Cement-Bonded Wood Composites as an Engineering Material

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Abstract

Wood-cement composites have been used in the fabrication of building materials for more than 60 years. Uses have focused primarily on the advantages of these composites: resistance to decay and insects, acoustical properties, and thermal insulating properties. Recent studies of wood particle- and fiber-based cement composites project expanded use in applications that require a durable material that exhibits consistent bending, shear stiffness, and shear strength along with a ductile, energy-dissipative failure mode. While most research in this area has dealt with "clean" fiber from roundwood, it appears that recycled pulp and solid wood waste could be used with acceptable tolerance for product variability. In this study, we report results from basic research on interactions between recycled wood and cement, and the effect of these interactions on the strength and durability of wood-cement composites. The results provide a solid basis for refining product fabrication processes. Although this effort focused on fiber-reinforced cements, many results can be applied to wood particle-cement composites. Using a larger quantity of wood or fiber waste in a less refined form adds to the attraction of wood particle-cement composites as environmentally friendly materials. It also adds to the challenge of defining them as an engineering material.

Introduction

Cement-bonded wood composites have the potential to provide a wide range of products for building applications by using a wide range of recycled wood-based materials. Recycled newsprint and magazines, old pallets, construction waste, and small-diameter tree stems have been used for both experimental and commercial products. The value of these products could be improved by a better understanding of the fabrication process and resulting material properties.

The development and use of wood-cement composites attest to their attraction as building materials. In addition to their resistance to fire, these materials have a special attraction for use in warm, humid climates where termites and decay are a major concern. The cement binder provides a durable surface as well as one that can be easily embossed and colored for an attractive, low-maintenance finished product. The raw materials used are compatible with a range of processing methods to provide a variety of products that are easily machined with conventional woodworking tools. Preliminary research results suggest that these composites can also be manufactured to exhibit a range of unique energy-dissipating properties, which are advantageous in areas subject to seismic and/or heavy wind loads. These attributes appeal to engineers, architects, and contractors for use in public and multifamily residential buildings.

More information on the strength, stiffness, toughness, and reliability of wood-cement composites is needed to extend their acceptance and use in the area of structural applications. Private industry has taken

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the lead in research to develop and use wood-cement composites in building construction. Cement-bonded wood-excelsior panels have been in use for more than 60 years, but the emphasis has been on acoustics, fire resistance, and aesthetics, rather than strength and stiffness. More recently, industry has focused on the development of fiber-reinforced cement cladding products. These products normally use 8 to 10 percent wood by weight compared to 20 to 40 percent for wood particle composites, and they rely on appearance and durability rather than on strength and stiffness for their acceptance.

Material resource and recycling demands suggest that the time is right for research to characterize the unique problems and properties associated with these composites and expand their use to structural applications in residential structures.

Objective

Basic research is needed to assess the feasibility of developing engineered products that will exploit the unique properties of wood-cement composites. The purpose of this paper is to summarize what we know about these materials and to recommend a course of action that will provide the basis for developing engineered composites from low-value wood resources.

History

Cement is perhaps the most widely used and versatile composite matrix material. In its most common form, cement is combined with stone aggregate to improve compressive strength and durability. Steel reinforcing bars improve bending capacity and resistance to cracking. Fiber reinforcement has also been used to improve fracture toughness. The best-known and most widely used material of this type is cement asbestos board, which has been used as a roofing and siding material throughout the world for nearly 80 years.

Wood-cement composites are generally placed into two categories: wood particle-cement composites and wood fiber-reinforced cement products. Wood particle-cement composites have been in use as architectural, fire-resistant, and acoustic panels. Wood fiber-reinforced cement products were developed primarily as a substitute for asbestos-cement and are relatively new, developed and promoted mostly in the last 25 to 30 years. These composite materials have been developed primarily by private companies and thus have received relatively little attention in published technical literature.

