MOISTURE-SENSITIVITY AND LONG-TERM DURABILITY CHARACTERISTICS OF WOOD FIBER REINFORCED CEMENT COMPOSITES

Volume I

By

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ABSTRACT

MOISTURE-SENSITIVITY AND LONG-TERM DURABILITY CHARACTERISTICS OF WOOD FIBER REINFORCED CEMENT COMPOSITES

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Wood fibers being fairly strong and stiff as well as low-cost and plentiful are particularly suited for the reinforcement of thin-sheet cement products. However, the affinity of wood fibers to moisture and their long-term performance in cement-based matrices have led to concerns regarding the moisture-sensitivity and longevity of wood fiber reinforced cement composites.

The main thrust of this research was to establish the mechanisms of moisture and ageing effects on wood fiber reinforced cement composites in order to contribute to the development of refined composites with improved stability under moisture and weathering effects. Statistical concepts were considered in design and analysis of experiments to ensure the reliability of the conclusions.

Several commercially available wood fiber types were selected and characterized for cement applications. Kraft fibers were observed to be resistant to alkali attack when exposed to the alkaline pore water of cement and some comparable solutions.

A comprehensive investigation of the effects of various proportioning and processing variables on the composite material performance led to the selection of optimum conditions for the production of wood fiber-cement composites.

The effects of moisture and weathering on the performance characteristics of wood

fiber-cement composites were quantified, and statistically reliable conclusions were derived regarding the interaction of some key proportioning and processing variables with the ageing process and moisture-sensitivity of wood fiber-cement composites. Microstructural studies were conducted in order to establish the mechanisms of moisture and weathering effects on the composite material. Some refinements in the matrix composition, fiber reinforcement conditions, and processing variables were devised to enhance the stability of composites under moisture and weathering effects. Through comprehensive experimental studies, refinements capable of enhancing the moisture resistance and longevity of wood fiber-cement composites were identified.

Dedicated to the memory of
my mother "*Jayalakshmi*"

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CHAPTER 1

INTRODUCTION

World use of hydraulic cements is close to one thousand million tons per year and along with steel and wood they are the most important construction materials. It has been proposed that by the year 2000 this usage of hydraulic cements could be doubled.

The low cost and ready availability of the raw materials for cement (limestone, clay etc.), the fact that the energy consumed in the manufacture of cement is considerably less than for metals and plastics (Table 1.1) and that hardening takes place with water at ordinary temperatures, provides the incentive for optimizing the strength, toughness and durability of hydraulic cements not only for their more conventional uses, but also so that they might be used in quite new applications as replacements for energy intensive plastics and metals [1].

Table 1.1 An Approximate Comparison of Cost and Energy of Production of Portland Cement and Other Materials [1]

Material	Density	Relative Cost	Relative Energy of Production (per unit weight)
Portland Cement	2.5	1	1
Polyester	1.3	20	15
Polyethylene	1.0	15	15
Glass	2.5	30	3
Steel	7.9	6	6
Aluminum	2.7	20	25

Cement-based materials suffer from one common fault-they are brittle. Most inorganic materials fail in a brittle manner under tensile stress or impact loading. In very general terms a material may fail by one of two fracture mechanisms: plastic flow or brittle cracking. The material will favor that mechanism which is weaker; metals which are ductile or tough generally yield before they crack; nonmetallic materials (apart from some polymers) crack before they yield, and are brittle (Figure 1.1) [2].

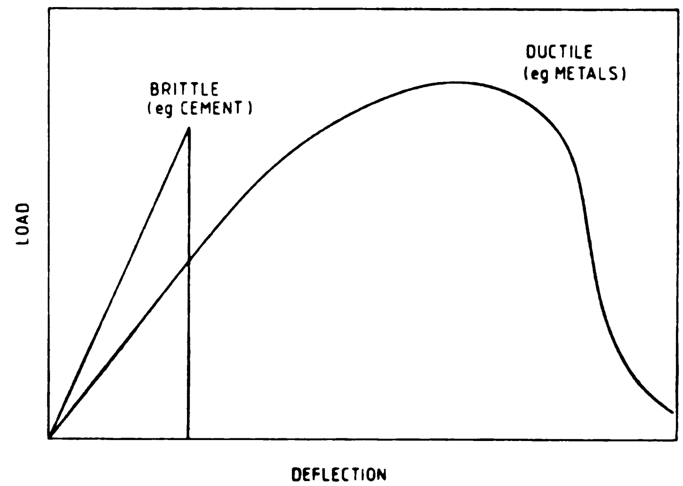


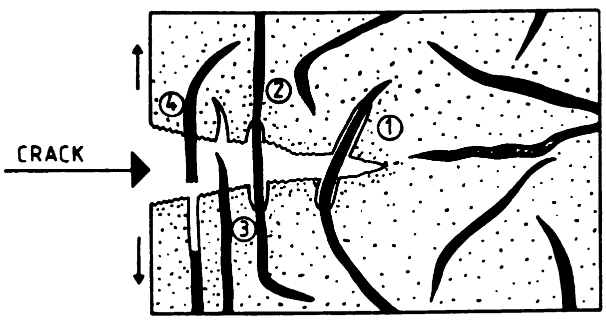
Figure 1.1 Typical Load-Deflection Curves for Brittle and Ductile Materials [2].

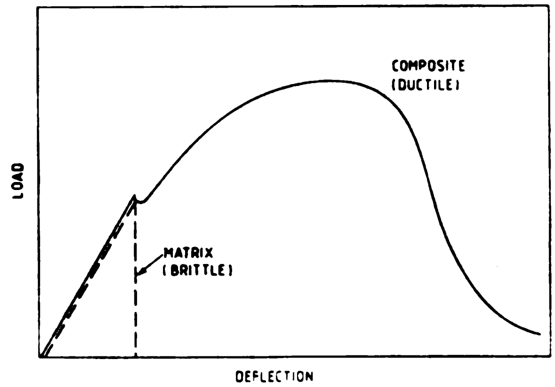
1.1 CONCEPT OF FIBER REINFORCEMENT

Brittle materials can be made stronger by very small additions of randomly distributed short fibers. Broadly, the reason why weak, brittle materials are made stronger by very small additions of fiber is that cracks are stopped or deflected by the presence of fibers and the toughness or ductility is dramatically increased.

Failure in a fiber-reinforced cement composite emanates from the defects in the material. These may be broken fibers, flaws in the matrix and/or debonded fiber-matrix interfaces. Figure 1.2 (a) shows a schematic representation of a cross section through a fiber reinforced matrix with several possible local failure events occurring before fracture of the composite [2].

The fibers are in fact starting to be influenced by the crack at some distance ahead of the crack which has started to travel through the section. In the high stress region near the crack tip, fibers may debond from the matrix (e.g., fiber 1 in Figure 1.2 a). This rupture of chemical bonds at the interface uses up energy from the stressed system. Sufficient stress may be transferred to a fiber (e.g., fiber 2) to enable the fiber to be ultimately fractured (as in fiber 4). When total debonding occurs, the strain energy in the debonded length of the fiber is lost to the material and is dissipated as heat. A totally debonded fiber can then be pulled out from the matrix and considerable energy is lost from the system in the form of frictional energy (e.g., fiber 3). It is also possible for a fiber to be left intact as the crack propagates. This process is called crack bridging.





(a) Schematic Representation of a Crack Travelling through a Composite

(b) Improvements in Material Ductility

Figure 1.2 Actions of Fibers in Cement Composites, and the Consequent Improvements in Material Ductility [2].

The net effect of the interaction of fibers with cracks in cement composites is the improvement of ductility and tensile strength of the cement-based material (Figure 1.2 b).

1.2 WOOD FIBER REINFORCED CEMENT COMPOSITES

Wood fibers have a long history of being used for reinforcing purposes. Despite this long history and the existence of well-established cellulosic materials such as wood, plywood, paper and paper laminates, recent developments in composites have been concerned with fibers such as asbestos, glass, carbon and steel.

The properties of wood fibers (Kraft pulp, Pinus Radiata) are compared with those of other reinforcing fibers in Table 1.2 [1]. It is evident from the ratio of cost to load carried by the fiber that wood fibers are highly cost-effective reinforcement. However, the lower absolute properties of the fibers means that considerable care should be exercised in the selection of the matrix.

Table 1.2 Comparisons of Cost and Strength of Wood Fibers with Other Fibers [1]

Fiber	Rel. Cost per Unit Weight	Specific Gravity (S_G)	Tensile Strength* (f_t, MPa)	f_t / S_G	Rel. Cost per unit Weight / (f_t / S_G)
Wood (Kraft Pulp)	1	1.5	500	333	1
Glass Rav-ings	4	2.5	1,400	560	2.2
Steel	1.4	7.9	2,100	267	1.6
Kevlar Pulp	20	1.5	2,800	1,867	3.3
Asbestos (JM 5R)	1.2	2.6	700	269	1.3

* Realistic tensile strength values for commercial fibers

Estimates of likely future costs can be obtained by examining the energies expended in obtaining the fibers. These energies are compared in Table 1.3 [3]. Wood fibers require less production energy than glass; however, they seem to be more energy intensive than asbestos.

Table 1.3 Energy Used in Obtaining Fibers [3]

Fiber	Relative Energy Per Unit Weight
Wood (Softwood Kraft)	1
Wood (Softwood Thermomechanical Pulp, Board Grade)	0.5
Glass	1.4
Asbestos	0.2

Worldwide, the asbestos cement industry has been searching for an alternate reinforcing fiber owing to the limited supply and rising cost of asbestos and the health risk associated with it [1, 4, 5, 6, 7]. Cellulosic fibers derived from softwood and hardwood residues, being fairly strong and stiff as well as cheap and plentiful, are possible contenders as reinforcing substitutes, particularly because fiber-cement products are made by a process somewhat similar to paper making. Wood fibers have been used for many years as an additive in the conventional asbestos industry; some of the asbestos cement replacement products also utilize wood fibers. In these cases, wood fibers contribute mainly to processing benefits rather than reinforcement effects. Recent studies have shown that the reinforcement action of wood fibers in cementitious matrices is quite good relative to other fibers such as glass [1, 2, 4, 5, 6, 7, 8, 9]. Figure 1.3 represents the typical flexural load deflection relationship of wood fiber-cement composite (in saturated condition) as compared with those of glass fiber reinforced cement and asbestos cement [8]. The desirable reinforcement properties of the relatively low-cost and energy efficient wood fibers are demonstrated in this figure.

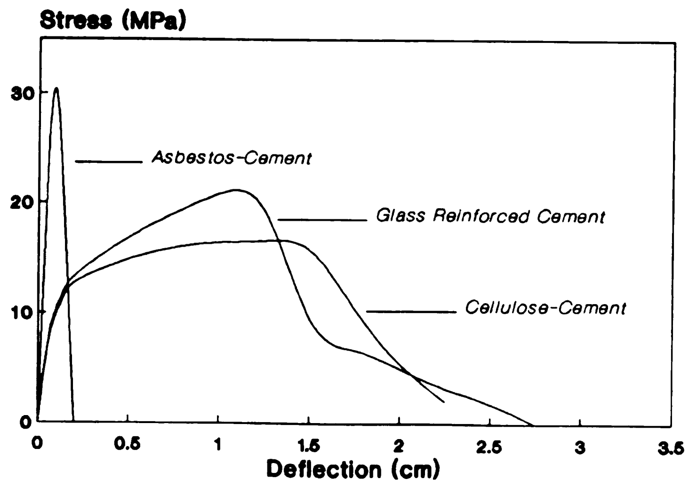
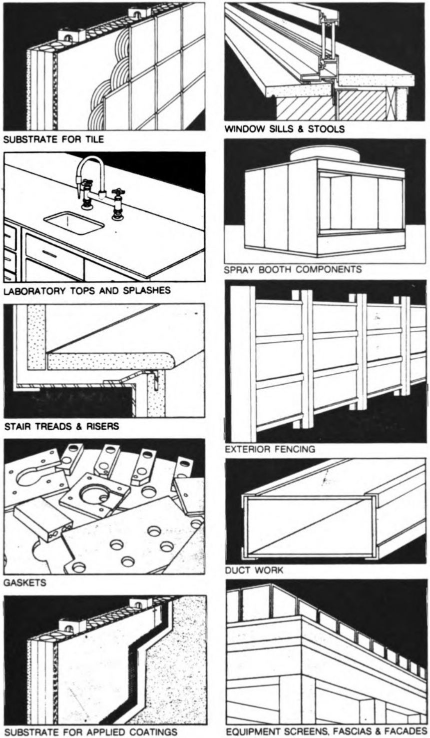


Figure 1.3 Flexural Performance of Saturated Wood Fiber-Cement Composite Compared with Glass Fiber Reinforced Cement and Asbestos Cement [8].

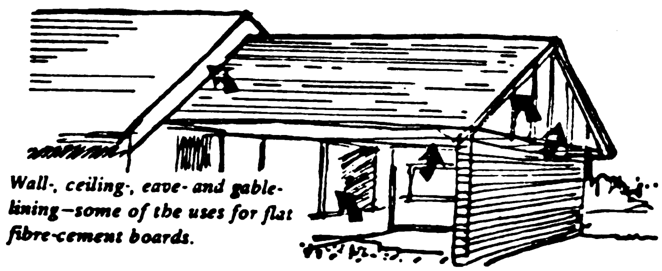
1.3 APPLICATIONS OF WOOD FIBER REINFORCED CEMENT COMPOSITES

The uses of wood fiber reinforced cement sheets are diverse. They range from major components in industrial manufacturing to uses in commercial, residential and agricultural construction (Figure 1.4) [4, 10]. The desirable flexural strength and toughness characteristics, dimensional stability, fire resistance and impact strength of wood fiber-cement composites suggest that they could be valuable in areas of application with demanding requirements on materials Heat shields and spray booths, sound barriers and modular flooring, duct lining and air shafts, gaskets and seals, laboratory tops and splashbacks, and fire walls in dry kilns are some of the typical industrial components made of wood fiber reinforced cement composites. Commercial and residential uses of wood fiber reinforced cement is mainly for the production of flat and corrugated sheets roofing elements, exterior and interior wall panelling, equipment screens, fascias, facades and soffits, substrate for tiles, window sills and stools, stair treads and risers, substrate for applied coatings, and utility building cladding panels. Agricultural uses of wood fiber reinforced cement composites are mainly for farm buildings sidings, stalls and walls, poultry houses and incubators, green house panels and work surfaces, and fencing and sunscreens [1, 4, 10, 11, 12].



(a) Industrial and Commercial Components

Figure 1.4 Application Areas of Cement Products Reinforced with Wood Fibers [4, 10].



(b) Residential and Commercial Construction

Figure 1.4 (cont'd) Application Areas of Cement Products Reinforced with Wood Fibers [4, 10].

1.4 OBJECTIVES

The sensitivity of wood fibers to moisture effects and alkali attack have led to concerns regarding the effects of moisture content on the performance of wood fiber reinforced cement composites, and the long-term durability of wood fibers in the alkaline environment of cement [13, 14]. It is thus essential to develop an in-depth understanding for the moisture-sensitivity and long-term durability characteristics of wood fiber reinforced cement composites.

The objective of this research was to optimize the fiber mass content in different manufacturing conditions, and to study the mechanical properties, physical properties, moisture-sensitivity and long-term durability characteristics of wood fiber reinforced cement composites containing different wood fiber types.

Chapter 2 presents a comprehensive review of literature on wood fiber types, production techniques, properties and pretreatment methods relating to cement applications. Mix proportioning and manufacturing procedures specifically suited for wood fiber reinforced cement composites are presented in Chapter 3.

An experimental study on mechanical and physical properties of wood fiber reinforced composites is presented in Chapter 4, along with a comprehensive review of the related literature. Several wood fiber types were selected and characterized for this research. Flexural performance, density, water absorption and moisture movement characteristics of wood fiber-cement composites were analyzed statistically to derive reliable conclusions.

In Chapter 5, a comprehensive review of the literature on moisture-sensitivity of wood fiber reinforced cement composites is provided along with the test results obtained in this research. The composites subjected to different moisture conditions were tested for flexural performance and were analyzed statistically. Chapter 5 also presents the results of matrix modification to reduce moisture effects through partial substitution of cement with pozzolanic admixtures.

Chapter 6 presents a comprehensive literature review on the durability characteristics of wood fiber reinforced cement composites along with the test results obtained in this research. Wood fiber-cement composites were subjected to repeated cycles of freezing and thawing, accelerated wetting and drying, hot water immersion and outdoor exposure to natural weathering, and the test results were analyzed statistically to derive reliable conclusions.

Chapter 7 summarizes the research program and presents its conclusions.

CHAPTER 2

WOOD FIBERS

2.1 INTRODUCTION

Man has always relied on wood as a construction material. Some of the properties of wood in a structural form can be altered during conversion. For example, drying with proper control of relative humidity and temperature can improve strength properties and dimensional stability. Chemical treatments can reduce biological degradation (preservatives) and combustibility (fire retardants). In addition, dramatic property modifications can be achieved through re-assembling smaller structural units of wood. Plywood, particle board, fiber board and paper are examples of wood being reduced to smaller particles and re-assembled to provide products providing specific performances.

