CEMENT-BONDED LIGNOCELLULOSIC COMPOSITES FOR BUILDING APPLICATIONS

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ABSTRACT

Various lignocellulosic materials are available locally from the agro-forestry industries in many parts of the world. Using these materials in a cementitious matrix, composites with a range of properties can be formed. These composites have diverse applications in building construction. However, the presence of the extractives in the lignocellulosic materials and their mixing difficulty with cement limit their use. This paper discusses these problems and reviews the current status of various approaches adopted to overcome these problems for making cement-bonded products. The properties of the resultant composites and their advantages and limitations are also presented.

Material Index: Cement, Lignocellulosic materials, Composites
Key words: (a) Cement, Wood, Natural fibres, Composites, (b) Compatibility, Strength, Hydration

1. INTRODUCTION

Lignocellulosic materials are obtained from wood and natural plants. The main chemical constituents of these materials are lignin and cellulose as the name suggests and can be seen in Table 1. Wood is being used with organic or inorganic binding materials to produce building products. One of the drawbacks with the composites made using organic binders is that they have very poor resistance to water, fire and termite or otherwise are not cost effective. To overcome this problem inorganic binders like ordinary Portland cement (OPC), gypsum and magnesite are being used since the early part of the twentieth century. However, major part of the research in this direction has been done after nineteen sixties due to the growing public concern about the health hazards associated with the use of asbestos in roofing sheets and pipes.[1, 2]

In cementitious composites the main function of the fibres is to enhance the tensile strength or toughness, whilst the lignocellulosic particles are introduced in a cement matrix to reduce the density. Cement–bonded particle-composites are mainly used in the fire resistance, thermal insulation and acoustic applications. On the other hand cement-bonded fibre composite products are used as substitutes for asbestos-cement products and for the reconstituted resin-bonded wood products, such as plywood, particleboard and medium density fibreboard (MDF).[3]

During the last four decades, several reports on the use of lignocellulosic materials in making cement-bonded composites have been published. These include a variety of wastes found in different countries. The studies indicated that not all the lignocellulosic materials are compatible with cement. Many of them actually inhibit the setting of cement. The main cause of inhibition is the presence of chemical compounds like sugar and tannin in the particles.[4] It is, therefore, necessary to either remove these compounds or use accelerators that can offset the retarding effect. The other problem in the use of cement-bonded composites is related to their durability and dimensional stability. This paper aims to discuss the current understanding on the manufacturing and compatibility aspects and properties of the cement-bonded composites.

Table 1 Chemical composition of some lignocellulosic materials.[5-7]

Chemical constituent (wt %)	Banana	Coir	Jute	Sisal	Straw	Wood
Cellulose	60-65	43	61-63	60-67	40	45-50
Hemicellulose	6-8	<1	13	10-15	28	23
Lignin	5-10	45	5-13	8-12	18	27
Extractives	—	2.52	—	5.47	—	<10

2. Manufacture of Cement–bonded composites

For making cement-bonded composites, lignocellulosic materials are used in various forms. They are mainly used as fibres or as particles. The manufacturing technology for fibre-reinforced composites is based upon the process used for making paper from the pulp, whereas for cement-bonded particleboards the manufacturing process is similar to that used for producing the resin-bonded particleboards. The lignocellulosic fibres are obtained from different parts of the natural plants, such as leaf, stem, fruit surface and wood.[8] Sisal, henequen and abaca are derived from leaves, whereas jute, hemp and flax are obtained from the stem of the plants. Coir is acquired from the husk at the surface of coconut fruit. Cellulosic fibres are also derived from the wood of various types of trees and by recycling waste paper.

Presently, the cement-bonded composites are manufactured in several countries including the United States, Australia and several European and Asian countries. A few of the leading manufacturers of cement-bonded particle boards are: Durisol AG in Deietikon (Switzerland), Eternit in Neubeckum (Germany), Fulgurit V mbH in Wunstorf (Germany)West Hungarian Timber Comine in Szombathely (Hungary), Metasaliiton in Hameelinna (Finland), Cemboard Sdn Bhd in Kuala Lumpur (Malaysia), Fama in Milan (Italy), Evest Roofing ‘Eternit’ in Mumbai (India), James Hardie Building Products Inc. in various locations in USA and Durisol in Canada.[3,5,9]

