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Developments in Cement-Bonded Composite Material Technology

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Abstract

Plain cement mortar and concrete are brittle materials having a very low tensile strength. Besides this they have high density and thermal conductivity. To overcome these problems synthetic fibres and lightweight aggregates or various lignocellulosic materials like wood, natural fibres and agro wastes are incorporated in cementitious matrix. The resultant composites are lightweight and have greater toughness. They have diverse applications in building construction. Cement bonded composites have emerged as an important building material during the later large part of the last century. Efforts have been made to use lignocellulosic wastes, which are generated in huge quantity throughout the world and causing various environmental problems. Use of these wastes in making construction materials could reduce the magnitude of the problem. However, in this effort there are various restraints like compatibility of these wastes with cement, their toxicity, and limited composite strength. Moreover, uniform quality of these wastes is not available to the industry throughout the year. This paper reviews the results of recent research into the use of these wastes and other wastes like fly ash and blast furnace slag in making cement-bonded composite materials. Various approaches adopted to overcome aforementioned problems are described. The benefits and limitations of the use of such materials in building construction are also discussed.

Introduction

Cement-bonded composites are emerging as an important class of construction materials. They are made of a cementitious matrix and fibres or particles. The fibres could be wood fibres, natural fibres or synthetic fibres. The particles are generally obtained from wood or other agro-forestry wastes. The production of wood cement composite panels began around mid sixties in the twentieth century, due to the growing public concern about the health hazards associated with the use of asbestos [1,2]. The production of fibre-reinforced composites is based upon a process similar to that used for making paper from the pulp, whereas manufacturing process of cement-bonded particleboards matches the method used for producing resin-bonded particleboards. The fibres are obtained from different parts of the natural plants, such as leaf, stem, fruit surface and wood [3]. Cellulosic fibres are also derived from the wood of various types of trees and by recycling waste paper. In comparison to the natural plant fibres, wood fibres are short and stiff, but they have better strength and durability in cement matrix [4]. Wood fibres are obtained by a process called 'pulping'. The natural fibre strands are also sometimes 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. The 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 [5]. 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. It has been found that the neat cement paste matrix yields stronger composite but with lower toughness. In the case of the cement-sand mortar matrix, strength was relatively lower and attributed to the fibre failure by pull-out due to inferior bond between fibre and mortar matrix [6]. The failure by fibre pull-out increases the toughness but lowers the strength of the composite. Generally,

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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 [7]. To achieve higher strength, in addition to cellulose fibres, alkali resistant glass fibres are also used. Nevertheless, despite all these advancements, about 90% plants around the world still use asbestos fibre [8].

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.

Wood wool cement composites are made by converting wood logs into ribbon-like particles called excelsior and mixing them with cement and additives. The density of the resultant composites varies between 350 and 650 kg/m^3. The main use of these composites is in making thermal insulation boards, acoustic surface panels, floors and roofs, and moulding panels [9-10]. Wood chip cement composite contains short wood chips of length less than 20 mm, cement, water and admixtures. The density range of this composite is 400 to 750 kg/m^3 and used for making masonry blocks and thermal insulation. The same raw material is used under pressure for making wood particle cement composite. The pressure causes increase in density of the composite, which varies between 1000 and 1200 kg/m^3. The main applications of this type of composite are in making partition boards, firewalls, ceilings and floors, fire doors and other similar applications. For producing structural wood concrete of density range 1200-1800 kg/m^3, short wood chips (<30 mm) along with cement, aggregates, water and admixtures are used. This type of concrete has lower thermal conductivity in comparison to the normal weight concrete. From this type of composites structural walls and slab components can be fabricated [8-9].

Cement-bonded composites are produced throughout the world. The leading manufacturers 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 [8, 11-12].

Table 1 Chemical composition of some lignocellulosic materials [11-14].

