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Wood-cement composites: a review

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Abstract This paper reviews the research reported mostly in the last 10 years in the most common journals on the wood-cement composites field. The focused topics include: the problem of the compatibility (or not) between cement and woods, what causes it, ways of overcoming the problem; methods for manufacture and the properties exhibited by common wood-composites; special techniques to accelerate the curing of cement and to improve the properties of wood-cement composites; manufacture of nonwood vegetable raw materials-cement composites; durability against weathering and fungi; and construction materials. A discussion on the state-of-the-art is also presented.

Holz-Zement-Werkstoffe: Ein Überblick

Zusammenfassung Dieser Artikel gibt einen Überblick über die Forschung der letzten 10 Jahre in den bekanntesten Zeitschriften, die über das Gebiet der Holz-Zement-Werkstoffe berichteten. Die konzentrierten Themen beinhalten: Das Problem der Kompatibilität oder Nicht-Kompatibilität zwischen Zement und Holz, was es verursacht und wie man es überwinden kann; Methoden zur Herstellung und die Eigenschaften, die bei üblichen Holz-Werkstoffen gefunden werden; spezielle Techniken, um die Aushärtung von Zement zu beschleunigen und die Eigenschaften von Holz-Zement-Werkstoffen zu verbessern; die Herstellung von Zement-Werkstoffen aus anderen Pflanzenrohmaterialien; Resistenz gegen Witterung und Pilze sowie Konstruktionsmaterialien. Eine Diskussion als Stand der Forschung wird ebenfalls präsentiert.

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1 The question of the compatibility (or not) between woods and cement

The term *compatibility*, when applied in the research area of wood-cement composites, refers to the degree of cement setting after mixing with water and with a given wood in a fragmented form. In general terms, if the chemical process of cement hardening is undisturbed, or disturbed just in a low extent, by the presence of wood it is said that this cement and this wood are compatible; on the other hand, if cement hardening is impaired by the presence of wood, then they are said to be incompatible. This phenomenon of interaction is commonly expressed by a lowering of the physical properties of the wood-cement composites, ultimately giving samples without physical integrity. Also, a common analytical method to assess the extent of such inhibitory effect is the measuring of the decrease of heat release during the exothermic chemical process of cement hydration (C_A-factor, defined as the ratio of the amount of heat released from a wood-cement mixture, and the heat released from a cement paste without interferences), or the lengthening of time (t_{max}) needed to reach the maximum temperature (T_{max}). Three parts can be defined in a typical plot of temperature *vs.* time during cement setting, from the beginning when components are mixed until reaching of T_{max}: 1. initial temperature rise (small rise during a short period); 2. dormant period (where temperature does not rise or may even show a small decrease); and 3. cement hardening exhibiting rapid temperature rise (Moslemi and Lim 1984).

In fact, T_{max} and the C_A-factor have been applied to distinguish between compatible and incompatible among a group of Australian acacias, with a cement control as the reference (Semple and Evans 1998), and three classes of compatibility based on C_A have been suggested: "compatible", C_A>68%; "moderately compatible", 28%<C_A <68%; and "not compatible", C_A<28% (Hachmi and Moslemi 1989). A less common thermal parameter is the hydration rate (R, °C/h), that expresses the rate at which temperature rises during the initial phase of cement hydration (Sandermann and Kohler 1964). This method has been used to assess the compatibility of several Australian eucalypt species (Semple at al. 2000).

Hofstrand et al. (1984) have developed a more sophisticated thermal indicator of cement setting inhibition, and applied it to compare the compatibility of 9 northern Idaho timber species. The inhibitory index (I) is a quantitative measure of the compatibility of any given wood species when mixed with cement, and is expressed as:

$$I = 100 \cdot \frac{(t_2 - t'_2)}{t'_2} \cdot \frac{(T'_2 - T_2)}{T'_2} \cdot \frac{(S'_2 - S_2)}{S'_2}$$

where:

T_2: maximum hydration temperature
t_2: time to reach maximum temperature
S_2: maximum temperature/time slope.

The character without a prime is for wood-cement mixture, and the primed character denotes the appropriate parameter for neat cement. The index I takes, therefore, into account three different data obtained from a temperature/time plot.

However, Hachmi et al. (1990) have experimented different thermal inhibition indicators and have concluded that they lack consistency in the classification of species. It can even happen that the classification of wood species regarding their compatibility with cement will depend on the classification method used. The authors have found that a given wood species can be classified as intermediately suitable by one method and extremely inhibitory by another, after comparing the indicators T_{max} (Sandermann and Kohler 1964), the index I (Weatherwax and Tarkow 1964) expressed as:

$$I = \left(\frac{t_2 - t'_2}{t'_2}\right) \cdot 100$$

and the index proposed by Hofstrand et al. (1984) (see above). With the aim of developing an accurate and repeatable classification method that could be used as a standard method in all laboratories, and after a thorough set of experiments that involved 40 Moroccan wood and bark species and the testing of several new models, it was concluded that the C_A-factor appears to be the best wood-species ranking method.