2.1. Cement–bonded fibre composites

Cement–bonded fibre composites are made of natural or refined wood fibres and a cement matrix that may or may not contain sand. In comparison to the natural plant fibres, wood fibres are short and stiff, but they have better strength and durability in cement matrix.[10] In addition, wood contains considerable amount of lignin and hemicelluloses (Table 1), which are known to have an adverse effect on the cement hydration and durability of the composite. Therefore, to reduce lignin and hemicelluloses, and to obtain wood in the form of fibres, wood chips are subjected to a process called 'pulping'. Sometimes the natural fibre strands are also subjected to pulping to improve the strength and durability of the composites. There are three types of pulping processes: mechanical, chemical and semi-chemical. Mechanical pulps are cheaper than the chemical pulps. These fibres, obtained by pulping, have an aspect ratio of about 50, a diameter of 20 - 60 µm for hardwoods and 30 to 120 µm for softwoods, and a length of 0.5 to 3 mm for hardwoods and 2.0 to 4.5 mm for softwoods.[11] These fibres are then used for making thin cementitious composite sheets. In these composites the composition of matrix has significant effects on the strength and toughness of the composites. Coutts[12] compared properties of the composites made using a neat cement paste matrix with those made using a cement-sand mortar matrix. The results show that neat cement paste matrix yields stronger composite but with lower toughness. In the case of the mortar matrix, strength was relatively lower and attributed to the fibre failure by pull-out due to inferior bond between fibre and mortar matrix. The failure by fibre pull-out increases the toughness but lowers the strength of the composite.

Generally, the lignocellulosic fibres are added in the range of 5 to 15% by weight of cement. Further addition of fibres causes difficulties in mixing and compaction. These problems also restrict the application of the composite as bulk concrete and make only suitable for making pre-cast products in the automated factories.[13] To achieve higher strength, in addition to cellulose fibres, alkali resistant glass fibres are also used. Nevertheless, despite all these advancements, Moslemi[3] points out that, about 90% plants around the world still use asbestos fibre.

2.2. Cement-bonded Particle Composites

This type of composites are made by using wood or other lignocellulosic materials, like, wood particles, oil palm shells, cork granules or hazelnut shells in aggregate form. The cement-bonded particle composites can be classified in the following categories depending upon the size of the particles: wood wool cement composite, wood chip cement composite, wood particle cement composite and structural wood concrete.

For making wood wool cement composites, wood logs are converted into ribbon-like particles called excelsior. They have a length of greater than 80 mm. These particles are then mixed with cement and additives. The density of this composite type ranges from 350 to 650 kg/m^3. It is mainly used for making thermal insulation boards, acoustic surface panels, floors and roofs, and moulding panels.[14, 15]

Wood chip cement composite is made of short wood chips of length less than 20 mm, cement, water and admixtures. The density of this composite varies between 400 and 750 kg/m^3. It is mainly used for making masonry blocks and thermal insulation. For example, Durisol blocks have a density of less than 710 kg/m^3.

Wood particle cement composite is denser than wood chip cement composites. However, the same raw materials are used but in different proportions. Density of this composite varies between 1000 and 1200 kg/m^3. This type of composite is used for making partition boards, firewalls, ceilings and floors, fire doors and other similar applications.

Structural wood concrete is made using wood in the form of short chips of length less than 30 mm, with other contributing materials being cement, aggregate, water and admixtures. The density of these composites ranges between 1200-1800 kg/m^3. Structural walls and slab components can be made from this type of composites.[3, 14]

3. Compatibility Problem

Lignocellulosic materials contain various soluble organic compounds, such as carbohydrates, glycosides and phenolic compounds. These compounds are well known as cement set retarders. Therefore the presence of natural plant and wood fibres or particles in cement paste can retard or inhibit the hydration reactions of cement.[16, 17] Although the properties of the cement-boned composites are also influenced by various parameters like press time and temperature, accelerators and water:cement ratio, the hydration rate of wood-cement composite is of prime importance. This is because a lower hydration rate slows the strength development in the composite and thus delays the demoulding of the products. This ultimately leads to a lower production rate.

