Fiber-Cement Composites for Housing Construction: State-of-the-Art Review

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Abstract

Fiber-reinforced cement-based materials have found increasing applications in residential housing construction. Currently, fiber-cement composite products can be largely found in non-structural housing components, including siding and roofing materials. Advantages associated with pulp fibers include widespread availability from renewable sources, high fiber tensile strength, high fiber modulus of elasticity, relatively low cost, and well-developed technology to extract the fibers. The fiber-cement composites themselves offer decay and fire resistance, dimensional stability, "nailability", and good mechanical properties, among other characteristics. In this paper, the production, mechanical properties, durability, and applications of current fiber-cement composite materials are reviewed. Composite durability will be addressed in detail. Future research needs and future applications of this class of material are also considered.

Keywords: cement; fiber; composite; housing; durability

Introduction

While portland cement concrete is the most widely used manufactured material (Mehta and Monterio 1993), plain concrete, mortars, and cement pastes are brittle, possess low tensile strength, and exhibit low tensile strains prior to failure. These shortcomings have been traditionally overcome by embedding within the cement-based material some other material with greater tensile strength.

Among the different types of fibers used in cement-based composites, natural fibers offer distinct advantages such as availability, renewability, low cost, and current manufacturing technologies. One promising and often-used natural fiber is wood pulp. Wood pulp fiber-cement composites offer numerous advantages when compared to both non-fiber-reinforced cement materials as well as other fiber-reinforced cement-based materials. Fiber-cement composites exhibit improved toughness, ductility, flexural capacity, and crack resistance as compared to non-fiber-reinforced cement-based materials. Pulp fiber is a unique reinforcing material as it is non-hazardous, renewable, and readily available at relatively low cost compared to other commercially available fibers (MacVicar et al. 1999). As a result of these various advantages, pulp fiber-cement composites have found practical applications in recent decades in the

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commercial market as a replacement for hazardous asbestos fibers. Today, pulp fiber-cement composites can be found in products such as extruded non-pressure pipes and non-structural building materials, mainly thin-sheet products (ACI 544.1R 1996). Perhaps the most widely known are fiber-cement siding materials, which have been called "tomorrow's growth product" (Kurpiel 1998). As of the late 1990's, fiber-cement makes up 7-10% of the North American siding market (Kurpiel 1997), with some projecting a 25% growth rate per year over the next few years (Hillman, 2003). Other currently available commercial fiber-cement products include cladding (which can replicate brick or stucco, for example), architectural elements, shakes and shingles, backerboard and underlayment, and fascia and soffit panels, among others.

Current State-of-the-Art

Since ancient times, natural fibers have been used to reinforce brittle materials. For example, thousands of years ago, Egyptians began using straw and horsehair to reinforce and improve the properties of mud bricks (Mehta and Monterio 1993; Bentur and Mindess 1990). In more recent times, large-scale commercial use of asbestos fibers in a cement paste matrix began with the invention of the Hatschek process in 1898 (ACI 544.1R 1996). However primarily due to health hazards associated with asbestos fibers, alternate fiber types have been investigated and introduced throughout the 1960's and 1970's (ACI 544.1R 1996). Among the most promising replacements for asbestos are natural fibers.

Wood pulp fibers constitute the major portion of the natural fibers used in cement-based materials. Pulp fiber-cement composites are gaining popularity because of the advantages associated with the fibers – including widespread resource availability, high fiber tensile strength, high fiber modulus of elasticity, relatively low cost, and the well-developed technology to extract the fibers – as well as advantages associated with fiber-cement composites themselves. Depending on their application, fiber-cement materials can offer a variety of advantages over traditional construction materials:

  ??as compared to wood, fiber-cement products offer improved dimensional stability, moisture resistance, decay resistance, and fire resistance;
  ??as compared to masonry, fiber-cement products enable faster, lower cost, lightweight construction;
  ??as compared to cement-based materials without fibers, fiber-cement products may offer improved toughness, ductility, and flexural capacity, as well as crack resistance and "nailability".

Their primary disadvantage is their vulnerability to decomposition in the alkaline environment present in portland cement (Velpari *et al.* 1980; Balaguru and Shah 1992).

Generally, natural fibers used in cement-based matrices can be divided into two categories – unprocessed natural fibers and processed natural fibers. The unprocessed natural fibers are available in many different countries and represent a continuously renewable resource. These fibers are obtained at low cost and energy consumption through the use of locally available manpower and technology. Such fibers are used in the manufacturing of low fiber content composites and occasionally have been used in manufacturing thin sheet high fiber content composites (ACI 544.1R 1996). Generally these fibers are used in low cost housing projects in less developed countries. On the other hand, processed natural fibers, such as kraft pulp fibers,

using sophisticated manufacturing processes to extract the fibers, have been used in commercial production since 1960's for manufacturing of thin sheet fiber reinforced cement products (Bentur and Mindess 1993). Initially, these have been used with asbestos fibers, and from mid 1980's as a sole reinforcement in place of asbestos fibers in all applications.

Fiber-cement composite products for residential housing have been generally limited to exterior applications, such as siding, and roofing. Their exterior use has been limited in the industry due to degradation to ambient wetting and drying. Thus, these components must be currently maintained by painting to avoid moisture problems. Futhermore, the applications of these composite products are non-structural (i.e., non-load-bearing) in nature.