The wood particle-cement composites have a slightly longer history as commercial products than do wood fiber-reinforced cements, but they have received far less rigorous research attention. These composites generally have densities in the range of 300 to 1,300 kg/m^3. Their maximum bending strengths are often limited to less than 10 MPa. Research in Europe in the 1920s led to the common practice of using wood chips in cement to make building blocks. By 1940, there were a number of manufacturers producing a cement-bonded wood composite commonly called woodwool, which uses a wood: cement ratio in the range 0.4 to 0.6 by weight. Woodwool is made with a ribbonlike particle called excelsior. These ribbons are coated with cement and pressed into panels that have densities in the range of 300 to 500 kg/m^3. Woodwool is attractive for use as noncombustible and sound-absorbing ceiling and wall panels. In 1973, a Swiss company called Durisol was among the first to produce a building panel consisting of small wood flakes bound in a cement matrix. In this case, the composite is roughly 20 percent wood by weight and has a density closer to 1,300 kg/m^3.

Interest in wood fiber-reinforced cement was sparked by the post-World War II shortage of asbestos fibers, which caused some private companies to consider cellulose fiber as a substitute for asbestos in fiber-reinforced cement. This interest faded as asbestos supplies recovered in the 1950s, but it regained strength by the mid- 1970s with growing concern over the health risks linked to asbestos. The controversy over asbestos led a number of companies in Australia, Europe, and Scandinavia to develop processes for fabricating fiber-reinforced cement boards using cellulose and other mineral fillers. Over the past 25 years, the American Concrete Institute has also sponsored research to develop high-performance fiber-reinforced cement composites that use discrete fibers, including steel, glass, synthetic polymers, and cellulose.

Today, cellulose fiber is used in a wide variety of fiber-reinforced cement products, many of which were originally developed using asbestos fiber. These materials use only 5 to 15 percent cellulose fiber by weight, have densities ranging from 1,100 to 1,800 kg/m^3, and have bending strengths ranging up to 30 MPa. The primary function of fibers in these cement composites is to increase the energy of fracture. By bridging gaps, the fibers prevent stress concentrations at crack tips, thus retarding brittle fracture mechanisms and dissipating energy in the form of fiber pullout or rupture.

Engineering properties

Many studies have evaluated various aspects of wood-cement composite fabrication and material properties (4,7, 10–16), but few have directly addressed issues of importance to their use in structural applications. The majority of these studies have been concerned with wood-cement compatibility, methods of gaining rapid cure, and effects of fiber type and mass on strength, stiffness, and toughness (5,18). While these studies have provided a necessary foundation for developing composite products for specific applications, they have lacked the sample size and load conditions needed to derive reliable design values. We need a basis for assessing what are the strength and stiffness distribution parameters and how they vary with changes in raw material properties, processing variables, long-term load, and environmental exposure.

Bending strength and stiffness

The majority of the work on bending strength of wood-cement composites was part of an effort to develop high-strength fiber-reinforced cement products. Concrete is used primarily in compression, developing strengths of 20 to 35 MPa, 68 MPa for high-strength fiber-reinforced concrete. In bending, strengths may range from 7 to 20 MPa. The addition of wood particles or cellulose fiber improves fracture toughness by blocking crack propagation. This permits the composite to carry load to a higher strain limit. Figure 1 shows a typical load deformation plot measured for a wood-cement composite, The initial portion of this plot (*A_R* zone) is fairly linear and represents the strength of the cement matrix. When the matrix begins to fail, the plot becomes nonlinear. At this point, the fiber or particle content begins to contribute by blocking fracture propagation. This action may permit the composite to take a siightly higher load or to exhibit a ductile failure, deflecting until a strain limit is reached for the fiber reinfomement. Normally, the strain-at-failure for the wood may range from 40 to 400 times that of cement.

