THE INFLUENCE OF CEMENT/WOOD RATIO AND CEMENT TYPE ON BENDING STRENGTH AND DIMENSIONAL STABILITY OF WOOD-CEMENT COMPOSITE PANELS[1]

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ABSTRACT

This study examined the influence of decreasing cement/wood ratios from 3.0 to 1.5 at 0.5 increments on flexural and dimensional stability properties of cement-bonded composite panels. In addition, two types of Portland cement (I and III) were employed to assess if a difference exists in properties over time between the two types. Cure periods were reduced from 28 to 14 days to investigate whether significant reductions occur in these properties.

Results indicate that modulus of rupture increases as the cement/wood proportion is lowered. A cement/wood ratio of 2.0 was found to demonstrate optimum bending strength. Modulus of elasticity, however, increased linearly with greater cement/wood ratios. Generally, wood-cement panels made in this study exhibited high dimensional stability when exposed to a 24-hour water soak. No significant differences were observed between the Lehigh cement types used in this study believed to be due to compound composition similarities. In most cases, reducing cure periods from 28 to 14 days had little influence on board properties.

Keywords: Wood-cement panels, modulus of rupture, modulus of elasticity, bending strength, dimensional stability.

INTRODUCTION

Cement-bonded wood composite panels are not a novel concept, having been on the market for over 70 years. In the past, these panels have consisted of excelsior and magnesite and have been used primarily as low-density insulation materials. By the early 1960s, a high-density cement-bonded structural flakeboard was developed leading to expanded applications (Deppe 1974). Today, wood-cement panels (WCP) have found acceptance in a number of countries as a result of certain desirable characteristics. Unlike conventional urea- and phenol-formaldehyde particleboard, WCP possesses high fire, insect, and fungal resistancy in addition to good weatherability and acoustic insulation. These qualities could provide a

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market niche in the United States for special applications where such properties are necessary.

Several problems, however, have hindered the development of a wood-cement panel industry in the United States. The primary difficulties include high species selectivity and heavy weight. Cement does not bond equally well with all wood species. Some species such as lodgepole pine (*Pinus contorta* Dougl.) bond well, whereas others such as western larch (*Larix occidentalis* Nutt.) present problems in cement bonding (Moslemi et al. 1983). The weight of the panel, largely brought about by cement addition, also has been a significant drawback that adversely affects the economics of WCP as a commercial building component. Since cement is more expensive than wood residue, adding greater quantities of cement will increase panel raw material costs.

The main purpose of this study was to address the weight problem using a wood species that has proven to be compatible with cement, specifically lodgepole pine. In a prior study, Moslemi et al. (1983) reported that lodgepole pine is one of the least inhibitory commercial softwood species in the Northern Rocky Mountain Region based on hydration parameters. Furthermore, lodgepole pine occupies more than 12 million acres (270 million dry tons) in this region and is an underutilized wood species. More than half of the growing stock (dry weight basis) is 6–8 inches at dbh in overmature or stagnant timber stands that are highly susceptible to insect and disease infestation. Hence, there is a need to economically convert lodgepole pine to wood products.

Currently, commercial WCP, incorporating 2.75 to 3.0 parts of portland cement to 1.0 part of wood particles (weight basis) are reported to attain acceptable mechanical and physical properties (Bahre and Greten 1977). Cement, as pointed out earlier, is a costly component of these boards, primarily due to the large quantities required. In addition, high cement/wood ratios yield heavy boards, resulting in increased shipping and handling costs. The economics of this technology may become more favorable if the proportion of cement in WCP can be reduced without significantly impairing properties. Reducing the cement/wood ratio would lower panel weight and would result in cost effectiveness by decreasing the percentage of cement and thus increasing the less expensive wood residue. A number of studies (Cziesielski 1975; Huffaker 1962; Kayahara et al. 1979; Namioka et al. 1976; U.S. Patent 1983; Prestemon 1976; Simatupang 1979) have reported the effect of cement/wood proportion on WCP properties, but the results vary widely depending on particle geometry, treatments, wood species, panel density, type of test, and other factors.