Fiber Pulping Processes

Chemical pulp processes are also referred to as kraft pulping and constitute the largest portion of pulp fibers manufactured. During the chemical soaking and processing of kraft fibers, most of lignin and hemicellulose is removed. Because of this, kraft pulp fibers are generally considered to be of the highest quality in terms of strength and bleached brightness potential (Thorp and Kocurek 1998). However, these important qualities come at the cost of a low yield potential of approximately 45-55% and high operating and capital costs compared to the other pulp processes. Additionally, any required refining (beating) must be done separately and at increased costs.

Mechanical pulps are made without chemical processing and thus only require mechanical energy, and often heat, to produce pulps with distinct properties often used in newsprint paper. High-temperature refining (thermomechanical) processes generally produce yields of 80-90% and are more economical that kraft pulping. Furthermore, post-processing refining is often not required as the thermomechanical (TMP) processes create the same effect as the refining operation after kraft pulping. Unlike bleached kraft fibers, TMP fibers contain lignin. Though mechanical pulps appear to be attractive in terms of their high yields and low costs, the mechanical properties of the TMP fibers suffer, compared to kraft fibers, due to their lower cellulose content. Cellulose is thought to be the most alkaline resistant component of pulp fibers. Thus, TMP fibers are thought to be degraded more quickly in a cement matrix than kraft pulp fibers because of the lower cellulose and higher lignin and hemicellulose contents of TMP fibers. (ACI 544.1R 1996).

Composite production methods

Several techniques have been used to produce pulp fiber-cement composites (Balaguru and Shah 1992; Souroushian and Marikunte 1990; Shao *et al.* 1995). These techniques can be generalized as cast-in-place techniques and precast manufacturing techniques. Most attention and research efforts through the last two decades have focused on precast manufacturing techniques, which include the Hatschek, slurry/dewatering, and extrusion processes.

The Hatschek process is performed through the formation of a thin laminate of dewatered fiber-cement-water slurry. By stacking of laminates while they are still wet, the final product can be formed to the desired thickness. In this process, the stacked laminates are obtained through

continuous winding of the laminate around a cylindrical form. The cylindrical product can be kept in the form of a pipe or cut to form a thin sheet, while the cement matrix is plastic. Up to 12% of fiber weight fraction can be incorporated in cement composites by the Hatschek process.

In the dewatering process, the fibers, cement, and water are made into slurry form using high speed mixing and agitation until the fibers are suspended in the slurry and well mixed with the cement. The mix is then left to settle and the excess water is removed using a vacuum process. The resulting de-watered material is then pressed in the final shape. A fiber weight percentage up to 12% can be easily incorporated in the composite using this method (Balaguru and Shah 1992). It has also been reported that upwards of 65% fibers by mass can be used for fiber-cement composites (Bayasi 2003).

The extrusion process, relatively new to the fiber-cement industry, involves the forming of a cohesive, fiber-cement composite by forcing it through a die that can be adjusted to the desired shape. These sections are then cut to the desired length. This method can produce composites with densified matrix and fiber packing, achieving low porosity, and strengthening of the fiber matrix bond (Shao *et al.* 1995; Shao and Moras 2002; Peled *et al.* 2000). Extruded composites can be manufactured with up to 8% fibers by weight.

The cast-in-place process for using cellulosic fibers in cement-based materials has received relatively little attention. This might be due to the fact that the fiber weight fraction that can be used in this method is limited to a maximum of about 2% by mass due to the difficulties associated with mixing and placing composites with high fiber mass fraction (Soroushian and Marikunte 1990; Lin *et al.* 1995). Fiber distribution is also a main problem facing the wider application of this technique. This technique involves in-situ molding and casting methods similar to those used with normal concrete or mortar. High range water reducer is usually needed for proper dispersion of the fibers and placing and compaction of the composite. Recently, a method for treating kraft pulp fibers has been developed (Nanko *et al*. 2001; El-Ashkar 2002; El-Ashkar *et al*. 2003) that permits uniform fiber distribution at a fiber mass fraction of approximately 6%. TMP fibers can typically be used at higher mass fractions do their shorter fiber length and stiffer cell wall.

To avoid problems with kraft pulp fiber dispersion, aligned fiber sheets have been used (Mohr *et al.* 2003c). The fiber sheets are manufactured by a dynamic sheet former that can be adjusted for various fiber sheet thicknesses (basis weight) and degree of fiber alignment. To achieve similar performance to distributed fiber composites, equivalent fiber mass fractions of the fiber sheets are smaller than that of distributed fibers. By reinforcing cement-based materials with sheets comprised of aligned pulp fibers additional benefits may be had in terms of tailoring the composite design for the desired mechanical behavior.

Composite Mechanical Properties

Effect of fiber volume fraction

The properties of wood pulp fiber cement-based composites are largely controlled by the manufacturing process. During manufacturing, different parameters, such as fiber content, the

properties of the matrix (i.e., water-to-cement ratio, sand-to-cement ratio), the molding pressure, and the curing method, can be varied to achieve the desired properties in the composite.

For composites produced by cast in place methods, it has been found that increasing the wood fiber content increased both flexural strength and toughness as well as impact resistance. On the other hand, the compressive strength and toughness are adversely affected due to the difficulties in compaction that have been reflected in the increase in the air content with the increase in the added pulp fiber amounts (Soroushian and Marikunte 1990; El-Ashkar 2002).