Chemical constituent (wt %)	Wheat straw	Jute	Sisal	Coir	Wood	Cork
Cellulose	40	61-63	60-67	43	45-50	9
Hemicellulose	28	13	10-15	<1	23	11
Lignin	18	5-13	8-12	45	27	22
Extractives	–	–	5.47	2.52	<10	15-20
Suberin	–	–	–	–	–	40

Compatibility Problem

Wood and other plant based materials contain soluble organic compounds, such as carbohydrates, glycosides and phenolic compounds in soluble form as extractives (Table 1). These compounds are well known as cement set retarders. Therefore, the inclusion of wood and natural fibres in cement paste can retard hydration of cement and proceed with slower strength development (Fig. 1), which may delay the demoulding time leading to a lower production rate. In view of this, prior to selection of suitable wood or natural fibres it is important to assess their compatibility with cement. To determine wood-cement compatibility, methods based on different properties are used, such as, hydration characteristics, strength, interfacial bond and morphology. Recently, Karade *et al.* [15] reviewed the methods of compatibility assessment and suggested a new method, which is based on the maturity concept. The usual method for this purpose is comparison of the hydration characteristics of cement and wood-cement mix under semi-adiabatic condition. Typical hydration curves are shown in Fig. 2.

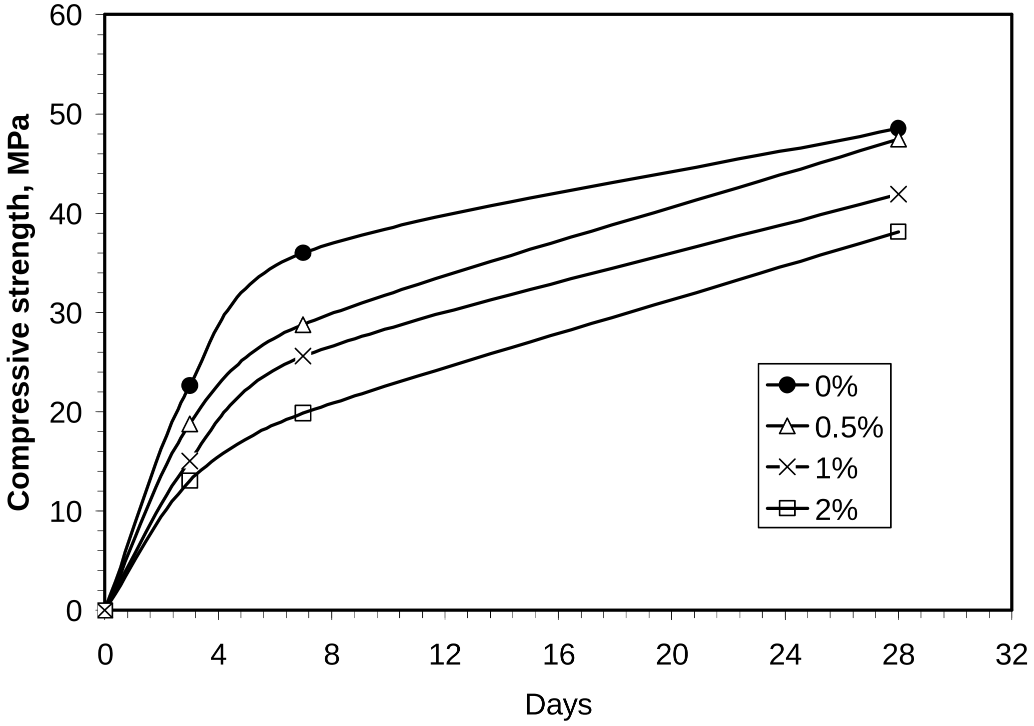

Fig.1 Effect of extractives on strength development of cement-bonded composites.

