ADVERSE EFFECTS OF HEARTWOOD ON THE MECHANICAL PROPERTIES OF WOOD-WOOL CEMENT BOARDS MANUFACTURED FROM RADIATA PINE WOOD

Kate Semple
Graduate student

and

Philip D. Evans†
Reader
Department of Forestry
The Australian National University
Canberra, ACT 0200, Australia

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ABSTRACT

Wood-wool cement boards (WWCBs) that are manufactured commercially in Australia from radiata pine occasionally contain localized areas in which there is poor bonding between wood and cement. The cause of this defect, which leads to the rejection of boards before they are sold, is not known, but it has been suggested that it may be due to the use of blue-stained wood or heartwood in the manufacture of boards. In this study, both wood types were tested for their effects on the hydration of Portland cement and the mechanical properties of WWCBs. Blue-stained sapwood slightly retarded the hydration of cement but had no significant ($P < 0.05$) effect on the mechanical properties of boards. In contrast, heartwood severely retarded cement hydration, and boards made from heartwood had little structural integrity. The appearance of such boards resembled the defective portions of commercially produced boards, and therefore it can be concluded that the defect arises from the inhibitory effect of heartwood on cement hydration. The problem could be eliminated by processing logs from young radiata pine trees, less than 12–15 years old, which will contain little or no heartwood.

Keywords: *Pinus radiata*, wood-wool cement board, heartwood, mechanical properties.

INTRODUCTION

Wood-wool cement board (WWCB) is an inorganic-bonded panel product manufactured from strands of wood (excelsior) and Portland cement (Moslemi 1989). In Australia, WWCB was manufactured originally from black poplar (*Populus euramericana* Lam. De Wit.) wood from plantations that were established for the Australian match industry; but radiata pine (*Pinus radiata* D. Don) wood obtained from forest thinning operations is now the preferred wood species (Woolley 1998). In general, radiata pine wood has proved to be an excellent raw material for the manufacture of WWCB, and the boards made from radiata pine are widely used in Australia in non-structural applications such as ceiling panels and soundproofing barriers alongside highways. However, occasionally boards manufactured from radiata pine contain localized areas in which there is poor bonding between wood and cement. The cause of this defect, which leads to the rejection of boards before they are sold, is not known; but it has been suggested that it may be due to the use of heartwood or wood with severe blue-stain in the manufacture of boards.

There have been no reports of the effect of radiata pine heartwood on the properties of WWCB, but abietic acid, which is one of a number of resin acids that constitute 71% of extractives in radiata pine heartwood (Uprichard 1991), has been shown to inhibit the setting of

† Member SWST.

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cement (Miller and Moslemi 1991a). In addition, previous studies have also shown that the heartwood of other *Pinus* species, for example loblolly pine (*Pinus taeda* L.) (Weatherwax and Tarkow 1964, 1967) and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) (Miller and Moslemi 1991b), inhibits the setting of cement to a greater extent than sapwood. The colonization of wood by blue-stain fungi has a positive effect on the compatibility of wood with cement (Davis 1966; Biblis and Lo 1968; Raczkowski et al. 1983) because the fungi metabolize low molecular weight polysaccharides that retard the setting of cement (Sandermann and Brendel 1956; Bruere 1966). In contrast, decayed wood, which contains sugars resulting from the enzymatic degradation of cellulose and hemicelluloses, strongly inhibits the setting of cement (Weatherwax and Tarkow 1964, 1967; Simatupang 1986; Meier 1990).

The aim of this study was to determine whether the use of radiata pine heartwood or severely blue-stained sapwood could lead to the production of defective wood-wool cement boards and, secondly, if they do, to suggest practical solutions to eliminate the problem.