However, even by using the C_A-factor, Semple et al. (1999) have found that the form by which the wood is applied (e.g., flour or wool) can result in a different species compatibility ranking, and Miller and Moslemi (1991a) have found little correlation between tensile splitting strength and t_{max}, T_{max} or C_A. Lee and Hong (1986) have argued that hydration temperature and/or hydration time, taken alone, may not reflect the actual compatibility in all cases. They have proposed instead a physical test as an indicator of wood-cement compatibility: a simple compression test of cylindrical samples. Results have indicated that compressive strength is linearly proportional to the maximum hydration temperature, but independent of hydration time, after applying several North American softwoods and hardwoods. The same physical test, applied at different times after the onset of curing, showed that among eight underutilised Tanzanian hardwoods tested, all species except two have had fairly comparable compatibility (Iddi et al. 1992). Results from the testing of wood-cement panels, made with 38 commercially important wood species, by MOR (modulus of rupture) and IB (internal bond) exhibited a positive correlation with T_{max} and t_{max} (Wei et al. 2000). These two latter parameters were, therefore, suggested as predictors of the general inhibitory properties and feasibility of using wood species as raw materials prior to manufacture of cement-bonded particleboard.

2 The cause of the incompatibility between some woods and cement

There is a general agreement that the inhibitory effect that some wood species have on cement hydration is due to their extractive content and kind of extractives. In fact, heartwood of radiata pine (*Pinus radiata* D. Don) was found to severely retard cement hydration, and the boards made with heartwood had little structural integrity, whereas boards made from sapwood have been made industrially and commercialised (Semple and Evans 2000). Experimentation with a group of 4 hardwoods and 5 softwoods from North America revealed that hardwoods adversely affected tensile strength and exothermic behaviour of cement more than softwoods, and softwood heartwood adversely affected the same parameters more than sapwood (Miller and Moslemi 1991a). A simple cold water soaking of the wood furnish comprising 8 temperate Australian eucalypt species have improved their compatibility (Semple et al. 2000) and, on the other hand, the addition of western larch (*Larix occidentalis*) hot water soluble extractives to a cement paste at a level of 0.6% could hinder totally the setting process (Zhengtian and Moslemi 1986).

However, the effect of the extractives may not be just a question of the absolute extractive content of a given wood. Among a group of 16 Moroccan woods and barks there was no clear relationship between the hot-water extractive content and wood-cement compatibility as measured by the C_A-factor. This parameter accounted for only approximately 50% of the C_A variation (Hachmi and Moslemi 1989). Among species with the same level of extractive content, different levels of compatibility were measured. These results that can be explained by the influence of the chemical composition of the extractives. The consideration of four wood extractive characteristics, namely hot-water extractive content, pH, base buffering capacity, and acid-to-base buffering capacity ratio, enabled the development of a highly predictive model with and R^2=0.95, for a group of 14 Moroccan woods and barks (Hachmi and Moslemi 1990).

Going further towards extractives identification, a fractionation of the methanol extractives of the wood of

Acacia mangium Willd., from Malaysia, revealed that a major component, teracacidin with a 7,8-dihydroxyl group in a leucoanthocyanidin structure, has a strong inhibitory effect as measured by a thermal index (Tachi et al. 1989). A procedure of the same kind with the heartwood of sugi (*Cryptomeria japonica* D. Don) revealed that sequirin-C and pinitol are the main inhibitory components (Yasuda et al. 1992), whereas in the wood of beech (*Fagus crenata* Blume) it is mainly sucrose (Imai et al. 1995). Research with model compounds for wood and extractive components revealed that models for cellulose, lignin, fatty acid, resin acid, sterol and terpene did not significantly decrease tensile strength of cement with concentrations up to 1.0% (Miller and Moslemi 1991b). Glucose caused the greatest decrease in that physical parameter (−40%), while hemicellulose, tannin and acetic acid caused a lesser extent decrease. The alkalinity of cement suspensions promotes the dissolution of wood carbohydrates, mainly when cements have a high alkaline buffering capacity, giving boards with lower mechanical strength than cements with lower buffering capacity (Roffael and Sattler 1991). Also, cement can degrade cellulosic pulps that have been applied as reinforcing material, leading to an increase in the amount of soluble carbohydrates with aging of boards.

Concerned with the measurement of extractives contents of two woods and a bark (cork) of Portuguese origin, with more than just organic solvents or water, Pereira et al. (2001) have also applied NaOH 0.1%, $Ca(OH)_2$ 0.1% and the filtrate from a cement suspension, to simulate the alkaline conditions and the chemical environment (e.g., cations) lignocellulosic materials are exposed to when mixed with water and cement. The values of “extraction yields” obtained with the calcium hydroxide solution and the filtrate from a cement suspension were negative, of the order of −3 to −9%. This means that the substrate increased in weight after being exposed to those solutions. One explanation for this result is that calcium, and maybe other cations, are taken out from solution and become adsorbed onto wood particle surfaces. In fact, ash measurements indicated an increase in the substrates, and elemental analysis showed an increase in the content of some cations, mostly calcium (Pereira et al. 2002). The fact that cations could be easily removed with an acid solution suggests that a cation-exchange phenomenon might have occurred, where cations like Ca^{2+}, K^+, and Na^+, have replaced the H^+ ions that have been previously displaced in the alkaline environment. If we take into account a series of reactions that happen in a neat cement-water mixture, as follows, where calcium plays an important role, then there is no doubt that the adsorption of calcium onto wood surfaces, concomitantly with its removal from solution, will disturb such chemical system impairing cement hydration. Some cement hydration reactions are (Coutinho 1997):