Figure 2.1 briefly illustrates the structure of wood [1]. If a piece of lumber is considered it may have defects (knots, cracks etc.); by selection, a piece of clear wood (near macro defect free) could be obtained with a tensile strength value of say 70 MPa (9.31 ksi). However, the single fibers which constitute the reinforcing unit of bulk wood have been tested and found to have tensile strengths of greater than 700 MPa (93.1 ksi). If one considers cellulose as the basic molecule which makes up the fiber, and if one could express the strength of the chemical bonds which make up the structure of cellulose in terms of tensile strength, an even greater value of around 7000 MPa (931 ksi) would be recorded. In this research, the emphasis will be on the use of individual wood fibers as the reinforcing element.

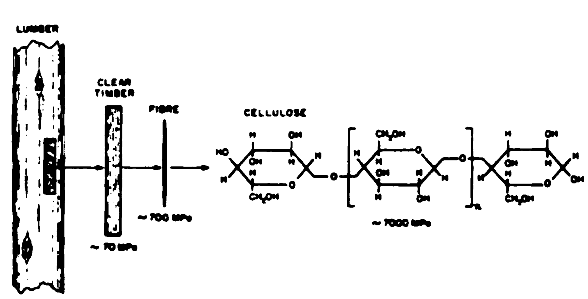


Figure 2.1 A Schematic Representation of the Substructure of a Tree [1].

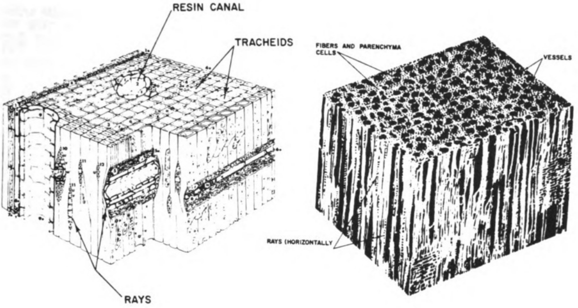
2.2 WOOD FIBER TYPES AND PRODUCTION

Trees serve as the major raw material for wood fibers. The trees harvested for the production of wood fibers are commercially known as "softwoods" and "hardwoods." It is important to note that these names do not represent the wood hardness, as some softwoods are quite hard and dense, and some hardwoods are relatively soft.

The cellulose structure of wood can be perceived through a microscope. Figures 2.2 (a) & (b) show three dimensional drawings of small cubes of wood from White Pine (a softwood) and Sweetgum (a hardwood) [15]. Various cell types that differ in size and function are identified. Softwood (Figure 2.2 a) primarily consists of longitudinal tracheids that are relatively long, 4-6 sides prismatic elements with tapered closed ends. These tracheids are the important wood fibers. In hardwoods, (Figure 2.2 b) the vessels, which are large tube-like structures, occupy a large portion of the total volume. They are, however, relatively thin walled and therefore contribute little to wood fiber mass. The important cell type is the fiber tracheid. It is similar to the softwood tracheid, rather thick walled and long with pointed ends. Hardwood paranchyma cells and vessels break up readily in the pulping process and produce much of the "fine" fraction of wood fibers. Volumetric compositions of the White Pine (softwood) and Sweetgum (hardwood) are presented in Table 2.1.

Table 2.1 Volumetric Composition of Representative Softwood and Hardwood [15]

Softwood (White Pine)		Hardwood (Sweetgum)	
Structure	Percent	Structure	Percent
Longitudinal Tracheids	93	Vessels	54.9
Longitudinal Resin Canals	1	Fiber Tracheids	26.3
Wood Rays	6	Longitudinal Paranchyma	0.5
		Wood Rays	8.3

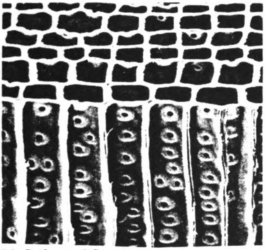


(a) Southern Pine (Softwood) (b) Sweetgum (Hardwood)

Figure 2.2 Schematic Drawings of Typical Softwood and Hardwood [15].

Worldwide, softwoods comprise a group of more than 550 tree species. Only a few of these trees, however, have commercial significance in the production of wood fibers.

Among commercial trees, softwoods are the source of so called "long fiber," which is actually a cell type called "tracheid," that composes more than 90% of softwood stem weight excluding bark. These cells (fibers) are aligned in a direction parallel to the stem axis, and have a major role in liquid conduction. They have closed ends, but their wall is characterized by numerous small openings called "pits" which allow intercellular communication (Figure 2.3 a). From a tangential perspective, fiber ends are pointed (Figure 2.3 b). The arithmetic mean length of unbroken wood fibers in important softwood species ranges from 2.5 to 7 mm (0.098 to 0.28 in), but the vast majority of these fibers average between 3 to 5 mm (0.12 to 0.20 in) in length. Even within the same tree species, fiber lengths can vary considerably. Such variability can be easily matched and even surpassed by variability within a single tree. Softwood wood fiber (i.e. tracheid cell type) has a width, or diameter, which varies from about 15 to 80 microns (0.6×10^{-6} to 3.2×10^{-6} in) but for most softwoods width or diameter falls in the range of 30 to 45 microns (1.2×10^{-6} to 1.8×10^{-6} in) [16].

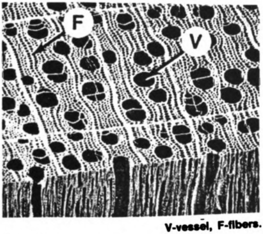


(a) Softwood Structure

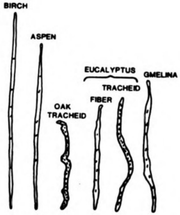
(b) Wood Fiber

Figure 2.3 Wood Fibers (Tracheid Cells) in Softwoods [16].

Among the many hardwood types, only a few are primary sources of wood fiber (e.g. Oak, Birch, Maple, Aspen, Redgum, etc.). Hardwoods yield wood fibers that, on the average, are about 1/3 to 1/2 the length and about 1/2 the width of softwood fibers. Wood fibers produced from hardwood also have higher fine contents when compared with those obtained from softwoods in the sense that they contain vessel elements (non fibrous cells) and in general a greater number of cell types [16]. Figure 2.4 (a) shows the micrograph of a typical hardwood (Birch), and various types of fibers found in hardwoods are presented in Figure 2.4 (b).



(a) Birch wood



(b) Hardwood Fiber Types

Figure 2.4 Wood Fibers in Hardwoods [16].

Figure 2.5 provides information on the geometry and appearance of the major cell types in softwoods and hardwoods [16]. All diagrams in this figure are at the same magnification to show the relative sizes of these elements.

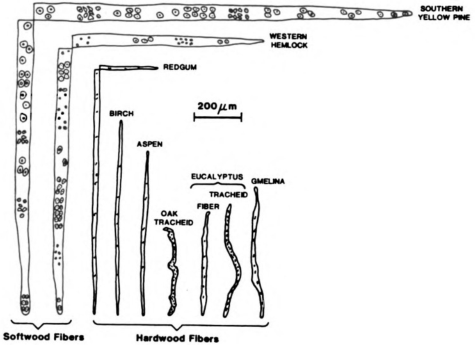


Figure 2.5 Diagrams of Major Cell Types in Softwoods and Hardwoods [16].

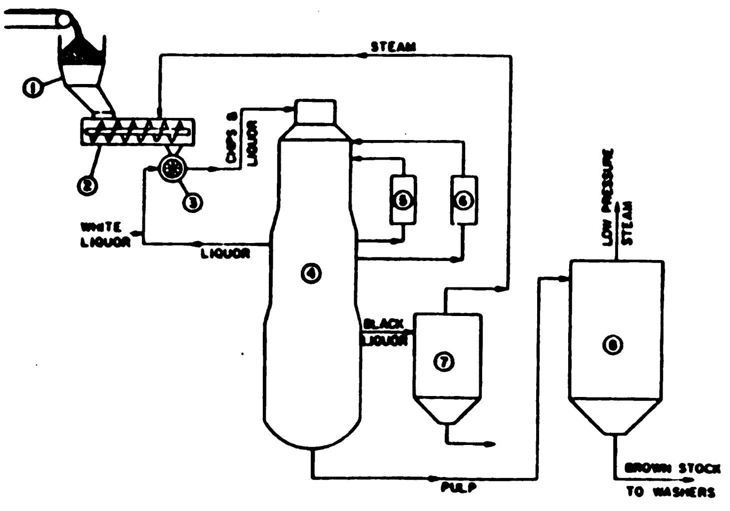
The cells in their natural arrangement in solid softwoods and hardwood, are bonded together by a layer of amorphous cementing material. It is this bonding that must be broken in the wood fiber production (pulping) process by either chemical or mechanical means.

Besides softwoods and hardwoods, bagasse, straw and many other annuals may also be used for the production of wood fibers. Some special wood fibers are also produced from cotton, linen and other textile rags. Kocurek et al. (1983) [16] suggest that these non wood plant fibers will play an increasingly important role in the future.

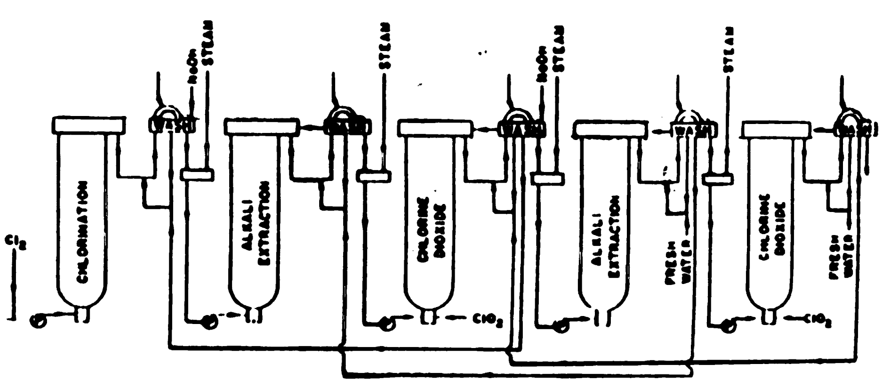
As mentioned earlier, reduction of wood or non-wood plants to a form consisting essentially of individual fibers comprises the production of wood fibers (pulping). Pulping processes are classified as either chemical, semichemical, or mechanical [17]. This classification refers to the nature of the defiberization process. In the chemical process the wood cells are separated from one another primarily by dissolving and removing the natural bonding agent. The chemical reactions occur under conditions of elevated temperature and pressure, and are very complex. In the mechanical pulping process the wood cells are separated by frictional forces often aided by steam pressure. Semi-chemical processes use a combination of both chemical reactions and mechanical power. Chemical pulps are commonly used in the production of book paper and writing paper, while mechanical pulps are regularly used for the manufacture of newsprint [17].

A typical chemical pulping process is shown in Figure 2.6. Chemical pulping begins with cutting the wood into chips. The chips are then screened, rejecting both oversized slivers or undersized fines, and are taken to the top of a "digester" or a high pressure cooking vessel. Chemicals are added and the reactions take place for sometime at a prescribed temperature dissolving lignin (main bonding agent) and hemicellulose of the wood chips. The cooked material is then discharged into a blow-tank where steam and other volatiles are flushed off. The cooking liquor, which is now a "black liquor" because of the dissolved lignin, is passed on to a chemical recovery cycle. The pulp is washed with sprays of water on a series of wire covered rotating drums. The washed brown stock is then screened, diluted and pasted onto arrays of centrifugal cyclonic cleaners to separate out the large and heavy "dirt" (e.g. silica or metal particles) before bleaching.

The thick brown stock is next subjected to a series of bleaching operations. These can vary widely both in the types of chemicals used and their sequences. In the most widely known CEDED system (Chlorine-Extraction-Chlorine-Dioxide-Extraction-Chlorine-Dioxide) the pulp is first bleached with chlorine gas, then extracted with Sodium Hydroxide and finally polished with Chlorine Dioxide. Chlorine Dioxide attacks lignin specifically to a far greater extent than it attacks cellulose, unlike chlorine which is a more indiscriminate oxidant but more expensive; it is thus used in final steps. After the final bleaching, the bright stock is washed and is ready for use.



(a) Continuous Kraft Pulping Process



(b) Bleaching Sequence CEDED

Figure 2.6 An Overall View of the Chemical (Kraft) Process of Pulping [17].

Chemical pulping processes may be categorized as alkaline (sulfate or kraft) or acid (sulfite) depending on the nature of chemical used [17]. The alkaline process is by far the most important pulping process today and is suitable for both hardwoods and softwoods; sulfite process, however, is limited to softwoods of low resin content. Wood fibers resulting from the sulfite process have somewhat lower strengths than those produced through the alkaline process. Sulfite pulps are light in color and relatively easy to bleach.

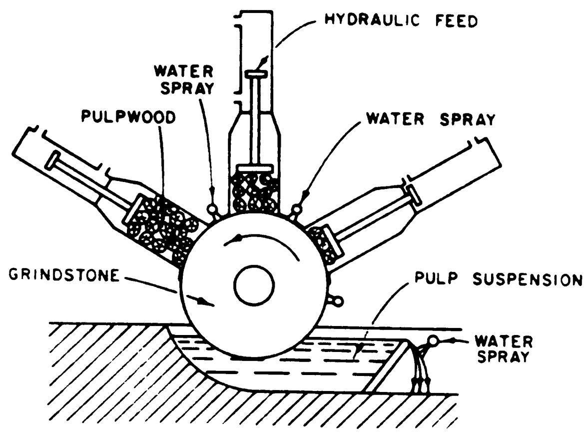
In mechanical pulping, the reduction of logs or chips to fibers occurs by mechanical action which is usually aided by thermal softening of the lignin between wood cells. No chemicals are added in mechanical pulping to dissolve the lignin or any other wood component. However, under severe physical conditions of this pulping process, sometimes certain chemicals of the wood substance may be dissolved.

Breakdown of wood in mechanical pulping may go beyond the fiber element, resulting in broken fibers and fibers with split ends or other damages. Some fiber bundles may also be produced, depending on the type of mechanical bonding process. These physical characteristics of the pulp can be controlled to some extent by the selection of the pulping method and pulping parameters.

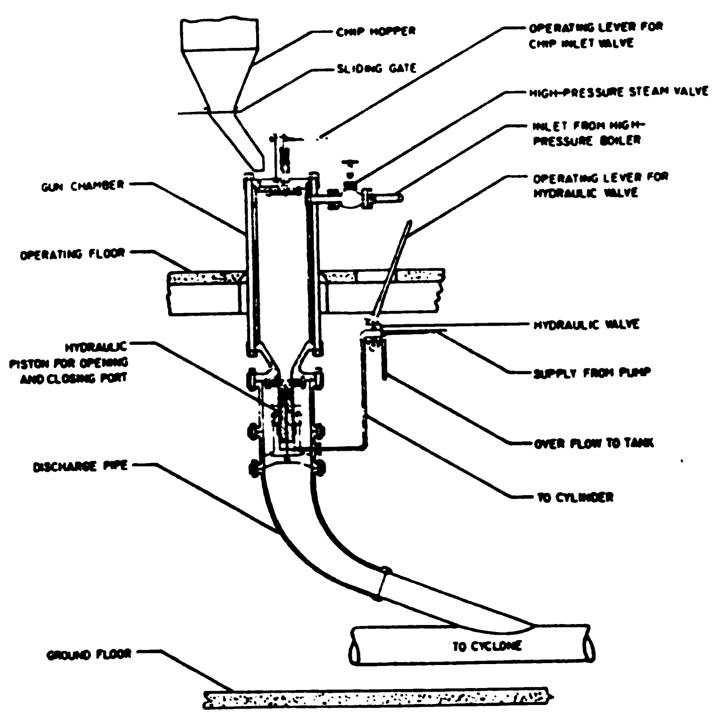
Mechanical pulping generally occurs in two stages [15]. The major break down occurs in the primary stage. The pulp characteristics are finely adjusted and their variations reduced in the secondary stage.

The thermal treatment of chips before or during the defiberizing process causes part of the hemicellulose content to go into solution. The higher the temperature or the longer the treatment, the more effective is the softening of the fiber bond and the greater the consolidation stage. But at the same time the process water becomes loaded with dissolved sugars. The increasing cost of energy and of water treatment will require process modifications and new compromises between process technology and product performance.

The mechanical pulping processes may be categorized as ground wood pulping, masonite explosion, atmospheric disk refining, and pressurized disc refining processes. Figure 2.7 illustrates the different mechanical pulping processes.

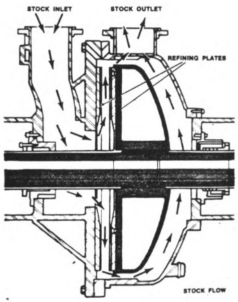


(a) Pulpwood Grinder



(b) Masonite Gun

Figure 2.7 Mechanical Pulping Processes [15].



