Assessment of Cement-Bonded Wood Composites as Means of Using Low-Valued Wood for Engineered Applications

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Abstract

A pilot study was conducted to characterize mechanical properties of cement-bonded wood composites of importance to structural applications. Two categories of cement-bonded wood composite panels were fabricated and tested. The first category was manufactured using ribbon-like wood particles called excelsior, which can be produced from low-quality forest thinnings. The second category used a varied particle geometry produced by grinding wood waste in a commercial tub grinder. Variables included particle geometry, chromated copper arsenate (CCA) treatment, wood species, method of panel formation, and composite density. Results support the premise that cement-bonded wood composites have capability for structural applications. Despite their relatively low strength compared to that of most other structural materials, these composites appear to have sufficient strength and bending resistance to serve as in-fill wall panels. They have potential for resisting freeze-thaw environments given the correct cement particle mix, and they exhibit energy-dissipative ductile failure modes, which suggests potential for applications subject to dynamic and impact load. These results should be useful to those interested in research on the development and use of structural products from cement-bonded wood composites.

Keywords: Wood-cement panels, freeze-thaw durability, modulus of rupture, modulus of elasticity, bending strength

Introduction

Cement-bonded wood composites (CBWCs) have been used in the United States for more than 60 years. As a general class of material, there is wide variation in form and function. High density products (1.5 to 2 g/cc) containing wood fiber amounting to 5% to 10% of the weight of the cement are often used in applications that require a durable wear-resistant surface, such as roof shingles or siding. Lower density materials (0.5 to 1 g/cc) have traditionally been used where sound absorption and fire resistance are important. Little attention has been given in the literature to the performance of these materials in engineered applications.

In recent years, CBWCs have received renewed attention as “environmentally friendly” materials. They provide a use for low quality wood that is resistant to fire, decay, and insect attack, involves no toxic chemicals, and can be broken down to relatively inert landfill at the end of service life. In tropical countries, CBWCs hold promise for adding value to the tropical timber resource as a source of building materials, rather than a nuisance that must be cut and burned to clear land for agriculture. In the United States, CBWCs could provide uses for wood waste and low-quality forest thinnings.

Low-density CBWCs offer advantages for structural applications. However, their use is discouraged in engineering applications by a lack of information defining strength and durability performance. Research to define performance limits and to identify strength properties within these limits is the first step to developing a new class of materials designed to reuse rather than dispose of wood waste.

Objective and Scope

The objective of this paper is to present information useful in judging the efficacy of future research to

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evaluate engineering properties of CBWCs fabricated using low quality wood resources. Experimental panels were fabricated from materials representative of low-value wood resources: an excelsior that could be obtained from forest thinnings and untreated and CCA-treated construction waste. Tests were conducted to evaluate bending strength, stiffness, and freeze-thaw durability. Strength of a laboratory-made cement-bonded excelsior panel was compared to that of a commercially produced structural cement–excelsior panel considered to represent the state of the art for low-density, high wood content cement composites. A CBWC was evaluated for potential use in highway sound barrier applications.

Materials

Composite properties presented in this paper were taken from two independent studies conducted at the USDA Forest Service Forest Products Laboratory (FPL). The first study (Wolfe and Geimer, in preparation) involved an initial evaluation of composites made using a ribbon-like particle called excelsior. The study assessed effects of species, excelsior geometry, and processing on composite strength and stiffness. The second study (Wolfe and Gjinolli, in preparation) was conducted using a short chunk-type particle formed by grinding construction waste material; it assessed the potential for using low-value waste material to form a composite suitable for use in highway sound barriers.