In composites produced at higher volume fractions using precast methods, it has been reported (Andonian 1979; Coutts 1984; Coutts and Warden 1985; Coutts 1987b, 1987c; Sorousian and Marikunte 1992) that increasing the fiber content increases the flexural strength of the composite, but beyond a certain limit the strength decreases. The optimum fiber amount for flexural strength and toughness has been found to range from 8 to 12%, with 10% being the recommended value (Coutts 1987b). The concept of the increase of flexural strength and toughness with the increase in pulp fiber content, using the dewatering method, have been supported by an experimental program for fiber weight fractions ranging from 4 to 8% by Soroushian (1995b).

Effect of curing conditions

Curing conditions play an important role in the composite behavior, which has been attributed primarily to the influence of curing on the matrix properties. Two curing methods that are generally used in wood fiber cement composites are air/moist curing (normal pressure and temperature) and autoclave curing (high pressure and temperature). It has been summarized (Bentur and Mindess 1990) that a contradictory effect of the autoclave curing condition compared to normal air or moisture curing has been reported. While Coutts (1984) and Coutts and Warden (1985) reported a reduction in flexure strength and no significant effect on flexural toughness for autoclaved curing specimens, an increase in flexural strength and significant reduction in flexural toughness have been reported elsewhere (Akers and Studinka 1989). These differences may result from different processing techniques used in these studies.

Effect of pulp fiber type

Some contradictory results have been reported concerning the effect of the kraft pulp fiber type on the mechanical performance of wood fiber cement composites. Blankenhorn *et al*. (2001) found enhancements in flexural toughness when using softwood fibers to reinforce cement composites compared to hardwood fibers, which are typically shorter than softwood fibers. In addition, Coutts (1987c) found that composites reinforced with softwood fibers have higher flexural strength and toughness than those reinforced with the hardwood fibers, over a wide range of fiber weight fractions from 2 to 12%. This effect has been attributed to the higher aspect ratio and length of the softwood fibers, as compared to hardwood fibers. However, Soroushian and Marikunte (1990) and Marikunte and Soroushian (1994) reported no significant differences in flexural strength or toughness between softwood and hardwood reinforced cement-based composites.

In regards to recycled fibers, Soroushian *et al.* (1995a) examined the use of fibers from wastepaper as a substitute for virgin wood fibers and found out that a composite with a comparable flexural strength, stiffness and toughness can be produced. An optimal composition was found to be 8% fiber by weight at a 50% substitution level of recycled fibers with a refinement (beating) level of 540 CSF (Canadian Standard Freeness). The optimal weight fraction suggested here is in the same range for virgin fibers (Coutts 1987b).

Effect of fiber pulping technique

The shorter fiber length of TMP fibers (approximately 1-2 mm) is thought to improve the microcrack bridging as more fibers are present for a given fiber volume fraction. This could result in a higher first crack strength. However, it has been observed that peak strength and toughness are decreased with TMP fibers due to lower tensile strengths and shorter fiber pull-out lengths (subsequently due to a lower fiber tensile strength), as compared to the higher strength kraft fibers, which are approximately 4-5 mm in length (Campbell and Coutts 1980; Soroushian *et al.* 1994; Mohr *et al*. 2003b). Since TMP fibers typically contain less cellulose (40-45%) than kraft fibers (65-80%), TMP fiber tensile strength is approximately 50-70% that of kraft fibers (Lehtonen 2003; McDonough *et al*. 1987). It was also determined that the fiber-cement bond strength for kraft pulp fibers is similar to that of TMP fibers (Mohr et *al*. 2003b).

Effect of fiber beating

Mechanical surface treatment by fiber beating – a mechanical process well known in paper industry – and its effect on the performance of the wood fiber cement composite has been studied (Coutts and Kightly 1982; Coutts 1984; Vinson and Daniel 1990). Generally, it has been found that beating enhances composites manufactured by the Hatschek process. Fiber beating improves the fibers' ability to retain particles and maintain sufficient drainage rate for processing in the Hatschek machine. However, beating also leads to fiber shortening, as well as fiber fibrillation. From the standpoint of mechanical behavior, it was found that beating affects flexural strength and toughness. The flexural strength was found to increase with beating to an optimum level (for CSF of about 550) but reduced after that level. On the other hand the flexural toughness was found to be reduced with fiber beating (Coutts 1984). This might be resulting from the fibers shortening effect and increased fiber-cement bonding due to the beating process.

Effect of fiber bleaching

Bleaching largely removes lignin, a polymer that binds the fiber cells together, from the fiber. Typical bleached kraft fibers contain 70-80% cellulose and 20-30% hemicellulose, while unbleached fibers typically consist of 65-75% cellulose, 17-32% hemicellulose, and 3-8% lignin (Stenius 2000). It has been shown that fiber bleaching increases the flexural strength of cement composites, but reduces composite toughness (Mai *et al*. 1983). However, it has been shown (Mohr *et al*. 2003a) that unbleached fiber-cement composites exhibited greater flexural strength and toughness than bleached fiber composites. The contradictory results may be attributed to differing manufacturing processes.