MATERIALS AND METHODS

Sampling and preparation of wood raw materials

Heartwood and sapwood wood-wool was obtained from 14-year-old radiata pine trees growing in plantation at Hepburn Springs in Central Victoria. Trees were felled, debarked, and converted into ten billets 20–25 cm in diameter and 46 cm in length. Billets were air-dried for 9 months and converted into wood-wool, measuring $0.3 \times 3 \times 460$ mm, using a van Elten shredder at WoodTex Pty Ltd in Bendigo, Victoria. Heartwood and sapwood wood-wool from each billet was separated during shredding and packed into separate bags. Further screening of heartwood and sapwood, based on the color of the two wood types, was then undertaken to obtain samples containing only heartwood or only sapwood. Two batches of wood-wool severely affected by blue-stain fungi were also obtained from WoodTex Pty Ltd in Bendigo, Victoria. Wood-wool for extractive content and cement compatibility testing was cut into short (2–3 cm) lengths using scissors and then placed in a conditioning room maintained at 20 ± 1°C and 65 ± 5% RH for 2 weeks. Wood-wool for the manufacture of experimental panels was similarly conditioned without cutting.

Wood extraction and determination of extractive content

The extractive content of the wood-wool was determined as follows: 20-g samples of chopped heartwood and sapwood wool from each billet were ground separately to 10-mesh size using a Wiley mill; 3 g of the resulting wood flour was added to a preweighed oven-dry cellulose extraction thimble (Whatman brand 19×90 mm), which was then immediately reweighed. This was placed in a 100-mL Soxhlet extraction apparatus and refluxed with 250 mL of ethanol (4), acetone (1), and toluene (1) for 4 h. After extraction the thimble was drained of excess solvent, oven-dried overnight at 105°C, and reweighed. Duplicate extractive content determinations were undertaken for each sample. The moisture content of air-dry samples was determined separately to enable calculation of extractive content on an oven-dry wood basis. Extracted heartwood wood-wool was also tested for its compatibility with cement. Extraction of wood-wool followed the procedure described above, except that 15 g of chopped wood-wool was placed in the Soxhlet extraction apparatus, rather than a cellulose extraction thimble, and the wood-wool was air-dried after removal from the Soxhlet.

Measurement of wood-cement compatibility

Duplicate samples of blue-stain-affected sapwood, extracted heartwood, and unextracted heartwood and sapwood from the ten billets were assessed for their compatibility with Portland cement using a method that measures the heat of hydration evolved by a mixture of wood cement and water under standard conditions. Then 100 g of fresh, dry cement (Blue Circle Southern Brand, batch no. 131/98) was placed in a sealable 'Dalgrip' polythene bag and evenly mixed with 41.5 g of distilled water at 20°C for 1 to 2 min to form a slurry. A 5-g sample of wood-wool was then added and thoroughly mixed with the slurry. The cement controls (containing no wood) used 40 mL of water. Immediately after mixing the cement and wood, the tip of a temperature thermocouple (Type J) was taped to the bag and enclosed within the body of the cement-wood mixture by folding and then securing the bag and contents around it. A cement hydration temperature measuring apparatus (Moslemi and Lim 1984; Irle and Simpson 1993) capable of measuring the heat of hydration of six wood-cement mixtures over a 23-h period was used to record temperatures at 15-min intervals. The curves were smoothed by progressive averaging and plotting of every three readings. All experiments were undertaken in a conditioning room at 20 ± 1°C and 65 ± 5% RH. Previous studies of the suitability of wood species or type for use in wood-cement composites have generally ranked them according to their effect on the maximum hydration temperature ($T_{max.}$) attained by a wood-cement mixture (Sandermann et al. 1960; Sandermann and Kohler 1964; Weatherwax and Tarkow 1964) or the time taken to reach $T_{max.}$ (Weatherwax and Tarkow 1964; Biblis and Lo 1968). Hachmi et al. (1990) developed a wood-cement compatibility index (C_A-factor) based on the ratio of the area under the hydration curve of a wood-cement mixture to that of a cement control, which they suggested was the best method of assessing the 'hydration behavior of any lignocellulosic material with cement.' To enable our results to be compared with those of previous studies, $T_{max.}$, time taken to reach $T_{max.}$ and C_A-factor were calculated for each hydration sample, and hydration rate ($T_{max.}$-$T_{min.}$/Time) was also used as an additional quantitative index of wood-cement compatibility. The $T_{min.}$ component of hydration rate was defined as the minimum temperature attained during the first 5 h of hydration.