(c) Disk Refiner

Figure 2.7 (cont'd) Mechanical Pulping Processes [15].

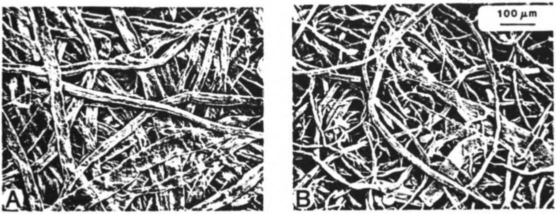
Chemical (kraft) pulps are popular for reinforcement of cement based materials. Higher yield mechanical or semi chemical pulps are also under consideration for cement applications [18, 19]. Besides the virgin wood fibers, high grade recycled wood pulp fibers are also available at much lower prices, and they may be considered for reinforcement of cement.

2.3 PROPERTIES OF WOOD FIBERS

Wood fibers are dead slender cells obtained from defiberization of plants or plant parts. Their cross sectional dimensions are microscopic, i.e. less than 0.1 mm, and their length varies in unaltered state from about 1 mm to well over 120 mm. Commonly, the length/diameter ratio of wood fibers lies in the range of about 50 to 200.

2.3.1 Morphology and Geometry

Modern pulping processes can impart a variety of both chemical and physical changes to the natural wood fibers. However, it is often the original physical attributes of these fibers that largely determine their final properties [16]. Several common types of pulp fibers are illustrated in Figure 2.8.



(a) Southern Softwood (b) Southern Hardwood

Figure 2.8 Micrographs of Several Wood Fiber Types [16].

Wood fibers can be classified on the basis of morphology into 4 groups, leaf, stem, wood and surface fibers. Coutts et al. (1983) [3] suggest that the thermomechanical pulp (separated at less than 130 deg. C, 266 deg. F) and kraft pulp are in a collapse ribbon form while softwood asplund fibers (separated at temperature above 170 deg. C, 338 deg. F) remain as hollow cylinders in the dried composites. Davis et al. (1981) [18] also indicates that, depending on the pulping procedure, fibers may be obtained in a collapsed or uncollapsed form. Chemical treatments for pulping make the fibers collapsed while most semi-chemical or mechanical treatments which retain most of the lignin provide stiffer fibers in which the lumina remain open. Ribbon composites differ from fiber composites in that there is reinforcement in a transverse direction as well as in the longitudinal direction. In theory, ribbons can also be packed very closely than fibers with circular cross section, but the limiting situation is not generally approached in cement composites. It has also been established that the collapsed kraft fibers remain collapsed and do not swell open by moisture effects during fabrication [20].

The nature of the surfaces of wood fibers also varies with the method of fiber separation. The kraft fibers have a highly oxygenated polysaccharids surface while the thermomechanical pulp and Asplund fibers have increasing amounts of lignin in their surfaces which are thus less oxygenated and less hydrophilic.

Different sources of fiber and different pulping techniques produce wood fibers with different properties. In the case of fibers obtained from softwoods, the arithmetic mean length of unbroken wood fibers in important pulpwood species ranges from about 2.5 to 7 mm, but in the vast majority of wood species it averages between 3 to 5 mm and standard deviation range from 0.3 to 1.3 mm (0.012 to 0.05) [16]. Therefore, even within the same tree species, and within a single tree, fiber lengths can vary considerably. The width, or diameter of softwood wood fibers varies from about 15 to 80 microns (0.6×10^{-6} to 3.2×10^{-6} in) but most pulpwoods fall in the range of 30 to 45 microns (1.2×10^{-6} to 1.8×10^{-6} in). Hardwoods yield wood fibers that, on the average, are about 1/3 to 1/2 the length and about 1/2 the width of softwood fibers.

The specific gravity of wood has an effect on the type of wood fiber obtained from it. High specific gravity woods yield stiff, rod-like fibers which drain water more easily (free pulp), while low specific gravity woods yield thin walled and easily collapsed (less free) fibers. These two types of fibers also respond differently to mechanical refining.

Many methods have been proposed for comparing the useful properties of different pulps. A common method consists of comparing the pulps for tear, burst, tensile and other sheet properties at different levels of laboratory beating. Canadian Standard Freeness (TAPPI-227) [21] is a measure of the level of beating, an important consideration in different applications which leads to the fibrillation of fibers. The beaten fibers have exposed fibrils on their surfaces, which help in the development of mechanical bonding and also tend to prevent the loss of cement particles during the suction stage of slurry-dewatering (the production method of wood fiber reinforced cement). A smaller CSF is indicative of a higher beating level. Desirable beating levels lead to improved fiber-to-matrix bonding to the point where gains in strength characteristics of cement composite are not accompanied with substantial losses in toughness characteristics.

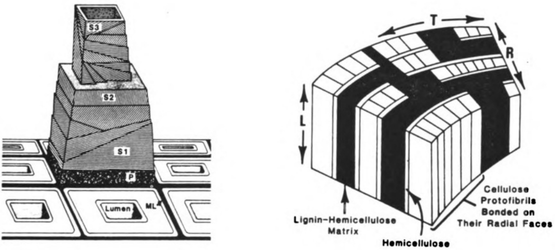
2.3.2 Structure and Composition

The major chemical components of wood are cellulose, hemicellulose, lignin and extractives. Table 2.2 shows the average chemical compositions of softwoods and hardwoods [15].

Table 2.2 Average Chemical Composition of Softwoods and Hardwoods [15]

Components	Percent	
	Softwoods	Hardwoods
Cellulose	42 ± 2	45 ± 2
Hemicellulose	27 ± 2	30 ± 5
Lignin	28 ± 3	20 ± 4
Extractives	3 ± 2	5 ± 3

Wood cells basically have a primary wall, commonly denoted by P, and a secondary wall consisting of three layers, commonly denoted by S_1, S_2 and S_3 (Figure 2.9 a). The distinguishing features of the individual layers are the organization and the orientation of the strands or fibrils [16]. The cellulose molecule is basically the building block of the fibrils in the cell walls. Hemicellulose and lignin are the matrix material in the secondary cell wall layer, and lignin is the primary component of the middle lamella, cementing the cells together. The distribution of these components in the cell wall is illustrated in Figure 2.9 (b).



(a) Diagrammatic Representation of Normal Fiber

(b) Ultrastructure

Figure 2.9 Distribution of the Principal Constituents within the Various Layers of Cell Wall [16].

2.3.3 Moisture Absorption

Water in the wood cell is held on and between the microfibrils at hydrogen bonding sites. As water is absorbed/adsorbed into the cell walls, the latter expand, giving rise to a gross change in the wood tissue as a whole. As this "bound" water is removed from the walls (by drying), the cell walls and wood tissue shrink.

If there is just enough water to completely saturate the cell wall substance and no liquid water is present in the cell lumens, the wood is said to be at its "fiber saturation point." Here the water is essentially that confined or "bound" to the wall substance and any microvoids therein. Wood exhibits its maximum swollen volume at fiber saturation point; any gain in moisture content above fiber saturation point induces no further changes in wood dimensions. The fiber saturation point is usually in the range of 25-30% on an oven dry basis, which is about 20-23% on a wet basis [16].

When there is sufficient wood water to cause an accumulation of liquid in the cell lumens, there is said to be "free water" (or "capillary held water") in addition to the bound water. Since this type of water is held in the wood's void system, gain or loss of free water causes no wood swelling or shrinkage, respectively.

Wood at any moisture content will eventually achieve an equilibrium moisture content if exposed to an environment containing water vapor, and the equilibrium moisture content will always be less than fiber saturation point. The equilibrium moisture content attained will vary with relative humidity of the environment, temperature and drying history of the wood. The equilibrium moisture content of wood achieved either by gaining moisture or by losing moisture is called "sorption hysteresis." Changes in wood dimensions (shrinkage and swelling) result from the change in the content of bound water, as far as the wood moisture is below fiber saturation point [16].

2.3.4 Temperature Effects

The temperature effects on wood can be partly described by the interaction of temperature with wood with moisture. Generally speaking, wood strength is reduced by increasing temperature at a given level of wood moisture below the fiber saturation point. Higher moisture contents at a given temperature usually lead to reduced strength of wood. However, the interaction between temperature, time and pH of the system will also influence the overall effects of strength on wood strength.

Thermal degradation (pyrolysis) of wood substances is affected by chemical breakdown of the various constituents of solid wood. The degree to which thermal degradation affects wood and the rate at which it occurs depend mainly on the temperature at which the reaction takes place, the amount of air present, and the time the reactions proceed [15]. The most obvious result of the thermal degradation of wood is weight loss. As Figure 2.10 shows the weight loss of wood and its major components is relatively minor at temperatures below 300 deg. C (572 deg. F). Hemicellulose, as represented by xylan, is the least stable wood component, whereas cellulose is practically unaffected at 300 deg. C (572 deg. F). Lignin decomposes gradually at temperatures approaching and above 300 deg. C (572 deg. F).

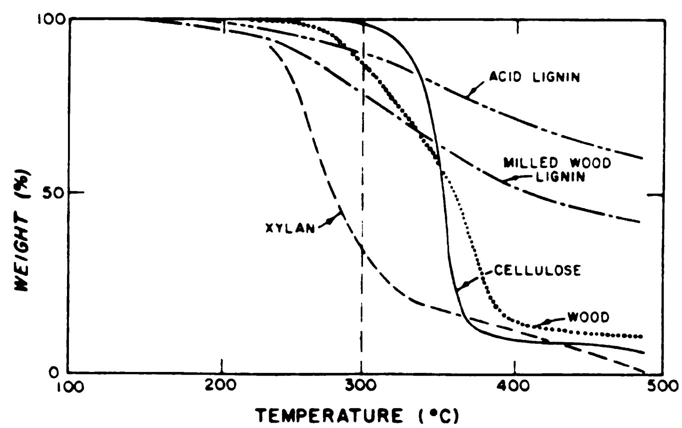


Figure 2.10 Weight Loss of Wood and Wood Components as Functions of Temperature [15].

2.3.5 Biological Deterioration

Wood may undergo biological deterioration under certain circumstances. This is generally caused by fungi, which are micro organisms deriving their nourishment from the degradation of an organic substrate. Where this substrate is wood, the material degraded can, depending on the type of fungus, be the cell wall substance. In addition to food source, fungi also require a relatively moderate temperature to be active (about 5 - 38 deg. C, 40 - 100 deg. F,). They also need oxygen and an adequate source of water. Some fungi preferentially attack hardwoods or softwoods, and some are more active in summer, or in any warm and moist climate [14].

2.3.6 Resistance to Alkali Attack

Table 2.3 presents the chemical composition, morphology and mechanical properties of sisal as well as some other fibers [14]. Approximately 65% of the sisal fiber consists of cellulose, 12% of hemicellulose, 1% of pectin and lignin about 10%.

Table 2.3 Composition, Morphology and Mechanical Properties of Some Natural Fibers [14]

	Sisal	Coir	Flax	Jute
Composition				
Cellulose (%)	65.8	46	64	64
Hemicellulose (%)	12.0		17	
Lignin (%)	9.9	48	2	20
Pectin (%)	0.8		3	
Fat and Wax (%)	0.3		2.4	0.3
Morphology				
Length (m)	1.0 - 1,3	0.05 - 0.35	0.5	1.8 - 3.0
Length of Fiber Cell (mm)	1.3 - 5.0	0.5	25 - 30	2.5
Breadth of Fiber (mm)	0.2 - 0.3	0.05 - 0.3		0.1
Breadth of Fiber Cell (μm)	20 - 30	5 - 8	15 - 18	23
Mechanical Properties				
Tensile Strength (N/mm^2)	568	200	1000	350
Youngs Modulus (KN/mm^2)	26.5	0.89	100	31.6
Elongation at Break (%)	3	29	1.8 - 2.2	1.7
Density (kg/m^3)	1450	1440	1540	1500

Lignin is composed of large three-dimensional molecules. It consists of aromatic substances and is easily broken down in an alkaline environment, where its color turns yellow and brown when oxidized.

The decomposition of cellulose in alkaline environments takes place in accordance with two different mechanisms [14]. One is the pealing off mechanism, which occurs at the end of the molecular chain. The end group which is reductive reacts with OH^- and forms Isosaccharin acid (CH_2OH) which is unhooked from the molecular chain, and end groups are liberated. The other form of cellulose decomposition consists of alkaline hydrolyses. This causes the molecular chain to divide and the degree of polymerization to decrease. Since division of the molecular chain entails the exposure of new reductive end groups, the pealing off mechanism can be started. The decomposition of hemicellulose in an alkaline environment follows the same pattern.

Alkali attack on natural fibers, which are groupings of wood fibers bonded together, at the middle lamella, generally takes place through the breakdown of the middle lamella.

The primary cause of the change in the characteristics of sisal fibers in concrete (an alkaline environment) is the chemical decomposition of the lignin and hemicellulose in the middle lamella [14]. The alkaline pore water in concrete dissolves the lignin and hemicellulose, and thus breaks the links between the individual fibers (Figure 2.11). The long sisal fiber loses its reinforcing capacity in concrete since it breaks down into numerous small units.

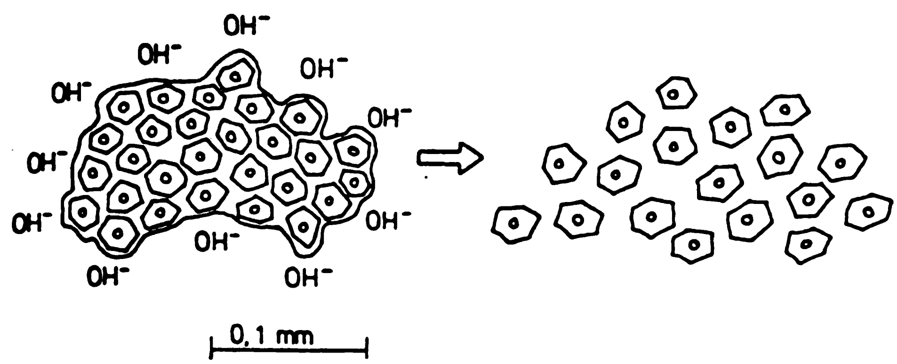


Figure 2.11 Schematic Sketch of the Decomposition of Sisal Fibers in Concrete [14].

The sisal fibers conditioned in solution with a pH value in excess of 12 have been observed to turn yellow, which indicates a reaction between the buffer solutions OH^- ions and the lignin in the sisal fibers [14]. Fibers stored in water also were discolored red and black with time, indicating that bacteria break down the components in sisal fiber when stored in neutral solution. Thus pH alone does not determine whether sisal fibers decompose or not.

The decomposition of fibers takes place more rapidly at high temperatures. Sisal fibers conditioned in concrete pore water (pH=13.7) at a temperature of 70 deg. C for 7 days retained only about 30% (tested dry) of their original dry strength. Wet fibers could easily be pulled apart by means of finger force. Gram (1983) [14] has also observed that fibers conditioned in solutions with Calcium ions are decomposed more than fibers conditioned in solutions of Sodium and Potassium ions with higher pH values. Sisal fibers are decomposed biologically and suffer a decrease in tensile strength if they are stored for a long period in water. In this case they are discolored red or black. No such red or black discoloring of sisal fibers could be noted in concrete specimens reinforced with sisal fibers that were conditioned outdoors or indoors in various laboratory environments.

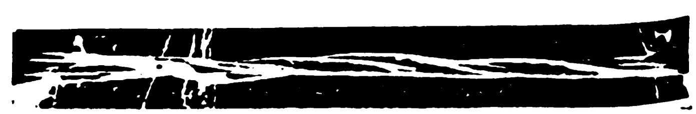
In the evaluation of durability test data for fibers stored in solutions, it should be noted that the complicated alkaline environment to which the fiber is exposed to in the cement matrix, alternating between moistening and drying out, the supply of oxygen, the temperature variations and the change in load on the fibers due to moisture and temperature movements in the composite cannot be simulated reasonably with simply storing the fibers in a solution. It is thus important to rely more on the durability test data generated for the fiber reinforced composites.

2.3.7 Mechanical Behavior

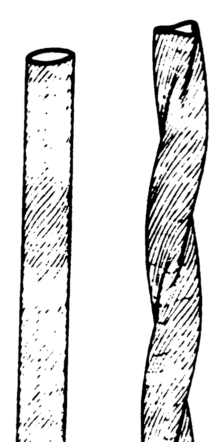
The stress-strain properties of a single wood fiber play an important role in deciding the properties of composites [22]. Figure 2.12 (a) shows a fiber before and after straining; the fiber appears to have twisted under strain, even though its ends have remained firmly glued to their non-rotational supports. A similar but more striking example is shown in the scanning electron micrograph of a strained fiber (Figure 2.12 b). The development of this twisted appearance has been observed many times under microscope, and it can be explained in terms of the structure of wood fibers and the theory of buckling of orthotropic shells. Wood fibers are hollow tubes composed of layers of cellulosic protofibers, embedded in a matrix of hemicellulose and lignin. Most of the cell wall material is contained in the S_2 layer, the protofibers of which trace a steep spiral around the fiber. The wood fiber can thus be considered as spirally wound fiber reinforced composite tubes. Detailed studies of the properties of such tubes and their stability under axial tensile strain have shown that, because of the induced shear stresses, buckling can occur.