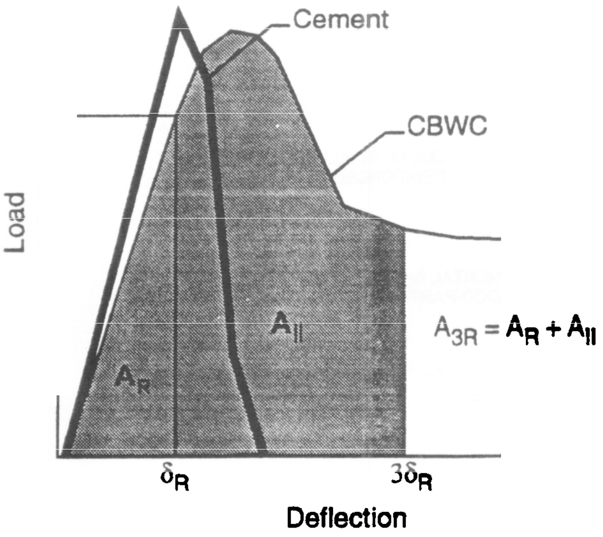

Figure 1. –Load versus deflection curves for cement-bonded wood composites (CWBC) and "near cement" in bending. Plot for cement-bonded wood composites shows bimodal failure. Zone A_R shows the initial linear portion up to the point where cement matrix begins to crack. Load continues to increase to maximum load, then drops 30 to 50 percent to the point where wood particles are left to resist stress.

Coutts (5) and Soroushian (18) reported wood fiber-reinforced cement product bending strengths of 7 to 30 MPa, depending on fiber mass, moisture content and type of fiber. Figure 2 shows how these parameters affect bending strength. Coutts attributed the drop in strength past 8 percent to a tendency of the fibers to pack less efficiently as fiber mass increases beyond this point. Moisture tends to reduce bending strength, making the fibers more flexible and less likely to inhibit cracking in the cement matrix. Data presented by Coutts also showed that high-yield, thermomechanical pulps do not give as high a strength as do chemical pulps. He attributed this result to damage to the fiber as well as "poisoning" of the cement by extraction of polysaccharides and wood acids. These substances, left behind by mechanical pulping, are removed during the chemical pulping process.

Coutts also compared autoclave curing to air seasoning (Fig. 2). Autoclave composites included a portland cement and fine sand mix with wood fiber that was subject to steam heat for 8 hours at 170° to 180°C. This curing process resulted in a decrease in strength with fiber content when high-yield thermomechanical pulps were used, but gave maximum strength of over 20 MPa when kraft pulp was used. Air curing, which took 14 to 28 days, gave a composite bending strength of 30 MPa when composites were made from an 8 percent kraft pulp mix.

The wood particle-cement composites cover a wide range of material configurations as well as a wide range of bending strengths. Dinwoodie and Paxton (6) presented information on a number of cement particleboard consisting of 20 percent wood by weight in which the wood was in the form of flakes 10 to 30 mm long and 0.2 to 0.3 mm thick. The authors reported densities in the range 1.2 to 1.3 g/cm^3 and bending strengths from 10.1 to 12.9 MPa.

Karam and Gibson (9) presented information on several commercially produced composites (Fig. 3), which included fiber-reinforced cement particleboard as well as a wood particle-cement composites containing 20 percent wood flakes by weight. In a study by Moslemi and Pfister (1987), wood content had little effect on bending strength of cement-bonded particleboard for wood:cement ratios between 1.3 and 2.3. For composites made from lodgepole pine flakes with an average thickness of 0.6 mm and a portland type I binder, there was no significant difference in strength at 90 percent confidence on the mean. Tests conducted at the USDA Forest Products Laboratory (FPL) by Wolfe and Geimer (20) yielded values rang-

