CEMENT BONDED COMPOSITES – A MECHANICAL REVIEW

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Over the last years promising cement bonded wood composites for structural purposes have evolved. Durability, toughness, high dimensional stability, resistance against environmental influences such as biodegradation or weathering but also availability of the raw material as well as economic factors are features which can make cement-bonded composites superior to conventionally bonded composites. This paper reviews the relationship of diverse parameters, including density and particle size on mechanical and physical properties of cement bonded composites, based on published sources from the last 60 years. For general and recent information about bonding mechanisms, compatibility and setting problems, determination and improvement of compatibility, the used raw materials as well as accelerators are discussed. The main part deals with failure mechanisms in connection with several production parameters. Furthermore, the influence of particle size and geometry, orientation of the particles, cement-wood ratio and the effect of accelerators and treatment of the particles on modulus of elasticity, modulus of rupture as well as thickness swelling are discussed.

Keywords: Cement bonded composites; Mechanical properties; Particle geometry;Particle size; Orientation; Bonding; Cement-wood ratio; Strand; Excelsior; Failure mechanism

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INTRODUCTION

Cement bonded wood has been investigated for more than one hundred years, whereas the industrial utilization of cement bonded particleboard started in the 1930´s. However, most of the innovations have been done in the last 40 years. The research was promoted by problems related to asbestos (Moslemi 1999). Furthermore, the shortage of resources in general is a fact which forces the utilization of recycled wood (Wei et al. 2003). The decline of wood quality – partly caused by the increased use of small dimensioned wood – also influences production and quality of Engineered Wood Products (EWP). In order to reduce inhomogeneities, solid wood is disintegrated and bonded to form wood products. Different methods were investigated e.g. sliding, crushing, steam explosion etc., besides cutting technologies, to disintegrate wood particles for the manufacture of wood composites with distinctive properties.

It is well known that with decreasing particle size the fragmentation consumes more and more energy. On the other hand, smaller particles also increase the adhesive consumption because of the enlargement of the surface (Teischinger 2006). Petroleum-based synthetic binders, such as phenolic and urea-formaldehyde, became costly items in the processing of wood panel products. An alternative is the use of mineral binder (Lee 1984). Different mineral binders, including Portland cement, magnesia and gypsum, are used to fabricate boards with different properties (Simatupang and Geimer 1990). However, the most expedient binder, concerning strength, durability and acoustic insulation properties, is Portland cement.

In the beginning cement bonded composites (CBCs), particularly low-density boards, were mainly used for insulating purposes. In 1973, a Swiss company called Durisol was among the first manufacturers that produced a building panel consisting of small wood particles bonded in a cement matrix (Wolfe and Gjinolli 1996b).

Many composites have evolved in the last decades, e.g. cement-bonded wood wool boards (CBWW), cement-bonded particleboards (CBPB), and fibre-reinforced cement boards. These CBCs are used for thermal as well as acoustic insulation purposes and consist of particles of different sizes (strands, flakes, chips, fibres). In this article the term particle is used for all kind of particles (varying sizes and shapes from fibres to strands). In recent years some products for structural use have been developed, e.g. cement bonded Oriented Strand Board (OSB) (Ntalos and Papadopoulos 2006; Papadopoulos et al. 2006), cement strand slab (Miyatake et al. 2000), or cement bonded composite beams (Bejó et al. 2005; Datye and Gore 1998). In comparison to wood and conventional wood products the CBCs are highly fire-, termite- and water-resistant. On the other hand, for some applications CBCs are competitive with reinforced concrete because of their relatively low density (Bejó et al. 2005).

Especially in warm and humid climates, where high resistance against termites and fungal decay is demanded for constructive materials (Eusebio 2003; Wolfe and Gjinolli 1996b), CBCs show a high potential as a building material. Further benefits of CBCs are easy machining with conventional wood-working tools and simple fabrication (Wolfe and Gjinolli 1996b), which make these materials interesting for less developed countries. However, the production and use of CBCs in these countries is small because of a lack of information and the limited economic sales potential (Ramirez-Coretti et al. 1998). Nowadays these countries show a big interest in these composite materials, whereas industrial countries mainly use CBCs, especially CBWWs, for insulation purposes. The increasing interest of less developed countries in CBCs can be explained by low costs and the availability of the raw materials. The raw material for the production of CBCs ranges from agricultural products or residues (Garcia-Jaldon et al. 1998; Hermawan et al. 2002b; Hermawan et al. 2001b; Irle and Simpson 1992; Khedari et al. 2001; Kim et al. 2005; Lawther et al. 1996; Rowell 2007; Sasaki et al. 2003; Savastano et al. 2003; Soroushian et al. 2004; Thygesen et al. 2005; Toledo Filho et al. 2000; Warden et al. 2000; Widyorini et al. 2005) to forest biomass, wood wastes, construction wastes (Wolfe and Gjinolli 1996a; Wolfe and Gjinolli 1999; Zhou and Kamdem 2002), and beetle-affected wood.

Wood-cement boards, fibre-cement boards, gypsum fibreboards, and gypsum particleboards are now manufactured in various parts of the world. The opportunity for this industry to expand is substantial, because the raw material is available locally in many nations and, worldwide, the need for durable building products is strong. It is important to note that much of the capacity in these industries (over 50%) has been added over the last three years (Moslemi 1999).

The raw material itself as well as the processing method influences the particle size and geometry which affect the mechanical properties of CBCs. This review aims at describing parameters that influence the mechanical and physical properties of CBCs. The manifold specifications about cement-wood ratios or water-cement ratios, which are usually declared by weight, different accelerators, etc., are not discussed in detail. Only trends will be given so as to estimate the influence of these additional parameters.