A primary objective of the study reported here was to examine such properties as bending strength and dimensional stability utilizing lodgepole pine at different cement/wood ratios. A secondary objective was to determine whether the type of cement is important in affecting the strength properties. An inherent manufacturing disadvantage of WCP is the long cure periods needed for cement to fully hydrate before attaining adequate strength. A type III (high early strength) portland cement is presently used commercially in WCP manufacture (Bison-Werke Bahre and Greten GmbH & Co. KG 1977). Schwartz and Simatupang (1983) confirmed the advantage of using type III cement when WCP containing Portland cement of a lower dicalcium and higher tricalcium silicate content is used. This type of

Table 1. *Chemical and physical composition of commerical portland cement types I and III, made by Lehigh Cement.*

Component	Composition (% wt.)	
	I	*III*
Chemical:		
Silica (Si_2)	21.4	22.0
Alumina (Al_2O_3)	5.6	4.0
Ferric oxide (Fe_2O_3)	2.0	3.4
Calcium oxide (CaO)	64.4	63.7
Magnesia (MgO)	2.6	1.9
Main compounds:		
Tricalcium silicate (C_3S)	50.5	51.5
Dicalcium silicate (C_2S)	23.3	24.2
Tricalcium aluminate (C_3A)	11.4	5.3
Tetracalcium aluminoferrite (C_4AF)	6.1	10.3
Physical:		
Specific surface (Blaine test method) (cm^2/g)	3,540	5,300
Time of set (Gillmore test method)		
Initial (h : min)	3:15	2:10
Final (h : min)	5:00	3:40
Compressive strength (psi)		
3-day	3,290	4,010

cement exhibited greater compressive strengths following a 24-hour cure period. Their study revealed that well-suited spruce wood demonstrated a strong correlation between compressive strengths and tricalcium silicate content, but the relationship was vague for less suitable beech.

EXPERIMENTAL METHODS

Three live lodgepole pine trees, averaging 66 years of age and 7 inches dbh, were felled in early spring and bucked to 14-inch bolts up to the crown base. After debarking, the bolts were reduced to flakes by means of a disk flaker, producing an average flake thickness of 0.022 inches (0.56 mm) with a standard deviation of 0.0024 inches. The green flakes were then spread out in rows 2 to 4 inches deep under ambient room conditions (approx. 22.2 C and 50% RH) until an average EMC of 9% (oven-dry basis) was realized. This step was included to minimize fungal degradation during storage before panel formation.

The air-dried flakes were flailed in a hammermill through a 4-mesh screen, followed by screening to a final $-8+16$ mesh particle size. Dimensions approximated wood geometry recommended by Kayahara et al. (1979) for optimum WCP bending strength. However, the random nature of hammermilling caused considerable variability in the slenderness ratio.

The bonding agent employed was commercial grade portland cement types I and III, meeting ASTM specification C-150 and made by Lehigh Cement Company. Chemical and physical characteristics of the two cement types are compared in Table 1. As noted in this table, appreciable differences exist in tricalcium aluminate composition with type I containing over twice that of type III. This type of cement demonstrated a higher specific surface and time of set values nearly 1.5 times those of type I, and a 3-day compressive strength slightly greater than type I. The tricalcium silicate and dicalcium silicate content of both cements obtained for this study was nearly identical, however. A type III cement normally contains a greater quantity of tricalcium silicate and lesser amounts of dicalcium silicate as compared to a type I cement.

For the cement used in this study, Lehigh achieves type III cement properties for concrete applications using the same type of clinker but refining the material to a finer powder, compared with "typical" data.

Calcium chloride ($CaCl_2$) is commonly introduced into the cement slurry to accelerate cement set during hydration (Neville 1981). Compared with other available accelerators (e.g., aluminum chloride, ferric chloride, diethanolamine, and sodium silicate), $CaCl_2$ is considerably lower in price while effectively enhancing WCP mechanical properties. Namioka et al. (1976) documented significant flexural strength increases in WCP when 3% (cement weight basis) $CaCl_2$ is incorporated.

In this study, preliminary hydration tests revealed that combining 1.5% $CaCl_2$ (cement weight basis) with lodgepole pine wood particles, water, and cement yielded maximum hydration temperatures that were 5 C below neat cement (i.e., 75 C vs. 80 C) with the same amount of $CaCl_2$. The times required to attain these temperatures were nearly identical. Since maximum hydration temperature and the time to reach maximum temperature are highly related to cement-wood compatibility (Sandermann and Kohler 1964; Yashiro et al. 1968; Weatherwax and Tarkow 1964), adding 1.5% $CaCl_2$ was felt to be adequate.