Effect of fiber moisture state

Due to their hygroscopic nature, fiber-cement composites are sensitive to moisture changes in the material itself and in the ambient environment. Several studies have been conducted to assess the performance of pulp fiber-cement composites under different moisture states, particularly in the wet and oven-dry states (Mai *et al.* 1983; Coutts and Kightly 1984; Hughes and Hannant 1985; Soroushian and Marikunte 1992; El-Ashkar 2002). Generally, flexural strength and stiffness tend to decrease as the moisture content increases. On the other hand, the toughness increases when the pulp fiber-cement composite is tested wet, as compared to oven-dried samples. It has been reported (Mai *et al.* 1983; Coutts and Kightly 1984; Coutts 1987a) that the decrease in fiber stiffness when wet and the resulting ductility gained changes both the behavior of the fiber as well as the interfacial characteristics between the cement matrix and the fibers. These changes in the fiber properties and in the cement matrix fiber interface leads to changes in the mode of failure of the fiber. In the wet state, it is believed that the bond between the fiber and cement matrix is weakened. Therefore, fiber pull out is the dominant mode of failure for the wood fibers. On the other hand, in the dry state, the bond strength is increased. This increase in the bond strength is believed to be a result of or can be explained in terms of hydrogen bond and/or hydroxide bridges between the cement-based matrix and the fibers (Coutts and Kightly 1984). The increase in the bond strength between the fibers and the matrix is believed to partly change the mode of fiber failure from fiber pull-out to fiber fracture.

The potential for fiber/matrix debonding and microcracking at the interface during wet/dry cycling of composites is dependent upon (among other factors) the dimensional stability of the fiber reinforcement in response to moisture fluctuations. Wood fibers are hygroscopic, taking up moisture from a wet environment and giving up moisture to a drier environment. As a result, wood fibers swell with increasing moisture content and shrinking upon its loss, below the fiber saturation point. Swelling/shrinking occurs primarily diametrically, with little dimensional change in the longitudinal direction. That is, 2-3% longitudinal expansion with swelling is typical, while the fiber cross section may change by 40-60%, depending on species, pulp type, and moisture content, among other factors. The initial drying state of a fiber, too, affects its dimensional stability during subsequent wetting and drying. Fibers which have been dried once (market pulp) prior to introduction to a matrix material are expected to swell less upon re-wetting, as compared to fibers which have not been previously dried (mill pulp). Results by Mohr *et al.* (2003a) show that composites produced with fibers which have been dried exhibited superior dimensional stability compared to composites produced with fibers which had never been dried. However, the drying state of the fibers did not appear to have any significant effect on composite mechanical properties.

Composite Durability: Wet/Dry Cycling

Changes in the fiber and fiber/cement interfacial region due to environmental interactions can affect the long-term performance of cement-based composites reinforced with natural fibers. A significant mechanism of changes in composite properties is pulp fiber degradation as a result of environmental interactions or changes in the fibers itself due to its presence in the strongly alkaline matrix.

There appears to be two related mechanisms which lead to composite degradation during wet/dry cycling: (1) the degree of fiber-cement bonding and (2) fiber mineralization. Recently, the fiber-cement bonding issue has been suggested as the initial cause of composite degradation. It has been shown by Gram (1983) and Mohr *et al.* (2003a), using sisal and softwood kraft pulp fibers, respectively, that the majority of losses in composite strength and toughness occur early in the accelerated exposure process. Scanning electron microscopy by Mohr *et al.* (2003a) revealed ductile fiber behavior, i.e., fiber pull-out and Poisson's effect at fiber tips, for those composite samples subjected to a low number of wet/dry cycles, even though the composites exhibited significant mechanical property losses.

However, the mechanism for this early increased fiber-cement bonding is unknown. One possible explanation for this behavior is the formation of CH (calcium hydroxide) or ettringite acting to densify the transition zone around the fibers. CH is soluble product of cement hydration that may reprecipitate in voids (i.e., fiber-cement interface) during wet/dry cycling. Ettringite may also form through a similar process known as delayed ettringite formation (DEF). The formation of hydration products around the fibers may restrict fiber swelling. It is possible that after sufficient accelerated exposure the fibers are restrained from further swelling and shrinking. Thus, cement hydration products can continually form within the interior of the fiber without being removed by the capillary forces created during fiber swelling and shrinking.

Backscattered images by Toledo Filho *et al.* (2000) and Savastano *et al.* (2001) confirm the transport of cement hydration products, mainly CH, within the lumen and voids of the fibers, as well as around the fibers during accelerated aging. Unexposed samples appeared to have relatively porous fiber-matrix interface regions. However, after 25 wet/dry cycles, the interface region was found to be densified. This decrease in interface porosity is suspected of increasing the fiber-cement bonding and thus leads to decreased composite ductility.

It has been proposed that embrittlement of the fibers is caused by cement hydration product formation within the middle lamella of the fiber (Bentur and Akers 1989). Once the fibers become mineralized, fiber fracture becomes the main fiber failure mode. The loss of energy dissipation during fiber pull-out accounts for significant decreases in toughness values. It has been suggested by Mohr *et al.* (2003a) that the embrittlement of fibers occurs after the increased fiber-cement bonding mechanism. This has been indicated by increases in flexural strength after reaching minimum values during the increased bonding stage support this chronology of degradation mechanisms.

Though these composite degradation mechanisms have been hypothesized, differences in published results complicate matters. Results obtained by Toledo Filho *et al.* (2000) using sisal and coconut fibers, and Akers and Studinka (1989) and El-Ashkar *et al.* (2002) using kraft pulp fibers, indicate that though a reduction in toughness occurred with wet/dry cycling, an increase in first crack strength was observed. These results contradict those by Mohr *et al.* (2003a) that indicate significant losses in first crack strength with wet/dry cycling. These differences cannot be directly explained at this time, but may be related to differing experimental methods. That is, in (Akers and Studinka 1989; Toledo Filho *et al.* 2000; El-Ashkar *et al.* 2002), samples subjected to accelerated exposure were tested at later ages than the control samples. Therefore, matrix strength improvements with increasing age due to continued cement hydration were not

considered as by Mohr *et al.* (2003a) and may account for the first crack strength increases with accelerated exposure.