It has been shown both experimentally and theoretically that the mode of buckling is as illustrated in Figure 2.12 c. The similarity of this form to the one observed in single wood fiber is apparent.

(a) Spruce Wood Fibers, Pulped by the Kraft Process, Before and After Straining



(b) Scanning Electron Micrograph of Twists in Strained Fiber



(c) Buckling of a Spirally Wound Tube under Axial Tensile Strain.

Figure 2.12 Buckling of Wood Fibers Under Direct Tension [22].

Test results indicate that the shape of the stress-strain curve tends to be influenced by the onset of buckling [22]. Fibers that exhibited no observable buckling had substantially linear stress-strain relationships, but fibers that buckled gave sigmoidal curves of the form shown in Figure 2.13. The first appearance of buckled shape coincided with the yield point of the stress-strain curve. Buckling theory predicts that the critical buckling stress is a function of the principle elastic constants and the fiber wall thickness. Preliminary data indicate that the critical stress can be predicted in this way and thus it seems that a quantitative application of buckling theory will give a more descriptional stress strain curve.

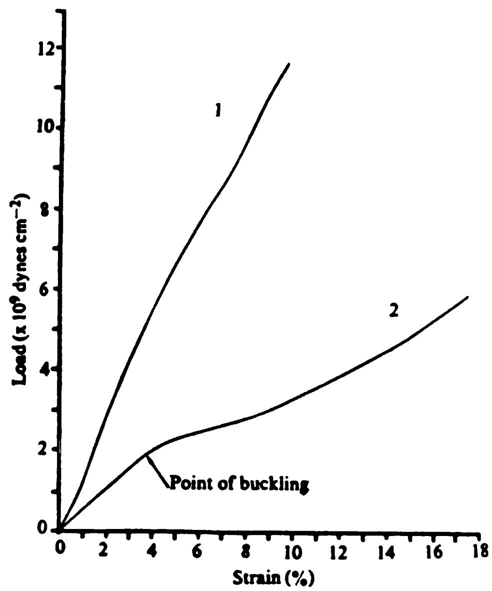


Figure 2.13 Stress-Strain Curves of Spruce Wood Fibers (1. for a fiber that does not buckle; 2. for a fiber that buckles at the point indicated) [22].

The implications of the finding shown in Figure 2.13 are technologically important. The stress-strain curve of fibers that are prevented from buckling are quite different from those of free fibers. Thus, the data obtained from isolated fibers may not be directly applied to the behavior in tightly bonded structures such as wood fiber reinforced cement.

According to Coutts et al. (1984) [20], a wood fiber has about the same strength in wet and dry conditions, but its stiffness is about 10 times greater when dried. The users of wood fibers should be aware of the relatively wide spectrum of values for any given property, both within a given class of fiber and between different classes. Fibers can be derived from leaf, stem, or wood, and their age of growth affects the values of fiber diameter and length. Wood fibers are hollow, and the central lumen vary in size at various stages of growth and also may be collapsed to some degree; thus altering the cross sectional area of the fiber within a given fiber type.

Pedersen (1980) [23] suggests that wood fibers, in spite of having many desirable characteristics, are all not positive in all respects. The main problem is their affinity to moisture, and changing properties from dry to wet; while they are rather stiff and hard they also do get softer with time.

2.4 WOOD FIBER PRETREATMENT

In order to improve the performance of wood fibers in cement composites a number of mechanical and chemical pretreatment techniques have been tried with different degrees of success. Mechanical pretreatment is generally in the form of beating the fibers to expose the microfibrils to improve the bonding of fresh and hardened cement paste to the fibers [13, 24, 25, 26]. The chemical pretreatment may involve coating of the fiber with a coupling agent to improve the bonding of wood fibers to the cement matrix, or it may be to protect the fibers against alkaline environment of cement and moisture. These approaches to the pretreatment of wood fibers are discussed below.

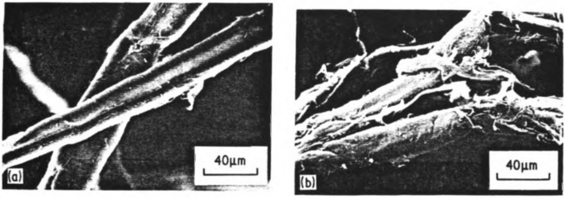
2.4.1 Beating of Wood Fibers

A typical beating process involves soaking of the dry wood fiber lap in water for a few hours. This is followed by beating process in the laboratory using a valley beater or disc refiner, or in plant using a PFI mill to disintegrate and beat the wood fibers [13, 24]. The operation conditions decide the degree of beating achieved following the process. Typical micrographs of unbeaten wood fibers (obtained in light operation conditions of valley beater) and beaten fibers are shown in Figure 2.14 (a) and (b) [25]. The process of beating wood fibers has three main effects.

1. The fibers shorten (often at nodes which are the points of weakness).
2. External fibrillation occurs causing partial or sometimes total removal of the primary wall.

3. Internal fibrillation occurs causing the fiber to become more conformable.

Beating of fibers help improve the mechanical bonding of beaten fibers to hardened cementitious surface.



(a) Unbeaten Fiber (b) Beaten Fiber

Figure 2.14 Typical Scanning Electron Micrographs Showing Fibrillation of Wood Fibers [25].

2.4.2 Surface Treatment by Coupling Agents

Bonding between the reinforcing fibers and the matrix has an important effect on the performance of a composite material. If the surface is to play its dual role of transmitting the stress between the two faces and increasing the fracture energy of the composite by deflecting the cracks and delocalizing stress at the crack tip, then control of interfacial bond strength is of great importance [27].

Coutts et al. (1979) [27] have studied modification of fiber surface using coupling agents in order to make the chemically inpatible fiber-cement component of the composite system produce an interfacial bond stable with time. The optimization of stress transfer across the interface involves more than improving the adhesion. The fracture energy of the material is often decreased by improving the adhesion such that, an increase in strength and modulus of a composite would be accompanied by decreasing its toughness. Even though maximum strength requires strong adhesion and maximum toughness requires weak adhesion. Composites prepared with suitable components can combine strength and toughness to a considerable degree.

The interfacial bond strength in wood fiber reinforced cement composites depends on the fiber surface treatment. Lignified wood fiber contains at its surface covalent hydroxyl (OH^-) groups. The purely organic surface is unlikely to be compatible with the inorganic polymers present in the cement matrix (silicates, aluminates and to a lesser extent ferrites of calcium). For this reason a coupling agent which promotes adhesion between the fiber surface and the matrix is desirable. The coupling agent would act as a link between fiber and matrix by the formation of a chain of covalent chemical bonds. This necessitates the coupling agent possessing chemical functionality which can accommodate a chemical reaction with both fiber and the matrix. Likewise, if the theory is applicable only a small amount of the coupling agent should be required. A possible coupling mechanism is shown in Figure 2.15.

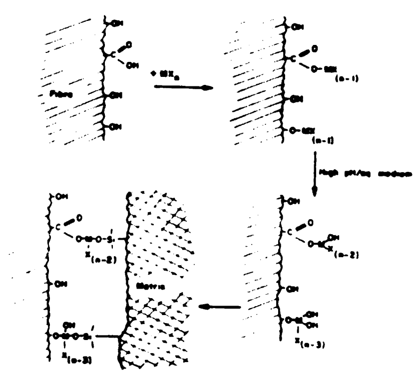


Figure 2.15 Possible Coupling Mechanism [27].

Coutts et al. (1979) [27] have examined a range of inorganic titanium derivatives containing functional groups theoretically capable of reacting chemically with both wood fiber and matrix and so providing a bridge of primary chemical bonds at the interface. The effect these compounds have had on the wood fiber reinforced cement is reported by Coutts et al. (1979) [27] along with the results from a range of commercially available coupling agents.

The coupling agents used include a range of alkoxides of titanium (RSC1-RSC4) which contained at least two alkoxide groups, enabling reaction with the organic hydroxyl groups on the fiber to take place. Several commercial titanate coupling agents (GTDOPP-138S, TTS, TTMDTP-55 and TTOPP-38S) were also used. The most extensive range of coupling agents used in the composite materials are silanes and three such coupling agents have also been included in the study along with two bis (cyclopetadiexyl) metal dihalides. The silanes (Z-1225, Z-6031 and Z-6040) are commercially available, and so are CP_2TiCl_2 and CP_2VCl_2. The test results showed varied degrees of success depending on the type of coupling agent used.

2.4.3 Protective Coating of Wood Fibers

An important factor causing the decomposition of wood fibers in concrete is the chemical attack by alkaline pore water in concrete. One way of avoiding or delaying this decomposition could be to impregnate the fibers with agents which react with certain fiber components and build up components which are difficult to dissolve in an alkaline environment. The impregnation variables are the impregnation agent, duration, temperature and sequence (when multiple agents are used). The agents can be divided into two categories. One group of agents were expected to contribute to blocking any possible reaction between the fibers and the surrounding components. The other group of agents were expected to have a water repellant effect. Gram (1983) [14] reports impregnation agents applied to natural fibers (sisal and coir) with a relatively small degree of success. The impregnation agents used were

1. Blocking agents: Photochemical, Barium Nitrate, Sodium Chloride, etc.
2. Water Repellant Agents: Polyvinyl Dichloride, Chromium Sterate, Steric Acid, etc.
3. Combination of Blocking and Water Repellant Agents

Impregnation agents showed relatively small improvements in strength and toughness.

CHAPTER 3

WOOD FIBER-CEMENT MIX PROPORTIONING AND MANUFACTURE

This section describes the constituents of wood fiber-cement composites, and presents the mix proportions generally used with different manufacturing techniques. An overview of these manufacturing techniques are also presented.

3.1 MIX CONSTITUENTS

The basic constituents of wood fiber-cement composites are wood fiber and cementitious binder (cement, sometimes combined with pozzolanic materials). Fine aggregates (e.g. ground silica) are also generally be used in wood fiber-cement composites [3]. Water is obviously another constituent of the wood fiber-cement mixture. The types and proportions of mix constituents would depend on the fiber type and volume content, and also the manufacturing process (slurry-dewatering, molding, etc.) and the method of curing (in air, autoclave, etc.). In the slurry-dewatering method of production a flocculating agent is generally added to the mix as a processing aid. It is important to optimize the mix constituents and their proportions, as well as the types and variables of the manufacturing and curing techniques in order to produce composites with desirable durability, strength and toughness characteristics.

3.2 MIX PROPORTIONING AND MANUFACTURING TECHNIQUES

There are two dominant manufacturing processes for wood fiber reinforced cement composites: molding and slurry-dewatering [3]. The molding procedure is performed similar to the construction of conventional mortar, and it basically involves the mixing of the constituents and molding them while compaction is achieved through external vibration.

In slurry-dewatering approach, on the other hand, first a slurry of high water content with other mix constituents is produced, and then the extra water is removed and compaction is achieved through vacuuming and pressuring of the slurry. Slurry-dewatering is the dominant method for commercial production of thin-sheet fibrous cement products reinforced with wood fibers.

The exact proportions of wood fiber reinforced cement composites depend on a number of factors, including the adoption of either the molding or slurry-dewatering technique for the manufacture of composite material. A discussion on the manufacturing procedures and the wood fiber cement mix proportions associated with them are given below.

3.2.1 Molded Wood Fiber-Cement Composites

This method of wood fiber cement construction is similar to conventional concrete manufacture, involving basically the mixing of mix constituents and compacting inside molds through vibration. The water content should be kept low in order to ensure desirable hardened material properties. There are limits on the volume fraction of fibers that can be dispersed inside cementitious mixtures when the molding procedure is used for manufacturing. Care should be taken in selecting the mix constituents and proportions for achieving desirable levels of fiber dispersability and fresh mix workability with reasonable hardened material properties. Molded wood fiber cements may be cured in air or moist conditions at ambient temperatures, or they may also be autoclaved.

Coutts et al. (1983) [18] and Campbell et al. (1980) [28] have reported on the manufacture of molded wood fiber-cement using high temperature thermomechanical pulp. The matrix was simply a cement paste with a water-cement ratio of 0.40, and fibers were added to this matrix at a weight fraction of 1.7% (cement : water : fiber by weight ratio of 40:16:1), which is equivalent to a volume fraction of about 3.3%. Coutts et al. (1983) [18] and Campbell et al. (1980) [28] have reported on the manufacture of molded wood fiber-cement composites with up to 8% weight fraction of wood fibers. Kraft and ground wood pulps also can be used in the production of molded wood fiber-cement composites, with the condition that these pulps should be soaked in water and then dispersed in a high-speed mixer before being added to the cement paste. The wood fiber-cement mixture is usually mixed in a heavy duty paddle mixer for about 5 minutes, and is then placed in steel molds and hand trowelled to a flat surface.

All the molded specimens were cured in Coutts et al. (1983) [18] and Campbell et al. (1980) [28] for 24 hours under polyethylene sheets, and were then removed from the molds, dampened with water and wrapped in polyethylene for 6 days. The samples were then unwrapped and air cured. Molded composites are generally used for research purposes.

An important consideration in the manufacture of molded wood fiber cement composites is related to preventing the balling of fibers during mixing in order to achieve a uniform dispersion of fibers. This was the main reason why kraft fibers had to be slushed in water before mixing with cement (and still showed some clumping tendencies, especially in cement pastes with lower water-cement ratios). The lignin-coated Asplund fibers were more dispersible and could be added directly to the mix; although they also showed some clumping tendencies at higher fiber concentrations. In general, for each fiber type and matrix mix composition, there is a limit on fiber concentration that can be conveniently incorporated into the mixture without major fiber clumping.

Coutts et al. (1979) [27] has reported on the use of wood fibers treated with coupling agents in the manufacture of wood fiber cement composites by the molding method. The pretreatment basically involved the immersion of fibers in solutions of coupling agents in methanol or ethanol and then drying the fibers before they were added to the mix. In some cases the treatments were performed using aqueous solutions of the coupling agent, which were used either to precoat the fibers (and then added to the mix together with fibers) or were added directly to the mix. Another approach to the improvement of the overall properties of wood fiber reinforced cement composites, especially bond strength, fracture toughness, impermeability and workability, is through addition of organic polymers to the mixtures.

3.2.2 Slurry-Dewatered Wood Fiber Reinforced Cement Composites

In the slurry-dewatering technique the wood fiber-cement product is formed from a dilute slurry (about 20% solids of fiber-cement or fiber-mortar) [1, 2]. The excess water is removed from the slurry through the application of suction and pressure. The slurry-dewatered wood fiber-cement composites are generally cured using high-pressure steam (autoclave). Curing may also be achieved in air or moist environments. The slurry-dewatering technique is the one adopted for the commercial manufacture of thin-sheet wood fiber cement products. The specific procedure for commercial use is referred to as the Hatschek manufacturing process.

The slurry-dewatering technique has also been used to manufacture asbestos cement and polymer thin-sheet and pipe products. An alternative manufacturing method, spray-suction, has found popularity in the production of glass fiber reinforced cement composites. In the spray suction technique a cement slurry with a water-cement ratio of about 0.6 is sprayed together with fibers on to a mold with a permeable base. The slurry and the fibers are actually sprayed from two nozzles, and the mixing takes place at the mold. The water is removed following spraying by suction, with the final water-cement ratio reaching 0.25 to 0.30.

A critical factor in successful application of the slurry-dewatering technique is the ability of fibers to retain cement particles during the application of a relatively small suction force. Asbestos fibers are ideal for retaining cement particles. Softwood kraft wood fibers also work rather satisfactorily to prevent removal of cement particles during suction. Coutts et al. (1983) [3] reports that untreated softwood Asplund fibers cannot retain sufficient cement for the manufacture of wood fiber-cement sheets. Defibrillation through beating, or possibly some chemical treatments, can be used to improve the ability of fibers to retain cement particles during suction.

Addition of a small dosage of flocculent (e.g. 1% diluted anionic polyacrylamide) to the mixture considerably reduce the amount of cement fines passing through the screens during dewatering. Flocculating agent helps to achieve agglomeration of cement solids in the slurry.

Two categories of slurry-dewatering technique have been used in conjunction with wood fiber-cement composite materials: continuous (Modified) Hatschek process for commercial manufacture, and batch-type (reduced scale) simulation of the Hatschek process for use in laboratory. These two techniques are described below.

3.2.2.1 Continuous (Modified) Hatschek Process for Commercial Manufacture of Wood Fiber-Cement Products

Coutts (1988) [1], Coutts (1983) [2] and Pedersen (1980) [23] have reported commercial manufacture of thin-sheet wood fiber cement products using a slightly modified version of the Hatschek process developed originally for the manufacture of asbestos cement products.