I. $2\ (3\ CaO.SiO_2)+6\ H_2O \leftrightarrow$ $3\ CaO.2\ SiO_2.3\ H_2O+3\ Ca(OH)_2$

II. $2\ (2\ CaO.SiO_2)+4\ H_2O \leftrightarrow$ $3.3\ CaO.2\ SiO_2.3.3\ H_2O+0.7\ Ca(OH)_2$

III. $3\ CaO.Al_2O_3+Ca(OH)_2+12\ H_2O \leftrightarrow$ $4\ CaO.Al_2O_3.13\ H_2O$

IV. $CaO.Al_2O_3.Fe_2O_3+7\ H_2O \leftrightarrow$ $3\ CaO.Al_2O_3.6\ H_2O+CaO.Fe_2O_3.H_2O\ CaO.Fe_2O_3.H_2O+2\ Ca(OH)_2+nH_2O \leftrightarrow 3\ CaO.Fe_2O_3.mH_2O$

V. $3\ CaO.Fe_2O_3.mH_2O+3\ CaO.Al_2O_3.6\ H_2O \rightarrow$ solid solutions

VI. $3\ CaO.Al_2O_3+3\ (CaSO_4.2H_2O)$ $+26\ H_2O \leftrightarrow 3\ CaO.Al_2O_3.3\ CaSO_4.32\ H_2O$

This complex system of reactions is influenced by the concentration of $Ca(OH)_2$, by pH and by temperature. Different conditions determine different yields for the reactions and different stabilities for the final products.

3 Overcoming the incompatibility between some woods and cement

As the inhibitory effect that some woods have on cement hydration is usually associated with their extractives, it is without surprise that the extraction of the wood furnish would improve the compatibility. Western larch, a highly inhibitory wood species, showed substantial improvements after extraction with hot water (Moslemi et al. 1983), and just cold water was enough for several tropical hardwoods (Gnanaharan and Dhamodaran 1985), although some species may require a more severe treatment, like NaOH 1% (Alberto et al. 2000). The fermentation of rubber wood saw dust has the effect of reducing the sugar content, leading to an increase in the compatibility (Simatupang and Handayani 2001).

Copper-chromium-arsenate—(CCA) and chromic acid-treated pine revealed to be more compatible than untreated pine, as seen through increased resistance to withdrawal of sticks embedded in cement and through increased flexural toughness of wood cement composites (Schmidt et al. 1994). Therefore, the application on wood-cement composites may be a feasible process to recycle CCA-treated wood.

The addition of some chemicals that act as cement curing accelerators has usually the effect of improving the compatibility of a wood-cement-water system, and that addition can also be made after an extraction of the furnish to further improve the cement setting. Among 30 inorganic and organic accelerators, $SnCl_2$, $FeCl_3$ and $AlCl_3$, followed by $CaCl_2$, on the average produced a maximum hydration temperature of above 60°C in a larch-cement-water system, while the time required to reach that temperature was significantly shortened (Zhengtian and Moslemi 1985). This effect could also be seen on the physical characteristics, like compressive strength, of hardened cement (Lee and Hong 1986). As seen by isothermal calorimetry, activated charcoal acts as a complementary compatibilizing agent when applied with $CaCl_2$. $CaCl_2$ acts mostly on aluminate hydration (the 2nd peak of the thermogram); silicate hydration (3rd peak) is influenced by the amount of mixing water and by activated charcoal. Combination of the 2 additives increased the enthalpy (hydration degree) by 50% (Sauvat et al. 1999).

4 Manufacture and physical properties of wood-cement composites

The simplest, but even tough effective and common procedure, to make a wood-cement composite is to mix together comminuted wood and water and cement. For panels production, then the material is pressed until cement setting. Most of the papers referred to in this review present a method to manufacture a given kind of wood-cement composite. We can easily identify a number of variables that would influence the properties of the final product: wood species (or in a more broader sense, lignocellulosic raw material species) and its physical and chemical characteristics, particle size and geometry, cement type, any additives (usually curing accelerators are common, but there are also curing retarders), wood-water-cement proportions, temperature of the environment, because a chemical reaction takes place, and time allowed for setting. All these group of variables, and their interactions, makes the theoretical prediction of properties very difficult, as is the development of a standard manufacture process that can be applied with all wood species. However, some guidelines can be devised.

Testing with three-layered panels (faces with sawdust and core with flakes, both from a mix of 3 tropical hardwoods) for variables like flakes length and thickness, and density of the boards, showed that these three variables were highly correlated with MOR, MOE, water absorption and thickness swelling. The longer and thinner the flakes, the stronger, stiffer and more dimensionally stable the boards, and the same trend was observed with increasing board densities (Badejo 1988).

Research with southern pine (*Pinus* sp.) showed that cement-wood ratio up to 2.6/1 has enabled the manufacture of cement excelsior boards with bending strength that met the requirements of commercial standards, even though the increase of the ratio above 2.0/1 had an adverse effect on the bending properties (Lee 1985a). Results obtained with a model developed to predict the properties of cement excelsior board, and the effect of the change of the levels of the variables, have suggested that variability in strand mechanical properties can significantly lower composite tensile and compressive strengths, while stiffness was not affected. The model also predicts that a relatively modest alignment of strands (a 3 to 1 ratio of strands aligned with the preferred direction to strands oriented 90° away from it) can lead to significant increases in strength and stiffness (respectively more about 25% and 33%) in the direction of the alignment (Stahl et al. 1997).

However, varying the cement-wood weight ratio from 13/1 to 4/1 with 6 North American woods resulted in that hydration temperature was drastically reduced, hydration time was prolonged and compressive strength was reduced (Lee et al. 1987). The same work outlined also that high cement-wood ratios used traditionally in laboratory for research purposes may not truly reflect the wood-cement compatibility at lower cement-wood ratios used in commercial production. Panels made with lodgepole pine (*Pinus contorta* Douglas ex. Loud) showed an increase in the modulus of rupture as the cement-wood proportion was lowered (from 3.0 to 1.5), but the modulus of elasticity increased linearly with greater ratios. Dimensional stability was high (maximum thickness swelling and water absorption respectively of 1.75% and 4.5%), and a reduction in the curing period from 28 to 14 days had little influence on board properties (Moslemi and Pfister 1987).