Manufacture of WWCBs and mechanical testing of boards

WWCBs were made from heartwood and sapwood wood-wool obtained from each billet, i.e. 10 boards each for sapwood and heartwood. Two boards were also made from the batches of blue-stained sapwood. A cement: wood ratio of just over 3:1 was used in accordance with commercial practice (Woolley 1998). One-hundred-fifty g of wood and 500 g of cement (Blue Circle Southern Brand, batch no. 247MA98) were used for the manufacture of each board. The wood-wool was placed in a netted bag, which was momentarily submerged in a bucket of clean tap water at 20°C before it was drained for 2 min. This imparted an average of 400 g of water to the wood-wool. The wet wood-wool was placed in a large plastic bowl, cement was progressively sprinkled through it, and wood-wool and cement were mixed by hand over a period of 10 min.

The resulting quantity of cement-coated wood-wool was placed on a 12-mm-thick plywood sheet within a hardwood frame that measured 25 × 310 × 240 mm. A second plywood sheet was then placed on top of the frame and the resulting assembly was pre-pressed. Wood-wool and cement mixture for a second board were prepared, and the first board assembly was removed from the press. A second frame was placed on top of the assembly, and the process of making the first board was then repeated. A third plywood sheet was then placed on top of the second board, and the two boards were pressed using a PHI platen press (model no. PW220g-X4A) for 24 h at 140 kPa. The platens were manually closed using a lever-operated hydraulic oil pump. After 24 h, the boards were removed from the press, labelled, and placed in a conditioning room at 20 ± 1°C and 65 ± 5% r.h. to cure for 28 days. This is the minimum time recommended for cement

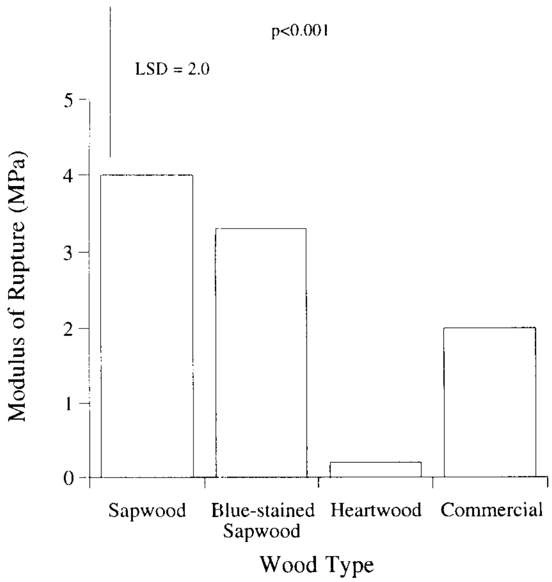

FIG. 1. Average modulus of rupture (MOR) for WWCBs made from sapwood, blue-stained sapwood, and heartwood compared to MOR of a commercially manufactured board.

type GP (formerly Type A/Type 1) to reach its maximum strength.

Two samples measuring 50 × 23 mm were cut from each board, and their dimensions (width and thickness) were recorded using Mitutoyo digital callipers. The modulus of rupture (MOR) of board samples was determined using a three-point bending cell attached to an H.T.E. (Hounsfield) testing machine using a span length of 100 mm, cross-head speed of 6 mm/min, and cross-head and bearer diameters of 5 mm. The results from the experimental boards were compared with measured MOR for two commercial WWCBs of the same cement:wood ratio, density, and thickness.

Statistical analysis

Matched data sets for heartwood and sapwood of each of the ten billets ($T_{max.}$, hydration time, hydration rate, C_A-factor, and board MOR) were compared by paired t-tests (one-tail, $P \leq 0.05$ significance level). The data sets were checked for normality prior to statistical analysis. A least significant difference (LSD, $P < 0.05$) bar is included on the graph depicting the mechanical properties of WWCBs in order to facilitate comparisons of means.