RAW MATERIAL PROPERTIES INFLUENCING THE WOOD CONCRETE INTERFACE

Bonding Mechanisms

Similar to synthetic resin adhesion also inorganic adhesion is thought to result from physical bonding mechanisms as well as mechanical interlocking. However, bonding mechanisms are not readily investigated; therefore several also contradictory theories are discussed in the following paragraphs.

Several investigations of the failure mechanism of CBCs indicate high interfacial bond strength between wood and cement. The study of the ultrastructure of CBCs leads to the conclusion that mechanical interlocking plays a major role in the bonding mechanism (Ahn and Moslemi 1980). By means of SEM the authors showed that mechanical interlocking is caused by spiky cement crystals. Growth of these crystals starts as soon as water is added to the cement. Beside that, the authors assumed that there are also some kinds of chemical forces involved. By contrast Bejó et al. (2005) took chemical bonding between cement matrix and wood into consideration.

Due to the chemical morphology of cement and cellulose, hydrogen bonding and/or hydroxyl bridges may play a major role in the bonding of these composites. By means of SEM, fibre to fibre contacts were observed by Coutts and Kightly (1984), who reported that the matrix is firmly bonded to the cellulose fibres. The formation of hydrogen bridges was proven by testing wet and dry composite samples. Dry composites showed high strength properties, which can be explained by a high number of hydrogen bonds or hydroxyl bridges. When stressed, mainly failure of the matrix material is observed. On the other hand hydrogen bonds of the wet samples are destroyed because of the insertion of water molecules between the bridging hydroxyl groups. Due to the pressure of the swollen cellulosic fibres, frictional forces are developed between fibres and the cement matrix. When the system is loaded these frictional forces can transmit stresses if the fibres are embedded in the matrix over a sufficient length (Coutts and Kightly 1984).

Analyzing cement bonded particleboards by means of x-ray diffractometry, diffusion of cement molecules, especially calcium, magnesium and silicon, into the cell wall of wood particles was observed (Parameswaran et al. 1977). Dewitz et al. (1984) examined mass transport during hydration of cement. The authors showed that mineral components penetrate deeply into the wooden structure. Fewer mineral components were found in early wood, whereas pitch streak, rays and lumen were found to be partially filled in by cementous components. These results underline the possibility of strong adhesive forces between wood and cement.

Problems during Setting and Incompatibility of Wood and Cement

During setting not-yet hydrated cement grains are surrounded by acicular hydrates. In the presence of sugar acids, sugars, and lignosulfonates, impermeable hydrates are formed around unhydrated cement grains, which inhibit or delay the setting of cement (Fischer et al. 1974; Sandermann and Kohler 1964; Sandermann et al. 1960; Sauvat et al. 1999). By means of SEM the formation of impermeable flaky calcium silicate hydrate (CSH) was shown (Milestone 1979). With increasing extractive content the proportion of unhydrated cement clinker also increases, which leads to strength reduction of the cement-wood composite (Wei et al. 2003). However, also the composition of cement shows a strong effect on the compatibility between wood and cement and on the resulting mechanical properties (Schubert et al. 1990a; Schwarz and Simatupang 1983).

Every substance and every process that interferes with crystal formation or crystal bonding affects the cohesive bond of cement (Ahn and Moslemi 1980). As already mentioned, wood contains several inhibitory substances, i.e. extractives.

The maximal hydration temperature of wood and cement is reduced by adding inhibitory substances, i.e. wood extractives, to cement water slurry. In comparison to pure cement water slurry, the presence of such substances also leads to a delayed maximal hydration temperature. Therefore, the maximal hydration temperature is used as an indicator for the compatibility of wood and cement.

These inhibitory substances, such as hemicelluloses, starches, sugars, phenols, and hydroxylated carboxylic acids, lead to hydration problems when cement is mixed with wood, in other words when these components are combined to form a composite (Weatherwax and Tarkow 1964). This problem is caused by the wooden components, which are attacked by the alkaline environment and diffuse into the cement paste. There they act as more or less effective retarders (Milestone 1979; Sauvat et al. 1999). The alkaline environment arises during cement hydration, where calcium hydroxide is produced; the result is an alkaline (pH = 12.5) cement paste. Since hemicelluloses are noncrystalline and alkalinesoluble, they dissolve in the cement paste and affect cement crystallization (Miller and Moslemi 1991b).

Sandermann and Brendel (1956) already knew that aldehyde groups are somehow responsible for “poisoning” cement. However, they were not able to clearly determine whether the sugars themselves or their degradation products, caused by the alkaline reaction, are responsible for the disturbance of hydration. Dewitz et al. (1984) assumed that both the extractives and their products of degradation are able to hinder hydration.

The different effects of the several extractives on strength and on strength development of cement respectively, were examined by Sandermann and Brendel (1956). By producing different samples consisting of different admixtures as well as different amounts of these, they could show that not all sugars have the same impact on cement hydration. They observed that some sugars, such as fructose, cause no essential effects on the cement hydration even at high concentrations of about 0.50%, whereas, other sugars completely inhibit hydration at concentrations of about 0.25%. Contrarily, some sugars, such as raffinose at concentrations up to 0.125%, can even improve properties of cement. More detailed information about the retarding effects of different polysaccharides are given by Peschard et al. (2004; 2006) and Semple and Evans (2000).