Effect of fiber beating

It was shown by Mohr *et al.* (2003a) that prior to wet/dry cycling, peak strength and post-cracking toughness values for unbeaten fiber composites were significantly greater than those of beaten fiber composites. First crack strengths were similar for both fiber types. After 25 cycles, the effect of fiber beating did not appear to have an effect on composite performance.

Effect of fiber bleaching

Results by Mohr *et al.* (2003a) indicated that bleached (i.e. low-lignin) fiber-cement composites exhibited accelerated progression of fiber mineralization as compared to unbleached fibers. Unbleached fiber-cement composites exhibited greater toughness, particularly for low numbers of wet/dry cycles. Without exposure, unbleached fiber composites exhibit greater flexural properties than bleached fiber composites.

Effect of fiber drying history

The fiber drying history has been shown by Mohr *et al.* (2003a) to have little effect on wet/dry cycling durability. Flexural strength and toughness were similar over the range of wet/dry cycles investigated. Thus, fiber swelling/shrinking does not seem to play any direct role in composite degradation.

Effect of fiber pulping process

ACI 544 (ACI 544.1R 1996) recommends the use of kraft pulp fibers because much of the lignin and hemicellulose, which are less alkali-resistant than cellulose, have been removed during the pulping process (ACI 544.1R 1996). However, the presence of lignin in TMP and unbleached kraft may actually slow the progression of composite degradation due to wet/dry cycling. Chemically, lignin stiffens the fiber cell wall, which may slow the ingress of cement pore solution into the fibers. Also, since lignin stiffens the fiber, TMP fibers exhibit better dimensional stability than kraft pulp fibers during wet/dry cycling. Hence, the contact between the TMP fiber and the cement is greater than that of kraft fibers during wet/dry cycling. It should be noted that fiber-cement contact is not equivalent to fiber-cement bonding. Contact is defined here as the frictional proximity between the fiber and cement, not physical interlocking or chemical bonding.

However, it was determined that the fiber-cement bond strengths, prior to wet/dry cycling, were similar for the kraft and TMP fibers. There may be two mechanisms acting influencing fiber-cement shear strength – fiber-cement contact and fiber-cement bonding. Based on changes in composite mechanical properties and fiber pull-out lengths, decreased fiber-cement contact with kraft fibers may allow cement hydration product formation around the fibers that results in increased fiber-cement bonding. As suggested by Mohr *et al.* (2003a; 2003b), increased fiber-cement bonding with kraft pulp fibers (as compared to TMP) may be the underlying cause of the

majority of initial composite mechanical property losses during wet/dry cycling in these composites. This is evidenced by significant reductions in strength and toughness after approximately 5 wet/dry cycles, even though fiber pull-out remains the predominant mode of fiber failure. Therefore, the increased fiber-cement contact of TMP fibers due to lignin cell-wall stiffening is considered to be a significant factor in the improved durability of these fiber-cement composites.

Effect of matrix composition

Efforts to improve the durability of natural fiber-reinforced cement materials to wet/dry cycling have largely concentrated on the addition of supplementary cementing materials. The use of artificial pozzolans has been shown to delay or minimize composite degradation by lowering the pore solution pH, reacting with calcium hydroxide to produce C-S-H, and refining the pore structure, all of which are thought to minimize the mineralization and subsequent embrittlement of fibers with a cement matrix.

Silica fume, used at relatively large amounts (i.e., 30% or greater replacement of cement by weight) appears to significantly minimize composite degradation due to wet/dry cycling (Toledo Filho *et al.* 2003; Gram 1983; Bergstrom and Gram 1984). Silica fume replacements of 17% and 33% of cement by weight reduced the pore water pH from 13.2 to 12.9 and 12.0, respectively (Gram 1983). Partial replacement of portland cement with 40% slag by weight by Tolêdo Filho *et al.* (2003) did not significantly improve the sisal fiber mortar composite durability after 46 wet/dry cycles. Additionally, Gram (1983) has also shown that replacement of cement with 70% slag by weight only reduced the pore solution pH from 13.2 to 13.0 and did not improve the durability of sisal fiber mortar composites after 120 wet/dry cycles. Using rice-husk ash, Ziraba *et al.* (1985) concluded that 45% replacement of portland cement by weight minimized sisal fiber-mortar composite degradation due to wet/dry cycling by reducing the pore solution pH by 15-20%. Fly ash replacement of cement has not been previously investigated as a means of minimizing composite degradation.

Despite improvements in composite durability with certain cement replacements, little is known as to the mechanism of improved durability. That is, does the cement pore solution play a significant role, or does the permeability of the composite? Or are durability improvements based on a combination of the two? Also, how is cement hydration altered by lowering the pore solution pH? These questions must be answered before establishing any criteria or recommendations for improving pulp fiber-cement composite durability.