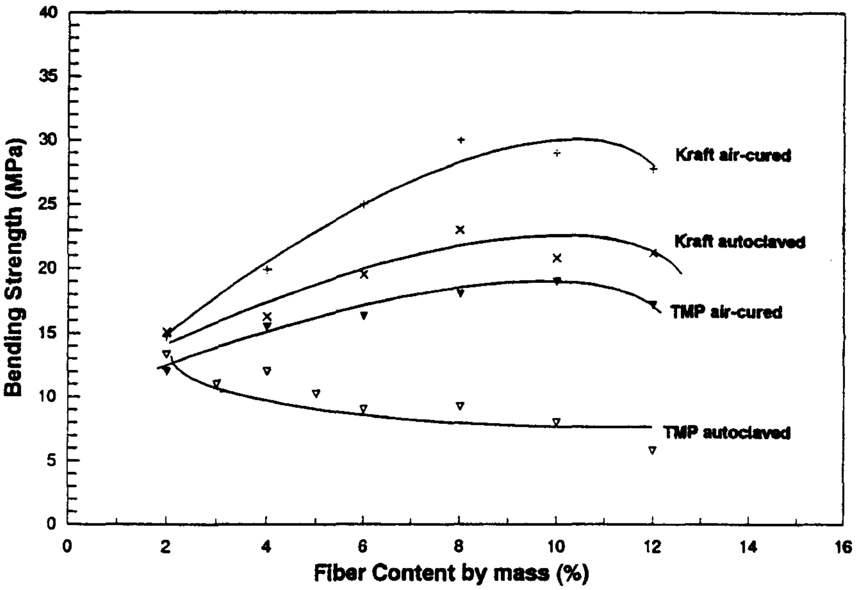

Figure 2. -Bending strength versus fiber content. Data (5) show effect of fiber content, fiber type (kraft versus thermomechanical pulp (TMP)), and curing method (autoclaved versus air cured).

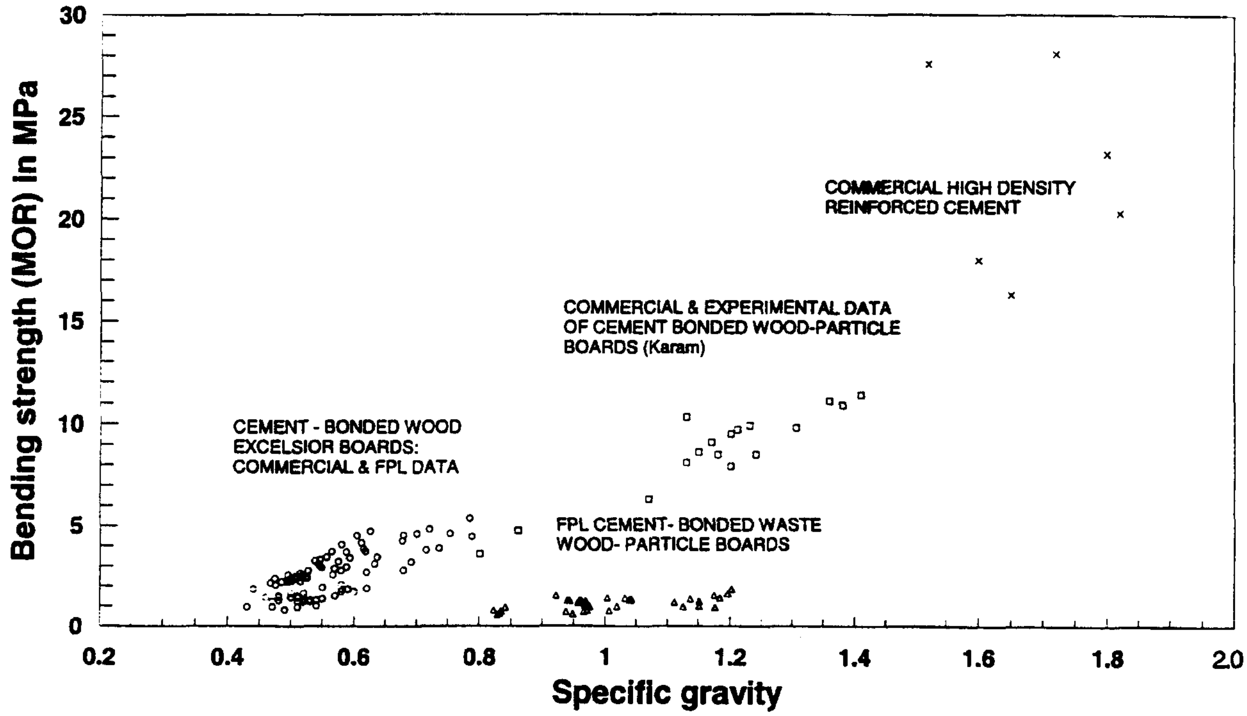

Figure 3. –Bending strength as a function of density. Comparison of FPL data and data presented by Karam and Gibson (9). Plots include commercial and experimental excelsior, a wood-waste composite, commercial fiber-reinforced cement composites, and a commercial high-density cement particleboard.