Also the pre-treatment of wood, as in the case of wood drying or production of the raw material (Mohr et al. 2004), and the time of harvest (Chapman et al. 1963) have great influence on the hydration behaviour. The content of sugar and starch respectively, depends on the season of the year. Hence, wood that is harvested in spring, before growth has begun, may be more inhibitory than wood that was cut in fall (Chapman et al. 1963; Hinterstoisser et al. 1992). The method of drying also influences the inhibiting characteristics of wood. Wood that is dried in a high-temperature kiln exhibits a sugar content that is four times as high as wood which is dried by conventional drying methods or open air drying (Hinterstoisser et al. 1992).

In general, high temperature and high pressure, such as that which occurs during drying, in the defibrator or by the water vapour steam explosion technique (Wei et al. 2003), lead to harmful chemical reactions of the extractives. Cellulose, hemicellulose, and pectin are degraded to lower molecular water soluble polysaccharides (Avellar and Glasser 1998; Garcia-Jaldon et al. 1998). Especially the hemicelluloses are hydrolyzed, and their water solubility increases due to the heat and pressure treatment (Hsu et al. 1988; Kim et al. 2005; Lawther et al. 1996; Widyorini et al. 2005). As Kühne and Meier (1990) reported, hemicelluloses cause the main inhibiting effects. Because of the alkaline milieu, which is caused by cement, the hemicelluloses are degraded to substances that harm cement setting.

The presence of bark does not stringently hinder cement hydration but leads to an increase in thickness swelling (TS) (Semple and Evans 2004).

With lower moisture content of the wooden raw material, which means a rising water-cement ratio, a faster impregnation of the wooden components can be expected. That implies that the use of dry wood can withdraw essential water for cement hydration, which results in a lack of necessary components, thus being indispensable for the development of strength. Additionally, the acid and alkaline components, which penetrate into the wood, will damage the wooden structure, which results in extra loss of strength. Furthermore the degradation products, which are developed by the penetration of acid and alkaline components, will influence hydration of cement (Dewitz et al. 1984).

The work of Knill and Kennedy (2003) gives more detailed descriptions and also chemical information on the degradation of cellulose in alkaline conditions.

Wood Species

Some species, such as spruce and fir, normally do not cause severe problems during cement hydration. But, as always, there are exceptions that prove the rule. As already mentioned, habitat, time of harvest, and others factors influence compatibility of wood and cement.

Negative implications for cement hydration can also be expected by the use of heartwood, independent of the time of harvesting. Particularly heartwood of *Pinus* or similar species should therefore be avoided (Weatherwax and Tarkow 1964). When Sandermann and Kohler (1964) examined different coniferous and deciduous species, they could observe a trend that showed better hydration by using coniferous sapwood compared to heartwood, while with deciduous species it seems to work the other way round.

It is assumed that species with a low content of water-soluble extractives are generally applicable for bonding with cement (Moslemi and Lim 1984; Schwarz and Simatupang 1984). In general softwoods are more compatible with cement than hardwoods, although there are exceptions such as western larch (Miller and Moslemi 1991a, b). However, every species is unique, and therefore has a different amount and a different composition of its extractives. A lot of research has already been done concerning tropical species (Alberto et al. 2000; Badejo 1988; Gnanaharan and Dhamodaran 1985; Semple et al. 1999) and eucalyptus (Eusebio et al. 2000b; Semple et al. 2000; Semple and Evans 2004). Additionally European wood species including oak, beech, and robinia were investigated (Eusebio et al. 2000a; Eusebio et al. 2000b; Hofstrand et al. 1984; Kavvouras 1987; Matsushita et al. 2003; Moslemi and Lim 1984; Papadopoulos 2007; Paribotoro 2000; Pereira et al. 2006a, b; Sandermann and Kohler 1964; Schubert et al. 1990b; Schwarz and Simatupang 1984; Semple et al. 2000; Semple and Evans 2004; Semple and Evans 2007; Yasuda et al. 2001). Even studies of chromate copper arsenate (CCA) treated wood are available (Huang and Cooper 2000; Zhou and Kamdem 2002). Beside different wood species, bamboo is considered to be an adequate material for the production of fibre-cement bonded composites. With respect to cement hardening and decay of fibre, bamboo performs better than pine wood (Shigekura et al. 1992).

IMPROVEMENT OF COMPATIBILITY AND CURING ACCELERATORS

Determining Compatibility

Different methods, such as measuring the hydration characteristics (Alberto et al. 2000; Brandstetr et al. 2001; Hachmi and Moslemi 1990; Hachmi et al. 1990; Karade et al. 2003; Sandermann and Kohler 1964; Sandermann et al. 1960; Sauvat et al. 1999; Schubert and Wienhaus 1984; Weatherwax and Tarkow 1964; Wei et al. 2000a; Wei et al. 2000b), measuring the mechanical properties of the cured wood cement mixtures (Lee and Hong 1986), the visual evaluation of the microstructural properties (Ahn and Moslemi 1980; Davies et al. 1981; Wei et al. 2004; Wei et al. 2003), and measuring the electrical conductivity during setting (Backe et al. 2001; Govin et al. 2005; Simatupang et al. 1991), exist so as to determine compatibility of wood and cement.

The peak of the hydration temperature, as well as the time duration until this temperature is reached, give information on the suitability of a specific species to be bonded with cement. This level of suitability is expressed by the “inhibitory index”. All these methods are based on the height and the delay of the maximum hydration temperature. Good suitability is normally expected when a hydration temperature of more than 60°C is reached, whereas a hydration temperature of less than 50°C signifies a completely unsuitable species (Sandermann and Kohler 1964). For comparison when neat cement is used, a maximum hydration temperature of more than 80°C can be observed (Sandermann et al. 1960). The relationship of hydration temperature and mechanical strength was proven by Sandermann and Kohler (1964). However, Miller and Moslemi

(1991a) do not recommend using hydration characteristics as estimates for actual strength, except for very general valuation.