Composite Durability: Freeze/Thaw Cycling

Freeze-thaw cycling has been used to evaluate the durability of fiber composites exposed to conditions where freezing and thawing conditions may occur. Freezing of water within the pore structure of the matrix causes internal tensile pressure leading to propagation of existing microcracks and formation of new cracks. To avoid this type of damage, small, uniformly spaced air bubbles are entrained in concrete to provide "escape routes" for freezing water. The use of air entraining chemical admixtures is common practice in concrete batching. However, the presence of fibers, such as pulp fibers, is expected to lessen damage by freeze/thaw cycles by

minimizing the propagation of cracks. Because pulp fibers are hollow and of the same scale as the entrained air used in concrete, it is possible that additional mechanisms for freeze/thaw protection may exist which would be unique to this type of fiber.

However, it is relatively unknown if and how the fibers are damaged during freezing. It is possible that the fibers will be sufficiently damaged due to ice crystal growth, such that the fibers will be ineffective in preventing crack propagation. Previous freeze/thaw cycling research by MacVicar *et al.* (1999) has shown that there are no changes in composite mechanical performance after freeze-thaw cycling. However, specimens were only subjected to a maximum of 21 freeze/thaw cycles. Thus, damage may not yet be apparent until additional cycling. However, results by Blankenhorn *et al.* (1999) have shown that the compressive strength of fiber-cement paste composites decreased by 50% after 252 freeze/thaw cycles. Using pulp fiber-reinforced concrete, Naik *et al.* (2002) has shown that the addition of pulp fibers significantly improves the resistance of concrete to freeze/thaw, as measured by dynamic modulus of elasticity, per ASTM C 666. It has also been shown that increasing the pressure during the Hatschek process improves the freeze/thaw durability of laminated fiber-cement panels (Kuder and Shah 2003).

Future Research Needs

Though pulp fiber-cement composites for housing applications have been commercially produced since the 1980's, their hold in the residential housing market has been largely limited to non-structural, components, most of which are thin sections. Future research is needed regarding composite durability and production methods, leading the way for the development of production techniques, materials and products.

Durability

Though the mechanisms of composite degradation due to wet/dry cycling have been fairly well-established, research must be undertaken to understand the progression of composite degradation and to establish means to prevent environmental degradation. Though it is known that mineralization of pulp fiber occur in the cement matrix, research must establish the role of fiber-cement bonding and composite permeability during wet/dry cycling. Matrix modifications (i.e., supplementary cementitious material/by-product utilization usage, polymer-modified cementitious matrices) and new production methods should be investigated to minimize composite degradation, while promoting sustainability.

Despite the exterior applications of current fiber-cement products, little research, compared to wet/dry cycling, has evaluated composite durability to freeze/thaw cycling. Though promising results have been reported, little is known about the effect of freezing and thawing on the fibers. In other words, are the fiber sufficiently damaged after freeze/thaw cycles, such that there are ineffective in preventing propagation? Do the fibers act in the same manner as entrained air? These questions must be answered to thoroughly understand composite durability.

Related durability is the development of appropriate non-destructive evaluation (NDE) tools to monitor performance over time in situ. In addition, NDE techniques could be used for quality assurance during production to ensure adequate fiber dispersion is achieved and that void volume is controlled. Such techniques should be developed for assessing both plastic fiber-cement mixtures (for cast-in place or extrusion) and hardened products.

Production Methods and Products

New production methods have expanded the functionality of fiber-cement composites. Extrusion technology has enabled composites to be manufactured into essentially any shape and size required. Possibilities for extruded fiber-cement composites for residential applications include structural sections, trusses, joists, gutters, and piping. In the interior, composites may be manufactured as cabinets, paneling, shelving, doors, moldings, railings, and stairs.

Some research effort has lead to techniques for aligning pulp fibers; further work in this area, and development of additional technologies for achieving alignment, is recommended. By aligning the pulp fibers, the relatively short length of the pulp fibers is less important in determining composite properties. By laying up a composite from such sheets aligned in specific directions, the strength and stiffness of fiber-cement products can then be engineered for specific applications.

New composite cast-in-place procedures also have the capability to expand the applications of these composites for housing. In this area, research goals include developing techniques (e.g., fiber treatment, mixing methods) to achieve uniform fiber distribution at high fiber contents, as well as rheological characterization of large-scale mixes. Establishing the technology for cast-in-place fiber-cement composites will allow for the introduction of large-scale structural elements, such as driveways, sidewalks, and foundations, with pulp fiber reinforcement.

Similarly, technological improvements that allow cast-in-place production also pave the way for modular construction using precast elements such as fiber-cement panels. To reduce transportation costs and energy requirements, reductions in self-weight of fiber-cement composites are an important research area. In addition, pulp fiber reinforcement of existing lightweight building materials like blocks and panels, similar to aerated autoclaved concrete members, should be investigated. Fibers will make these materials more robust and crack resistant during transport and construction.

Because cement-based materials are well-known insulators, another avenue for further research and product development is the strategic use of fiber-cement composites for sound and heat insulation. Such products might be composed wholly of fiber-cement (likely aerated) or where fiber cement is just one component in an insulating panel or member.

References

ACI544.1R. (1996). "State-of-the-Art Report on Fiber Reinforced Concrete," American Concrete Institute, Detroit, Michigan.

Akers, S. A. S. and Studinka, J. B. (1989). "Aging behavior of cellulose fiber cement composites in natural weathering and accelerated tests," *The International Journal of Cement Composites and Lightweight Concrete*, 11, 93-97.