Once the wood furnish was screened to acceptable size, panel fabrication began. First, a 20-inch (508-mm) × 22-inch (559-mm) × 6-inch (152-mm) deckle frame was placed on a vegetable oil lubricated aluminum caul. Superimposed on the frame lay a similar form containing a #2 mesh screen to ensure uniform particle-binder distribution within the mat.

Following form setup, a predetermined quantity of air-dry wood particles and a $CaCl_2$ (anhydrous) distilled water solution were thoroughly blended. Cement was subsequently added, and the constituents were mixed until the cement paste completely hydrated. The quantity of distilled water added was calculated using a relationship developed by Simatupang (1979). In his formulation, the water requirement was determined as follows:

$$\text{water (liters)} = 0.35C + (0.30 - MC)W$$

where

C = cement weight (kg)
MC = wood MC (oven-dry basis)
W = oven-dry wood weight (kg).

After 5 minutes of manual mixing, the cement-wood-water mixture was screened onto the caul. Upon screen removal, the mat was evenly distributed to provide as uniform a density as possible, and prepressed to a thickness of 2–3 inches (51–76 mm).

Cold pressing took place under an initial pressure of 250–700 psi (1.7–4.8 MPa),

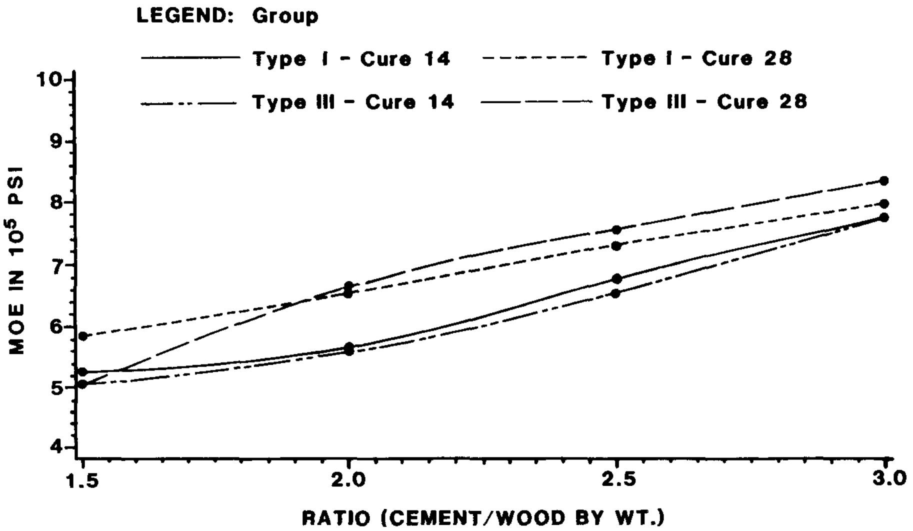

FIG. 1. Correlation of MOE with the cement/wood ratio for cement type and curing period.

depending on the cement/wood ratio to a 0.5-inch (13-mm) thickness, after which the panel was retained in compression for 24 hours.

Immediately following the 24-hour setting period, from each sample, four specimens measuring 14 inches (356 mm) × 3 inches (76 mm) were sawn and stored for final curing. To minimize cement capillary desiccation and enhance hydration, specimens were misted with distilled water, then wrapped in cellophane before storing at ambient room conditions.

Panel fabrication procedures were repeated for both cement types I and III at cement/wood ratios of 3.0, 2.5, 2.0, and 1.5 (by weight) with each treatment replicated 4 times.

After a 14- and 28-day curing period, two samples from each treatment were subjected to bending tests in accordance with ASTM D1037-78 (1979) specifications. From these test results, moduli of elasticity (MOE) and rupture (MOR) were determined.

Upon completing static bending tests, one 3-inch (76.2-mm) × 3-inch specimen and a 1-inch (25.6-mm) × 3-inch specimen were sawn one inch from either side of the bending fracture. The former specimen was retained to evaluate thickness swelling and water absorption after a 24-hour water soak, while the latter was used to determine panel density and moisture content at the time of test.

A general linear model was used to statistically analyze the WCP treatments involving bending strength and water absorption characteristics. Appropriate multiple comparisons using Tukey's studentized range test were performed for cement type, cement/wood ratio, and curing duration to determine whether significant differences existed between sample population means at a 5% level.