Table 1 summarizes the differences in the composites tested in these two studies. Samples I–IV were fabricated with excelsior. Sample I was taken from commercially produced structural panels that consisted

Table 1—Fabrication of cement-bonded wood composites[a]

		Particle[b]					
	Sample	Species	Geometry	Wood/ cement	H_2O/ cement	Additive	Forming method[c]
I	Comm. excels.	SP	515	0.67	0.34	5% $CaCl_2$	Continuous press
II	Lab excels.	Poplar	604	0.40	0.60	5% $CaOH_2$ CO_2	Static press
III	Lab excels.	Poplar	732	0.40	0.60	5% $CaOH_2$ CO_2	Static press
IV	Lab excels.	Poplar	604	0.40	0.60	4% $CaCl_2$	Static press
V	Cement-bonded wastewood	CCA-treated SP	3–13 mm dia × 13–30 mm L	0.54	0.52	4% $CaCl_2$	Low pressure plus vibration
VI	Cement-bonded wastewood	CCA-treated SP	3–13 mm dia × 13–30 mm L	0.57	0.53	4% $CaCl_2$	Low pressure plus vibration
VII	Cement-bonded wastewood	CCA-treated SP	3–13 mm dia × 13–30 mm L	0.52	0.52	4% $CaCl_2$	Low pressure plus vibration
VIII	Cement-bonded wastewood	SP	3–13 mm dia × 13–30 mm L	0.54	0.70	4% $CaCl_2$	Low pressure plus vibration

[a] Abbreviations: SP is Southern Pine; Comm. excels., commercially made excelsior.

[b] Excelsior code: first digit is thickness in units of 0.003 in. and remaining digits represent reciprocal of strand width in inches. L is length. (Note 1 in. = 25.4 mm)

[c] Low pressure method used 0.5 Hz vibration.

of Southern Pine excelsior with portland cement binder. Samples II, III, and IV were formed at the FPL using poplar excelsior and portland cement. The water/cement ratio includes the water necessary to hydrate the cement while maintaining fiber saturation in the wood particles. In general, this required a quantity of water equal to 50% of the weight of dry wood plus 25% of the weight of cement. Additives were used to accelerate the hydration process, resulting in less press and cure time to the point when the panels could be handled. The amount of additive required varied with species and the presence of free sugars, which tend to inhibit cement hydration. The laboratory-made boards were also produced to compare the effects of using CO_2 gas injection to accelerate cement hydration.

Variations in the fabrication procedures for these composites may also have a major influence on their strength, stiffness, and durability. The commercially produced composites were formed using a conveyor system and proprietary combing tines to impart directional properties to the final product. These panels were pressed to a thickness of 38 mm (1.5 in.), then cut to lengths of 2.44 m (8 ft) and trimmed to a width of 0.81 m (2.7 ft). The laboratory-made excelsior panels were manufactured in a small stationary press to a thickness of 38 mm (1.5 in.) and plan dimensions of 0.61 by 0.66 m (2 by 2.2 ft). In this case, excelsior particles coated with cement were formed by hand into a thick mat with random alignment and then pressed while CO_2 gas was injected through the mat to accelerate hydration. After pressing, the panels were trimmed to square the edges.

Samples V through VIII were made in a commercial press called a dry-cast molder, in which a combination of pressure and vibration was used to compress the cement-wood mat into a steel form 1.22 m (4 ft) on a side by 15 mm (0.6 in.) thick. Samples V through VII were made from CCA-treated Southern Pine particles and Sample VIII from untreated Southern Pine particles. The particles were formed using construction waste ground and splintered to chunk-type geometry using a commercial tub-grinder. For sample V, the particles were sifted through a 6-mm (0.24-in.) mesh screen to remove many fines from the mix; for sample VI, the fines were left in the mix and sample VIII had negligible fines.

A relatively low pressure, ranging from 69-140 Pa (10-20 lb/in^2) was used in conjunction with low frequency vibration (0.5 Hz) to compact the mat in the form. After the panels were taken from the forms, they were cured in a hydration kiln for 14 days at 20°C to 30°C.

Procedures

The tests reported here were conducted as individual phases of a program to consider potential engineered uses for CBWCs. The commercial excelsior panel (sample I) and laboratory-made excelsior panels (samples II-IV) were intended for use in building applications. The commercial panels are currently used as fire-resistant acoustic panels and are recognized as structural in some applications where they serve as diaphragms as well as plate elements. This material served as a basis for evaluating similar experimental panels. The laboratory-made excelsior panels were evaluated as a possible alternative product that would be made from lower value forest thinnings. The waste-wood panels (samples V–VIII) were evaluated for their durability in the freeze-thaw environment required for highway noise barrier applications.