Wood-cement composites have been taken as very stable dimensionally when subjected to water soaking, as compared to common organic binder wood composites, like plywood. Also, the water absorption and residual water absorption are much less (Lee 1984). However, dimensional variations may still remain higher than some national standards. Water transfers between wood particles and cement matrix can be reduced by pulverization of the particles with and organic hydrophobic component. Polyethyleneglycol has presented the best results, but bitumen, a petroleum residue, has given a cheaper solution (Mougel et al. 1995). It has been investigated the behaviour of cement paste under constant and varying relative humidity conditions to evaluate the contribution of cement paste to the dimensional instability of cement-bonded particleboard (Fan et al. 1999).

As wood-cement composites present a good resistance to fire, the thermal insulation is also a characteristic they can be used for (Lee 1985b). However, when wood is aided to clayey concrete, to lower its density, an improvement in its insulation characteristics is, nevertheless, accompanied by a reduction in its mechanical strength and an increase in its deformability (Rim et al. 1999).

5 Rapid curing of cement and enhancement of properties of wood-cement composites

Conventional pressing techniques in the manufacturing process of cement-bonded particleboard require usually an 8-h to 24-h clamp time, so that the hydration process takes place in an extent enough that sufficient board strength and cohesiveness was developed in the board to permit the release of consolidation pressure. Then, a curing period can take 28 days, for example, to allow full crystallization and, hence, full strength development. The implication this has on the productivity of an industrial line is a big disadvantage, as compared to the very short pressing cycles of hot presses (typically 6–9 s per mm in thickness, although very variable) to manufacture resin-bonded particleboard. There are, however, several techniques that enable to lower very much clamping time for wood-cement boards.

CO_2 injection into the wood-cement furnish provides a method of reducing the pressing time. Exposure of Portland cement to carbon dioxide reduces the duration of the initial hardening stage. The phenomenon results from the chemical reaction of carbon dioxide with calcium hydroxide to form calcium carbonate and water (Berger et al. 1972):

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$$

The initial formation of calcium carbonate provides a bond in the initial stages of hydration and precedes other phases of crystallisation. Boards 14-mm-think and fabricated with southern pine (*Pinus* sp.) particles, and with the required amount of cement replaced by calcium hydroxide in 5%, could be removed from the press in less than 4.5 min (Geimer et al. 1992). Another major advantage of this gas system is the decrease in wood-cement incompatibility. The CO_2-injected boards were up to 1.9 times greater in MOE and up to 2.5 greater in MOR than similar boards pressed in the conventional manner.

However, obtaining uniform gas distribution throughout the board can be a technical problem. The addition of carbonates, like those of ammonium, sodium or potassium, can be an alternative method to introduce carbon dioxide in the pressed mattress. The carbonates decompose during pressing and carbon dioxide is released to react with calcium hydroxide. Pressing times of 15 min were attained with pressing temperatures of the order of 85°C (Simatupang et al. 1995). However, as recognised by the authors, the open time of a cement paste provided with either a solution of ammonium or sodium carbonate is too short to allow an application in the industrial production of wood-cement particleboard.

The application of CO_2 in the form of a supercritical fluid enabled the manufacture of cement-bonded particleboard with improved physical and dimensional stability properties in comparison to conventional curing (Hermawan et al. 2000). Being the production of high calcium carbonate content during the hydration of cement an explanation for these results, the authors present also a mechanism for the generation of calcium hydroxide that will react with carbon dioxide:

$$2Ca_3SiO_5 + 6H_2O \rightarrow Ca_3Si_2O_7.3H_2O + 3Ca(OH)_2$$
tricalcium silicate   tobermorite gel   calcium hydroxide

$$2Ca_2SiO_4 + 4H_2O \rightarrow Ca_3Si_2O_7.3H_2O + Ca(OH)_2$$
dicalcium silicate

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O + \text{energy}$$

Although the optimum properties of the boards manufactured by supercritical CO_2 curing can be similar to those of gaseous CO_2 curing, the optimum properties of the first could be achieved earlier than in the case of gaseous CO_2 cured one (Hermawan et al. 2001a). As revealed by X-ray diffractometry (XRD), thermal gravimetry (TG-DTG) and scanning electron microscopy (SEM), the high production of calcium silicate hydrate and calcium carbonate during the hydration of cement, the interlocking between these hydration products with wood surfaces, were considered the main reasons for the superior strength properties obtained in CO_2-cured boards.