RESULTS AND DISCUSSION

Cement compatibility and board mechanical properties

Radiata pine sapwood was significantly ($P < 0.001$) more compatible with Portland cement than heartwood. Hence, $T_{max.}$, hydration rate, and C_A-factor (Table 1) were all significantly higher for sapwood than for heartwood, and wood-cement mixtures containing sapwood reached their maximum hydration temperature more quickly than those containing heartwood (Table 1). These results accord with previous studies that have shown that the heartwood of *Pinus* species inhibits the setting of cement to a greater extent than sapwood (Weatherwax and Tarkow 1964, 1967; Miller and Moslemi 1991b). As expected, the average extractive content of radiata pine heartwood (4.3%) was greater than that of sapwood (1.2%), although there was considerable variation in the extractive content of heartwood wood-wool samples obtained from different billets, ranging from 1.2% to 8.8%. Removal of heartwood extractives resulted in considerable improvement in the compatibility of the wood-wool with cement (Table 1).

TABLE 1. *Average cement compatibility indices and extractive contents for sapwood, heartwood, and blue-stained sapwood.*

	$T_{max.}$ (°C)	Time (h)	Hydration rate (°C/h)	C_A-factor (%)	Extractive content (%)
Sapwood	50.7 (2.1)*	10.9 (0.6)	2.25 (0.25)	89.5 (7.6)	1.2 (0.4)
Heartwood	43.8 (3.0)	13.9 (1.2)	1.36 (0.31)	72.0 (11.8)	4.3 (2.7)
Blue-stained sapwood	42.0 (4.5)	10.7 (0.7)	1.79 (0.03)	70.7 (14.7)	—
Extracted heartwood	48.0 (0.8)	12.5 (0.1)	1.70 (0.04)	86.4 (1.3)	—
Neat cement	55.5 (0.4)	9.2 (0.2)	2.63 (0.03)	100 (0.0)	—

* Standard deviation in parentheses.