Andonian, B., Mai, Y. W., and Cotterell, B. (1979). "Strength and fracture properties of cellulose fiber reinforced cement composites," *The International Journal of Cement Composites*, 1(3), 151-158.

Balaguru, P. N. and Shah, S. P. (1992). *Fiber Reinforced Cement Composites*, McGraw Hill, New York.

Bayasi, Z. (2003) "Recycled Cellulose Fibers," *Concrete International*, 25(9), 66-70.

Bentur, A. and Akers, S. A. S. (1989). "The microstructure and aging of cellulose fiber reinforced cement composites cured in a normal environment," *The International Journal of Cement Composites and Lightweight Concrete*, 11, 99-109.

Bentur, A and Mindess, S. (1990). *Fiber Reinforced Cementitious Composites*, Elsevier Science Publishers, Ltd.

Bentur, A. and Mindess, S. (1993). "Effect of drying and wetting cycles on length and strength changes of wood fiber reinforced cement," *Durability of Building Materials*, 2, 37-43.

Bergstrom, S. G. and Gram, H. (1984). "Durability of alkali-sensitive fibres in concrete," *The International Journal of Cement Composites and Lightweight Concrete*, 6(2), 75-80.

Blankenhorn, P. R., Silsbee, M. R., Blankenhorn, B. D., DiCola, M., and Kessler, D. M. R. (1999). "Temperature and moisture effects on selected properties of wood fiber-cement composites," *Cement and Concrete Research*, 29, 773-741.

Blankenhorn, P. R., Blankenhorn, B. D., Silsbee, M. R., and DiCola, M. (2001). "Effect of surface treatments on the mechanical properties of wood fiber-cement composites," *Cement and Concrete Research*, 31, 1049-1055.

Campbell, M. D. and Coutts, R. S. P. (1980). "Wood fiber-reinforced cement composites," *Journal of Materials Science*, 15, 1962-1970.

Coutts, R. S. P. and Kightly, P. (1982). "Microstructure of autoclaved refined wood-fiber cement mortars," *Journal of Materials Science*, 17, 1801-1806.

Coutts, R. S. P. (1984). "Autoclaved beaten wood fiber-reinforced cement composites," *Composites*, 15, 139-143.

Coutts, R. S. P. and Kightly, P. (1984). "Bonding in wood fiber-cement composites," *Journal of Materials Science*, 19, 3355-3359.

Coutts, R. S. P. and Warden, P. G. (1985). "Air cured wood pulp fiber cement composites," *Journal of Material Science*, 4, 117-119.

Coutts, R. S. P. (1987a). "Fiber-matrix interface in air-cured wood-pulp fiber-cement composites," *Journal of Materials Science Letters*, 6, 140-142.

Coutts, R. S. P. (1987b). "Air cured woodpulp, fiber-cement mortars," *Composites*, 18, 325-328.

Coutts, R. S. P. (1987c). "Eucalyptus wood fiber-reinforced cement," *Journal of Materials Science Letters*, 6, 955-957.

El-Ashkar, N. H. (2002). "Wood Pulp Microfibers in Cement-Based Composites: Improving Fiber Distribution and Characterizing Composite Behavior." Ph.D. Thesis, Department of Civil and Environmental Engineering, Georgia Institute of Technology.

El-Ashkar, N. H., Mohr, B. J., Nanko, H., and Kurtis, K. E. (2002). "Durability of pulp fiber-cement composites to wet/dry cycling," In: Anson, M., Ko, J. M., Lam, E. S. S., editors. Proceedings of the International Conference on Advances in Building Technology. Oxford: Elsevier, 233-237.

El-Ashkar, N. H., Nanko, H., and Kurtis, K. E. (2003). "Investigation of Flexural Properties of Wood Pulp Microfiber Cement-Based Composites," In: El-Dieb, A. S., Lissel, S. L., Reda Taha, M. M., editors. Proceedings of the International Conference on Performance of Construction Materials in the New Millennium. Cairo, Egypt, 1055-1064.

Fisher, A. K., Bullen, F., and Beal, D. (2001). "The durability of cellulose fiber reinforced concrete pipes in sewage applications," *Cement and Concrete Research*, 31, 543-553.

Gram, H. E. (1983). "Methods of reducing tendency towards embrittlement in sisal fiber concrete," *Nordic Concrete Research*, 5, 62-71.

Hillman, Dave (2003), Independent consultant to the pulp and paper industry, personal communication, December 16, 2003.

Hughes, D. C. and Hannant, D. J. (1985). "Reinforcement of Griffith flaws in cellulose reinforced cement composites," *Journal of Materials Science Letters*, 4, 101-102.

Kuder, K. G. and Shah, S. P. (2003). "Effects of Pressure on Resistance to Freezing and Thawing on Fiber-Reinforced Cement Board," *ACI Materials Journal*, 100, 463-468.

Kurpiel, F. T. (1997). "Diffusion of cellulose fiber-cement siding and roofing into North America," In: Moslemi AA, editor. Proceedings of Inorganic-Bonded Wood and Fiber Composite Materials, 41-44.

Kurpiel, F. T. (1998). "Fiber-cement siding is tomorrow's growth product," *Wood Technology*, 125(1), 50-54.

Lehtonen, L. (2003). Institute of Paper Science and Technology, Atlanta, GA, unpublished results.