Sample Preparation

Bending test spans varied with the composite product and its intended application. The commercial panels provided 53 bending test specimens 130 mm (5 in.) deep and of varying spans to evaluate the influence of shear displacement on bending stiffness. The laboratory-made excelsior panels provided ten 610-mm- (24-in.-) long by 130-mm- (5-in.-) wide specimens for each panel type.

Ten third-point bending specimens were cut from each wastewood panel and 12 freeze-thaw durability specimens were cut from all panels except sample VII. Each panel was divided into nine sections, each 406 mm (16 in.) square (Fig. lB). These sections were denoted as representing one of three distinct zones (A, B, C) of possible variation in cross-section uniformity and density. Durability specimens cut from each of these zones were identified in an effort to detect any location effects on density or durability. Bending test samples 816 mm (32 in.) long were taken from A-B zones of each panel.

The equipment used for the freeze-thaw tests dictated the dimensions of the wastewood bending specimens. A programmable Humbolt HM-20 weatherometer maintained by the University of Wisconsin Civil Engineering Department required samples cut in the form of prisms 76 mm (3 in.) thick by 102 mm (4 in.) wide by 406 mm (16 in.) long. These requirements set the cross-section dimensions used for both freeze-thaw and bending test specimens.

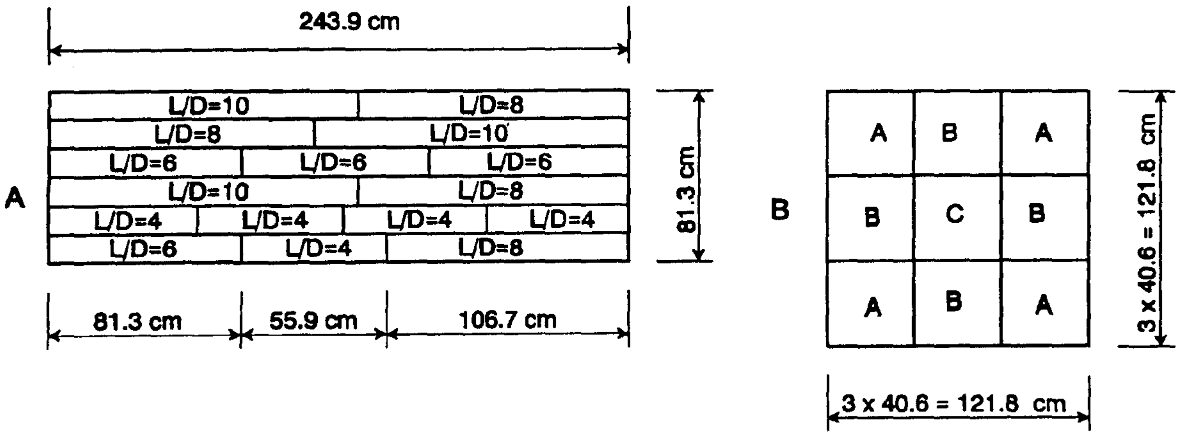

Figure 1—Cement-bonded wood composite (CBWC) panels. (A) Cutting pattern for cement/excelsior board samples; (B) panel zones for cement/wastewood samples.

Test Methods

Test methods referenced in this study included ASTM D 198 (ASTM 1992) for third-point bending, the Wisconsin Department of Transportation (1993) certification of noise barriers, and ASTM C 666 (ASTM 1990) for freeze-thaw durability.

For samples I through IV, density was determined using oven-dry weight and gross volume measured at ambient conditions compatible with a 12% equilibrium moisture content (EMC) in wood. For the wastewood study, density measurements were determined for the full-sized test specimens on the basis of mass and volume measured under ambient conditions of 19°C (66°F) and 80% relative humidity. At these conditions, water would constitute 16% of the mass of the wood, which is half the weight of the material. However, it is difficult to determine what portion of the weight of the cement is water.

For this study, variation in density had little influence on performance across composite types but was significant within composite type. For purposes of comparing density within panel type, we therefore report a "density index." For samples I through IV, the density index is specific gravity. For samples VI through VII, the density index is weight per unit volume measured at ambient conditions and reported as a fraction of the weight of water.