It appears that the compatibility tests that use relatively fine particles are suitable for comparing the compatibility of different wood species in the laboratory, but under real manufacturing conditions, where different particle sizes are used, this comparison may not be valid. Wood that is found to be incompatible using fine particles might be compatible with coarse particles. Analysis of fine particles, however, can provide valuable information on the maximum possible effect of wood-extractives, as finer particles expose more surface area to the cement paste, and thus more extractives can enter into the solution (Karade et al. 2003).

A more sophisticated method, because of the unpredictable influences of the wood particles and the long curing times, is to determine compatibility by measuring the mechanical properties of cured samples (Morrissey et al. 1985; Sandermann and Brendel 1956; Sandermann et al. 1960; Seddig and Simatupang 1988).

Improvement of Compatibility and General Properties

Because of their inhibiting contents some "aggressive" wood species, such as *Larix decidua*, are able to completely stop hydration of cement (Sandermann and Kohler 1964), which can be seen in a degradation of the physical properties (Jorge et al. 2004).

On this account, strong inhibiting species need some special treatment to make them suitable for the production of cement bonded wood based materials (Moslemi et al. 1983). By removing soluble compounds, the compatibility can be improved. There are different methods to accomplish this aim, conventional hot or cold water extraction and soaking, respectively (Eusebio et al. 2000b; Moslemi and Lim 1984; Okino et al. 2005; Schwarz and Simatupang 1984; Sutigno 2000), long-time storing of the raw material (Cabangon et al. 2002), many chemical extraction methods (Alberto et al. 2000; Kavvouras 1987; Moslemi et al. 1983; Schwarz and Simatupang 1984), and even treatment by fungi (Thygesen et al. 2005), whereby the latter can cause more or less severe damage that will manifest itself in declined mechanical properties of the CBC. In some cases, the addition of small amounts of cement setting accelerators, such as $CaCl_2$ or $MgCl_2$, can even eliminate the need to pre-soak the wood particles (Semple and Evans 2004).

The coating of the wooden particles prior to mixing with cement is a possibility to improve compatibility. On this issue, Okino et al. (2005) describe the use of $CaCl_2$ as an aqueous solution. Also quite common is the use of Na_2SiO_3, which can either be applied as described above or for extraction of the raw material. However, improvement of the mechanical properties as well as mitigation of thickness swelling by the use of Na_2SiO_3 is weak compared to water- or NaOH-extraction (Kavvouras 1987).

In addition, Simatupang et al. (1987) mention the possibility of applying different kinds of blocking layers around wood particles. Naturally, this method could have the disadvantage of hindering the direct contact between wood particles and matrix, which could result in weakened mechanical properties.

Another promising method, which additionally accelerates setting as well as curing time and improves mechanical properties, is the use of gaseous or supercritical CO_2 (Geimer et al. 1994; Geimer et al. 1993; Hermawan et al. 2002a, b; Hermawan et al.

2000; Hermawan et al. 2001a; Simatupang and Habighorst 1992; Simatupang et al. 1991). The high production levels of calcium silicate hydrate and calcium carbonate during the hydration of cement, and the interaction between those hydration products with wood surfaces are considered to be the main reasons for the superior strength properties obtained in CO_2-cured boards (Hermawan et al. 2001a).

Another approach is the replacement of parts of cement by fumed silica (SiO_2) in combination with superplasticizers. This combination should increase the cohesiveness of the fresh composite and reduce the water content (Okino et al. 2005). Also Meneéis et al. (2007) observed an improvement of mechanical properties as well as mitigation of thickness swelling when fumed silica (10%) was added. However, Moslemi et al. (1994) could not confirm the positive effects of fumed silica. On the contrary, the addition of laboratory-grade fumed silica resulted in the reduction of most board strength properties.

Fast setting cement mixtures are also promising as the binder set much faster and give no time to wash out extractives into the cement slurry (Bietz and Uschmann 1984; Simatupang et al. 1991).

The total water amount of the bonding components also represents an important factor in the hydration of cement. This total amount is made up of the moisture content of the solid wood and the water from the cement slurry. If too dry wood is used, water, which is necessary for the cement hydration, will be withdrawn from the slurry. This will lead to a decrease in final strength (Dewitz et al. 1984). Contrarily, if too much water is added, negative effects on the strength properties can also be expected (Miyatake et al. 2000).

Accelerators

Extraordinarily long pressing and clamping times represent a huge problem in manufacturing CBCs due to cost-intensiveness, as pressing should continue until the maximum hydration temperature is reached. Different methods are applied to reduce the setting time in the production, either by the addition of assorted admixtures, an increase in temperature during pressing or clamping, or by the use of CO_2 during pressing and/or clamping (Geimer et al. 1994; Geimer et al. 1993; Hermawan et al. 2002b; Hermawan et al. 2000; Qi and Cooper 2007; Qi et al. 2006; Simatupang and Bröker 1998; Simatupang and Habighorst 1993a, b, c; Simatupang et al. 1995; Simatupang and Neubauer 1993; Simatupang et al. 1991; Soroushian et al. 2004; Soroushian et al. 2003; Wagh et al. 1994; Wagh et al. 1997; Young et al. 1974). Several accelerators, including NaOH, $CaCl_2$, Na_2CO_3, and NH_4Cl, were tested concerning their potency to shorten the setting and curing time as well as improving the specific properties of CBCs (Badejo 1988; Bejó et al. 2005; Hermawan et al. 2002b; Hofstrand et al. 1984; Kavvouras 1987; Moslemi et al. 1983; Papadopoulos et al. 2006).