Wood-cement compatibility can be defined as the ratio of a parameter related to characteristics of a wood-cement composite to that of a neat cement paste. The compatibility is often expressed as a percentage value. To determine wood-cement compatibility, methods based on different properties are used, such as, hydration characteristics, strength, interfacial bond and morphology. The methods that various researchers have used include: the measurement of hydration characteristics of a cement-aggregate mix;[16, 18, 19] the comparison of the mechanical properties of cement-aggregate mixes;[20-22] and the visual assessment of microstructural properties of the wood-cement mixes.[23] Besides these methods, Aggarwal and Singh[7] used setting time for investigating the effects of plant fibre extractives on setting of cement. Recently, Karade *et al.*[24] reviewed the methods of compatibility assessment and suggested a new method, which is based on the maturity concept.

Compatibility is affected by several parameters, such as type of species, location, part of the tree, season during wood cutting, degree of decay, storage condition, particle size, water:wood:cement ratio, insulation condition, temperature, and admixture.

The precise mechanism of inhibition of cement setting due to the lignocellulosic particles is still unresolved. However, based upon the speculations made by several researchers, it appears that first the extractives are pulled into the cement solution and then the extractives composed of various organic compounds make complexes with the metal ions present in the cement solution. This decreases the concentration of Ca^{2+} ions in the solution and possibly disturbs the equilibrium of the solution, which delays the start of nucleation of $Ca(OH)_2$ and C-S-H gel.

Generally, fresh woods are found to be more inhibitory than seasoned woods. This is because with seasoning of wood, free carbohydrates are decreased but phenolic compounds are not. Likewise hardwoods are generally less compatible than softwoods because of the presence of large amount of soluble xylan in hardwoods.[4, 16, 17]

Biblis and Lo[17] found better compatibility of winter-cut sapwood than that of spring-cut sapwood. In addition, the heartwood was found to be more detrimental to the setting of cement than sapwood. However, Semple *et al*.[25] report that the size and geometry of wood particles influence the compatibility. They found that the compatibility of wood wool-cement composite increases with heartwood content, but the trend was opposite when wood wool was replaced with wood flour. They interpreted that because specific surface area of wood flour is higher than that of wood wool, it is possible that the inhibitory extractives from heartwood leach and retard the hydration of cement.

From this discussion it appears that there are several factors that influence the compatibility of lignocellulosic materials with cement. Generally, woods with lower concentrations of carbohydrates such as softwood, sapwood and seasoned woods are more compatible than their respective counterparts. For other factors the results are not consistent and the outcomes are often contradictory.

To improve the wood-cement compatibility several methods are employed, such as extraction of the detrimental compounds by cold water, hot water or by alkaline solution; addition of cement set accelerators, exposure to CO_2 gas; and the use of additives to adsorb the organic compounds. A number of metal salts, such as $CaCl_2$, $FeCl_3$, $SnCl_2$, and $AlCl_3$, can be used to accelerate cement setting,[26] but $CaCl_2$ is widely used throughout the world due to its relatively lower cost. An alternative method of accelerating the setting of the wood-cement mix is the injection of CO_2 gas. Geimer *et al*.[27] found that by the injection of CO_2 into the cement-bonded particleboard, the compaction pressure on the board could be released in 4.5 minutes, whereas the conventional process takes 8 to 24 hours.

It appears that before using the lignocellulosic materials with cement, it is important to assess their compatibility with cement. Accordingly, it may be necessary to use a suitable pre-treatment method or a suitable dose of accelerator. In general, cold and hot water extraction are effective pre-treatments for improving the compatibility, but it takes a considerable long time in processing that could lead to reduced productivity. On the other hand, the use of accelerators may increase production costs. Alternatively, CO_2 can be injected, but obtaining a uniform gas distribution throughout the product is difficult and needs more research. Curing at higher temperature is another possibility. Altogether, the use of low cost accelerators like $CaCl_2$ still seems to be the best option for improving compatibility.

4. COMPOSITE PROPERTIES

An assessment of the properties of the composites is very important for finding suitable applications for the composites. The physico-mechanical properties are useful in the initial stages for designing the building components, whilst the durability properties indicate the long-term performance of the composites in service.

4.1. Physico-mechanical Properties

There are several variables that influence the properties of the final products of cement-bonded composites. These variables include wood species or lignocellulosic raw materials, their particle size and geometry, cement type, additives, proportions of the constituents and process and curing temperature and time. Due to these variables and the interactions between the constituents of the mix, the theoretical prediction or comparison of the properties and standardisation of the manufacturing process are very difficult. However, the properties of the composites made with a variety of raw materials and different processes are discussed in the following paragraphs.