***Strength and* Stiffness** —Bending strength and stiffness were evaluated using third-point bending tests conducted in accordance with ASTM D 198. The specimens were supported by metal bearing plates to prevent damage to the beam at the point of contact between specimen and reaction support. The bearing plates were supported on one end by rollers and on the other end by fixed knife edge reaction. Commercially produced excelsior boards were tested to the point of maximum load. The wastewood samples were tested to well beyond maximum load in an attempt to characterize the energy-dissipative behavior of these composites.

Datability-Freeze-thaw durability was evaluated using a hybrid of the ASTM C 666 standard (ASTM 1990) and that described by the Wisconsin Department of Transportation (1993) to accommodate the material and objectives of this pilot work. The Wisconsin Department of Transportation recommendation for freeze-thaw tests calls for a "diked flat surface" on which a 6-mm- (0.25-in.-) deep 3% NaC12–water solution is pooled for cyclic freezing and thawing. The sample is then evaluated on the basis of deterioration of the exposed surface. Mass loss is limited to 0.96 kg/m^2 (0.20 lb/ft^2). The porosity of the CBWC limits its ability to contain a liquid. We therefore used the ASTM C 666 standard test for rapid freeze-thaw of concrete, which involves total immersion of the test sample. This test not only exposed all surfaces of the sample but also subjected the entire mass to saturation. It was therefore deemed a more rigorous test than that requird by the Wisconsin Department of Transportation.

The weatherometer used for these tests can be programmed to cycle temperature conditions on the basis of a combination of cycle time and temperature at the core of one of the samples. The weatherometer is composed of refrigeration and heating units that control temperatures in a liquid-filled stainless steel tank. Test specimens were placed in individual pans within the chamber; a temperature sensor was sealed in the core of one specimen. Programmed minimum and maximum temperatures in the monitored specimen triggered the change from heating to cooling cycles and vice versa. Temperature extremes were set at -12.2°C to 12.3°C (10°F to 54°F). Once these extremes were met, the temperature was maintained for a period considered sufficient to attain uniform temperature at that extreme prior to changing the temperature in the chamber. One cycle was completed every 8 to 10 h with 5.5 to 7 h for freezing and 2.5 to 3 h for thawing.

The ASTM C 666 test for freeze-thaw of concrete suggests two methods of monitoring material deterioration. One involves a periodic measure of stress-wave transit time. The other is a periodic measure of particulate matter that is drained along with the salt solution. In an initial series of freeze-thaw tests, an attempt to use a stress-wave timer proved to be not only ineffective but slightly detrimental. We saw no significant change in stress-wave time with cycling. However, we observed fractures in several specimens from samples VI and VIII after several stress-wave tests. In the chance that these fractures were caused by hammer blows required to get a stress-wave signal in the saturated samples (making them more vulnerable to freeze-thaw damage), we conducted a second series of tests with no stress-wave monitoring.

Evaluation of mass retention was based on a comparison of sample weight after 50 cycles of freeze-thaw and subsequent drying in a conditioning room to weight determined at the same environmental conditions just prior to the freeze-thaw test. These measurements were used along with the evaluation of sample appearance to judge durability.

Results

Results of the density and bending strength tests are shown in Table 2. Because of the variations in sample size and composite configuration, comparisons across the various samples are of limited value. Within each sample, the variation in density was relatively low. Targets for the excelsior-type panels were in the range 0.3 to 0.6, the range in which these composites may be easily machined using common carpenter tools. For sound barrier applications, higher density is desirable. There seemed to be no consistent variation in density among the panels.