The slurry used in the Hatschek process has a solid content of only 10-20%. A schematic illustration of the Hatschek process is shown in Figure 3.1. This dilute slurry of fibers, cement and silica is fed into a tank containing a number of screen cylinders, which pick up a veneer of the formulation and build up a ply of the product on a felt band or screen; the ply passes over a vacuum box where the water content is reduced. The ply is subsequently laminated on an accumulator roll or calendar until the desired thickness is reached and at this point a cutting wire cuts the sheet, which is then usually conveyed to an autoclave to be cured under high-pressure steam.

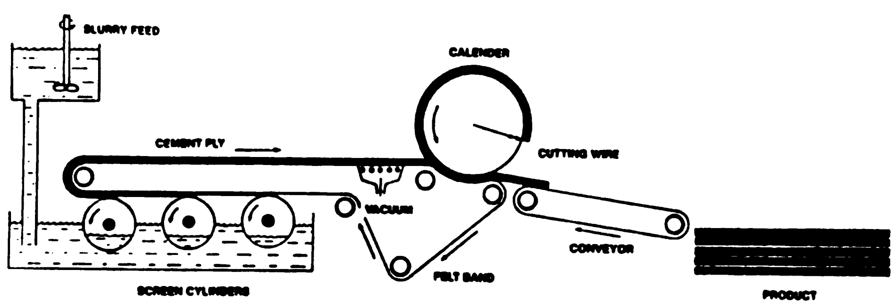


Figure 3.1 The Hatschek Process for the Manufacture of Fiber-Cement Sheets [2].

An important role of wood fibers during the Hatschek manufacturing process is to prevent cement particles from being removed during the filtering of the slurry through a wire mesh. For this purpose, a "pick up effect" (adhesion) between cement particles and fibers is essential. In case the fiber cannot prevent cement particles from being removed under the vacuum action, the sheet will develop a deficiency of binder and the final product will have a tendency to absorb an excess amount of moisture (as a result of the tendency in exposed unprotected wood fibers to absorb moisture). The tendency towards leaving the slurry under vacuum also exists in the case of sand particles.

Some wood fibers are not particularly effective in preventing cement and sand particles from being evacuated during dewatering by suction [1, 2]. The open nature of the wood fiber webs may permit a rapid drainage and loss of matrix particles, resulting in poor product strength. The reduction in drainage rate of the slurry would be effective in minimizing the loss of solids. This could be achieved by using less water in the slurry or through fibrillating the fibers. The first option was ruled out in CSIRO (1981) [4] and Coutts (1983) [2] because it could not be adopted in the Hatschek method. Fibrillation of wood fibers, however, enabled them to form a web capable of retaining the particulate matrix containing flocculating agent, whilst still maintaining a sufficient drainage rate.

The fibrillation of wood fibers in large scale for use with Hatschek machine can be achieved through processing fibers through a mill refiner.

3.2.2.2 Laboratory Scale Slurry-Dewatering Method for the Manufacture of Wood Fiber-Cement Products

Coutts (1987) [13], Coutts et al. (1982) [25], Coutts (1987) [29] and Coutts (1987) [30] have reported investigations involving small scale simulations of the Hatschek process to suit laboratory facilities. The laboratory scale slurry-dewatering methods generally consist of the following steps: (1) a weighed dry lap of wood fiber is soaked in water for a minium period of 4 hours; (2) a British Standard disintegrator is used at 3000 counter revolutions to defibrillate wood fibers; (3) the wood fibers are refined in a valley beater with a bed-load of 2.5 kg (5.5 lb) at a fiber concentration of about 15.7 gm/ liter (0.009 lb/gallon) of water. The refinement could also be achieved through the use of a laboratory size disc refiner. Refined wood fibers with Canadian Standard Freeness ranging from 100-550 have been used in the laboratory manufacture of wood fiber-cement composites. The fibers prepared as mentioned above are then mixed in a slurry of approximately 20% solids, with the slurry typically having equal proportions of cement and finely ground silica; fiber mass fractions with respect to dry weight of constituents typically range from 2 to 14%. Coutts (1986) [19] suggests that relatively high-consistency slurries (about 50% solids) are needed in case of high-temperature thermomechanical wood fibers in order to eliminate settling of the matrix and fibers during sample preparation. These fibers have been drained of excess water after being disintegrated to a moisture content greater than 75%, and their high-consistency slurry has been mixed in a heavy duty paddle mixer.

A relatively small dosage of 1% diluted flocculent (anionic polyacrylamide) has been added to each composite mix. Flocculating agent helps to achieve agglomeration of cement solids in the slurry, and reduces the amount of cement solids that would be lost through the filtering screens during vacuum-dewatering [8, 31].

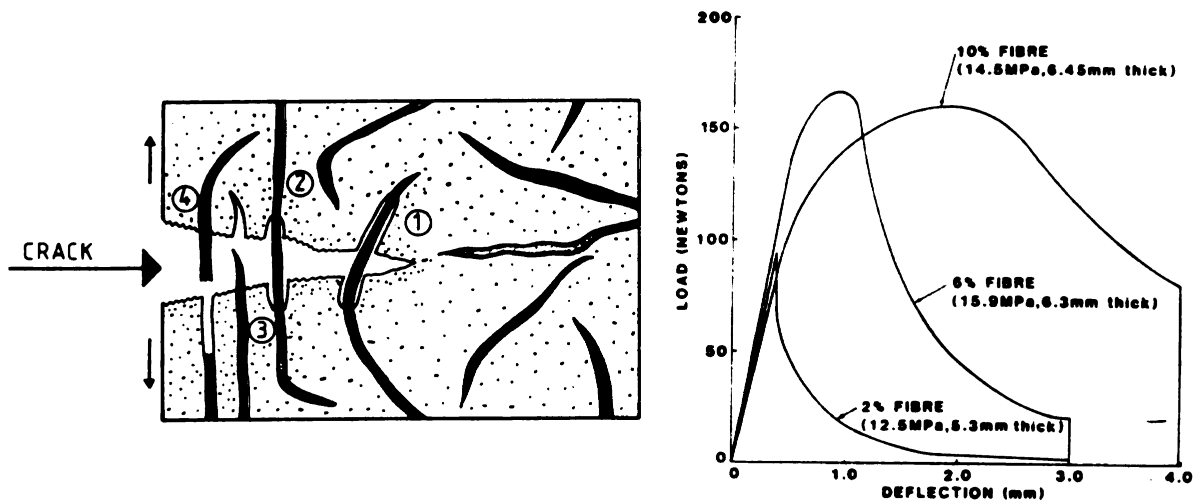
The mixture, after stirring for 5 minutes, is poured in an evacuable casting box 125 x 125 mm (5 x 5 in) and distributed over the screen. The vacuum pump is then switched on and water drawn off until the sheet appears dry on the surface. It is then flattened carefully with a tamper. A vacuum of 60 kPag (8.7 psig) has been applied for 2 minutes. The sheet is then removed on the filter screen. The sheet together with the screen are stored between two steel plates and the procedure is repeated until a stack of 6 sheets are prepared. The stack of 6 sheets is then pressed for 5 minutes at a pressure of 3.2 MPa (461 psi). Initially the load is applied slowly to prevent damage to the sheets. The preparation is completed within 1 hour of starting the mix. After the completion of pressing the screen is carefully removed from the sheets which were stacked flat in a plastic bag for 24 hours. The sheets are then taken from the bag, and the curing is completed in an autoclave for 8 hours at a steam pressure of 0.86 MPa (124 psi). Wood fiber-cement composites can also be air cured, in which case the sheets after pressing are stacked flat in a sealed plastic bag for 5 days and then placed in the laboratory (50 $\pm$ 5% relative humidity and 22 $\pm$ 2 deg. C, 72 $\pm$ 3 deg. F) until testing age of 28 days.

CHAPTER 4

MECHANICAL AND PHYSICAL PROPERTIES OF WOOD FIBER REINFORCED CEMENT COMPOSITES

4.1 INTRODUCTION

Wood fibers are effective in increasing the fracture energy of cementitious matrices, and thus enhancing the tensile strength, flexural strength and toughness, and the impact resistance of the material [2, 3, 28]. These improvements are mainly achieved through the stopping and deflection of cracks by fibers and through the pullout action of fibers at cracks which dissipates frictional energy. Figure 4.1 (a) shows the debonding, pullout and fracturing of fibers bridging the cracks in cement composites. The fracture of fibers takes place when excessive bonding exists between fibers and matrix. Insufficient bonding, on the other hand, could reduce the energy absorbed through fiber debonding and pullout. Typical improvements in the flexural strength and ductility of cementitious matrices resulting from wood fiber reinforcement are shown in Figure 4.1 (b). These improvements largely result from the interaction of wood fibers with cracks (Figure 4.1 a).



(a) Fiber Interaction with Cracks (b) Flexural Performance

Figure 4.1 Basic Concepts and Performance Characteristics of Wood Fiber Cement Composites [2].

4.2 OBJECTIVES

The main thrust in this phase of research was to assess the reinforcing action of wood fibers in cement-based matrices. Several wood fiber types were selected and characterized for cement applications. Fiber mass fractions were optimized for use in different manufacturing techniques. Mechanical properties of wood fiber reinforced cement composites were assessed with emphasis on flexural performance and physical properties (density, water absorption, and moisture movement). An effort was also made to modify the matrix through partial substitution of cement with pozzolans (fly ash or silica fume) and latex to achieve better performance. The results obtained in this study were analyzed statistically using the analysis of variance and multiple comparison techniques in order to derive statistically reliable conclusions.

4.3 BACKGROUND

Mechanical test results on wood fiber reinforced cement composites are reported by Coutts et al. (1983) [3], Coutts (1984) [13], Coutts 1986) [19], Coutts et al. (1982) [24], Coutts et al. (1987) [30], Coutts (1987) [32], Coutts (1983) [33] and Campbell et al. (1980) [28]. Wood fiber mass fraction has generally been the key variable in the reported investigations. The effects of fiber type (P. Radiata kraft, Abaca, Eucalyptus and New Zealand Flax) have also been studied, noting that P. Radiata has developed in Australia as the standard wood fiber in cement applications. The effects of refining wood fibers by beating [13, 24] and coupling agents [27] have also been studied. Wood fiber cements have generally been characterized mechanically through flexural strength and toughness tests and physically by evaluating their density and water absorption characteristics. Davis et al. (1981) [18], Coutts et al. (1984) [20], Coutts (1987) [26] and Coutts et al. (1982) [25] have also reported the results of microscopic studies which can be used to justify the trends observed in the performance characteristics of wood fiber reinforced cement composites.

The results of investigations on the mechanical, physical and microstructural properties of wood fiber cements are presented below.

4.3.1 Mechanical Properties of Wood Fiber-Cement

This section presents the mechanical test procedures adopted for characterization of wood fiber cements, and then reviews test results on the flexural strength and toughness of wood fiber composites.

4.3.1.1 Experimental Methodologies

Results of flexural tests on specimens sawed from thin wood fiber-cement sheets manufactured by either slurry dewatering or molding techniques and cured in air, moist room or autoclave are available in the literature [3, 13, 19, 24, 29, 30, 32, 33, 34]. The rectangular specimens used for flexural tests measure approximately 125 mm (4.92 in) in length and 40 mm (1.57 in) in width, and have various thicknesses typically 6-8 mm (0.24 - 0.31 in). The flexural tests performed generally follow the 3-point bend experimental procedure on a typical span of 100 mm (3.94 in) with displacement rate of 0.5 mm/min. (0.02 in/min). Both loads and midspan deflections have been monitored throughout the deflection-controlled flexure tests. The fracture energy was defined as the area underneath the flexure load-deflection curve, and the flexural toughness has been simply defined as the energy absorption divided by the cross sectional area of the flexure specimen. It should be noted that comparative studies of materials based on these energy absorption and toughness definitions should be done only if the specimen geometries are the same.

Some investigators have also performed impact tests on wood fiber reinforced cement composite using a puncture tester (General Electric Model No. 9015228 GI) [24]. This test measures the energy required to force an indenter of designed size and shape, completely through a sample of the material (sheets obtained from the laboratory scale slurry-dewatering machine with dimensions of 125 x 125 x 6 - 8 mm, 4.92 x 4.92 x 0.236-0.315 in). The dynamic nature of impact test distinguishes its outcomes from the toughness obtained as the area underneath the cohesive-static flexural load-deformation curve.

An Izod impact tester on a notched specimen has also been used by some investigators to assess impact resistance of wood fiber reinforced composite. The specimens used are 80 x 50 x 5 - 8 mm (3.15 x 1.97 x 0.197 - 0.315 in), with a 0.64 mm (0.025 in) wide cut within which the thickness is 2 mm (0.079 in). Impact specimens are produced using slurry-dewatered sheets of wood fiber-cement composites.

4.3.1.2 Flexural Test Results

Coutts (1987) [32] has reported the results of flexure tests on cement composites reinforced with the "basic" unbeaten P. Radiata kraft fibers (Canadian Standard Freeness of 700). The test specimens following typical precuring period of 24 hours in molds were either air cured in an atmosphere with 50 ± 5% relative humidity and 22 ± 2 deg. C (72 ± 3 deg. F), or were autoclaved for 8 hours at 0.86 MPa (124 psi) steam pressure, and then exposed to air. The flexural strength test results for the slurry-dewatered cement paste and mortar (silica sand/cement = 1) are presented in Figure 4.2. There is clearly an increase in flexural strengths with increasing fiber content, and the fiber effects on flexure strength seem to depend on the composition of the matrix (cement vs. mortar) and the curing conditions. While the air cured and autoclaved mortars gave rather comparable results, air cured cements are observed to have higher flexure strengths than autoclaved samples. The maximum flexural strength in any case seems to be achieved at a fiber fraction by weight of 8%. The wood fiber-cement reaches a flexural strength exceeding 30 MPa (4320 psi) after 28 days of air curing, and the autoclaved mortar reaches flexural strengths exceeding 20 MPa (2880 psi).

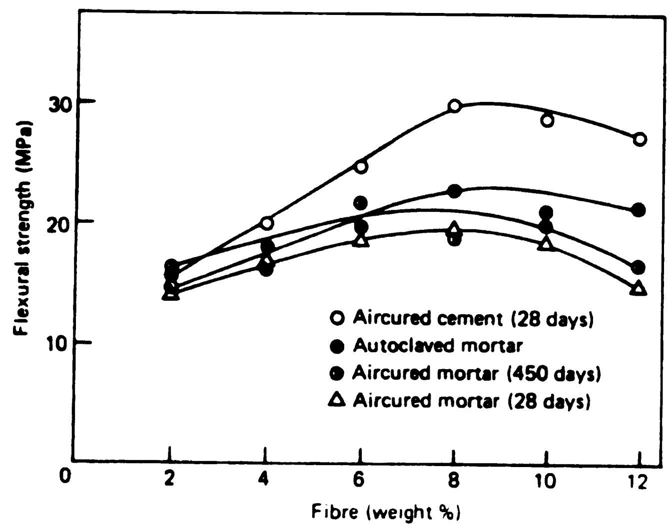


Figure 4.2 Flexural Strength Test Results for Cements and Mortars Reinforced with Different Mass Fractions of P. Radiata Kraft Pulp [32].

Fracture toughness is a material property which may be as desirable as strength or stiffness in application to building products. Coutts (1987) [32] has reported fracture toughness test results for cement composites reinforced with unbeaten P. Radiata kraft pulp. Figure 4.3 shows the fracture toughness test results for slurry-dewatered cement pastes and mortars (silica sand-cement ratio = 1) reinforced with different mass fractions of P. Radiata pulp after different curing regimes (all test results were obtained at 50% RH). The fracture toughness in Figure 4.3 is obtained by dividing the total area underneath the flexural load-deflection curve by the cross sectional area of the test specimen. There is clearly a significant increase in fracture toughness with increase in wood fiber content in cementitious materials. There seems to be little difference in fracture toughness of air cured cements and autoclaved mortars reinforced with P. Radiata kraft pulp. Air cured fiber reinforced mortars, which gave strength values below those of fiber cement, resulted in relatively high fracture toughness values.

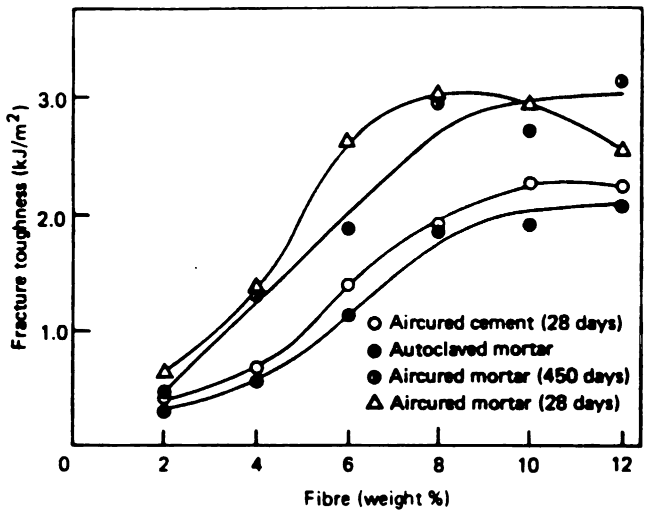


Figure 4.3 Fracture Toughness Test Results for Cementitious Matrices Reinforced with Different Mass Fractions of P. Radiata Kraft Pulps [32].