ing from 2 to 4 MPa for composites containing 40 to 50 percent wood particles by weight and densities ranging from 0.5 to 1.2 g/cm^3. The commercial excelsior board referenced in Figure 3 was made from 0.38-mm-thick southern pine excelsior with a width: depth ratio of 4:5. The poplar excelsior used for the FPL boards was slightly thicker than these boards, but the width: thickness ratios of the FPL boards bracketed that of the commercial board. The woodwaste board was made from southern pine chunk-type particles that varied in size from fiber bundles to 12 mm diameter by 1.5 inches long. Within each sample, the ratio of wood to cement was the same; variation in density resulted from variation in void volume.

Coutts (5) also compared autoclave curing to air seasoning (Fig. 2). The autoclave composites include a portland and fine sand mix with the wood fiber, which is subject to steam heat for 8 hours at 170° to 180°C. Air curing is normally done at ambient temperatures or in a hydration kiln at 80°C and takes 14 to 28 days. The strength of autoclave composites increased with fiber content when kraft pulp was used but not when thermomechanical pulps were used. Air curing resulted in strength increase with fiber content up to 8 percent by weight for both thermomechanical and kraft pulps, but strengths were still greater for the kraft pulp mix. The maximum strength at 8 percent fiber content was due to a "balling" of the wood fiber at higher concentrations, reducing effective cement coating.

Compressive strength

The compression characteristics of wood-cement composites vary depending on the wood: cement ratio and the type of particles used. Sorfa(17) reported that bricks developed for use as mining supports exhibited compression properties similar to compression perpendicular-to-grain in wood. These bricks were fabricated using pine planer shavings and had densities ranging from 0.5 to 1.32 g/cm^3, depending on the bulk density of the wood fiber and the wood: cement ratio.

Sorfa (17) reported compression curves in which the load increased linearly with deformation up to a point of matrix cracking (Fig. 5). The initial slope increased with density or drop in the wood: cement ratio. Beyond this point, the load continued to increase with increased compression but at a slope that was similar for all the cementwood mixes used. An actual point of failure was never reached in a 15-mm displacement equal to 20 percent of the depth of the test specimens.