On the other hand, the application of steam injection pressing to a wood furnish with sodium hydrogen carbonate ($NaHCO_3$) incorporated into the cement revealed that the initial hardening of the cement could be achieved within 2 s of steam injection time and 3 min of total pressing time, with at least 5% $NaHCO_3$ addition. Moreover, the particleboard could be handled immediately after pressing, without the necessity of clamping, although it was recognised that the mechanical properties were significantly small and dimensional stabilities were relatively poor, needing further research (Eusebio et al. 1995). Too high $NaHCO_3$ contents (15–20%) hinder the cement hydration, as too much $CaCO_3$ is produced and it covers the cement clinker, leading to lower strengths in the final condition (Nagadomi et al. 1996). In a system of this kind, and among several cement curing accelerators ($MgCl_2$, $CaCl_2$, $AlCl_3$ and NH_4Cl), $MgCl_2$ was the most effective accelerator for cement hydration which imparted a favourable effect on the mechanical properties and thickness swelling of the boards, although it seemed to affect adversely the linear expansion and the linear shrinkage (Nagadomi et al. 1996b). Latter it was found that the addition of Na_2SiO_3 was more effective than $NaHCO_3$ as a fortifier, with or without the addition of $MgCl_2$, having a favourable effect on the linear dimensional stability (Nagadomi et al. 1996c). The mechanisms proposed for this rapid curing of cement-bonded particleboard during steam injection pressing were the production of calcium carbonate ($CaCO_3$) when $NaHCO_3$ was added, and the production of amorphous silicate hydrate and cementation of SiO_2 gel when Na_2SiO_3 was used as a fortifier (Nagadomi et al. 1996d).

The addition of silica fume as an additive for cement hydration, in a steam injection pressing system, revealed to be effective, and more effective with the addition together of Na_2SiO_3 as a fortifier. It improved the mechanical properties of cement-bonded particleboard by accelerating the cement hydration and filling the gap in the cement structure (Nagadomi et al. 1996e). Furthermore, autoclave curing applied with silica fume improved also the dimensional stability by eliminating the production of ettringite (Nagadomi et al. 1996f).

The addition of isocyanate resin to a wood-cement furnish has shown to improve the properties of the composite (Eusebio et al. 1993a, b). After tensile strength testing and SEM observations of boards pressed at 60°C, it was concluded that isocyanate incorporation improved the crystallisation of cement and produced an unstratified network of isocyanate-cement complexes which formed better fixing of the cement crystals to the surfaces of adherends. Also, the addition of isocyanate resulted in boards that could be handled adequately even after a 3-hour cold-pressing time, while 1 h of hot-pressing at 60°C yielded boards with enhanced properties. Greater internal bond values were obtained and the dimensional stability was improved.

The incorporation of discontinuous inorganic fibre materials as additives, such as alkali-resistant glass fibre, normal glass fibre and mineral wool, into the furnish for manufacturing wood-cement particleboard resulted in significant enhancements of strength and dimensional stability properties, depending the improvement degree on the fibre and additive content (Wei and Tomita 2001).

6 Miscellaneous topics

More than just wood for the manufacture of cement-bonded composites, there have been also applied non-wood lignocellulosic materials, often residues from other operations. Hermawan et al. (2001b) have manufactured boards with oil palm fronds. In this case, the addition of $MgCl_2$ improved the compatibility (the C_A-factor increased up to 90% more), as well as the strength properties. Similar composites were also manufactured with the application of gaseous and supercritical CO_2 as curing methods (Hermawan et al. 2002). Boards were of high performance, cured within several minutes, and setting accelerators (e.g. $MgCl_2$) were not required, which caused a decrease in the dimensional stability.

Rattan (cane) furniture waste was tested as furnish material for the manufacture of cement-bonded particleboard (Olurunnisola and Adefisan 2002). Chopped strands were hot water-extracted, and $CaCl_2$ was added to the mixture, but the low strength and water resistance properties of the boards made them only suitable for use in low-stressed interior applications. Among kraft pulps from sisal and banana waste and from *Eucalyptus grandis* pulp mill residues, the eucalypt fibre was the preferred reinforcement for low-cost fibre-cement (Savastano et al. 2000).

In order to develop a lighter weight and a lower cost cement-masonry unit, it has been investigated the replacement of the light weight aggregate (expanded clay) by wood residue (fine sawdust and notch particles from white spruce) (Rashwan et al. 1992). The laboratory investigation concluded by the feasibility of the process, that involved a water treatment and a setting accelerator, but it was needed, however, a full scale additional research before launching the product into the market. Panels fabricated from southern pine particles derived from construction waste, treated with CCA, as well as untreated particles, were tested for freeze-thaw durability, strength and toughness. Results indicated that these composites can be designed to meet the requirements for highway sound barriers, and have also energy-dissipating properties (Wolfe and Gjinolli 1999).

Data about the long-term durability of cement-bonded wood composites are scarce. However, it has been found that some commercially produced wood-cement composites appeared in sound condition after exposure in a soil-block test to a white-rot and a brown-rot fungi species (Goodell et al. 1997). Microscopic observations revealed that the samples exposed to the fungi were colonised only at sites where wood particles were exposed to the sample surface, but with limited wood cell wall decay; wood particles in the interior of the samples that were completely encapsulated be cement were not attacked. Alteration of the normal pH environment of the wood was suggested as the mechanism that protects the composites from fungal decay even under severe decay exposure conditions.

MacVicar et al. (1999) submitted commercially produced fibre reinforced cement composites to two different accelerated aging methods: one method consisted of different cycles of water immersion, carbonation, and heating exposures; in the other method, cycles of water immersion, heating and freeze-thaw exposures were used. A comparison was made to material naturally weathered for 5 years in roofing. Both natural weathering and accelerated aging in CO_2 environment reduced the porosity, water absorption, and nitrogen permeability in the cement matrix, and enhanced the durability of the cellulose fibre-cement composites.