The degree of refinement by beating of wood fibers (represented by the Canadian Standard Freeness) is another factor influencing the flexural strength of wood fiber reinforced cement composites. The beaten fibers would have exposed fibrils on their surfaces which help in the development of better fiber-to-matrix interfacial bonds, and also tend to prevent the loss of cement particles due to suction in the slurry-dewatering method of manufacturing the composite material. Coutts (1984) [13] and Coutts et al. (1982) [24] have reported flexural strength test results on slurry-dewatered wood fiber-cement composites incorporating different volume fractions of wood fibers with different degrees of refinement (represented by Canadian Standard Freeness, noting that a smaller CSF is indicative of a higher refinement level). The results presented in Figure 4.4 indicate that at fiber contents up to 6% by mass, the degree of beating has relatively small effects on flexural strength. At higher fiber contents, the beating levels which bring the CSF down to about 514-546 CSF tend to increase the flexural strength, but further beating (160-288 CSF) tends to bring flexural strength below that obtained with unbeaten fibers (700 CSF). Thus, the best results were obtained by beating levels which give a CSF value of about 550, for which the optimum fiber content was about 10% by mass, as shown in Figure 4.4. Besides pretreatment by beating, some researchers [24] have also tried to immerse wood fibers in cement paste prior to mixing in order to more effectively coat the fibers by the paste and enhance the eventual fiber-to-matrix interfacial bond characteristics. This procedure has not been successful and actually the conventional immersion of fibers in tap water prior to mixing gave better results than those obtained with fibers immersed in cement paste.

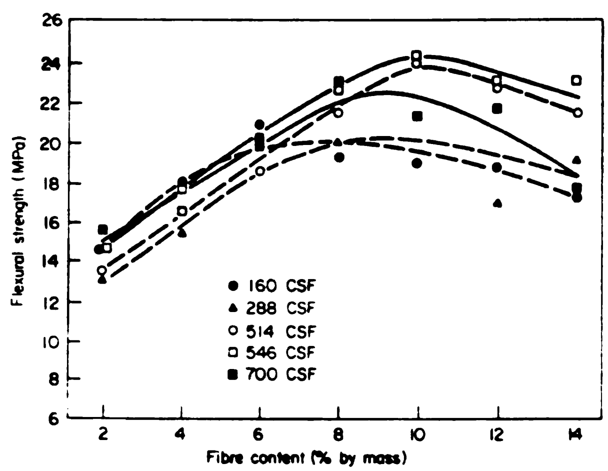


Figure 4.4 Effects of Fiber Beating on the Flexural Strength of Autoclaved Composites with Different Mass Fractions of P. Radiata Kraft Pulp [13].

The degree of fiber beating also has an effect on the fracture toughness of fiber reinforced cement composites. As shown in Figure 4.5 there is a tendency for fracture toughness to decrease as the beating of fibers increases [13]. For fiber loadings below 10% by mass, at higher fiber loadings there seems to be an initial increase in flexural toughness by beating. The overall tendency in fracture toughness is, however, to decrease with beating; this may be attributed to the shortening of fibers by the beating action, which often occurs at fiber nodes (points at which fibers and rays have crossed in wood). External splitting (partial or sometimes total removal of primary walls and fibrillation) and internal splitting along the fibers, as well as the production of debris due to refinement are also among the factors influencing the effects of refinement on the action of wood fibers in cement composites.

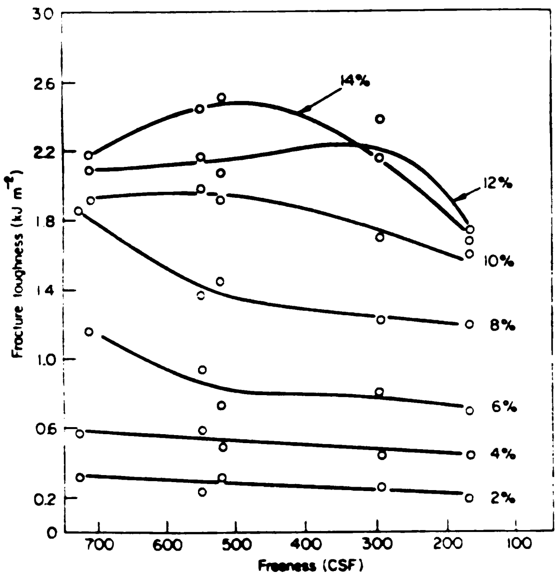


Figure 4.5 Effects of the Refinement of Wood Fibers on the Flexural Toughness of Fiber-Cement Composites [13].

It is often stated that the use of pressure in the manufacture of fiber reinforced cements increases the strength of the composite, while at the same time reducing the fracture toughness. Coutts et al. (1990) [37] have reported the effect of casting pressure on the flexural performance of air-cured wood fiber reinforced composites containing 8% P. Radiata kraft pulp. The specimens after slurry-dewatering were subjected to a range of casting pressures for 24 hours. Test results (Figure 4.6) indicate that as the casting pressure is increased from 0.14 MPa (20 psi) to a maximum of 3.17 MPa (460 psi) there is a continuous increase in flexural strength. However, the fracture toughness remains virtually constant. The increase in strength is greater than 50%. The increase in flexural strength and decrease in fracture toughness are due to the improvement in fiber-to-matrix bonding.

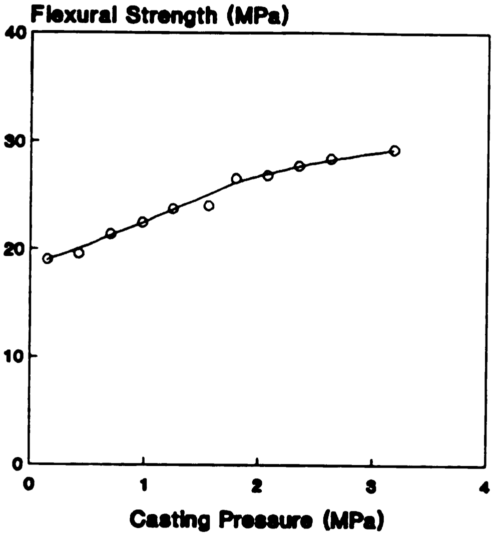
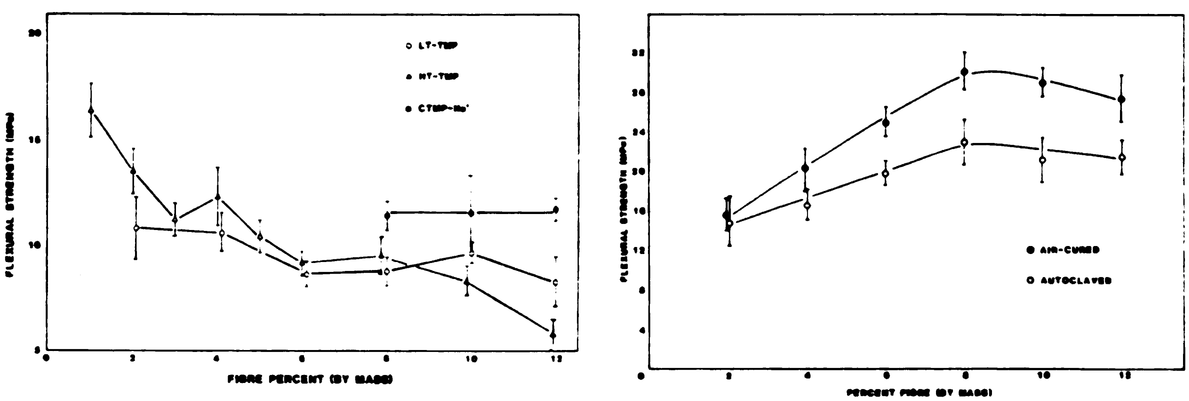


Figure 4.6 Effects of Casting Pressure on the Flexural Strength of Wood Fiber-Cement Composites [37].

Kraft pulp has been established as an effective wood fiber for the production of cement composites, when compared with the high and low temperature thermomechanical and chemithermomechanical pulps. Kraft pulps, however, have a lower yield (i.e. lower amount of fiber obtained from the same amount of wood). Coutts (1986) [19] has compared different pulp types (with different yields) obtained from P. Radiata for the production of slurry-dewatered autoclaved or air cured cement composites.

In case of autoclaved cement reinforced with high-temperature or low-temperature thermomechanical pulps, the flexural strength actually decreased with increase in fiber content (Figure 4.7 a). At fiber contents above 6% by mass, the flexural strength was even below that of the plain matrix. In composites containing chemithermomechanical pulp (CTMP-Na^+) at 8-12% by mass the flexural strengths were somewhat higher than thermomechanical pulp, but still relatively low and unsatisfactory. The inferior performance of the thermomechanical and chemithermomechanical pulps when compared with kraft pulps in autoclaved cement composites has been attributed by Coutts (1986) [19] to the fact that cement at the high temperature of autoclave induces swelling and reaction with polysaccharides of wood acids which are not removed from thermomechanical and chemithermomechanical pulps during their production. Another factor may be the negative effects of some wood chemicals on the setting and hydration, especially at high temperatures of the autoclave [19].

In contrast to autoclaved samples, the flexure strength of air cured products tends to increase with increase in thermomechanical and chemithermomechanical fiber content up to a limit beyond which this tendency is reversed (Figure 4.7 b). This trend is similar to the one obtained with kraft pulps, but the absolute values of flexural strength are still lower when thermomechanical and chemithermomechanical pulps are used.



(a) Autoclaved (b) Air Cured

Figure 4.7 Flexural Strength Test Results for Cementitious Matrices Reinforced with Different Mass Fractions of Thermomechanical and Chemithermomechanical Pulps [19].

Coutts (1986) [19] attributed the undesirable reinforcement properties of high temperature thermomechanical pulps in cementitious matrices partly to the fact that these fibers are known to be coated with lignin and are thus relatively stiff. Their lack of conformability may reduce the surface bond between fibers and matrix, leading to inferior strength values.

The fracture toughness test results for air cured and autoclaved fiber-cement composites made with different wood fiber types are shown in Figure 4.8. It may be concluded from comparisons of Figures 4.8 (a) and (b) that autoclaved fiber cements incorporating kraft pulp have much higher (about 3 times) fracture toughness than those obtained with high and low temperature thermomechanical and chemithermomechanical pulps at comparable fiber mass fractions. This may be attributed to the smaller cross sectional dimensions of kraft pulps, which lead to an increase in the number of fibers crossing a unit area of each crack and give a higher interfacial area for bonding of fibers to the matrix at the same fiber content. The fracture toughness of mortars containing low temperature thermomechanical and chemithermomechanical pulps is observed to increase consistently as the fiber content increases from 2 to 12% by mass. In the case of high temperature thermomechanical pulp, a peak value of fracture toughness is obtained at 8% fiber mass fraction, beyond which the fracture toughness tends to drop below those of composites with other fiber types. These observations may be partially attributed to the higher stiffness of the high temperature thermomechanical pulps, which may reduce their effective packing and fiber-to-matrix bonded area, thereby damaging the pullout resistance of fibers (which has important effects on fracture toughness). Figure 4.8 also indicates that the high temperature thermomechanical pulps give higher toughness values than other fibers at loadings ranging from 6-8% by mass. This could be due to the fact that the high temperature thermomechanical pulps poison the cementitious matrix to a lesser extent than the well fibrillated low temperature thermomechanical pulps [19].

Another observation in Figure 4.8 is that the fracture toughness of air cured mortars reinforced with high temperature thermomechanical pulps is always below that obtained with low temperature thermomechanical and chemithermomechanical pulps. In this condition, with curing performed in air, due to the low temperature of the curing, the poisoning of the matrix by non-cellulose components of fibers has smaller effects and the fibrillated low temperature thermomechanical pulps may develop better bonding to the matrix than the smooth lignin-coated high temperature thermomechanical pulps, which seems to be the factor dominating the pullout performance and thus the toughness characteristics of air-cured fiber mortars. It should also be mentioned that the fracture toughness values obtained with all thermomechanical pulps tend to increase with increase in moisture content of composites as was observed in specimens reinforced with kraft pulps [19].

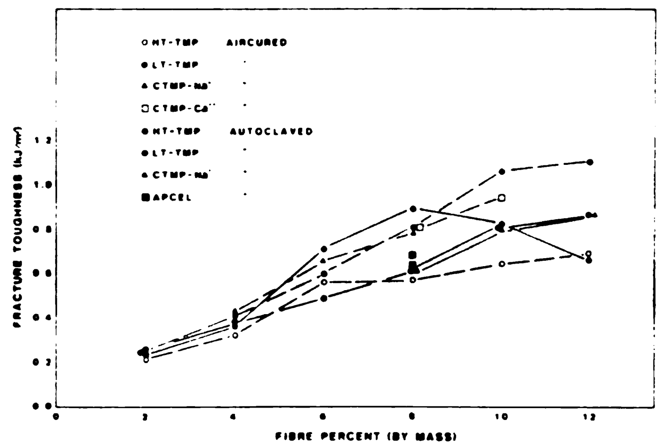


Figure 4.8 Effects of Fiber Mass Content of Different Pulps on the Fracture Toughness of Air-Cured and Autoclaved Mortars [19].

In search of alternatives to P. Radiata for cement applications, Coutts (1987) [29], Coutts et al. (1987) [30] and Coutts (1983) [33] have reported the results of experimental studies on cement composites reinforced with New Zealand flax kraft pulp (CSF 555 and 100), and also with Abaca fibers and some hardwood fibers (E. Regnans, E. Saligna and E. Grandis). The slurry-dewatering technique was adopted for the manufacture of flax pulp reinforced cement sheets by Coutts (1983) [13]. The matrix was prepared from equal proportions of ordinary Portland cement and finely ground silica (100 mesh washed quartz). At fiber mass fractions ranging from 2-12%, the results obtained with flax kraft pulp (Figure 4.9) were similar to those obtained with P. Radiata kraft pulp [13, 24, 32]. The maximum flexural strength (approximately 23.5 MPa, 3380 psi) was obtained at fiber mass fractions of about 8-10%. As shown in Figure 4.8 the flexural specimens tested when wet had moduli of rupture values ranging from 60-80% of the corresponding dry specimens, an observation similar to that of P. Radiata kraft pulp.

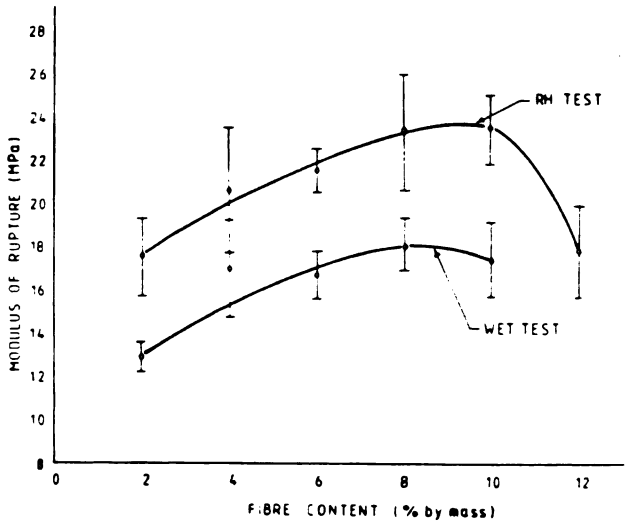


Figure 4.9 Flexural Strength of Cement Composites Incorporating Different Mass Fractions of New Zealand Kraft Pulp [33].

New Zealand flax fibers, due to their relatively high aspect ratio, were expected to produce composites with relatively high fracture toughness. Test results, however, indicated that cement composites incorporating New Zealand flax fibers have only half the fracture toughness of softwood fibers in spite of the fact that New Zealand flax has an aspect ratio approximately 2.5 times that of softwood fibers. This observation indicates that the fiber aspect ratio may not be so important a factor in the mechanisms taking place during work of fracture in wood fiber reinforced cement composites. The fiber diameter and the number of fibers seem to be among factors dominating the fracture energy of wood fiber cement.

Figure 4.10 indicates that the fracture toughness of wood fiber reinforced cement composites tends to increase consistently with increase in fiber content up to the maximum value or 12% by mass considered in the study of flax fiber by Coutts (1983) [33]. The maximum flexural toughness obtained with flax fibers was approximately 15 to 20 times that of plain matrix. The wet samples are also observed to have higher toughness than those tested at 50% relative humidity. Here also, as described earlier for P. Radiata kraft pulp, moisture seems to break the hydrogen bonds and make fibers soft and deformable, encouraging fiber pullout and reducing chances for the fracture of fibers at cracks.

The frictional forces present during fiber pullout seem to absorb a significant amount of energy, providing the composite material with desirable flexural toughness characteristics. These frictional forces may have increased due to the swelling of fibers in the presence of moisture.