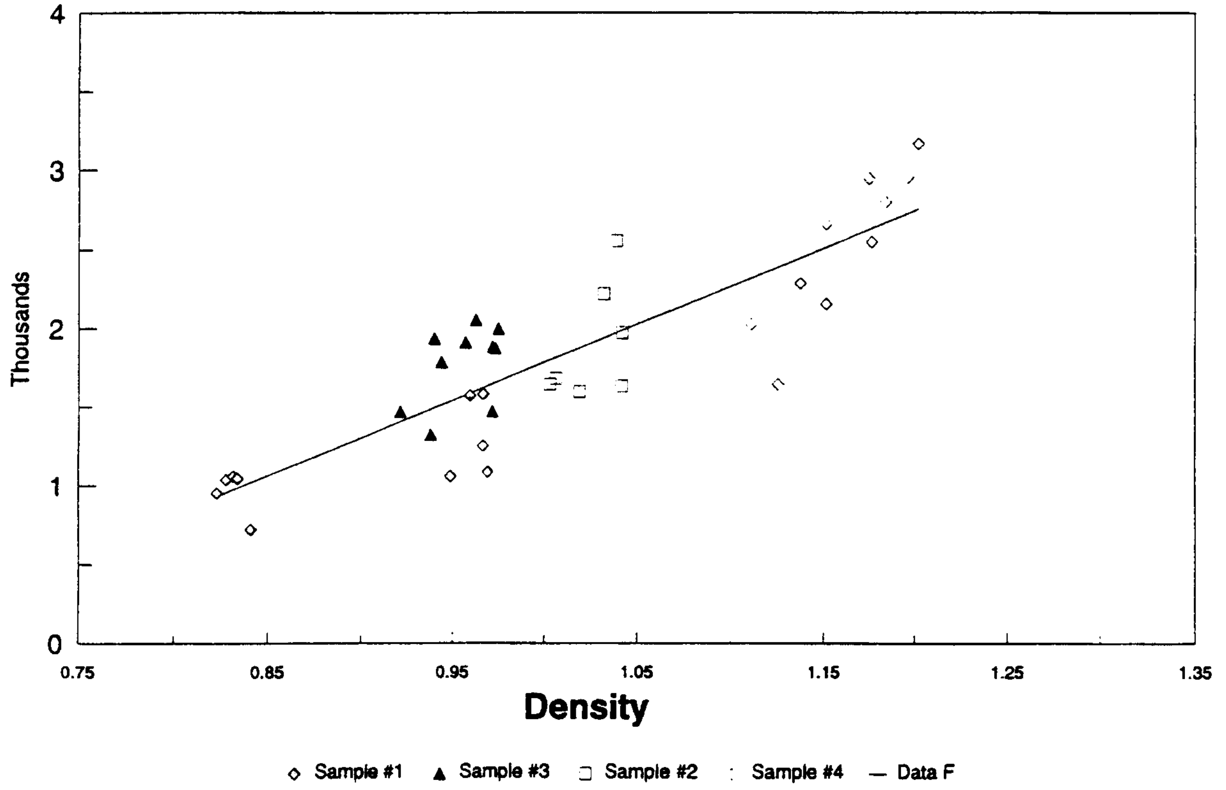

Figure 4. -Bending modulus of elasticity as a function of density.

Compression tests conducted at the FPL on wood-cement particle composites differed from those reported by Sorfa in that the height of the test samples was greater than their width, and failure resembled a buckling type of failure more than pure compression. In this case, the load deformation plot resembled that shown in Figure 1, except for a slight initial stiffening zone caused by compaction of the material. After the matrix began to fail, the samples began to crack; the load fell 30 to 50 percent, then decreased gradually as displacement continued to increase. As was the case with the bending tests, wood: cement ratios for the FPL samples were on the order of 1:2.

Toughness

Toughness is a measure of the energy absorbed by the test sample during the test. It is determined as the area under the load deformation curve. Coutts reports toughness as energy per unit area (Joules/m^2). These units normally refer to fixture toughness in which a test specimen fracture initiates at a notch and the toughness is the energy per generated crack area (length times width). This terminology is commonly found in discussion of the fracture toughness of paper tested in tension.

In the concrete industry, the ASTM C 1018 standard (1) defines a set of toughness indices for fiber-reinforced cement, which is reported as the area under the load deformation curve up to deformations of 3, 5.5, and 10.5 times the deformation at first crack as a multiple of the area to first crack. Concrete has a toughness index of 1 as the first crack normally defines failure strength.

The FPL study (21) evaluated bending and compressive toughness for four panels of varying density (Table 1). Toughness indices were evaluated using an index derived as the area (A_{3R}) under the load displacement curve between 0 and 3 times the displacement at the point where the cement matrix cracks (δ_R (Fig. 1, A_R and $A_{||}$) divided by the area under the curve between 0 and δ_R (A_R in Fig. 1) (ASTM C 1018, ref. 1). For cement, this index is designated 15. This was derived from the evaluation of fiber reinforcements and denotes the average value of 5 for the toughness index of these products. In these tests, the composite consisted of wood particles rather than individual fibers and the wood: cement ratio was close to 50 percent. Test results indicated a toughness index of more than 6.5 for both bending and compression.

The different approaches to defining toughness make it difficult to compare values across studies. However, the energy-dissipating properties of wood-cement composites make toughness a valuable meas-