Strength and Stiffness

The contrast between the excelsior and chunk-type particle composites suggests that long, thin strands (samples I-IV) provide greater strength. The higher density of the chunk-type particle panels reflects less void space and more continuous bonding of cement. This resulted in higher initial stiffness than that obtained for samples II through IV. Strength varied with excelsior strand aspect

Table 2–Results of tests on cement-bonded composites[a]

		Density[b]		Modulus of rupture		Modulus of elasticity	
Sample	n	Index	COV (%)	MPa	COV (%)	GPa	COV (%)
I	53	0.62	13	3.53	24	2.60	27
II	10	0.52	6	1.39	22	1.06	23
III	10	0.53	11	1.65	20	1.20	30
IV	11	0.51	8	1.30	20	1.01	21
V	10	0.90	7	0.87	28	1.14	22
VI	10	1.03	15	1.22	20	1.90	13
VII	10	1.16	21	1.31	19	2.60	18
VIII	10	0.96	18	1.11	22	1.77	17

[a] 1 lb/in^2 = 6.894 kPa.

[b] Density index is specific gravity for samples I–IV and weight/volume at 19°C (66°F) and 80% RH for samples V–VIII.

ratio and panel density. Among the three laboratory-made excelsior panels, the use of carbon dioxide had little effect on strength or stiffness. The factor that appeared to have the greatest effect was the aspect ratio of the individual fibers: narrow fibers were better than wide ones. For the four chunk-type particle panels, density appeared to exert the strongest influence on strength. Sample V, which was fabricated using about half the fabrication pressure used for the other panels, had the lowest strength values and sample VII the highest. Sample VII had more small fibers and fewer void spaces than the other panels. In all cases, the predominant failure mode was tension in the constant moment section.

Ductility

The chunk-type particle composites showed fairly elastic behavior to the point that the cement matrix began to crack and exhibit characteristic ductile failure beyond maximum load. Figure 2 shows a typical load-deflection curve measured for the bending test- Load was increased in a linear manner (zone I) to roughly 75% of the maximum load. Maximum load (zone II) represented failure of the cement matrix, beyond which the load dropped off in a ductile manner. The area under the load-displacement curve, which represents energy absorption or toughness, averaged 6.6 times the energy at the first crack by the time it reached a deflection three times the displacement at first crack of the binding matrix. For fiber-reinforced cements, this value averages 5 (ASTM C 1018; ASTM 1989). We did not load these specimens beyond 2.5 mm (0.098 in.) displacement but at that point sample VII averaged 22 times the area at first crack of the cement matrix.

Durability

Samples subjected to accelerated freeze-thaw tests exhibited a range of responses. In all cases, there was a noticeable bleaching of the exposed surfaces as cement particles were washed away. In some cases, this was the extent of the damage. For samples VI and VIII, some specimens were broken into two or more pieces, with substantial mass loss between the pieces. This was especially prevalent for untreated wood specimens from sample VIII. The lower density treated wood specimens from sample V fared best, with little sign of cracking or spalling in either series 1 or 2. Visual damage, attributed to stress-wave impact, was confined to samples VI and VIII in the first series of freeze-thaw tests. This led us to discount the series 1 data as stress-wave measurements were not part of the requirements of the Wisconsin Department of Transportation tests.

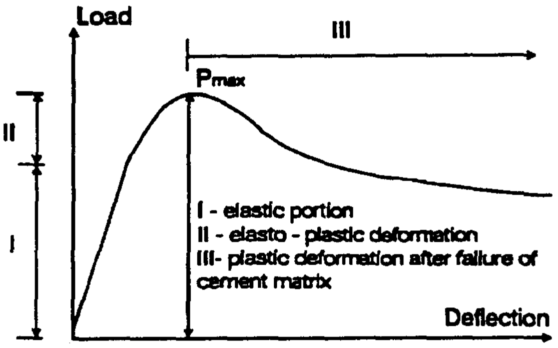

Figure 2—Characteristic load–deflection plot for bending test of wastewood samples.

All samples exhibited some swelling. In general, swelling was symmetrical with some directional bias. For samples taken from an outside edge, the cement-coated outer surface did not swell as much as the surface with exposed wood end-grain; for these specimens, the swollen cross-section appeared slightly warped. Some specimens swelled enough to bind in the weatherometer pans, making them difficult to remove until they had dried. As with conventional wood-based composites, the samples did not return to their pressed shape upon drying, but retained a slightly swollen volume.