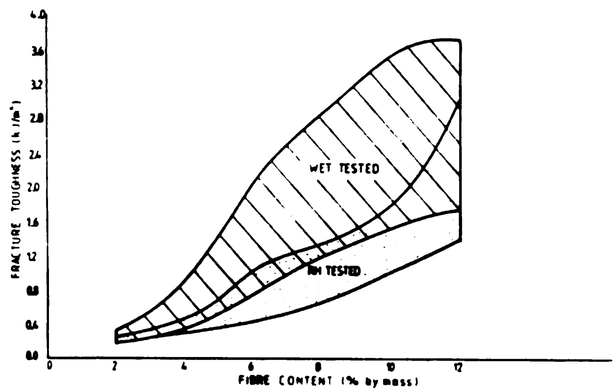


Figure 4.10 Effects of New Zealand Flax Fibers at Different Mass Fractions on the Flexural Toughness of Cementitious Matrices [33].

Coutts (1987) [30] has reported flexural strength test results for air cured Abaca fiber reinforced cement composites manufactured by slurry-dewatering technique. The fiber mass fractions ranged from 2-10% and the maximum flexural strength (about 27 MPa, 3890 psi) in the case of relative humidity tested specimens was obtained at a fiber mass fraction of 8% (see Figure 4.11). The wet specimens are observed in Figure 4.11 to have flexural strengths ranging from 60-70% of those obtained from the relative humidity tested specimens. The Abaca fibers resulted in composite flexural strengths which were slightly higher than those with P. Radiata at lower fiber mass fractions, but slightly lower at higher fiber contents.

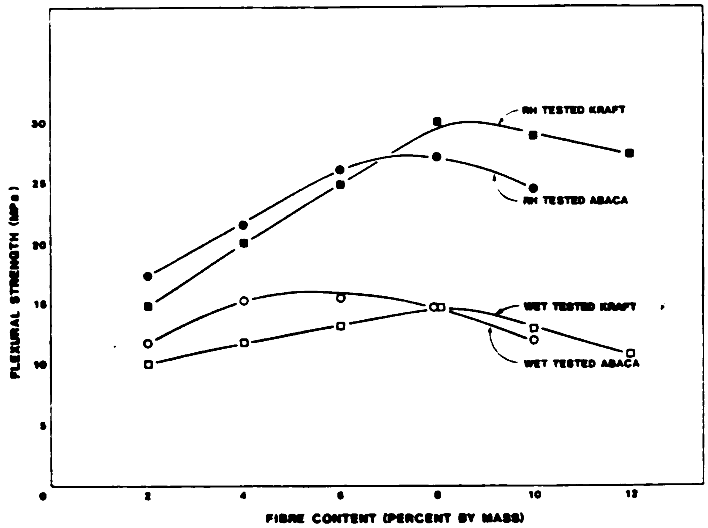


Figure 4.11 Flexural Strength of Cement Composites Incorporating Different Mass Fractions of Abaca Versus P. Radiata Pulp [30].

The effects of Abaca fiber content on the fracture toughness of air cured fibrous mortars tested in wet and 50% RH conditions are compared in Figure 4.12 with fracture toughness values obtained with P. Radiata. The Abaca fibers, in spite of their very high aspect ratio of 400, give fracture toughness values similar to those obtained with P. Radiata kraft (when both are cured in air). The wet Abaca fiber reinforced mortars with lower than 8% fiber mass fractions, however, produce fracture toughness values which are higher than those of kraft pulp. This may be attributed to the better fiber distribution at lower loadings, which offers less restrictions to pullout of fibers leading to a more dominant role of fiber pullout in failure mechanism of wet wood fiber-cements, noting that moisture itself reduces interfacial bonding by rupture of the hydroxyl bridges and or hydrogen bonds [30].

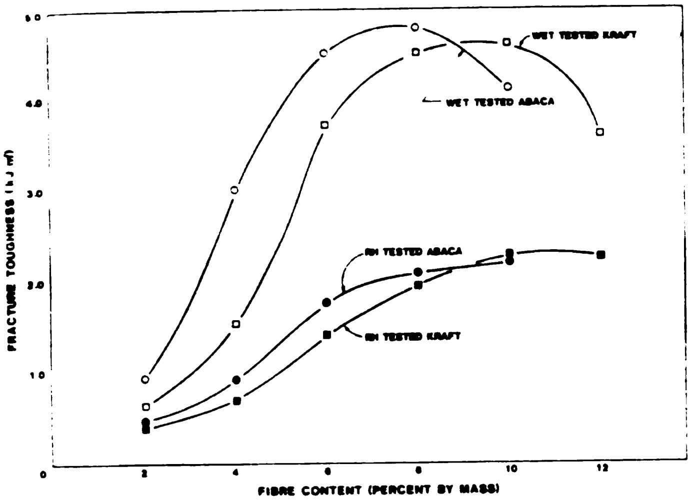


Figure 4.12 Effects of Abaca Fibers at Different Mass Fractions on the Fracture Toughness of Air Cured Cementitious Materials [30].

Coutts (1987) [29] has made a comparative study on the flexural performance of E. Regnans hardwood and P. Radiata softwood kraft pulp used as reinforcement for slurry-dewatered and autoclaved cement composites. It was found that the hardwood fibers produced lower flexural strengths when compared to softwood fibers (see Figure 4.13). The maximum flexural strength with E. Regnans (obtained at 8% fiber mass fraction) was about 20 MPa (2880 psi), which is about 30% less than the maximum values obtained with P. Radiata pulp.

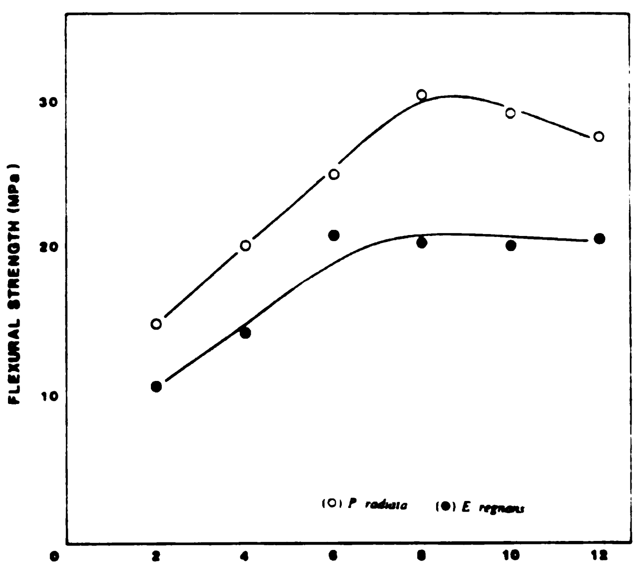


Figure 4.13 Flexural Strength of Cement Composites Incorporating Different Mass Fractions of E. Regnans Hardwood Versus P. Radiata Kraft Pulps [29].

A comparison between fracture toughness of air cured cements reinforced with E. Regnans and P. Radiata are shown in Figure 4.14. The shorter E. Regnans hardwood fibers (average length of 1 mm, 0.04 in) are observed to give lower fracture toughness values than the longer P. Radiata fibers (average length about 3 mm, 0.12 in). This is indicative of the contributions made by the pullout action of longer fibers to fracture energy of fiber cements [29].

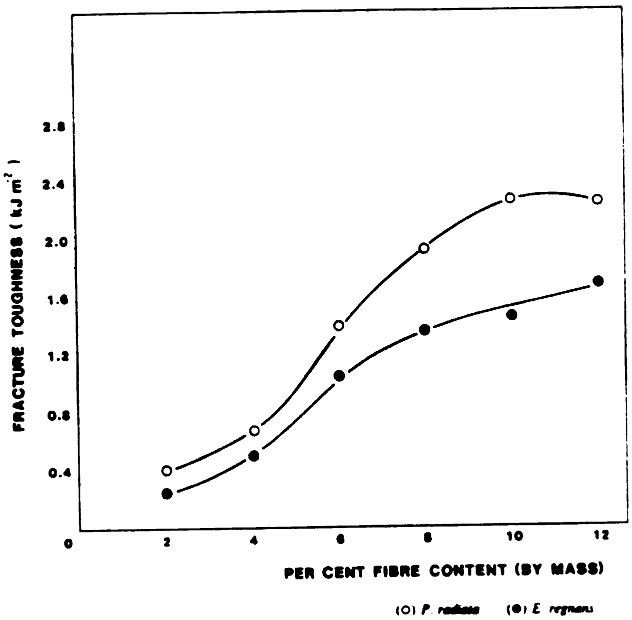


Figure 4.14 Effects of E. Regnans Hardwood Versus P. Radiata Softwood Fibers at Different Mass Fractions on Flexural Toughness of Cement Composites [29].

Figure 4.15 concludes the discussions on fiber type effects on fracture toughness by comparing the maximum toughness values obtained with different fiber types. This figure is indicative of the superiority of P. Radiata and Abaca softwood over the E. Regnans hardwood and New Zealand flax softwood fibers in providing cementitious materials with improved toughness characteristics.

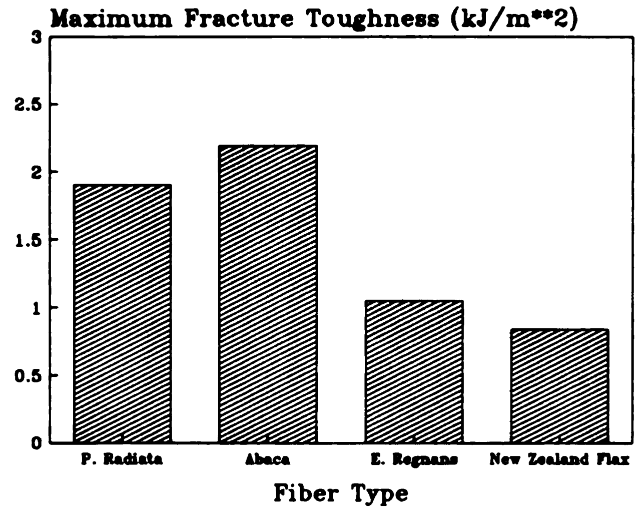


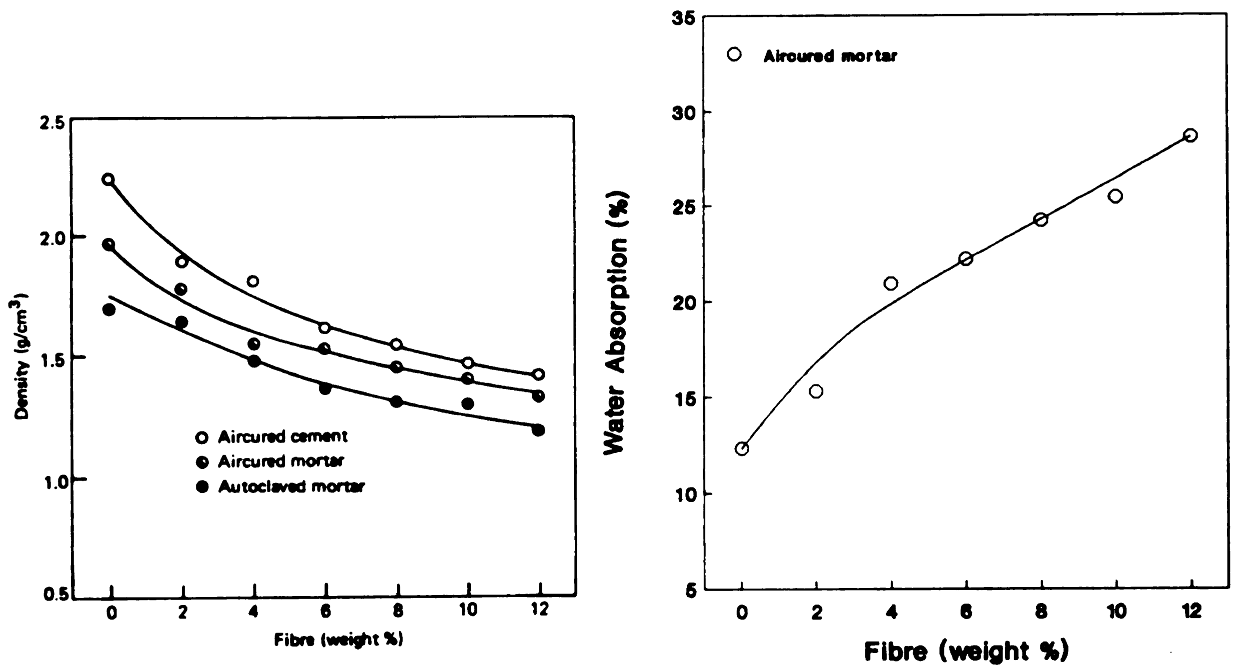
Figure 4.15 Maximum Fracture Toughness Values Obtained for Relative Humidity Tested Cement Composites Incorporating Different Fiber Types [29, 30, 32, 33].

4.3.2 Physical Properties

The physical properties which are significant in wood fiber reinforced cement composites are density, water absorption, porosity, moisture movement, thermal expansion, heat insulation and fire resistance. Test results on density, water absorption and porosity has been reported by Coutts et al. (1983) [3], Coutts (1984) [13], Coutts (1986) [19], Coutts et al. (1987) [30], Coutts (1987) [32] and Coutts (1983) [33]. Test results on moisture movement are reported by Sharman et al. (1986) [38] and Sharman (1983) [39]. However, there is not enough information available on thermal expansion, heat insulation and fire resistance. Density, water absorption and porosity are all interrelated in so far as their magnitude depends upon the free space or the void volume present in the material.

4.3.2.1 Density and Water Absorption

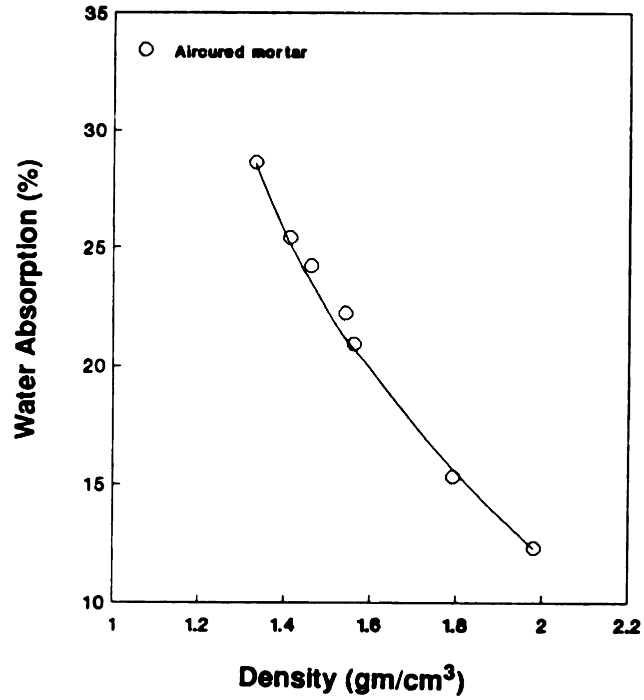
Coutts (1987) [32] has reported test results on density and water absorption of composites reinforced with P. Radiata kraft pulp. Figure 4.16 (a) shows the relationship between density and fiber content for air cured cement, air cured mortar and autoclaved mortar. The autoclaved mortar was found to be the least dense of the materials and, due to the high temperature hydrothermal reactions of its cure, is not affected greatly by ageing in the atmosphere. By contrast, air cured products have calcium hydroxide present which react with carbon dioxide from the air by a process known as carbonation. Thus the increase in volume and mass associated with transforming calcium hydroxide to calcium carbonate will decrease the voids in the matrix. Figure 4.16 (b) shows the effects of wood fiber content on the water absorption capacity of cementitious materials, and Figure 4.16 (c) shows the relationship between water absorption and density of autoclaved wood fiber reinforced composites reinforced with P. Radiata kraft pulp. From Figure 4.16 (b) it is clear that the water absorption of the composite increases as the fiber content increases. It can be concluded from Figure 4.16 (c) that density decreases and water absorption increases as the fiber content of the composite increases. The overall density of the composite reflects the changing proportions of the constituent fibers and the matrix. However, the void volume of the composite also increases, but in a non-linear fashion, as the fiber content increases and the fibers pack less efficiently.



(a) Density Vs. Fiber Content

(b) Water Absorption Vs. Fiber Content

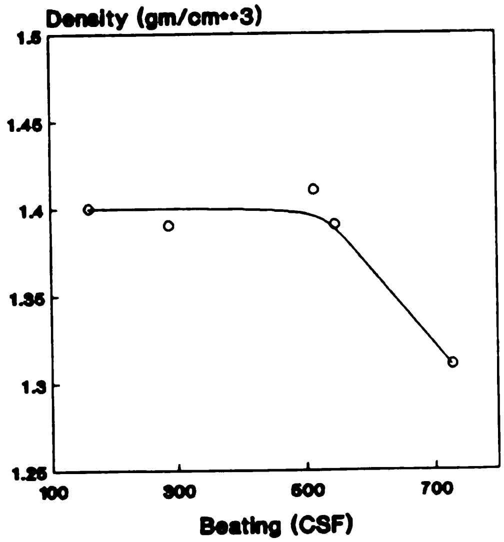
Figure 4.16 Density and Water Absorption of Cement Composites Reinforced with P. Radiata Kraft Pulp [32].