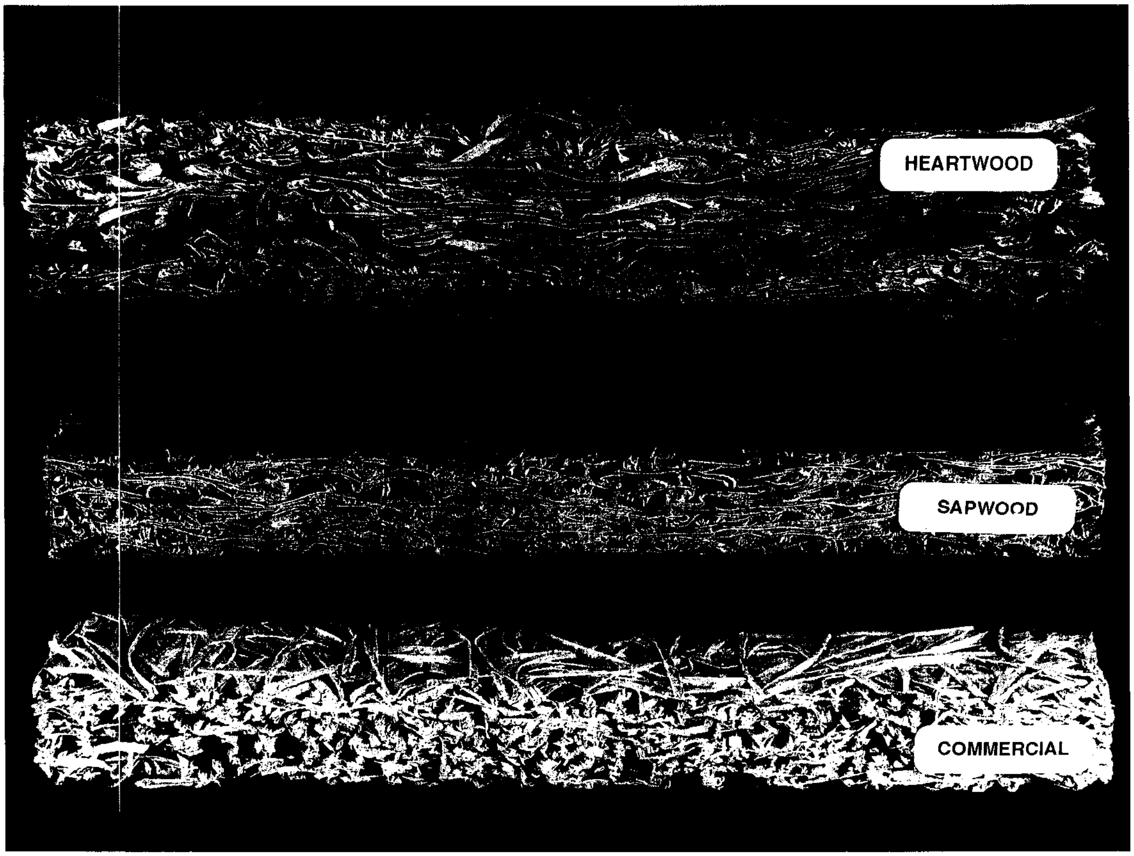

FIG. 2. Appearance of experimental WWCBs made from sapwood or heartwood wood-wool compared to a commercially produced board.

Results in Table 1 suggest that blue-stained wood was less compatible with cement than sapwood, in contrast to previous studies that have found that blue-stained wood has a positive effect on the setting of cement (Davis 1966; Biblis and Lo 1968; Raczkowski et al. 1983). The blue-stained wood tested here was obtained from radiata pine billets that had been stored outside for 9 months. It is possible that during this prolonged storage period the billets were colonized by decay fungi as well as blue-stain fungi. Since decayed wood strongly inhibits the setting of cement (Weatherwax and Tarkow 1964), this may explain why the blue-stained wood tested here inhibited rather than accelerated cement hydration. In accord with this suggestion, Meier (1990) noted that the beneficial effects of long-term storage of wood on cement hydration may sometimes be masked by attack of the wood by decay fungi.

Differences in the properties of boards containing sapwood or heartwood were apparent during the process of manufacturing them. Boards made from sapwood were dry and stiff as soon as they were removed from the press, whereas those made from heartwood were damp and spongy. Boards made from radiata pine heartwood were significantly ($P < 0.05$) weaker in bending than those made from sapwood or blue-stained sapwood (Fig. 1). The MOR of boards manufactured from blue-stained sapwood, which was obtained by testing four samples cut from two boards, was slightly lower, but not statistically different ($P > 0.05$) from that of boards made from sapwood. The MOR of