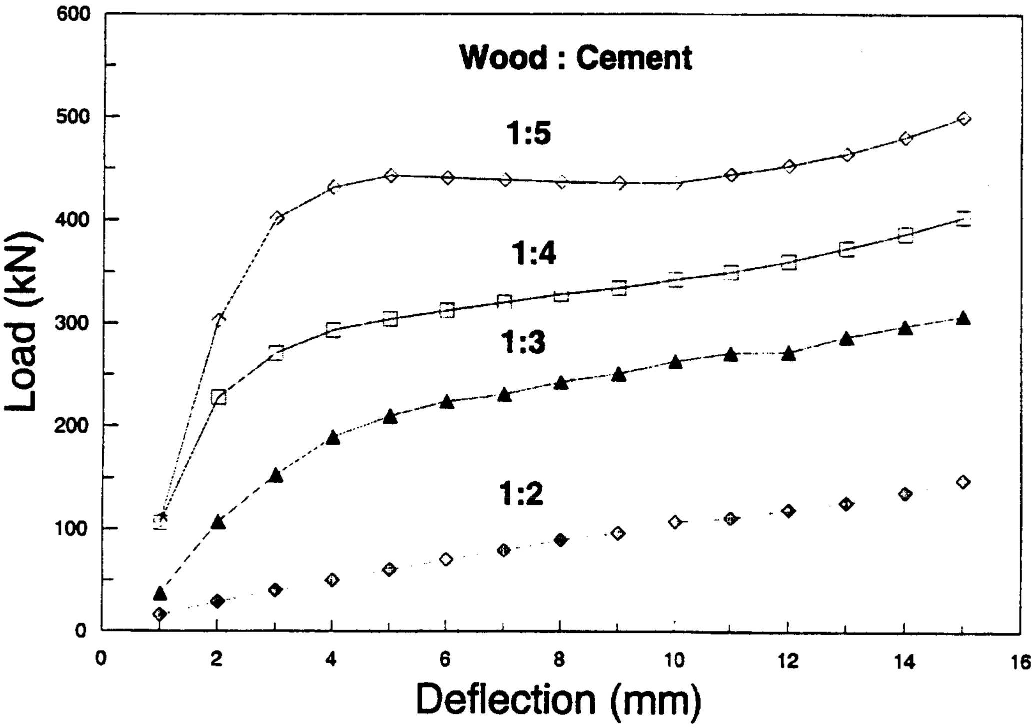

Figure 5. –Load versus compressive deformation. Data shows the effect of wood: cement ratio in cement particleboards on stiffness and strength of composite bricks to be used in mine supports (17).

ure of the advantages of adding fibers and or wood particles to cement. Soroushian (18) showed an almost linear increase in toughness with fiber mass content (Fig. 6) and an increase in toughness with fiber moisture content. Coutts (5) also demonstrated these same relationships.

Table 1. -Summary of toughness values determined for compression and bending.[a]

Panel	Specimen	δ_R	A_R	A_{3R}	I_5[b] Average	I_5[b] COV
	(n)		(N·mm)			(%)
Compression						
1	5	0.68	2,100	11,000	6.4	11
2	5	0.70	3,000	17,000	6.5	3
3	6	0.90	3,700	17,000	5.6	18
4	8	0.76	6,800	36,000	6.3	18
Bending						
1	10	0.67	240	1,200	6.4	20
2	9	0.55	240	1,400	6.9	14
3	8	0.63	250	1,200	6.3	18
4	10	0.45	190	1,100	6.8	13

[a] See Figure 1 for an explanation of the terms.
[b] Ratio of A_{3R}/A_R.

Potential applications

From a structural viewpoint, toughness appears to be the primary advantage of cement-bonded wood composites. These materials are not particularly strong, having roughly only 5 to 30 percent of the strength of wood. Strength limitations can be accommodated to some extent through use of increased section properties or reinforcement. However, the premise that wood-cement composites can be designed to give a characteristic ductile failure is attractive. In cases where it is not feasible for the design to resist the maximum possible load, a material that dissipates a lot of energy as it fails can save lives. Examples include buildings in areas prone to heavy wind, particularly tornadoes; highway crash barriers; break-away walls in surge zones; and mine supports. With the proper mix of materials, these composites could also be used to develop a structural fuse whose failure could serve as an indicator of a structural system overload or weakness.