There is no specific mechanism of retardation of cement setting due to the lignocellulosic particles, but it is believed that initially the extractives are pulled into the cement solution and then the organic compounds present in the extractives make complexes with the metal ions available in the cement solution. This consumes Ca^{2+} ions and decreases their concentration in the cement solution, which disturbs the equilibrium and delays the start of nucleation of $Ca(OH)_2$ and C-S-H gel. Wood-cement compatibility is affected by several parameters like the 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. It has been found that fresh woods are generally more inhibitory than the 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 [16-18].

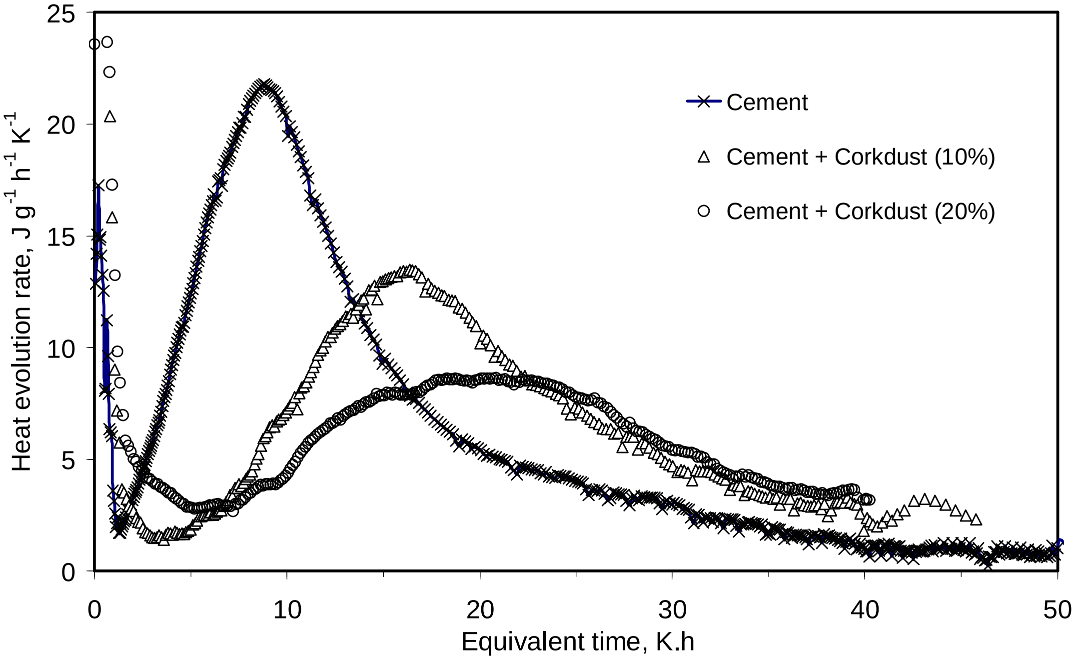

Fig. 2. Effect of cork powder addition on heat evolution rate of cement

Alternative Raw Materials

Substantial research had been done on use of various forms of wood to make cement-bonded products [8-9, 19]. While doing so the emphasis was upon the use of 'clean' or virgin wood. However, later in view of the increasing rate of depletion of the forest resources efforts have been made to explore the use of alternative raw materials like agro-forestry and construction wastes.

Agro-forestry wastes

Several types of agro-forestry wastes like wheat straw, rice straw, arhar stalks, bagasse, coir, hazel nut shells, oil palm shells and fronds, cork granules and various cereal plant wastes have been investigated for their possible use as raw materials in making cement bonded composites. Presently these wastes are either feed to animals or burnt. The composites made with these wastes have shown good potential in making building components [19-31].