Lin, X., Silsbee, M. R., and Roy, D. M. (1995). "The microstructure of wood fiber reinforced cementitious composites," Materials Research Society, Microstructure of Cement-Based Systems/Bonding and Interfaces in Cementitious Materials, 370, 487-496.

MacVicar, R., Matuana, L. M., and Balatinecz, J. J. (1999). "Aging mechanisms in cellulose fiber reinforced cement composites," *Cement and Concrete Composites*, 21, 189-196.

Mai, Y. W., Hakeem, M. I., and Cotterell, B. (1983). "Effects of water and bleaching on the mechanical properties of cellulose fiber cements," *Journal of Material Science*, 18, 2156-2162.

Marikunte, S. and Soroushian, P. (1994). "Statistical evaluation of long term durability characteristics of cellulose fiber reinforced cement composites," *ACI Materials Journal*, 91(6), 607-616.

McDonough, T. J., Aziz, S., Rankin, K. L. (1987). "The strength of mechanical pulp fibers," ICP Technical Paper Series #267, The Institute of Paper Chemistry, Appleton, WI.

Mehta, P. K. and Monteiro, P. J. M. (1993). *Concrete: Microstructure, Properties, and Materials*, McGraw-Hill, New York.

Mohr, B. J., Nanko, H., Kurtis, K. E. (2003a). "Durability of pulp fiber-cement composites to wet/dry cycling," Submitted to *Cement and Concrete Composites*, June 2003.

Mohr, B. J., Nanko, H., Kurtis, K. E. (2003b). "Durability of thermomechanical pulp fiber-cement composites to wet/dry cycling," Submitted to *Cement and Concrete Composites*, December 2003.

Mohr, B. J., Nanko, H., Kurtis, K. E. (2003c). "Aligned Kraft Pulp Fiber Sheets for Reinforcing Mortar," Submitted to *Cement and Concrete Composites*, December 2003.

Naik, T. R., Chun, Y-M., Kraus, R. N. (2002). "Enhancing strength and durability of concrete with pulp and paper mill residuals," Report No. CBU-2002-25, Center for By-Products Utilization, The University of Wisconsin-Milwaukee.

Nanko, H., Kurtis, K. E., El-Ashkar, N. H. (2001). US Patent 20020160174, 6 November.

Peled, A., Crye, M. F., and Shah, S. P. (2000). "High Content of Fly Ash (Class F) in Extruded Cementitious Composites," *ACI Materials Journal*, 97(5), 509-517.

Savastano, H., Warden, P. G., and Coutts, R. S. P. (2001). "Ground blast furnace slag as a matrix for cellulose-cement materials," *Cement and Concrete Composites*, 23, 389-397.

Shao, Y., Marikunte, S., and Shah S. P., (1995). "Extruded Fiber Reinforced Composites," *Concrete International*, 17(4), 48-52.

Shao, Y. and Moras, S. (2002). "Strength, toughness, and durability of extruded cement boards with unbleached kraft pulp." *Concrete: material science to application, SP-206,* American Concrete Institute, Detroit, 439-452.

Soroushian, P. and Marikunte, S. (1990). "Reinforcement of Cement-Based Materials with Cellulose Fibers," *Thin-Section Fiber Reinforced Concrete and Ferrocement, SP-124*, American Concrete Institute, Detroit, 99-124.

Soroushian, P. and Marikunte, S. (1992). "Moisture effect on flexural performance of wood fiber cement composites," *Journal of Materials in Civil Engineering*, 4(3), 275-291.

Soroushian, P., Marikunte, S., and Won, P. J. (1994). "Wood pulp fiber cement composites under wetting-drying and freezing and thawing cycles," *Journal of Materials in Civil Engineering*, 6(4), 595-611.

Soroushian, P., Shah, Z., and Won, P. J. (1995a). "Optimization of wastepaper fiber-cement composites," *ACI Materials Journal*, 92(1), 82-92.

Soroushian, P., Marikunte, S., and Won, P. J. (1995b). "Statistical evaluation of mechanical and physical properties of cellulose fiber reinforced cement composites," *ACI Materials Journal*, 92(2), 172-180.

Stenius, P. (2000). *Forests Products Chemistry*, TAPPI, Atlanta.

Toledo Filho, R. D., Scivener, K., England, G. L., and Ghavami, K. (2000). "Durability of alkali-sensitive sisal and coconut fibers in cement mortar composites" *Cement and Concrete Composites*, 22, 127-143.

Tolêdo Filho, R. D., England, G. L., Ghavami, K., and Scrivener, K. (2003). "Development of vegetable fibre-mortar composites of improved durability," *Cement and Concrete Composites*, 25, 185-196.

Thorp, B.A., and Kocurek, M.J., ed. (1998). *Pulp and Paper Manufacture, V. 7: Paper Machine Operations*, Technical Section Canadian Pulp and Paper Association, Montreal.

Velpari, V., Ramachandran, B. E., Bhaskaran, T. A., Pai, B. C., and Balasubramanian, N. "Alkaline resistance of fibres in cement," *Journal of Materials Science*, 15, 1579-1584.

Vinson, K. D. and Daniel, J. I. (1990). "Specialty cellulose fibers for cement reinforcement," *Thin-Section Fiber Reinforced Concrete and Ferrocement, SP-124*, American Concrete Institute, Detroit, 1-18.

Ziraba, Y. N., Baluch, M. H., Azad, A. K. (1985). "Use of plasticized sulphur in sisal-fibre concrete," *Durability of Building Materials*, 3, 65-76.