RESULTS AND DISCUSSION

As stated earlier, flexural strength data are based on MOE and MOR values. The MOE results, presented in Fig. 1, depict a near linear correlation between

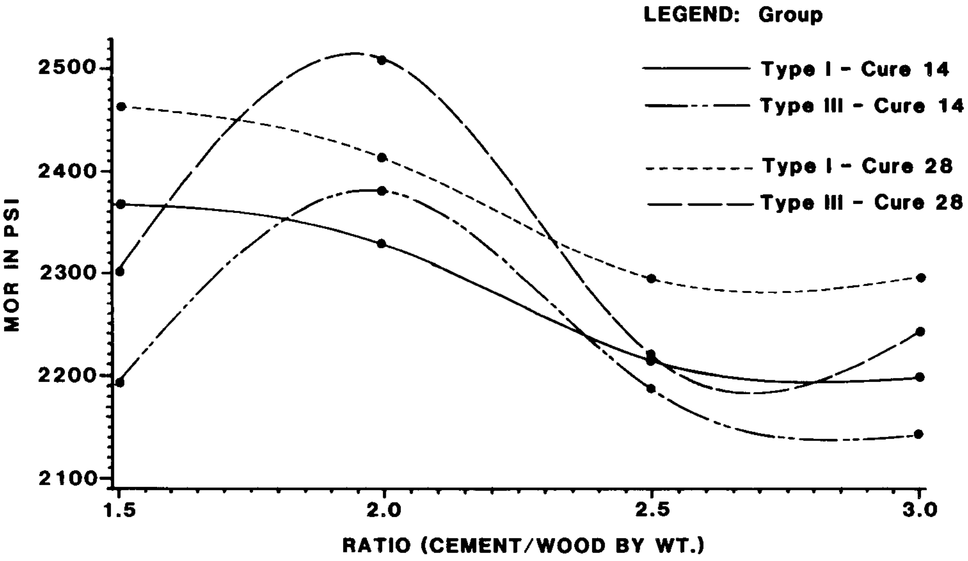

FIG. 2. Influence of cement/wood ratio on MOR for cement type and curing period.

MOE and cement/wood ratio. For these particular ratios, type III cement cured for 14 days loses stiffness at an increasing rate below a 2.0 cement/wood ratio. Stiffness characteristics are also more a function of cement/wood ratio than cement type. This relationship is based on the fact that cement is inherently a more rigid material than wood. Therefore, greater cement/wood ratios result in higher MOE values over the range covered in this study. These data closely agree with those

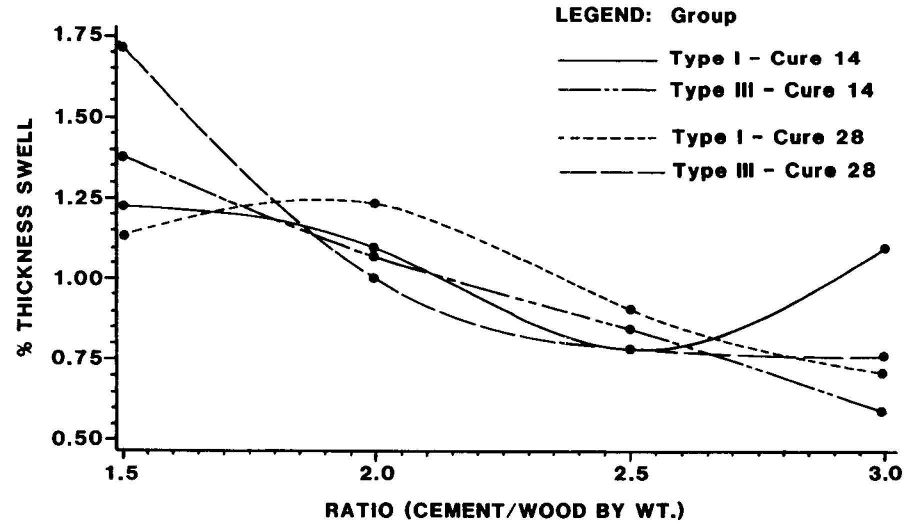

FIG. 3. Thickness swelling after 24-hour water immersion for cement type and curing period.