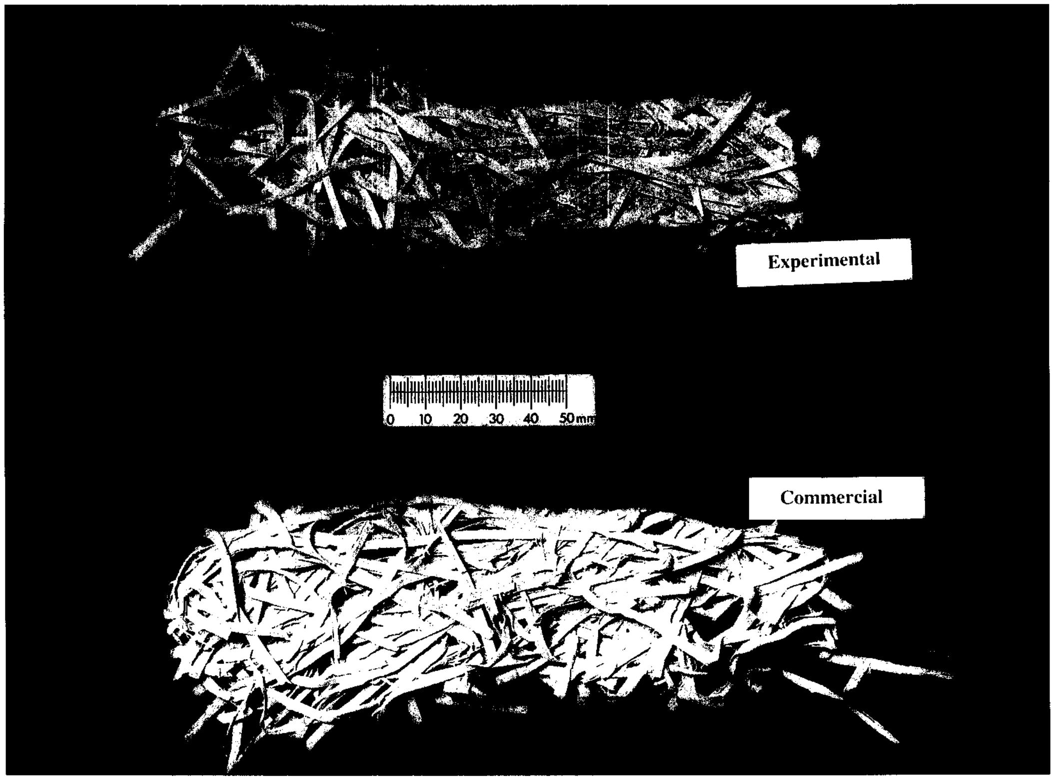

FIG. 3. Appearance of an experimental WWCB made from heartwood compared to a defective portion from a commercial panel showing poorly bonded wood strands and cement.

boards made from blue-stained sapwood was higher, but not statistically different from the average MOR of the commercial board samples (2 MPa).

The results of this study clearly show that radiata pine heartwood inhibits cement hydration and is highly unsuitable for the manufacture of WWCB. The appearance of the WWCB specimens manufactured from radiata pine heartwood (Fig. 2) bears a strong resemblance to the defect (Fig. 3) characterized by poor bonding between wood and cement that is occasionally found in commercially produced WWCBs made from radiata pine.

Radiata pine heartwood extractives are composed of resin acids (71%), fatty acid esters (11%), fatty acids (2%), phenols (6%), and unsaponifiables (10%) (Uprichard 1991). Resin acids and fatty acid esters have been shown to interfere with the hydration of cement and reduce bonding between cement and wood (Steward 1986; Miller and Moslemi 1991a). Furthermore, the heartwoods of loblolly and lodgepole pine, which contain similar types of extractives to those found in radiata pine heartwood (Erdtman 1952), also inhibit the setting of cement to a greater extent than sapwood (Weatherwax and Tarkow 1964, 1967; Miller and Moslemi 1991b). Therefore it can be concluded that the defect in commercially produced radiata pine WWCB, which is characterized by poor bonding between wood and cement and leads to the rejection of boards at the plant level, is caused largely by the inhibitory effects of heartwood on cement hydration.

Minimizing the effects of heartwood

Heartwood usually begins to form in radiata pine between 12 and 15 years of age (Bamber and Burley 1983), and there is a strong negative correlation between growth rate and site productivity and heartwood volume (Bamber 1976; Hillis 1987). In order to minimize any deleterious effects of radiata pine heartwood on the properties of WWCB, wood from fast-grown young trees (< 15 years old) should be used for the manufacture of WWCBs. If radiata pine wood for use by WWCB plants is derived from forest thinning operations, care should be taken to ensure that first thinnings (< 15 years) are used as these generally contain little or no heartwood. In contrast, logs from long-delayed first thinnings (past 15 years) and later thinning operations should not be used for the manufacture of WWCB as they will contain considerably more heartwood.

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REFERENCES

BAMBER, R. K. 1976. Heartwood, its function and formation. Wood Sci. Technol. 10(1):1–8.

———, AND J. BURLEY. 1983. The wood properties of radiata pine. Commonwealth Agricultural Bureaux, London, UK. 84 pp.