Research needs

Cement-bonded wood composites have been proven to be economically feasible as cladding materials. Preliminary research has shown that these ma-

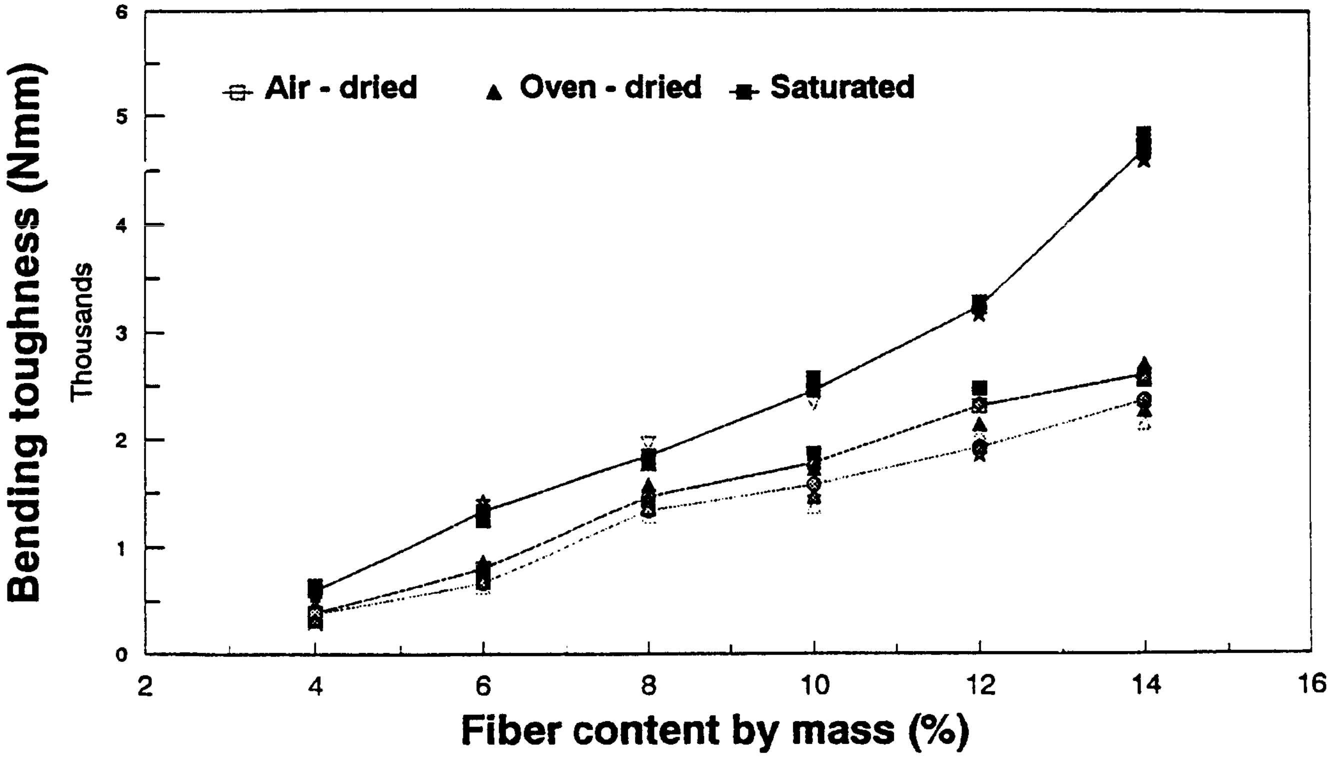

Figure 6. –Toughness as a function of fiber content. Data show linear increase in toughness with fiber mass and effect of fiber wetting on toughness (18).

terials can be fabricated to resist cyclic moisture and temperature effects (6,9,21), but there is a need for further research and development to evaluate shear strength, toughness, connections, and creep under constant load.

These materials have been developed to the point where we now need an organized effort to establish standard evaluation procedures to simplify recognition of the influences of additives and processing variables on mechanical properties. Test specimen sizes should be selected with some recognition of the effect of particle size. Standard tests are needed for evaluation of toughness, creep, and shear. Standard methods should also address reporting methods of properties such as moisture content, fiber content, density, wood species, geometry, orientation, and alignment.

Conclusions

There are many advantages to combining wood and cement that benefit the use of such composites in construction. Preliminary studies suggest that some wood-cement composites also have attributes that could qualify them as engineered structural materials. On the basis of available test results, the most prominent attribute of this nature appears to be toughness. The adoption of standards for fabrication and structural performance evaluation would help to promote the research needed to gain acceptance of these composites as engineered materials and encourage their development as a use for recycled wood-based material.

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