Wheat straw possesses the desirable geometric and mechanical characteristics for making cement-bonded particleboards, but its inhibitory effects on cement hydration constraining wider use of cement-bonded strawboard [21]. Nevertheless, using accelerated processing techniques based on carbonation reactions cement- wheat straw boards were successfully made. Using combination of pre-treatment and accelerators cement-bonded boards are also made using coir, bagasse and arhar stalks. These boards meet the minimum standard mechanical, durability and physical requirements. However, the cement bonded rice straw boards made by Fernandez and Taja-on [22] using two cement: rice-straw ratios of 60:40 and 50:50 and various chemical admixtures could achieve the flexural strength up to 7.0 MPa only, while the minimum requirement according to ISO:8335-1987 is 9.0 MPa. The water absorption of these boards was also rather high. Thus, there is a need of more research work on use of rice straw. Lightweight composite concrete was made using other agro-forestry wastes like cork granules, hazelnut shells, oil palm shells and bark [20, 26-30]. The density of these concretes ranges from 400 to 1800 kg/m^3 and compressive strength 1 to 26 MPa [19].

Construction demolition wastes

After their life-span or for other purposes a large number of old, deteriorated and unwanted structures such as buildings, railways, telephone and fencing poles, furniture items and bridges are being demolished. From this activity considerable waste in the form of treated timber, MDF and rattan is generated. Most of these wastes contain toxic or polymeric materials making them difficult to biodegrade. Consequently, they can not be land filled or incinerated. Therefore attempts have been made by various researchers to make cement-bonded composites using these wastes.

Kasai *et al.* [32] used wood particles from construction waste in Japan for making wood-chip concrete. They made concrete with a density range of 920 to 1250 kg/m^3, flexural strength 4 to 7 MPa and compressive strength 5 to 8 MPa. By addition of synthetic lightweight aggregates they further reduced the density to about 780 kg/m^3, which resulted in comparatively lower bending and compressive strength values of 2.05 and 2.2 MPa, respectively. Wolfe and Gjinolli [33] carried out a pilot study on the use of southern pine wood particles derived from construction waste for making cement-wood composites (CWC). They used copper chromium arsenate (CCA) - treated wood particles for making lightweight panels. They reported that there were no compatibility problems between CCA-treated wood and cement. In another study by Schmidt *et al.* [34] on the use of CCA- and chromic acid-treated pine, it was found that the treated pine was more compatible than the untreated pine. The results from these studies demonstrate that the manufacture of wood-cement composites should be a promising and viable method of disposal for CCA-treated wood waste.

Medium density fibreboard (MDF) is a popular lignocellulosic material used in building construction and in furniture industry. Presently, the world production rate is about 22 million m^3 and growing day by day. A large quantity of after service MDF is available as waste, which further increases with the addition of cutting wastes obtained during manufacturing and fabrication. Qi *et al.* [35] used wastes of medium density fibreboard (MDF) for making wood–cement composites, which had lower values of water absorption, but showed slightly lower splitting tensile strength and lower tensile toughness properties than those containing new wood fibres particularly at a high fibres/cement ratio. The new wood fibres were obtained from the wood that had been used for making MDF. Olurunnisola and Adefisan [36] investigated the use of rattan (cane) furniture waste for the manufacture of cement-bonded particleboard. The resultant product has low flexural strength and water resistance. Therefore, it is suitable only for use in low-stressed interior building applications.

Developments in Manufacturing Process

During the last two decades, several reports on the use of wood and agro-forestry wastes in making cementitious composites have been published. The main constrain in wider use of these organic materials in cement-bonded composites is their inhibition effect on cement setting due to the presence of chemical compounds like sugar and tannin. It is, therefore, necessary to either remove these compounds or use accelerators that can offset the retarding effect. The retarding chemicals are removed by washing the wood particles in cold water or in hot water or in an alkaline solution [37]. Several types of metal salts, such as $CaCl_2$, $FeCl_3$, $SnCl_2$, and $AlCl_3$, can be used to accelerate setting. $CaCl_2$ is generally used as an accelerator, but its detrimental effect on the durability of metal bars embedded as reinforcement in concrete and masonry is well known [38]. An alternative method of accelerating the setting of the wood-cement mix is the injection of CO_2 gas. Geimer *et al.* [39] 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. However, the effectiveness of this method highly depends on access of CO_2 to all portions of the composite. Thus, it suits more for the panel products than the blocks, because the gas can be easily injected along both the surfaces of the panels, while it is difficult to inject CO_2 upto the inner portions of the blocks. Nevertheless, Simatupang *et al.* [40] suggested that instead of CO_2 injection, water-soluble carbonates could be used as a source of CO_2. The carbonation technique has been applied in making wheat straw composite panels by Sorushian *et al.* [21]. Fermentation of lignocellulosic material can also improve compatibility by reducing the sugar content [41].