The use of CO_2 is a promising method to accelerate the hydration process (Geimer et al. 1992; Hermawan et al. 2002a; Simatupang and Habighorst 1992). Under the influence of pressurized CO_2, the hydration of cement is enhanced so that demolding can be accomplished after three minutes (Simatupang and Habighorst 1992). For the sake of completeness, also fast setting cement mixtures, as described by Simatupang et al. (1991), should be mentioned in this chapter.

The study of Semple and Evans (2007) offers more information on accelerators. In their study various accelerators with different volumes and their ability to increase setting time were assayed.

EFFECT OF PARTICLE GEOMETRY AND WOOD CONTENT ON MECHANICAL/PHYSICAL PROPERTIES

Failure Mechanisms

As a building material pure concrete is primarily used in compression, developing strengths of 32.5-52.5 N/mm² (DIN-EN197-1 2004). In bending, strength may range from 7 to 20 N/mm². The addition of wood particles improves fracture toughness by blocking crack propagation. This permits the composite to carry load to a higher strain limit (Wolfe and Gjinolli 1996b). Wood cannot, however, improve compressive strength, because the compressive strength of cement is much higher than that of wood (Karade et al. 2003).

The typical load deformation plot of a wood composite that is loaded in bending shows a bimodal failure. The initial part of the load displacement curve is fairly linear, representing the stiffness of the cement matrix. When first cracks appear, the curve becomes nonlinear. At this point the particles begin to carry loads, and further failure of the matrix is stopped by blocking fracture propagation. In comparison to pure cement, wood cement composites are able to carry slightly higher loads in tension or bending and/or exhibit ductile like failure compared to brittle failure of neat cement (Wolfe and Gjinolli 1996b).

Coutts and Kightly (1982) showed that two different failure mechanisms for fibre cement composites can occur, i.e. fibre fracture and fibre pull-out. Controversial results are reported concerning the predominating failure mode. Investigations during the eighties of the last century assumed fibre fracture (Coutts and Kightly 1982, 1984; Morrissey et al. 1985); on the other hand fibre pull-out was thought to be the predominating failure mode. However, new results suggest that the interfacial bond between the two components is relatively strong. Therefore, the failure mode depends on the fibre length and whether the fibre length is above or below the critical fibre length of the composite.

In the study by Morrissey et al. (1985) the types of tensile failure of a fibre reinforcing a matrix can be explained more clearly by considering a single fibre protruding from the surface. The system may fail under tension by fracture of the fibre outside the cement, by fracture within the cement followed by pull-out, or by pull-out of the total fibre. It must debond before it can pull out. After debonding, pull out forces have to exceed friction forces between the fibres and the matrix. In some cases there will also be some kind of mechanical interlocking of the rough fibre surface inside the cement matrix. Since some of the load is transferred to the matrix by shear, the maximum load applied to the system may be higher than the load at the failure site. After debonding and partial pull-out, anchor points are created due to non-uniformities of the fibres. The probability of developing such anchor points increases with the length of the embedded fibre.

Due to the fact that the fibres are swelling because of water insertion, considerable frictional forces are developed, which again could lead to fibre fracture (Coutts and Kightly 1984; Morrissey et al. 1985). Therefore, the interfacial bond strength between the fibre and the cement matrix is influenced by the moisture content (Coutts and Kightly 1984). Wolfe and Gjinolli (1996b) proposed that the changing mechanical behaviour can be explained by the reduced bending strength of wet fibre, making it more flexible and less likely to inhibit cracking in the cement matrix.

As wood particle volume increases, the regions of stress concentration around adjacent particles become more diffuse, resulting in an increased resistance to the stresses applied. For example, concrete strength increases because of a decrease in the average stress concentration caused by the inclusion of smaller aggregate particles. Larger quantities of aggregates distribute internal stresses over a larger specific surface per unit volume, reducing areas of high stress concentration where critical failure is more likely to occur. However, the reduced cement quantity must remain high enough so as to afford a complete matrix formation. For example, at a cement-wood ratio below 2.0, complete matrix formation may not occur, thereby impairing panel strength (Moslemi and Pfister 1987).

Problems with existing mathematical models of failure processes occur because of simplified assumptions, including the uniformity of fibres and circular cross-sections (Morrissey et al. 1985).

Particle Size/Geometry, Orientation, and Cement-Wood Ratio

The aim of using particles with cement is mainly to increase modulus of rupture (MOR), and to enhance heat-insulating properties (Cziesielski 1975), but also to displace more or less expensive cement. Particles of every size and shape are used to fabricate CBCs: chips, excelsior, strands, and fibres. The geometry of particles has a strong effect on properties of CBCs. That is why care has to be taken when mixing strands with cement, because of breakdown of the strands can result in a negative alteration of the final dimensions (Papadopoulos et al. 2006). Due to the elongated nature of strands difficulties arise when mixing with cement, leading to incomplete coating of cement on the particles (Ma et al. 2000). However, apart from fibreboards, there are limited published studies about the effect of particle dimensions on the properties of CBCs.