Analysis

The analysis of results indicated that panel strength and durability can be controlled to some extent by using the proper fiber geometry and mix of wood, cement, and water. There seems to be some tradeoff between strength and durability of the chunk-type wastewood composites. For the samples tested, low density composites exhibited less mass loss but lower strength than did higher density samples.

Density —The commercial cement-bonded excelsior panels had higher density than that of the laboratory-made excelsior panels, but the difference does not seem to be enough to account for the difference in MOR (Fig. 3). It is likely that this result was due in part to differences in particle alignment and in part to the effect of the different kinds of excelsior used.

Bending Strength —Figures 4 and 5 show scatter plots of MOR and MOE versus density index with a least squares fitted regression. In all cases, strength and stiffness increased with density, with slightly less scatter around the regression for MOE than for MOR. The commercial composites were stronger than any of the test composites, although stiffness of the high density wastewood composite was comparable to that of the slightly lower density commercially produced CBWC. Compared to the properties of a structural panel such as oriented strandboard, which has an MOR of 30-50 MPa and MOE of 50 GPa, it is obvious that CBWCs have much lower properties (Forest Products Laboratory, 1987). For CBWCs, MOR was 5%-10% and MOE was 10%-20% that of oriented strandboard.

Durability -The durability of three test samples on the basis of retained mass after 50 cycles of freeze-thaw in a salt solution is shown in Figure 5. Each specimen had a surface area of 0.16 m^2 (1.7 ft^2). The Wisconsin Department of Transportation requirement of no more than 0.96 kg (0.20 lb/ft^2) mass loss per square meter translates to a loss of 150 g or a 4%-6% mass loss for samples tested in this study. Sample V specimens performed best; no specimens had a final mass below 95% of the initial mass (Fig. 5). The untreated wastewood sample (VII) performed much worse than either of the two treated samples, suggesting that cement hydration may have been better with the treated wood, producing more durable bonds. The differences between samples V and VI included void volume and range of particle sizes. The poorer performance of the higher density material suggests that there may be some positive effect of void volume similar to that found for air-entrained cement.

Conclusions

The results of this study suggest that cement-bonded wood composites have the potential to serve in a variety of structural applications. Although their strength and stiffness are about 10% that of other structural panels, it may be possible to make a consistent product with ductile/energy-dissipative failure characteristics that could find application in areas where those attributes are important. In addition to a proven history of sound absorption and an inherent resistance to fire, termites, and decay, these panels can be produced to meet the strength and freeze-thaw requirements for highway sound barriers. Cement-bonded wood composites also provide a potential use for CCA-tre.ated wastewood. While these products seem well-suited to housing applications in tropical and semitropical environments, they should also be evaluated for possible application in areas where wind, fire, and seismic loading are controlling factors in design.

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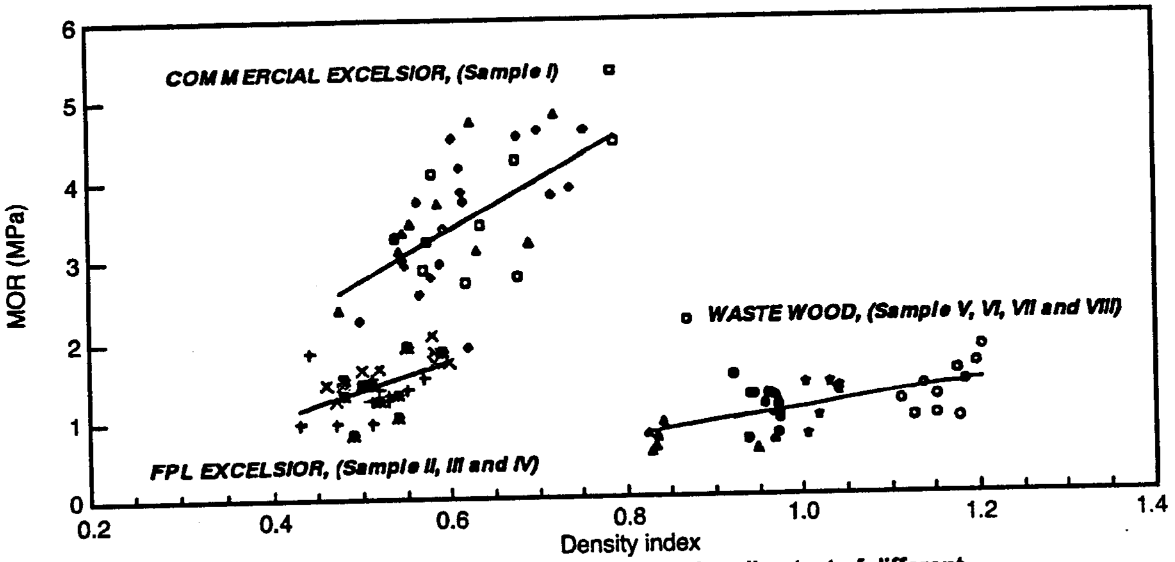