The properties of the composites are further improved by addition of pozzolonatic materials and polymer. The pozzolanic materials like fly ash, slag, silica fume, metakaolin have been used successfully [42, 43]. The advantages are low porosity, improved durability and higher strength. Some other approaches include surface treatment of the organic fibres or particles. Juárez *et al*. [43] protected the fibres with paraffin and modified the composite matrix with a pozzolan admixture such as fly ash. The performance of the composite was acceptable when exposed to aggressive environments and variable humidity and temperature. The paraffin protective treatment allows reducing the water absorption of fibres as well as maintaining sufficient tensile strength even after one year of exposure to humid and alkaline environments. The material properties can also be improved by saturating the wood particles with a sodium silicate solution. The improvement is caused by formation of ettringite needles resulting in better bonds between wood particles and cement paste [44].

Discussion

A large amount of lignocellulosic wastes can be used in making cement-bonded composites. The advantages in comparison to the resin bonded composites are low processing temperature, low cost binder and a finished product with better resistance to water, fire and biodegradation. However, there are certain issues which need to be addressed. For example, non-availability of a standard method to assess their compatibility with cement, a lack of understanding on the influence of storage conditions and duration on the properties of these wastes and how their degradation with time can be controlled. Moreover, their low modulus of elasticity, high moisture absorption, decomposition in alkaline environments, dimensional instability and variable physico-mechanical properties also need due consideration. These problems can not be completely vanished, but research is in progress on reduction of their magnitude. For example, moisture absorption and dimensional instability can be controlled by impregnating water soluble polymers in the cell wall of lignocellulosic materials like natural fibres. Mannan *et al.* [30] used surface treatment on oil palm shell to improve durability. It has also been reported that the use of pozzolanic materials or certain cement replacement materials can improve the composite durability. However, the mechanism of durability improvement is still not well understood, whether it is due to reduction in alkalinity of the cement paste or due to reduction in water transport properties.

To improve compatibility of the wood and other wastes with cement a suitable pre-treatment or a suitable dose of chemical accelerator may be required. Pre-treatments like cold or hot water extraction is simple and low cost option, but it needs a long time and adversely affects the productivity. The use of chemical accelerators like $CaCl_2$ may corrode steel that may come in contact with the composite. Alternatively, CO_2 can be injected but obtaining a uniform gas distribution throughout the product could be a potential technical problem. Consequently more research is required in this direction. Curing at higher temperature is another possibility. Nevertheless, in spite of various disadvantages, the composites have sufficient strength for several non-structural applications like partition, sound absorption, thermal insulation and low cost housing. The strength properties of these composites can be further enhanced by the incorporation of fibres such as jute, sisal, 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 [45]. Use of these wastes can help in reducing the consumption of virgin wood and the rate of deforestation, which is very important from an environmental point of view.

Conclusion

Research is in progress throughout the world on making cement-bonded composites from various lignocellulosic materials mainly from the wastes causing environmental problems and from the renewable natural resources. The results indicate that these wastes can be used in making versatile cementitious composite that can be used for fabricating various building components. For most of these wastes some kind of pre-treatment or chemical accelerators are required. The composites made from these are lignocellulosic materials have low density and thermal conductivity, but more research is required to enhance their strength. It has been found that the preservative treated wood can be used in making cement-bonded composites of moderate strength, but further research on the health and safety aspects is required.

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