Earlier work claimed that the effect of particle size and geometry on mechanical properties is the same for resin- and cement-bonded particleboards. Results of new studies suggest otherwise; cement-bonded boards require a much larger particle size than resin-bonded panels (Semple and Evans 2004), as there is no chemical bonding between cement and wood (Bejó et al. 2005). The study of Badejo (1988) shows that flake geometry is highly correlated with board key properties, including MOR, modulus of elasticity (MOE), internal bonding strength (IBS) and thickness swelling (TS). He found that the longer and thinner the strands or particles, in other words particles with a high slenderness ratio, the stronger, stiffer, and more dimensionally stable the boards. The extensive study of Semple and Evans (2004) confirms this statement, long particles rather than small particleboard flakes should be used when the aim is to produce boards of high strength. By using small particles more compact matt structure can be produced, which results in reduced void space and irregularities. However, the better compaction is offset by negative effects of cement setting caused by much larger surface area-to-volume ratio of the wood (Semple and Evans 2004). As there is a relationship between surface and volume ratio of particles, a greater surface area needs more adhesive for equivalent internal bonding development (Li et al. 2004).

A comparison of MOE of boards containing strands of different thicknesses shows slight differences. Thin strands tend to give higher MOE values than boards made from thicker strands (Ma et al. 2000). The comparison of the properties of cement-bonded Parallel Strand Lumber (PSL) and Laminated Strand Lumber (LSL) shows that PSL, with its long and easily oriented veneer strips, performs better than LSL, which is explained due to the enlarged bonding surface area compared to the relatively small surface of the strands of LSL. As there is no chemical bonding between wood and cement, the short strands of LSL pull out of the matrix relatively easily compared to long veneer strips of PSL (Bejó et al. 2005).

The orientation of strands is, as well as in common wood composites, an important factor that directly influences mechanical properties of the board (Cabangon et al. 2002; Klar and Van Kov 1975; Meneéis et al. 2007). The MOR values in the oriented direction of oriented cement-bonded strandboards, which were examined by Ma et al. (2000), were 2.5 times greater than in boards with randomly oriented strands. For the same boards the MOE has increased about two times. Orienting even only 25% of the strands, in the surface, results in significant increases in MOR and MOE. Stahl et al. (1997) developed a finite element model for CBWW to predict elastic and strength properties. With the aid of this model they could show that a relatively modest alignment of the particles led to an approximately 25% increase in composite strength and a 33% increase in stiffness of the preferred direction of the board. By adapting this model for other materials, this model could be used as a tool to aid in the development and optimization of composite materials.

Concerning mechanical properties the studies by Moslemi and Pfister (1987), as well as by Papadopoulos et al. (2006), indicate that MOR increases as the cement-wood ratio is lowered. In general, the particular cement-wood ratio is dependent on the final product and the used particles, respectively. The cement-wood ratio for OSB, in order to manufacture with acceptable bending properties (MOR in particular), an optimum cement-wood ratio has to be lower than 2.0 (by weight). This proposed cement-wood ratio for OSB manufacture appears to be lower than the corresponding ratio for particleboard or flakeboard manufacture (Papadopoulos et al. 2006). On the other hand, research on excelsior board showed that the cement-wood ratio higher than 2.0 has enabled the manufacture of cement excelsior boards with acceptable bending strength (Lee 1985). Altering cement-wood ratio is a parameter that has a big influence on the mechanical properties and also on the physical properties such as thermal conductivity or sound insulation. The influence of the cement-wood ratio will be discussed in the following section.

Mechanical and Physical Performance

From a structural viewpoint, toughness, which is defined as the area under the load deformation curve, appears to be the primary advantage of cement-bonded wood composites compared to conventional bonded wood composites. Strength limitations can be accommodated to some extent by the use of increased section properties of reinforcement. In cases where it is not feasible for the design to resist maximum possible load, a material that dissipates a lot of energy as it fails can save lives (Wolfe and Gjinolli 1996b). This is important because these composites are used for housing constructions, particularly in less developed countries. As quoted above, fracture toughness can be significantly enhanced by the use of reinforcing material. For example a fibre inclusion of 12%, even by using waste fibres, enhances fracture toughness 25 times, compared to neat cement (Savastano et al. 2000).

Besides the amount of reinforcement in CBCs, the mechanical properties are also significantly influenced by the format and arrangement of the reinforcement (Badejo 1988; Pablo et al. 1994). Ma et al. (2000) observed higher values for MOE when thinner strands were used for board production compared to boards made out of thicker strands.

The geometry and size of the particles as well as density depend on the future purpose of the CBC. Little fibre compression occurs on low density boards, like CBWW, which are considerably different from the structure of a high density board, where isolated wood fibres are encased in a continuous cement matrix. Bending and stiffness properties primarily depend on the number of fibre intersections and the distance between them as the structure of low density boards resembles that of a mesh consisting of stiffened interwoven strands (Pablo et al. 1994).

Stiffness characteristics are a function of cement-wood ratio. This relationship is based on the fact that cement is inherently a more rigid material than wood. Therefore greater cement-wood ratios result in higher MOE values (Moslemi and Pfister 1987), as MOE is dependent on the total amount of the stiff and incompressible cement matrix (Pablo et al. 1994). Moslemi and Pfister (1987) proved a linear correlation between MOE and cement-wood ratio. The relationship between cement-wood ratio and MOR is considerably different from that of MOE. MOR values are inversely related to cement-wood ratio from levels 3.0 to 2.0. An optimum ultimate bending strength is attained at a cement-wood ratio at or near 2.0. Although elasticity decreases as the wood aggregate content rises, the zone of plasticity increases. Therefore, material with a high wood aggregate content is weaker but less brittle, which means its capacity in terms of deformation increases. The increase in deformability with rising wood content can be explained by the fibrous nature of wood, which allows it to accommodate the deformations and provide good adherence to the matrix (Al Rim et al. 1999).

Expectedly, compressive strength correlates with density and decreases regularly in correspondence with the wood aggregate content (Al Rim et al. 1999). Further, Bejó et al. (2005) claim that there is a direct correlation between density and mechanical properties, which they explain as being due to enhanced wood densification, elimination of gaps, and improved connection between matrix and fibre.