The properties of the cement-bonded fibre/particleboards or panels like products are given in Table 2 and the properties of lightweight concrete like products from the lignocellulosic wastes are given in Table 3. Generally, the cement-bonded fibre composites are denser and stronger than the cement bonded particle composites. The density of the fibre products lies between 1100 and 1800 kg/m^3 and a bending strength up to 30 MPa can be achieved.[15] Due to the high bending strength these composites are used for making building products like thin sheet or panels, pipes and several other moulded products.[1] Roofing tiles and cladding elements are also made from these composites. As can be seen in Table 2 the properties of the cement bonded boards closely match with the minimum requirement according to ISO:8335-1987.[28] It can also be noticed that the composites made with pulps have higher density and superior strength properties than the composites made with unpulped lignocellulosic materials have.

Further information on the use of other natural fibres in cement-bonded composites can be found in literature.[8, 34-36]

Table 2 Properties of some cement bonded composite boards.[9, 28-33]

Property	ISO:8335-1987	Coir-cement composite	Baggase-cement composite	Rice straw board	Wood-cement particleboards	E-Board (Pulp)	Pulped Sisal reinforced composites
Density	1000 (min.)	1300-1400	1550-1650	1513-1723	1060-1380	1374	1260 -1680
Thickness swelling, %	2 (max.)	0.8-1.2	0.30-0.46	2.84 – 4.38	0.34 –2.10	0.49	--
Bending strength, MPa	9.0 (min.)	9.0 –11.0	8.85-9.60	3.8 – 7.0	6.30 –15.0	10.10(dry) 8.22 (wet)	18.0 -- 22.0
Modulus of elasticity, MPa	3000 (min.)	2500-2800	—	—	2860 -6660	4040	11,000
Tensile strength Perp. to the board plane	0.45 (min.)	0.35 - 0.50	1.06-1.14	—	0.34 –1.06	0.35-0.59	--
Moisture content, %	6 - 12	6 – 7	6.5 – 6.8	—	—	—	—
Water absorption, %	—	14.0 – 16.0	12.5 – 14.5	24.61 – 37.54	—	—	18.0 – 37.5

From Table 3 it can be noted that when the lignocellulosic materials are used as lightweight aggregates, the resultant composites have poor bending strength. However, they have enough compressive strength for many building applications, such as thermal insulation, partitions and masonry blocks.

Table 3 Properties of some cement-bonded composites incorporating lignocellulosic wastes.[22, 37-43]

Organic aggregate	Source	Comp. Strength, MPa	Flexural strength, MPa
Pine wood	Construction waste	1.10 - 6.64	0.57 - 1.65
Conifer (Cedar, Cypress and Pine)	Construction waste	5.00 - 8.00	4.00 - 7.00
Hazelnut shell	Agro-forestry	26.50 - 43.70	4.40 - 7.00
Oil Palm shells	Oil Palm industry	15.00 - 20.00	—
Oil Palm frond	Oil Palm industry	—	5.00 - 23.00
Cork granules	Cork industry	1.00 - 26.00	0.50 - 4.00
Bark of Japanese Cedar	Forestry waste	10.00 - 22.00	2.00 - 8.00
Rattan (Palmae)	Cane Furniture	—	0.50 - 1.60

4.2. Durability and Dimensional Stability

One of the main reasons that limit the wide use of cement-bonded natural fibre or wood composites is that their properties change with time. For example, the natural fibres or wood may degrade due to the surrounding high alkaline cement matrix. The rate of degradation depends upon the transport of alkaline water into the lumen of the fibres. It is possible that the lignin in the fibres dissolves and degrades the fibre-matrix bond.[8] In the alkaline environment, $Ca(OH)_2$ penetrates into the fibre and mineralises or petrifies it. This can severely reduce the strength of the fibre, but if the composite is exposed to carbon dioxide, the carbonation reactions will convert $Ca(OH)_2$ into $CaCO_3$ and water and the rate of strength reduction can be controlled.[13]

Many studies indicated that cement-bonded composites are generally more durable than the resin-bonded composites. For example, Aggarwal[44] reports that the cement-bonded panels made using coir fibres performed better than the resin-bonded particleboards and plywood under accelerated weathering tests. Nevertheless, the flexural strength and toughness of cellulose fibre-cement composites has been found to decrease with the ageing due to the decomposition of the reinforcing fibres.[45] Attempts have been made to reduce the alkalinity of cement by using pozzolana such as silica fume, rice husk ash and fly ash,[46] and to improve water resistance property of fibre by applying surface coatings or impregnation.[47-48]