Fly ash has been incorporated in the mixture to make wood-cement composites in order to replace cement. Fly ash is a by product of the combustion of fuels, especially coals. When it is added to cement it acts as an inert fine aggregate in the early stages of curing. In the presence of moisture, the silica and alumina of the fly ash gradually react with calcium hydroxide released in the hydration of Portland cement. Additions of fly ash to wood-cement composites substantially increased the ease of mixing and the coating of wood particles (Miller et al. 1989). Also, it had no effect on dimensional stability and replacement up to 30% cement did not statistically decrease strength.

7 Discussion

Wood-cement composites, or in a broader sense, composite of cement and lignocellulosic materials, are now being investigated and made industrially in many countries in the world, mostly in the form of panels. Resin-bonded panels are, anyway, produced in much higher volumes, but wood-cement panels present several advantageous properties that make them more competitive for some niche applications. Wood-cement composites present a high durability against natural weathering or accelerated aging, a high dimensional stability, and high resistances against fire and biodegradation, namely against fungi. Although heavier than resin bonded-composites, they are lighter than concrete and, therefore, wood-cement composites can replace it in construction, namely prefabricated construction, in elements that are not subjected to loads, like walls. Wood-cement composites, that are of low cost, have been regarded as an important contribute to mitigate the housing problem in developing countries (Ramirez-Coretti et al. 1998).

Making wood-cement composites can be a feasible way of recycling wood residues, like waste from construction demolitions or preserved wood out of service, or nonwood residues from agriculture or food processing operations. On the other hand, this kind of composites also offer the possibility of recycling fly ash, as a partial replacement for cement.

Although some lignocellulosic materials might exhibit some degree of incompatibility with cement, there are established techniques to assess the degree of incompatibility, that are either based on the thermal characteristics of a cement setting process or on the physical properties of the composites made in the laboratory, as compared to the same parameters but obtained with a neat water-cement mixture. In the case of an unacceptable degree of incompatibility, an extraction of the furnish with water, or with a diluted alkaline solution, may be enough to upgrade the raw material to the desired level. Also, some common cement curing accelerators, like the chlorides of tin, iron, aluminium, magnesium or calcium, have the effect of improving the compatibility. They can be applied with the purpose of making faster the setting of cement, improving the physical properties of the composite, or rendering a given wood species suitable for making composites with cement. This latter application can also be made subsequently to an extraction of the material.

Some advanced techniques have been developed that allow the manufacture of wood-cement composites in a much shorter time than with the conventional procedures. Contrary to this latter, where can be required a 24 h-clamp time, followed by a 28 day-curing period, techniques like the injection of CO_2 into the mattress, either in its gaseous or supercritical form, or released from the decomposition of given chemicals, enable the removal from the press in a question of several minutes. Additions of silica fume or isocyanate resin have also demonstrated to improve the properties of the product. The challenge now is to transfer these developments to the industrial sector.

It must be also referred that, although many contributions in this field have been reported, their adoptions by other researchers or by industrial companies should be done with care. This is because, due to the high variability of natural materials, wood and lignocellulosics in our case, generalisations are often difficult in the wood science area, as highlighted by Rosenberg et al. (1990). Testing of materials, definition of manufacturing methods and of the levels of the variables, measurement of properties, all should be made again if raw materials come from a different plant species.

References

Alberto MM, Mougel E, Zoulalian A (2000) Compatibility of some tropical hardwoods species with Portland cement using isothermal calorimetry. Forest Prod J 50(9):83–88

Badejo SOO (1988) Effect of flake geometry on properties of cement-bonded particleboard from mixed tropical hardwoods. Wood Sci Technol 22:357–370

Berger RL, Young JF, Leun K (1972) Acceleration of hydration of calcium silicates by carbon dioxide treatment. Nature Physical Sci 240(97):16–18

Coutinho AS (1997) Manufacture and properties of concrete. Vol. I. LNEC—National Laboratory of Civil Engineering, Lisbon (in Portuguese)

Eusebio DA, Imamura Y, Kawai S, Sasaki H (1993a) Isocyanate-inorganic bonded composites I. Tensile strength an scanning electron microscope observations of isocyanate-cement mixtures. Mokuzai Gakkaishi 39(1):31–39

Eusebio DA, Imamura Y, Kawai S, Sasaki H (1993b) Isocyanate-inorganic bonded composites II. Shortening the pressing time of cement bonded particleboard. Mokuzai Gakkaishi 39(11): 1267–1275

Eusebio DA, Kuroki Y, Nagadomi W, Kawai S, Sasaki H (1995) Rapid curing of cement-bonded particleboard I. Steam injection pressing of cement-bonded particleboard with sodium hydrogen carbonate. Mokuzai Gakkaishi 41(3):309–317

Fan M, Dinwoodie JM, Bonfield PW, Breese MC (1999) Dimensional instability of cement-bonded particleboard: behavior of cement paste and its contribution to the composite. Wood Fibre Sci 31(3):306–318

Geimer RL, Souza MR, Moslemi AA, Simatupang MH (1992) Carbon dioxide application for rapid curing of cement particleboard. In: Proc. Inorganic Bonded Wood and Fibre Materials Symposium, Univ. Idaho, Moscow, Idaho, USA, Sept. 1992

Gnanaharan R, Dhamodaran TK (1985) Suitability of some tropical hardwoods for cement-bonded wood-wool board manufacture. Holzforschung 39(6):337–240

Goodell B, Daniel G, Liu J, Mott, Frank R (1997) Decay resistance and microscopic analysis of wood-cement composites. Forest Prod J 47(11/12):75–80

Hachmi M, Moslemi AA (1989) Correlation between wood-cement compatibility and wood extractives. Forest Prod J 39(6):55–58