Density, water absorption, and porosity are all interrelated physical properties. When particle content is increased, water absorption increases, whereas density decreases (Savastano et al. 2000). The thermal conductivity again is reduced as the percentage of wood particles rises, whereas, as expected, density decreases. This decrease in conductivity is linked to the increase in porosity imparted by the wood (Al Rim et al. 1999). Depending on the desired properties of the CBC, the cement-wood ratio will be adjusted correspondingly. CBCs for thermal insulating purposes exhibit high porosity, which is achieved by low cement-wood ratios. On the other hand, high cement-wood ratios lead to high density, which leads to increased sound insulating properties.

The positive effect of pretreatment, like soaking and extracting of, respectively, wood in water is sufficiently investigated and known to enhance compatibility and therefore mechanical properties (Eusebio et al. 2000b). For the economic production of CBCs it is unavoidable to use accelerators. The positive side effect of using these additives is the fact that the possibility to wash out aggressive extractives from the wooden particles is minimized, and therefore mechanical properties are increased as well. The use of chemical admixture or treatment with CO_2 accelerates cement hydration but additionally enhances physical properties. For example, the bending strength of CBPB in the study of Ahn and Moslemi (1980) was nearly quadrupled compared to controls when 3% $CaCl_2$ was added. Another strong fact is that CBCs that were treated with CO_2 perform much better in ageing tests than boards not submitted to fast carbonation (Qi and Cooper 2007).

Thickness swelling (TS), as an important attribute concerning dimensional stability, is highly correlated with the cement-wood ratio. In general a higher cement content of a board lowers TS. It seems that the embedding of wood inside CBCs restricts expansion (Moslemi and Pfister 1987). In order to minimize TS, with the negative side effect of decreased MOR, reducing cement-wood ratio is a possibility whereby water absorption is also decreased (Meneéis et al. 2007). Increasing cement coating on the particles may have a positive effect on TS (Eusebio et al. 2000b). But also pre-treatment of the wood has an effect on TS. Eusebio et al. (2000b) could prove that untreated, in this case unsoaked, particles exhibit higher values of TS. Also chemical additives can decrease TS. By using $CaCl_2$ as an accelerator, TS could be reduced. This improvement is explained by better fibre to fibre contact as a result of improved bonding ability with cement. Besides $CaCl_2$ also hot water soaking or $MgCl_2$ treatment are effective methods to reduce TS (Semple and Evans 2004).

As the particle geometry influences almost all properties of CBCs, also TS is highly dependent on particle geometry. TS increases with increasing particle thickness and decreasing particle length. The use of thicker particles results in greater heterogeneity and a more irregular “open” board surface, which is more easily penetrated by water (Semple and Evans 2004). Semple and Evans (2004) argue that the rough surface and greater internal-void space caused by the use of thicker particles are responsible for higher TS. On the other hand Lee (1984) uses the same argument, namely to explain the low TS of CBWW, in which many voids in the board allow internal swelling. But he also mentions coating of particles with cement, which restrains swelling of the wood, as a reason for reduced TS. By using low cement-wood ratios the wood particles are not encapsulated by cement, which results in low bonding and therefore in low internal bond (IB) values and increased TS (Meneéis et al. 2007).

Meneéis et al. (2007) found a negative correlation for MOR and parallel compression concerning TS. This means that higher MOR or compression values are associated with lower TS. Also internal bond (IB) is correlated with TS. Panels with high IB can resist the stress due to wood expansion, which results in lower values for TS.

The study by Semple and Evans (2004), in which small diameter stems of mallee eucalypt where used to produce CBPBs, could demonstrate that the presence of bark, with the exception of *Eucalyptus loxophleba ssp*., did not affect strength properties significantly but resulted in unacceptably high water absorption and swelling. Dimensional stability of CBCs at different levels of relative humidity as well as its improvement were extensively investigated by Fan et al. (2004a; 1999a; 1999b; 1999c; 2002; 2004b; 2004c; 2004d). Creep behaviour of CBPB was studied by Kondrup (1990).

CBPBs require an especially high cement-wood ratio, which makes them difficult to handle, cut, nail, and transport (Zhou and Kamdem 2002) while suitable values of MOR are missing because of the short particles. By using low cement-wood ratios, at about 1.0, it is possible to decrease density to about 800 kg/m³ with adequate mechanical properties when particles of appropriate dimensions and orientation are used. However, as mentioned before, because of lack of cement, values of IB and therefore also of TS are not satisfactory (Meneéis et al. 2007). Another advantage of decreasing the cement-wood ratio, considering the economic viewpoint, is the fact that wood is less expensive than cement (Zhou and Kamdem 2002).

Summarizing these facts it is evident that high cement-wood ratios combined with elongated particles result in high strength and low TS but yield high density.

To synthesize, Fig. 1 shows five different CBCs, i.e. excelsior board, cement bonded particleboard, oriented strandboard, strandboard made of excelsior like strands and fibreboard, and their mechanical properties (MOR, MOE) as well as dimensional stability (TS) and density (ρ). As MOR and MOE are important mechanical properties, they are listed on the left, in the positive side of the graph. TS and density are listed on the right, the negative side. Therefore, as they increase, their increases are considered to be negative properties. The highest value of a specific property of all products was considered to be 100%.

CONCLUSION

Long particles combined with high density lead to high strength and stiffness and also to reduced TS. Short particles lead to low MOE, caused by insufficient particle to cement contact. Comparing particleboard with strandboard makes it evident that the use of long particles is important for high MOR. High density, in other words high cement-wood ratio, leads to high MOE but also, because of the missing reinforcement, to a decrease in MOR.