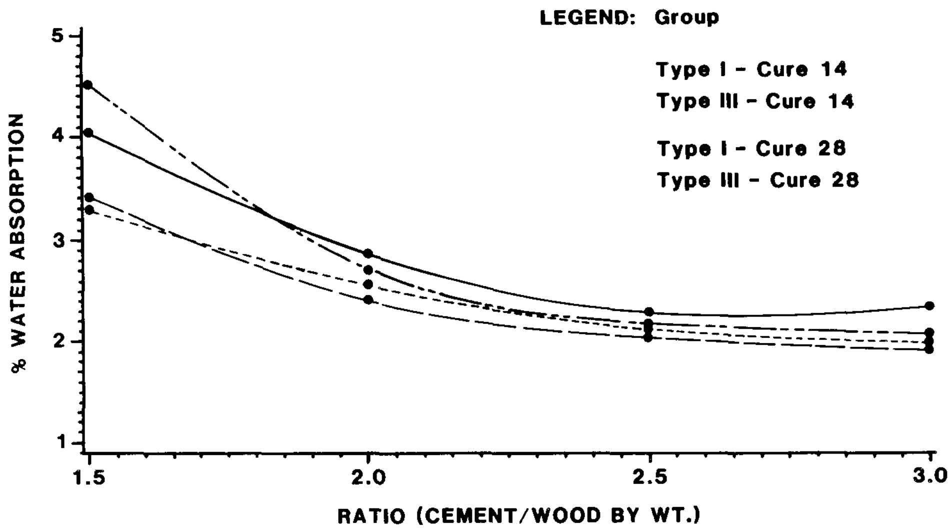

FIG. 4. Water absorption after 24-hour water immersion for cement type and curing period.

presented by Simatupang (1979) using a spruce furnish and testing WCP in compression after a 24-hour cure period.

The relationship between cement/wood ratio and MOR (Fig. 2) is considerably different from that of MOE. All MOR values are inversely related to cement/wood ratio from levels 3.0 to 2.0. Below a cement/wood ratio of 2.0, bending strength decreases for panels containing type III cement, but MOR continues to increase in the case of type I cement. Apparently, optimum ultimate bending strength for type II cement, as measured by MOR, is attained at a cement/wood ratio at or near 2.0 under the given conditions.

It is not entirely clear as to why the panels containing type III cement show a maximum MOR at a cement/wood ratio of approximately 2.0. It is known that the presence of aggregate in concrete induces stress concentrations at the aggregate–cement interface (Sorka 1979). As wood particle volume increases, these regions of stress concentration around adjacent particles become more diffuse, resulting in an increased resistance to the stresses applied. For example, concrete strength increases because of a decrease in the average stress concentration caused by inclusion of smaller aggregate particles. Larger quantities of aggregate distribute internal stresses over a larger specific surface per unit volume, reducing areas of high stress concentration where critical failure is more likely to occur. However, the reduced cement quantity must remain high enough to afford a complete matrix formation. At or just below the 2.0 cement/wood ratio, complete matrix formation may not occur, thereby impairing panel strength. The same explanation probably holds true for type I panels near the 1.5 cement/wood ratio.

Figure 3 indicates reduced thickness swelling with increased cement/wood ratio after a 24-hour soak period. Again, no significant differences between cement type and curing time are observed as these pertain to thickness swelling. The "encased" nature of wood within the WCP panel probably restricts wood from expanding volumetrically. Nonetheless, maximum thickness swelling is 1.7%, substantially

TABLE 2. *MOE and MOR by cement type, cement/wood ratio and curing time.*[a,b]

Cement type	Ratio	14-day MOE			28-day MOE		
		(10^5 psi)[c]	(MPa)	Std. dev.	(10^5 psi)[c]	(MPa)	Std. dev.
I	3.0	7.76 a[d] a[c]	(5,351)	0.559	7.97 a[d] a[e]	(5,495)	0.909
I	2.5	6.78 ab a	(4,675)	0.308	7.31 ab a	(5,040)	0.985
I	2.0	5.69 bc a	(3,923)	0.989	6.55 bc b	(4,516)	0.187
I	1.5	5.25 c a	(3,620)	0.093	5.84 c a	(4,027)	0.348
III	3.0	7.75 a a	(5,344)	0.152	8.36 a a	(5,764)	0.841
III	2.5	6.56 ab a	(4,523)	0.272	7.59 ab b	(5,233)	0.372
III	2.0	5.60 bc a	(3,861)	1.265	6.65 b b	(4,585)	0.356
III	1.5	5.04 c a	(3,471)	0.130	5.05 c a	(3,482)	0.051
		14-day MOR			28-day MOR		
		(psi)	(MPa)	Std. dev.	(psi)	(MPa)	Std. dev.
I	3.0	2,197 b[d] a[e]	(15.1)	114	2,296 b[d] a[e]	(15.8)	230
I	2.5	2,213 b a	(15.3)	51	2,294 b a	(15.8)	98
I	2.0	2,328 ab a	(16.1)	188	2,412 ab b	(16.6)	102
I	1.5	2,367 ab a	(16.3)	86	2,463 ab a	(17.0)	91
III	3.0	2,142 b a	(14.8)	99	2,241 b a	(15.5)	176
III	2.5	2,185 b a	(15.1)	163	2,218 b b	(15.3)	89
III	2.0	2,380 a a	(16.4)	143	2,508 a b	(17.3)	141
III	1.5	2,194 ab a	(15.1)	84	2,302 ab a	(15.9)	149