Hachmi M, Moslemi (1990) Effect of wood pH and buffering capacity on wood-cement compatibility. Holzforschung 44(6): 425–430

Hachmi M, Moslemi AA, Campbell AG (1990) A new technique to classify the compatibility of wood with cement. Wood Sci Technol 24:345–354

Hermawan D, Hata T, Umemura K, Kawai S, Kaneko S, Kuroki Y (2000) New technology for manufacturing high-strength cement-bonded particleboard using supercritical carbon dioxide. J Wood Sci 46:85–88

Hermawan D, Hata T, Umemura K, Kawai S, Nagadomi W, Kuroki Y (2001a) Rapid production of high-strength cement-bonded particleboard using gaseous or supercritical carbon dioxide. J Wood Sci 47:294–300

Hermawan D, Subiyanto B, Kawai S (2001b) Manufacture and properties of oil palm frond cement-bonded board. J Wood Sci 47:208–213

Hermawan D, Hata T, Kawai S, Nagadomi W, Kuroki Y (2002) Manufacturing oil palm fronds cement-bonded board cured by gaseous or supercritical carbon dioxide. J Wood Sci 48:20–24

Hofstrand AD, Moslemi AA, Garcia JF (1984) Curing characteristics of wood particles from nine northern Rocky Mountain species mixed with Portland cement. Forest Prod J 34(2):57–61

Iddi S, Hamza KFS, Ringo WN, Ishengoma RC (1992) The suitability of some Tanzanian hardwoods for the manufacture of cement particleboards. Holz Roh- Werkstoff 50:280–281

Imai T, Suzuki M, Aoyama K, Kawasaki Y, Yasuda S (1995) Manufacture of wood-cement boards VI. Cement-hardening inhibitory compound of beech (*Fagus crenata* Blume). Mokuzai Gakkaishi 41(1):44–50

Lee AWC (1984) Physical and mechanical properties of cement bonded southern pine excelsior board. Forest Prod J 34(4):30–34

Lee AWC (1985a) Effect of cement/wood ration on bending properties of cement-bonded southern pine excelsior board. Wood Fibre Sci 17(3):361–364

Lee AWC (1985b) Bending and thermal insulation properties of cement-bonded cypress excelsior board. Forest Prod J 25(11/12):57–58

Lee AWC, Hong Z (1986) Compressive strength of cylindrical samples as an indicator of wood-cement compatibility. Forest Prod J 36(11/12):87–90

Lee AWC, Hong Z, Phillips DR, Hse CY (1987) Effect of cement/wood ratios and wood storage conditions on hydration temperature, hydration time, and compressive strength of wood-cement mixtures. Wood Fibre Sci 19(3):262–268

MacVicar R, Matuana LM, Balatinecz JJ (1999) Aging mechanisms in cellulose fibre reinforced cement composites. Cement Concr Compos 21:189–196

Miller DP, Moslemi AA, Short PH (1989) The use of fly ash in wood-cement composites. Forest Prod J 39(9):34–38

Miller DP, Moslemi AA (1991a) Wood-cement composites: species and heartwood-sapwood effects on hydration and tensile strength. Forest Prod J 41(3):9–14

Miller DP, Moslemi AA (1991b) Wood-cement composites: effect of model compounds on hydration characteristics and tensile strength. Wood Fibre Sci 23(4):472–482

Moslemi AA, Francisco Garcia J, Hofstrand AD (1983) Effect of various treatments and additives on wood-Portland cement-water systems. Wood Fibre Sci 15(2):164–176

Moslemi AA, Lim YT (1984) Compatibility of southern hardwoods with Portland cement. Forest Prod J 34(7/8):22–26

Moslemi AA, Pfister SC (1987) The influence of cement/wood ratio and cement type on bending strength and dimensional stability of wood-cement panels. Wood Fibre Sci 19(2):165–175

Mougel E, Beraldo AL, Zoulalian A (1995) Controlled dimensional variations of a wood-cement composite. Holzforschung 49(5): 471–477

Nagadomi W, Kuroki Y, Eusebio DA, Ma L, Kawai S, Sasaki H (1996a) Rapid curing of cement-bonded particleboard II. Curing mechanism of cement with sodium hydrogen carbonate during steam injection pressing. Mokuzai Gakkaishi 42(7):659–667 (in Japanese)

Nagadomi W, Kuroki Y, Eusebio DA, Ma L, Kawai S, Sasaki H (1996b) Rapid curing of cement-bonded particleboard III. Effects of sodium hydrogen carbonate and some cement hardening accelerators. Mokuzai Gakkaishi 42(8):762–768 (in Japanese)

Nagadomi W, Kuroki Y, Eusebio DA, Ma L, Kawai S, Sasaki H (1996c) Rapid curing of cement-bonded particleboard IV. Sodium silicate as a fortifier during steam injection pressing. Mokuzai Gakkaishi 42(8):769–775 (in Japanese)

Nagadomi W, Kuroki Y, Eusebio DA, Ma L, Kawai S, Sasaki H (1996d) Rapid curing of cement-bonded particleboard V. Mechanism of strength development with fortifiers and accelerators during steam injection pressing. Mokuzai Gakkaishi 42(10):977–984 (in Japanese)

Nagadomi W, Kuroki Y, Kawai S, Sasaki H (1996e) Rapid curing of cement-bonded particleboard with silica fume I. Effects of an additive for cement hydration during steam injection pressing. Mokuzai Gakkaishi 42(11):1090–1097 (in Japanese)

