing. Figure 8 shows average weight loss values obtained with maple, both

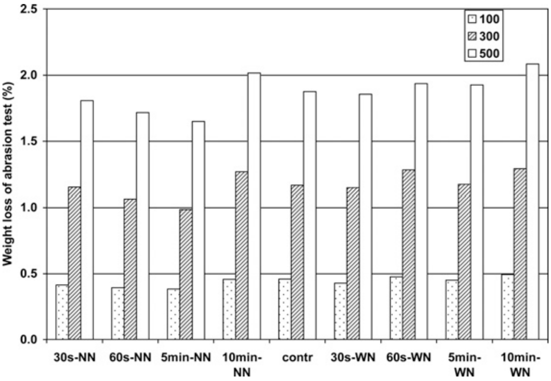

Figure 8. Weight loss in maple after 100, 300, and 500 cycles Taber abrasion (WN, formulation with nanoparticles; NN, formulation without nanoparticles).

treated and untreated, after 100, 300, and 500 Taber abrasion rotation cycles. Weight loss of the maple control was 0.46, 1.16, and 1.87%, respectively, after 100, 300, and 500 cycles. The lowest weight loss for treated maple was 0.38, 0.98, and 1.65%, respectively, after 100 cycles (Duncan group E), 300 cycles (Duncan group C), and 500 cycles (Duncan group D), the maple being impregnated with formulations containing no nanoparticles at a 5-min vacuum (Fig 8). When maple was treated with the same formulation but with a 60-s vacuum, weight loss observed was slightly higher than with the 5-min vacuum. However, both lots still fell in the same low weight loss groups, eg DE for 100 Taber rotation cycles, BC group for 300 cycles, and CD for 500 cycles. Maple impregnated with nanoparticle-containing formulations and a 10-min vacuum presented the highest weight loss percentages of 0.49% (Duncan group ABC), 1.29% (Duncan group A), and 2.08% (Duncan group A) for 100, 300, and 500 cycles, respectively. These results were similar to those from control specimens under the same test conditions. At each different rotation cycle, weight loss values of treated maple fell into various groups. For the first 100 cycles, weight loss was scattered among five Duncan groups (A to E), whereas three Duncan groups (A to C) were observed for the first 300 cycles and four Duncan groups (A to D) were observed for the 500 cycles.

For surface-densified oak, Taber rotation tests produced two different Duncan groups for the

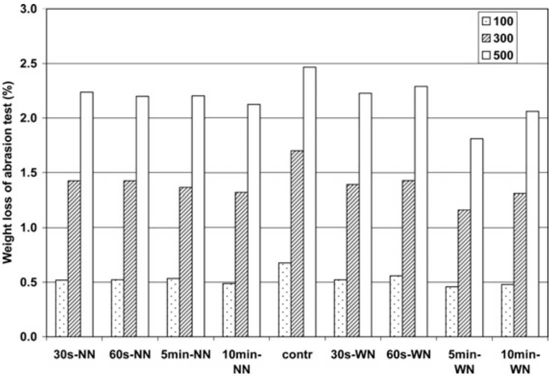

Figure 9. Weight loss in oak after 100, 300, and 500 cycles Taber abrasion (WN, formulation with nanoparticles; NN, formulation without nanoparticles).

100, 300, and 500 abrasion cycles (Fig 9). For oak control specimens, weight loss in the first 100 Taber cycles was 0.68% (Duncan group A) compared with 1.70% (Duncan group A) for 300 cycles and 2.46% (Duncan group A) for 500 cycles. The lowest weight loss values were observed with oak treated with a 5-min vacuum and a formulation containing nanoparticles. They were 0.46% (Duncan group B) in 100 cycles, 1.16% (Duncan group B) in 300 cycles, and 1.86% (Duncan group B) in 500 cycles. All weight losses incurred in the treated oak specimens qualified them for Duncan group B, whereas the control specimens were in group A, indicating that the wood treatment had a significant effect on abrasion resistance.

These Taber abrasion tests demonstrated that a short, one-step vacuum impregnation process decreased weight loss in surface-densified maple and oak, which showed that this process improved abrasion resistance.

CONCLUSIONS

Surface-densified wood products were successfully prepared by impregnating wood flooring components with low-viscosity resins and nanoparticles using a simplified vacuum process lasting 30 s to 10 min without further pressurizing. Specimens of maple and oak, the most widely used species in the wood flooring industry, were treated with the short, one-step vacuum process and resin formulations with or without nanoparticles. Brinell surface hardness, impact resistance, and abrasion resistance of treated wood specimens were measured. The greatest gain in Brinell surface hardness, from 5.05-15.42 MPa, ie 205%, was observed with maple treated with a 30-s vacuum. Brinell surface hardness of oak improved from 5.25-10.38 MPa, a 98% improvement, for wood treated with a 60-s vacuum. Impact resistance was tested with a falling-ball method and evaluated on the basis of indentation diameters and depths. For maple impregnated with nanoparticle-containing formulations and a 60-s vacuum, indentation diameters decreased from 4.96-2.84 mm, a 42.7% decrease, and indentation depths decreased from 0.172-0.027 mm, a 84.3% decrease. For both maple and oak, impact resistance of wood treated with the short vacuum process improved dramatically and abrasion resistance of the surface-densified wood also improved. Weight loss caused by abrasion testing decreased as a result of treatment. Overall, surface hardness improvement, indentation depth and diameter decrease, and Taber abrasion resistance improvement with limited chemical penetration into the product surface achieves a good balance between performance and cost, particularly with respect to flooring.

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