[a] All MOE and MOR values are corrected to a base specific gravity of 1.250.
[b] Each value represents the mean of 4 replications.
[c] Means with the same letters are not significantly different at the 5% level using Tukey's studentized range test.
[d] Pairwise comparisons between cement/wood ratios.
[e] Pairwise comparisons between cure periods.

below the magnitude (5–20%) found in resin-bonded particleboard subjected to similar conditions.

The relationship between water absorption and panel cement/wood ratio and curing period is illustrated in Fig. 4. No significant difference exists over the cement/wood ratios of 2.0–3.0. But when the cement/wood ratio is reduced to 1.5, water absorption increases substantially. At the 1.5 cement/wood ratio level, water absorption varies more because of curing period than cement type. A 28-day cure brings about approximately a 1% decrease in water absorption when compared with a 14-day cure for panels containing type III cement. The reduction is slightly less for type I as compared to type III. The only difference between cement types occurs after a 14-day cure when the type I panel absorbed 0.5% less water than the type III. Although differences exist at the 1.5 cement/wood ratio level, these represent insignificant variations.

Static bending results (Table 2) show that significant differences occur in MOE with changing cement/wood ratios and the differences are identical regardless of cement type or cure period. In each of the cement types and cure period pairings, MOE values obtained at cement/wood ratios 3.0 and 2.5 were significantly greater than a 1.5 ratio, while the data for ratios 2.5 and 2.0 were not significantly different. Likewise, cement/wood ratio levels of 2.0 and 1.5 were not significantly different, except in the case of type III cement cured for 28 days at a 2.0 ratio, which was greater than a similar panel composed of a 1.5 cement/wood ratio. Modulus of elasticity increased with cement/wood ratio, independent of cement type and cure length.

TABLE 3. *A comparison of strength gains for the 14- and 28-day cure times.*

Type	Ratio	MOE 14/28 (days) (%)	MOR 14/28 (days) (%)
I	1.5	89.9	96.1
I	2.0	86.9	96.5
I	2.5	92.7	96.5
I	3.0	97.4	95.7
III	1.5	99.8	95.3
III	2.0	84.0	94.9
III	2.5	86.4	98.4
III	3.0	92.7	95.6

Conversely, cement/wood ratio did not significantly influence MOR for panels containing type I cement. For type III cement, panels consisting of 2.0 cement/wood ratios displayed MOR values significantly higher than the three other levels examined in this study.

Panel specific gravity varied with cement/wood ratio because of springback and increased wood quantities. Mean specific gravity was 1.347 (std. dev. 0.0796), ranging from 1.214 to 1.430. To nullify the effect of specific gravity variations, all bending strength data were transformed to a base specific gravity of 1.250 to parallel industry standards for structural WCP.

Table 2 illustrates that no significant differences exist between bending strengths

TABLE 4. *Percent thickness swelling (T.S.) and water absorption (W.A.) after a 24-hour water immersion.*