Nagadomi W, Kuroki Y, Kawai S, Sasaki H (1996f) Rapid curing of cement-bonded particleboard with silica fume II. Effects of autoclave on cement hydration. Mokuzai Gakkaishi 42(12): 1202–1210 (in Japanese)

Olorunnisola AO, Adefisan OO (2002) Trial production and testing of cement-bonded particleboard from rattan furniture waste. Wood Fibre Sci 34(1):116–124

Pereira C, Caldeira Jorge F, Irle M and Ferreira JMF (2001) Investigation of the extractives of portuguese maritime pine, blue gum and cork, to understand their influence on cement hardening. First data: extractive contents. In: Proc. 5th European Panel Products Symposium, Llandudno, North Wals, UK, 10–12 October 2001

Pereira C, Caldeira Jorge F, Irle M and Ferreira JMF (2002) Adsorption of calcium, and other cations from a cement suspension, on lignocellulosic substrates and their influence on cement setting. In: Proc. 6th European Panel Products Symposium, Llandudno, North Wals, UK, 9–11 October 2002

Ramirez-Coretti A, Eckelman CA, Wolfe RW (1998) Inorganic-bonded composite wood panel systems for low-cost housing: a Central American perspective. Forest Prod J 48(4):62–68

Rashwan MS, Hatzinikolas M, Zmavc R (1992) Development of a lightweight, low-cost concrete block using wood residue. Forest Prod J 42(5):57–64

Rim KA, Ledhem A, Douzane O, Dheilly RM, Queneudec M (1999) Influence of the proportion of wood on the thermal and mechanical performances of clay-cement-wood composites. Cement Concr Compos 21:269–276

Roffael von E, Sattler H (1991) Studies on the interaction between lignocellulosics (straw pulps) and cement. Holzforschung 45(6):445–454 (in German)

Rosenberg NP, Ince P, Skog K, Plantinga A (1990) Understanding the adoption of new technologies in the forest products industry. Forest Prod J 40(10):15–22

Sandermann W, Kohler R (1964) Studies on mineral-bonded wood materials. IV. A short test of the aptitudes of woods for cement-bonded materials. Holzforschung 18:53–59

Sauvat N, Sell R, Mougel E, Zoulalian A (1999) A study of ordinary Portland cement hydration with wood by isothermal calorimetry. Holzforschung 53(1):104–108

Savastano Jr H, Warden PG, Coutts RSP (2000) Brazilian waste fibres as reinforcement for cement-based composites. Cement Concr Compos 22:379–384

Schmidt R, Marsh R, Balatinecz JJ, Cooper PA (1994) Increased wood-cement compatibility of chromated-treated wood. Forest Prod J 44(7/8):44–46

Semple KE, Evans PD (1998) Compatibility of some Australian acacias with Portland cement. Holz Roh- Werkstoff 56:24

Semple K, Evans PD (2000) Adverse effects of heartwood on the mechanical properties of wood-wool cement boards manufactured from radiata pine wood. Wood Fibre Sci 32(1):37–43

Semple KE, Cunningham RB, Evans PD (1999) Cement hydration tests using wood flour may not predict the suitability of *Acacia mangium* and *Eucalyptus pellita* for the manufacture of wood-wool cement boards. Holzforschung 53(3):327–332

Semple KE, Evans PD, Cunningham RB (2000) Compatibility of 8 temperate Australian *Eucalyptus* species with Portland cement. Holz Roh- Werkstoff 58:315–316

Simatupang MH, Habighorst C, Lange H, Neubauer A (1995) Investigations on the influence of the addition of carbon dioxide on the production and properties of rapidly set wood-cement composites. Cement Concr Compos 17:187–197

Simatupang MH, Handayani SA (2001) Fermentation of saw dust from freshly cut rubber wood to improve its cement compatibility. Holz Roh- Werkstoff 59:27–28

Stahl DC, Cramer SM, Geimer RL (1997) Effects of microstructural heterogeneity in cement excelsior board. Wood Fibre Sci 29(4):345–352

Tachi M, Tange J, Nagadomi W, Suzuki Y, Terashima N, Yasuda S (1989) Manufacture of wood-cement boards IV. Cement-hardening inhibitory components of the Malaysian fast-growing tree, *Acacia mangium*. Mokuzai Gakkaishi 35(8):731–735

Weatherwax RC, Tarkow H (1964) Effect of wood on setting of Portland cement. Forest Prod J 14:567–570

Wei YM, Zhou YG, Tomita B (2000) Hydration behavior of wood cement-based composite I: evaluation of wood species effects on compatibility and strength with ordinary Portland cement. J Wood Sci 46:296–302

Wei Y, Tomita B (2001) Effects of five additive materials on mechanical and dimensional properties of wood cement-bonded boards. J Wood Sci 47:437–444

Wolfe RW, Gjinolli A (1999) Durability and strength of cement-bonded wood particle composites made from construction waste. Forest Prod J 49(2):24–31

Yasuda S, Iwase Y, Seguchi Y, Takemura T, Matsushita Y (1992) Manufacture of wood-cement boards V. Cement-hardening inhibitory components of sugi heartwood and behavior of catechol as a simple inhibitor model with vicinal phenolic hydroxyl groups in cement paste. Mokuzai Gakkaishi 38(1):52–58

Zhengtian L, Moslemi AA (1985) Influence of chemical additives on the hydration characteristics of western larch wood-cement-water mixtures. Forest Prod J 35(7/8):37–43

Zhengtian L, Moslemi AA (1986) Effect of western larch extractives on cement setting. Forest Prod J 36(1):53–54