Figure 3—Variation of MOR with density index in third-point bending test of different CBWC samples.

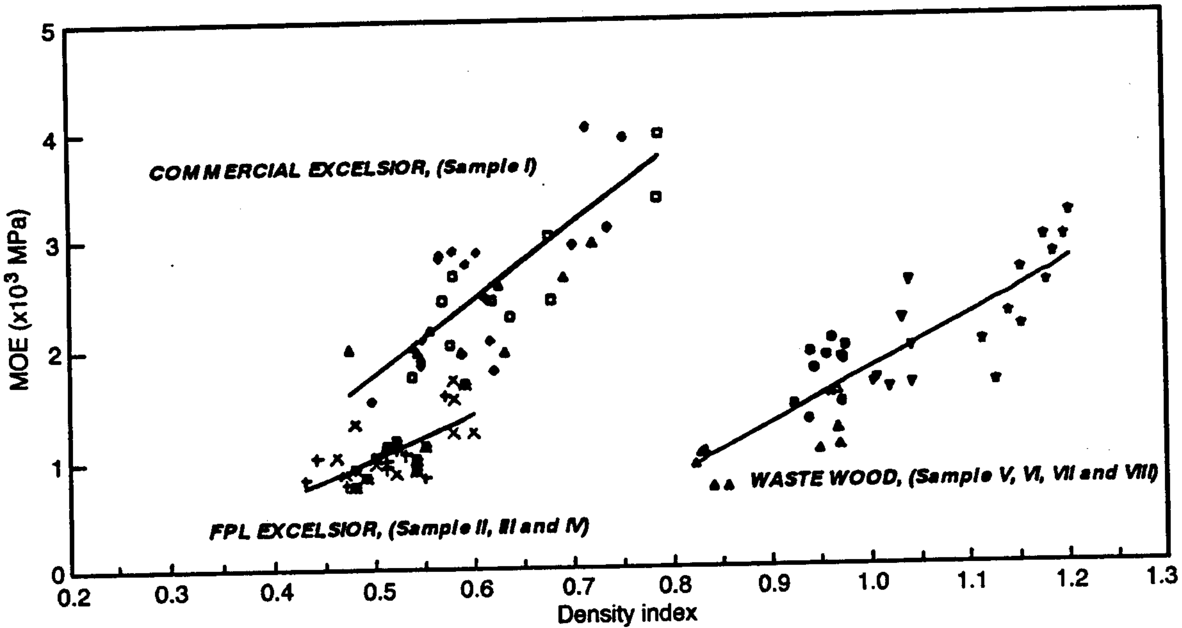

Figure 4—Variation of MOE with density index in third-point bending test of different CBWC samples.

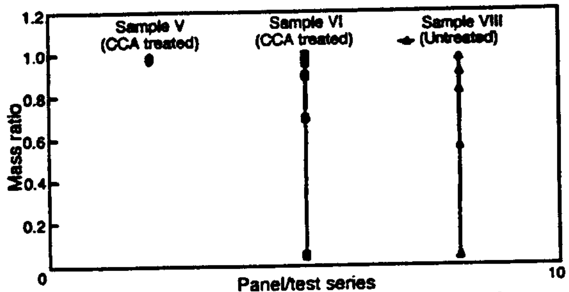

Figure 5—Distribution mass retention ratios of untreated and CCA-treated wastewood samples.