BIBLIS, E. J., AND C-F. LO. 1968. Sugars and other wood extractives effect on the setting of southern pine-cement mixtures. Forest Prod. J. 18(8):28–34.

BRUERE, G. M. 1966. Set-retarding effect of sugars in Portland cement pastes. Nature 212(5061):502–503.

DAVIS, T. C. 1966. Effect of blue stain on setting of excelsior-cement mixtures. Forest Prod. J. 16(6):49–50.

ERDTMAN, H. 1952. Chemistry of some heartwood constituents of conifers and their physiological and taxonomic significance. Pages 34–40 *in* J. W. Cook, ed. Progress in organic chemistry. Butterworths, London, UK.

HACHMI, M., A. A. MOSLEMI, AND A. G. CAMPBELL. 1990. A new technique to classify the compatibility of wood with cement. Wood Sci. Technol. 24(4):345–354.

HILLIS, W. E. 1987. Heartwood and tree exudates. Springer-Verlag, Berlin, Germany, 268 pp.

IRLE, M., AND H. SIMPSON. 1993. Agricultural residues for cement-composites. Pages 54–58 *in* R. L. Geimer, ed. Inorganic bonded wood and fiber composite materials. Forest Products Research Society, Madison, WI.

MEIER, W. 1990. The effect of various fungi and the influence of storing the components on the inhibition of cement by wood constituents. Holztechnologie 31(2):74–77.

MILLER, D. P., AND A. A. MOSLEMI. 1991a. Wood-cement composites: effect of model compounds on hydration characteristics and tensile strength. Wood Fiber Sci. 23(4):472–482.

———, AND ———. 1991b. Wood-cement composites: Species and heartwood-sapwood effects on hydration and tensile strength. Forest Prod. J. 41(3):9–14.

MOSLEMI, A. A. 1989. Wood-cement panel products: Coming of age. Pages 12–18 *in* A. A. Moslemi, ed. Fiber particle boards bonded with inorganic binders. Forest Products Research Society, Madison, WI.

———, AND Y. T. LIM. 1984. Compatibility of southern hardwoods with Portland cement. Forest Prod. J. 34(7/8):22–26.

RACZKOWSKI, J., A. KRAUSS, AND R. PACHA. 1983. Setting of cement in the presence of Scots pine wood affected by brown stain. Holzforsch. Holzverwert. 35(2):41–43.

SANDERMANN, W., AND M. BRENDEL. 1956. Studies on inorganic-bonded wood materials- Part 2: The cement poisoning effect of constituents of wood and their dependence on the chemical composition. Holz Roh-Werkst. 14(8):307–313.

———, AND R. KOHLER. 1964. Studies on inorganic-bonded wood materials- Part 4: A short test of the aptitudes of woods for cement-bonded materials. Holzforschung 18(1/2):53–59.

———, H-J. PREUSSER, AND W. SCHWEERS. 1960. The effect of wood extractives on the setting of cement-bonded wood materials. Holzforschung 14(3):70–77.

SIMATUPANG, M. H. 1986. Decomposition of glucose, cellobiose and wood under the influence of Portland cement paste. Holzforschung 40(3):149–155.

STEWARD, D. 1986. Interactions between ordinary Portland cement and wood. Unpublished Ph.D Thesis, University of Wales, Bangor, UK.

UPRICHARD, J. M. 1991. Chemistry of wood and bark. Page 4–24 *in* J. A. Kininmonth and L. J. Whitehouse, eds. Properties and uses of New Zealand radiata pine. Vol. 1. Wood Properties. FRI, Rotorua, New Zealand.

WEATHERWAX, R. C., AND H. TARKOW. 1964. Effect of wood on setting of Portland cement. Forest Prod. J. 14(12):567–570.

———, AND ———. 1967. Effect of wood on the setting of Portland cement: decayed wood as an inhibitor. Forest Prod. J. 17(7):30–32.

WOOLLEY, J. 1998. Manufacture of wood-wool cement boards at Woodtex Australia Pty Ltd, Bendigo, Victoria, Australia. Personal communication.