The strength properties of cellulose fibre-cement composites are highly moisture sensitive. Soroushian *et al.*[45] report a considerable difference in the flexural properties (strength and toughness) of these composites, when tested at different moisture contents. They found that with the increasing moisture content, flexural toughness increases, but strength decreases. Dinwoodie and Paxton[49] found that if cement-bonded wood particleboards are maintained under unstressed conditions at a temperature of 20 ºC and 65% relative humidity, the flexural strength and stiffness increases due to hardening of cement matrix with time. Furthermore, they show that under a wide range of ageing conditions, the cement-bonded wood particle composites perform better in the long-term than the resin-bonded particle composites.

Wood cement composites are generally considered as a material that is resistant to bio-degradation. Parameswaran and Broker[50] examined a wood-cement composite that had been buried in soil for 30 years. They found that its outer surfaces were fungal affected, but the inner part remained unaffected. They did not find any sign of wood cell degradation in the inner parts of the composite. This is in agreement with the findings of Dinwoodie and Paxton[49] for a 15 years aging period. According to their results, cement bonded wood composites are highly resistant to fungi and European subterranean termites. This might be because the alkaline environment (pH>11) is not suitable for fungal or bacterial growth.[14] However, Shukla[51] reports that the wood-wool board samples made of mango wood and deodar wood with cement, that were buried in termite mounds in India for six months showed slight to heavy damage. This suggests that whilst wood-cement composites are generally resistant to biodegradation, termites may still affect them.

One more problem that restricts the wider use of wood-cement composites is their vulnerability to dimensional instability in outdoor conditions with varying humidity. The variation in external humidity causes changes in wood, cement and at the interface. With a change in the external humidity wood cement composites can undergo a dimensional change of 3 to 5 mm/m.[47] Consequently, a long time is required for their stabilisation after manufacturing.

5. Discussion

The advantages associated with the use of cement-bonded composites are that they are lightweight, tough, water-resistant, fire resistant, durable, machinable (cutting), and cost effective. They can also be nailed into. However, there are some problems in making these composites, such as inconsistent quality of raw material (wood waste), unreliable dimensional stability and lower strength of the composite in comparison to the normal strength concrete. Despite these disadvantages, the composites have sufficient strength for several non-structural applications like partition, sound absorption, thermal insulation and low cost housing. When compared to resin-bonded products, the cement-bonded products are better in all respects, with exception of density. The main limitation of the resin-bonded composites is their poor resistance to moisture, fire and microbial attack. In recent years, efforts have been made to overcome these limitations by incorporating inorganic fillers like fly ash and red mud in the resin-bonded natural fibre reinforced composites.[52-54] However, these inclusion of inorganic fillers increase the density of the composites.

The strength properties of the cement-bonded composites can be further enhanced by the incorporation of fibres such as alkali-resistant glass fibre, normal glass fibre and mineral wool. For example, a significant improvement in the strength and dimensional stability properties was achieved by using inorganic fibres in a study conducted by Wei and Tomita.[55]

In making cement-bonded composites there is a great potential of use of waste materials like construction demolitions wastes or after service preserved woods, agro-forestry wastes and food processing industrial wastes. Although, agriculture wastes do not have consistent properties throughout the year and cannot be stored for a long period, they can be used in combination with wood fibres. Further, inorganic wastes like fly ash can be used to reduce the alkalinity of the cement paste by partially replacing the cement.

If these wastes can be utilised in making cement-bonded wood composites, it would be very beneficial from an environmental point of view, since recycling of these wastes can reduce the level of timber harvesting, burning of the wastes and landfill areas.

6. CONCLUSION AND RECOMMENDATIONS

The lignocellulosic materials are used in various forms for making cement-bonded composites. These composites have versatile applications in building construction. A large volume of agro-forestry wastes can be utilised in making such composites. However, the variation in properties of lignocellulosic raw materials and their incompatibility with cement cause some problems. These problems can be overcome by applying suitable measures, such as mixing of the different raw materials, pre-treatments and use of accelerators. Some treatment can also be applied for improvement of the durability of these composites. However, the current understanding is not enough and more research is required towards improvement of the compatibility and durability of the cement-bonded composites. This can help in improvement of the strength of these composites and can extend their applications.

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