Logically, also the amount of particles, in other words the cement-wood ratio, has a direct influence on TS, MOR, and MOE. Materials with high wood content, which results in low density, exhibit higher values for TS than material with low wood content or high density. Contrarily, a low cement-wood ratio results in high values for MOR, as can be seen with strandboard.

TS is also dependent on the size of the particles. Thick particles lead to higher TS compared to thin particles, as in the case of strand- or excelsior board. Low TS values for CBPB are thought to be caused by the high amount of cement which is reflected in high density values. Lowest TS, as exhibited by fibre-reinforced concrete, arises because of sufficient encapsulation of the wood particles at high cement-wood ratios and the minimal swelling of the small particles.

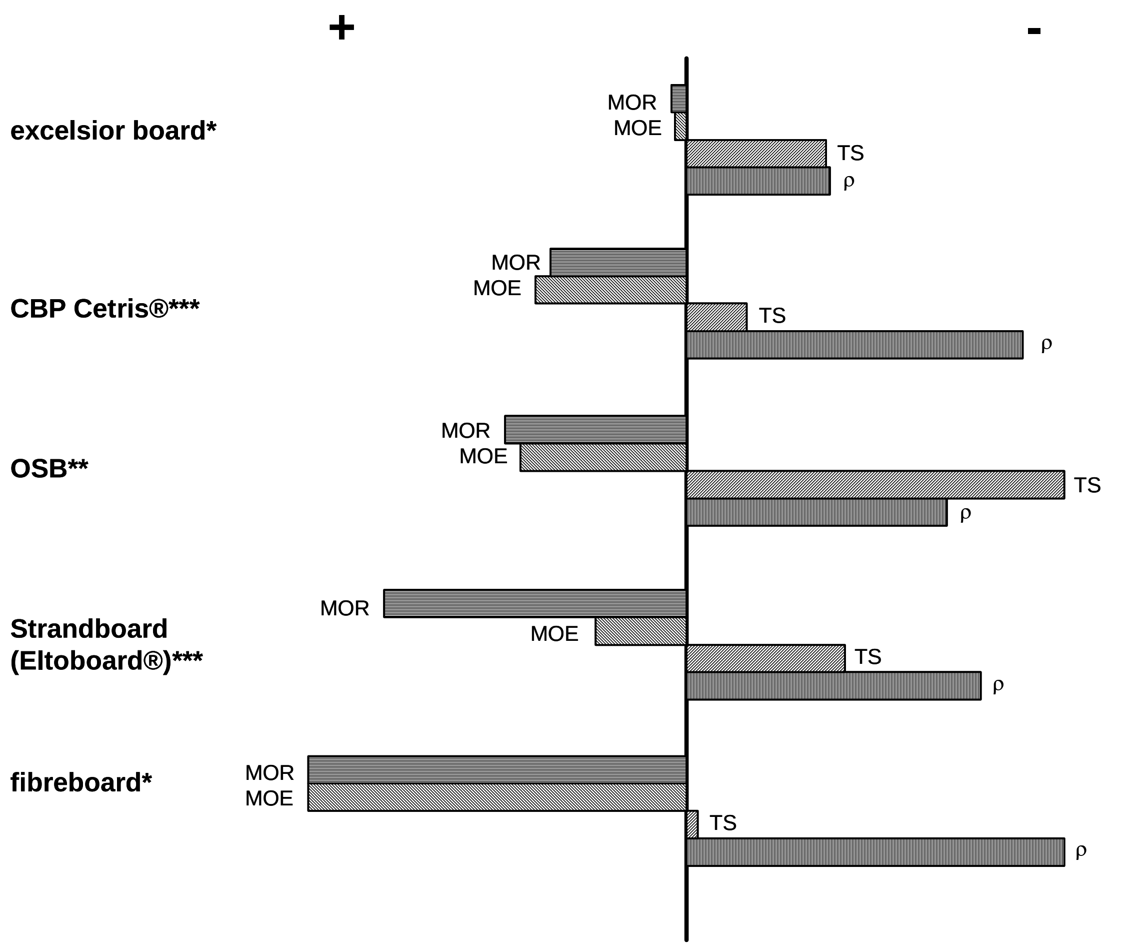

Fig. 1. Comparison of main properties (MOR = modulus of rupture, MOE = modulus of elasticity, TS = thickness swelling, ρ = density) of five CBCs consisting of different particle geometries. *(Simatupang and Lange 1992), **values from official homepage (Anonymus 2007), ***(Papadopoulos et al. 2006), ****(Anonymus 2005)

Although excelsior board is made out of long and thin particles, values of MOR and MOE are unsatisfactory. This is caused by non-elongated particles and especially low cement-wood ratio, resulting in a discontinuous matrix and therefore insufficient particle to matrix contact. Because of lack of cement, also values for TS and IB are unsatisfactory. However, this composite is not intended for structural use, as they are mainly produced for heat insulating purposes.

CBPB, with diffusely oriented particles to a greater or lesser extent, is an exception compared to the other composites. As the more or less flat particles are bonded parallel to the surface, TS is higher than in the longitudinal or transverse direction.

The advantage of high MOR, MOE, and low TS of fibre-reinforced concrete is compensated by its high density, which makes it difficult to handle.

CBWW is also mentioned for comparison, although it is not a load bearing material. Because of its porosity, CBWW is a material that is used for heat insulating purposes. The high porosity is accomplished by using low cement-wood ratio, which results in low MOE and MOR.

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