		Cure period					
		14 days			28 days		
Type	Ratio	T.S. (%)[b]	Std. dev.	MC (%)[c]	T.S. (%)	Std. dev.	MC (%)[c]
I	1.5	1.225 a	0.368	19.3	1.134 a	0.212	18.5
I	2.0	1.093 a	0.340	17.8	1.229 a	0.338	17.4
I	2.5	0.779 a	0.190	16.9	0.900 a	0.166	16.4
I	3.0	1.091 a	0.438	16.9	0.705 a	0.411	16.2
III	1.5	1.380 a	0.121	19.6	1.715 a	0.201	18.5
III	2.0	1.065 a	0.145	18.6	0.995 a	0.238	18.1
III	2.5	0.840 a	0.365	17.5	0.781 a	0.054	17.2
III	3.0	0.585 a	0.245	17.4	0.756 a	0.264	17.4
		W.A. (%)	Std. dev.	MC (%)	W.A. (%)	Std. dev.	MC (%)
I	1.5	4.030 a[d] a[e]	0.262	19.3	3.286 a[d] b[e]	0.325	18.5
I	2.0	2.861 b a	0.105	17.8	2.554 b a	0.138	17.4
I	2.5	2.284 c a	0.122	16.9	2.115 c a	0.126	16.4
I	3.0	2.342 c a	0.085	16.9	1.975 c a	0.193	16.2
III	1.5	4.529 a a	0.102	19.6	3.415 a b	0.389	18.5
III	2.0	2.721 b a	0.169	18.6	2.406 b a	0.151	18.1
III	2.5	2.179 c a	0.060	17.5	2.033 bc a	0.084	17.2
III	3.0	2.064 c a	0.029	17.4	1.899 c a	0.246	17.4

[a] Each value represents the mean of 4 replications.

[b] Means with the same letters are not significantly different at the 5% level using Tukey's studentized range test.

[c] Mean initial moisture content at time of test.

[d] Pairwise comparisons between cure periods.

TABLE 5. *Bending property comparisons of WCP with property requirements of mat-formed wood particleboard (ANSI A208.1–79).*

Conventional particleboard			Wood cement panels		
Grade	MOR (psi)	MOE (psi)	Cement : wood ratio	MOR[c] (psi)	MOE[c] (psi)
1-H-1[a]	2,400	350,000	1.5	2,367	525,000
1-H-2	3,000	350,000	2.0	2,328	569,000
1-H-3	3,400	400,000	2.5	2,213	678,000
			3.0	2,197	776,000
2-H-1[b]	2,400	350,000			
2-H-2	3,400	400,000			

[a] High density particleboard made with urea-formaldehyde resins or equivalent bonding systems.
[b] High density particleboard made with phenol-formaldehyde resins or equivalent bonding systems.
[c] WCP panels containing type I portland cement cured for 14 days with 4 replications per ratio level.

of type I and type III cement used in this study. European researchers (Schwartz and Simatupang 1983) attribute strength gain in different cement types to the proportion of tricalcium silicate and dicalcium silicate present. As pointed out previously, the tricalcium silicate and dicalcium silicate components of the particular cement types employed in this study were nearly identical. An additional reason for similarities in strength data between the two cement types is the fact that type III produces higher strengths at very early stages of hardening (1–7 days) but generates nearly equal strength data after the first two weeks. Thus, testing at 14 and 28 days is not likely to reveal the differences.

Curing duration did not influence MOR at any cement/wood ratio, but it significantly increased MOE. These increases occurred at a 2.0 cement/wood ratio for both cement types, in addition to a 2.5 cement/wood ratio for type III. Prolonged curing intervals did not enhance panel bending strength significantly whether cured for 14 or 28 days.

Table 3 supports the finding that MOE is somewhat more dependent on cure period than is MOR. In all but two instances, MOR gains a greater percentage of its 28-day strength in 14 days as compared with MOR.

Dimensional changes (Table 4), although relatively low in magnitude, are considerably more variable for water absorption than thickness swelling. No significant statistical differences in thickness swelling were detected for any treatments used. Increased wood content significantly increased water absorption below a 2.0 cement/wood ratio. Furthermore, significant differences in water absorption occurred between ratio levels 2.0 and 1.5.

Comparing WCP bending strength properties to those required of commercial mat-formed, resin-bonded wood particleboard (ANSI Standard A208.1-79) reveals that WCP panels consisting of type I portland cement and cured for 14 days surpass MOE requirements of high density (>50 pounds per cubic foot) grade boards (Table 5). On the other hand, MOR values for WCP made in this study fell below those of standard particleboard.

CONCLUSIONS

The bending strength (MOR) of wood-cement composite panels made with lodgepole pine and Lehigh portland cement types I and III was significantly enhanced by decreasing the cement/wood ratio from 3.0 to 2.0. Board stiffness (MOE) was reduced by the same treatment, however. In general, doubling the cement curing time from 14 to 28 days only marginally improved panel MOR, MOE, or dimensional stability. The cement types used resulted in homogeneous panel behavior probably because of similar compound composition of cements and test data collection exceeding a week. On the whole, wood-cement particleboard was dimensionally stable after a 24-hour water soak.

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