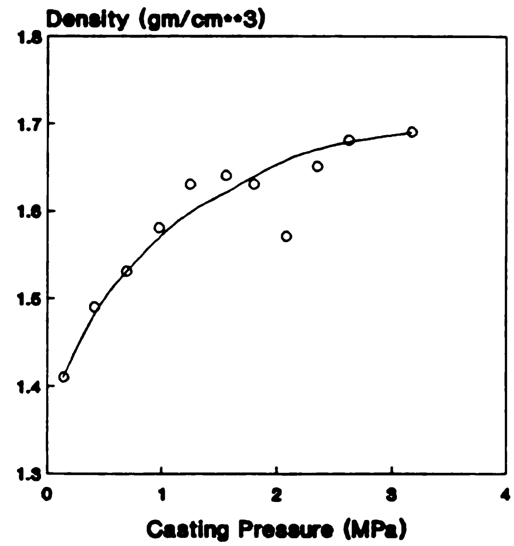
(c) Density Vs. Water Content

Figure 4.16 (cont'd) Density and Water Absorption of Cement Composites Reinforced with P. Radiata Kraft Pulp [32].

Coutts (1984) [13] and Coutts et al. (1990) [37] have also studied the effect of beating and casting pressure, respectively, on density of wood fiber reinforced cement composites. It has been found that composites incorporating unbeaten fibers show lower value of density compared to beaten fibers (Figure 4.17 a). Higher beating level increase the density of composites, probably due to the increase in fines, generated by beating, which allows close packing of the fibers and matrix and hence less voids in the composite. Figure 4.17 (b) shows the variation of density with change in casting pressure. There is a rapid increase in density as higher casting pressure are employed. This is due to reduction in voidage with increasing casting pressure.



(a) Beating Vs. Density



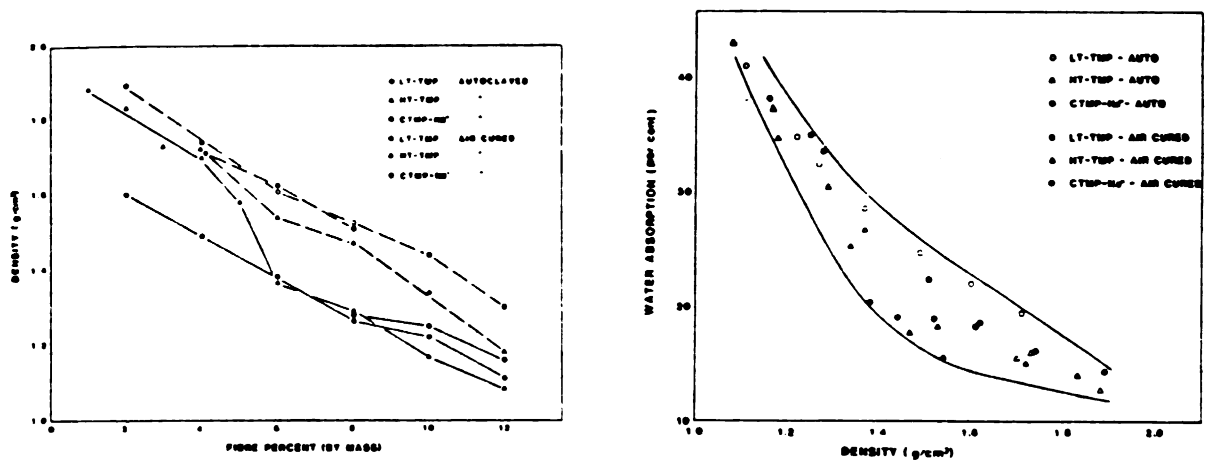
(b) Casting Pressure Vs. Density

Figure 4.17 Effects of Beating and Casting Pressure on Density of Cement Composites Reinforced with P. Radiata Kraft Pulp [13, 37].

Coutts (1986) [19] has reported on the density and water absorption characteristics of composites reinforced with thermomechanical and chemithermomechanical pulps. Figure 4.18 (a) and (b) present the relationship between water absorption, density and fiber content. High-temperature thermomechanical fibers do not pack as efficiently, at high fiber loadings as low-temperature thermomechanical and chemithermomechanical fibers. It can be observed in Figure 4.18 (a) for autoclaved high-temperature thermomechanical fiber-cement composites that the density of 1.83 gm/cm^3 (114 lb/ft^3) at 2% fiber content by mass drops to 1.08 gm/cm^3 (67 lb/ft^3) at 12% fiber content. For comparable loadings of 2 and 12% (by mass) of low-temperature thermomechanical fibers, the values are 1.60 gm/cm^3 (100 lb/ft^3) and 1.11 gm/cm^3 (69 lb/ft^3), respectively. These values are approximately similar to that of composites reinforced with unbeaten P. Radiata kraft fiber (densities of 1.65 gm/cm^3 and 1.19 gm/cm^3, 103 lb/ft^3 and 74 lb/ft^3, at 2% and 12% fiber contents by mass). However, mortars reinforced with kraft fiber show slightly higher values (densities of 1.69 gm/cm^3 and 1.30 gm/cm^3, 105 lb/ft^3 and 81 lb/ft^3, at 2% and 12% fiber mass fractions, respectively), indicating a better packing of these flexible fibers within the matrix.

The density of air cured fiber cements displays similar tendencies. High-temperature thermomechanical fiber composites have densities in the range of 1.72 gm/cm^3 to 1.18

gm/cm^3 (107 to 74 lb/ft^3) for samples containing 4 to 12% fiber (by mass), respectively; however low-temperature thermomechanical fiber cements over the same fiber range have densities between 1.74 gm/cm^3 to 1.38 gm/cm^3 (109 to 86 lb/ft^3), and again indicate more effective packing of fibers and hence greater values of density. Associated with the changes in density are changes in water absorption (Figure 4.18 b), which in turn are dependent upon the void volume of the composite. There is considerable variation between the water absorption and density values of samples containing either high-temperature thermomechanical or low-temperature thermomechanical fibers as the fiber content is changed, where as the relationship between water absorption and density does not vary to the same extent.



(a) Density Vs. Fiber Content (b) Water Absorption Vs. Density

Figure 4.18 Relationship between Water Absorption, Density and Fiber Content of Composites Containing Thermomechanical and Chemithermomechanical Pulps [19].

Coutts (1983) [33] has reported test results on water absorption and density for autoclaved composites containing New Zealand Flax fibers. These composites like other wood fiber reinforced cement composites show that the density decreases and water absorption increases as the fiber content of the composite increases. The amount of water absorbed by the wood fiber reinforced cement composites depends on their densities as shown in Figure 4.19. The overall density of the composite reflects the changing proportions of the constituent fibers and matrix.

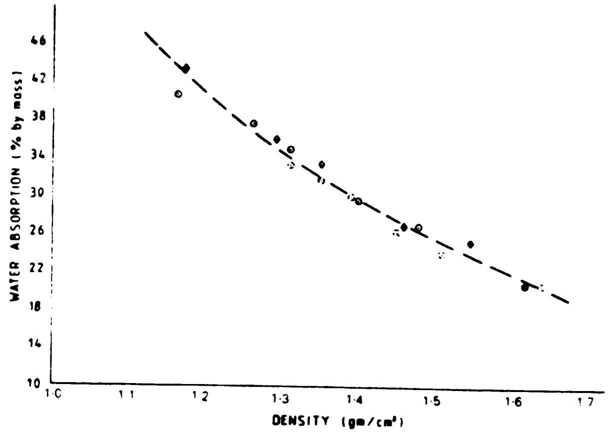


Figure 4.19 Relationship between Water Absorption and Density for Composites Containing New Zealand Flax Fibers [33].

Coutts et al. (1987) [30] have reported test results on the density and water absorption for air cured Abaca reinforced cement composites (Figure 4.20). Both the overall density and the water absorption of composites are dependent upon the relative proportions of the constituent fibers and matrix. The results are very similar to those obtained for composites reinforced with P. Radiata kraft pulp.

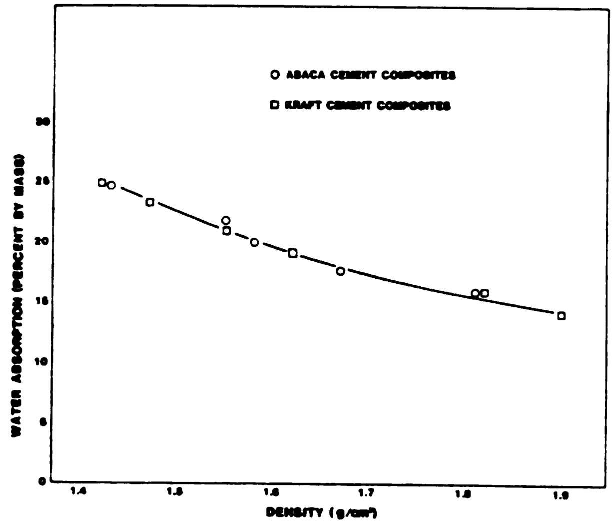


Figure 4.20 Relationship between Water Absorption and Density for Composites Containing Abaca Fibers [30].

Coutts (1987) [32] finally concludes that the differences in the curing process have a much greater influence on the physical properties than the choice of reinforcing wood fiber. The variation in physical properties could be associated with rapid formation of the matrix in autoclaved samples, with no further change in physical state, compared to the slow hydration reactions taking place during air curing. In the latter case liberated calcium hydroxide can migrate into the voids between matrix particles, reducing the porosity of composites which leads to reduced water absorption and increased density of the composites.

4.3.2.2 Moisture Movement

Moisture movement in wood is much greater than temperature movement [38], and hence much more significant when considering changes in properties. Moisture movement studies on wood fiber-cement composites has been reported by Sharman et al. (1986) [38]. The experiment consisted of measuring linear dimensional changes of square panel specimens from oven dry to saturation condition. For achieving saturation the specimens were soaked in water at 20 deg. C (68 deg. F) for 24 hours. The specimens were then oven dried at 105 deg. C (221 deg. F) for 24 hours, cooled in a desiccator and the measurements were taken to the nearest 0.025 mm (0.001 in) using a strain bridge in both saturated and oven dried conditions.

The test results on composites containing 8% wood fibers indicate moisture movement ranges from 0.3 to 0.5%. The information in commercial manufacturer's literature [10, 11, 12] provide moisture movement values similar to the results obtained by Sharman et al. (1986) [38].

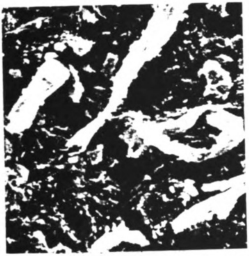
4.3.2.3 Thermal Expansion and Fire Resistance

Much of the information available on thermal conductivity, thermal expansion and fire resistance of wood fiber reinforced cement composites are through manufacturer's literature [10, 11, 12]. The coefficient of thermal conductivity of these composites (ASTM C518) ranges from 1.3 to 1.8 Btu.in/hr.ft^2.deg.F, and the coefficient of thermal expansion (68 -212 deg. F, ASTM B 95) ranges from 3.9 to 6.0 x 10^{-6} in/in, deg.F. A continuous maximum temperature of 250 -500 deg. F is recommended for wood fiber reinforced cement composites.

Fire resistance of wood fiber reinforced cement composites is based on surface burning characteristics and combustibility. Manufacturer's literature [10, 11, 12] reports zero flame spread and zero smoke development, and are classified as non-combustible according to ASTM E 136.

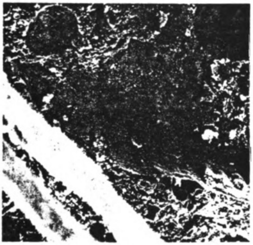
4.3.3 Microstructural Observations

Results of Scanning Electron Microscopic analysis of wood fiber-cement composites have been reported by Davis et al. (1981) [18], Coutts et al. (1984) [20], Coutts et al. (1982) [25], Coutts (1987) [26] and Morissey et al. (1985) [40]. The flexural failure planes of cement composites reinforced with P. Radiata kraft pulp, thermomechanical pulp untreated and treated (soaked in a solution of Na_2SO_3) chemithermomechanical pulps were observed under scanning electron microscope by Davis (1981) [18]. Typical fracture surface micrographs of cement composites containing kraft pulp and surface treated chemithermomechanical pulps are presented in Figures 4.21 (a) and (b). The projected kraft pulps are observed to be ribbon like (collapsed) and flexible, but the projected fibers of modified chemithermomechanical pulps have maintained their lumen configuration and appeared to be quite stiff. This indicates that the kraft pulps do not swell in the alkaline environment of cementitious matrices. Both Figures 4.21 (a) and (b) show fiber pullout as well as fracture of fibers occurring at the failure plane (the holes in the matrix in these figures are indicative of fiber pullout). In the case of untreated chemithermomechanical pulps (Figure 4.21 c and d), however, fiber pullout dominated the performance, which means lower adhesion between matrix and fiber. The bond could have been damaged by the extractives bleached from the thermomechanical pulps by the alkali of cementitious matrix, resulting in weakening of cement; on the other hand, the better bonding of surface treated chemithermomechanical pulps could simply be the direct result of the chemical compatibility of the treated fiber surfaces with the cementitious matrix.



(a) Kraft Pulp (100x)

(b) Chemithermomechanical Pulp Treated with Surface Reagent (20x)



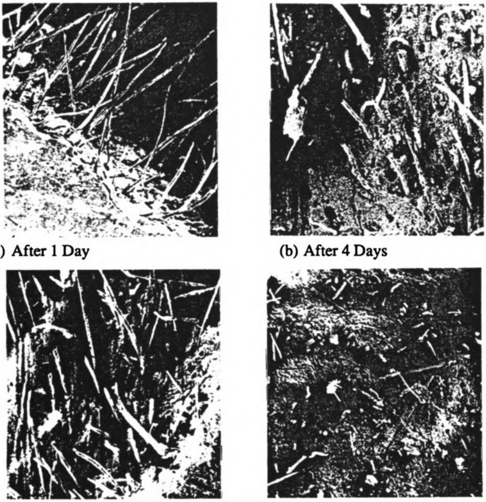
(c) Chemithermomechanical Pulp (300x)

(d) Chemithermomechanical Pulp (20x)

Figure 4.21 Micrographs of the Composite Fracture Surfaces [18].

Wood fibers when tested individually do not normally break cleanly, but usually separate between layers of secondary wall. When incorporated in cement, however, the fracture tends to be relatively clean, which indicates that chemicals from the cement matrix enter the fibers (when the mixture is fresh), and cause further internal bonding within the fibers, resulting in a clean rupture.

Fresh cementitious matrices have relatively high moisture content and they gradually dry as the cement cures. Figures 4.22 (a), (b), (c) and (d) show micrographs of the flexural fracture surfaces of cement composites reinforced with chemithermomechanical pulps at ages of 1, 4, 7 and 90 days, respectively. After 1 day the composite still is very wet and the bond is incomplete; hence, most of the fibers are loosely held and tend to pull-out completely (Figure 4.22 a). After 4 and 7 days it can be seen in Figures 4.22 (b) and (c), respectively, that some of the fibers pullout completely, but many break somewhere along their length, indicating improved bonding between wood fibers and the matrix. After 90 days, Figure 4.22 (d) indicates that most of the fibers tend to rupture close to the composite fracture surface; this phenomenon decreases the toughness of composites at later periods [18].



(a) After 1 Day

(b) After 4 Days

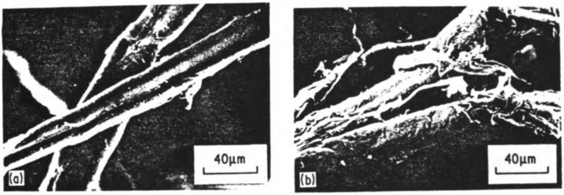
(c) After 7 Days (7x)

(d) After 90 Days (10x)

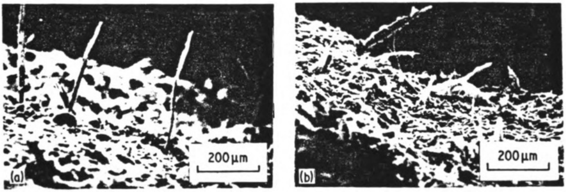
Figure 4.22 Fracture Surfaces of Cement-Based Matrices Reinforced with Chemithermomechanical Pulp [18].

Coutts et al. (1982) [25] has reported the results of microstructural studies performed on autoclaved cement composites reinforced with refined kraft pulp. This study was undertaken to resolve the problems with earlier contradictory reports of Campbell et al. (1980) [28] and Andonian et al. (1979) [34] about the dominance of fiber pullout versus fracture of fibers in deciding the failure mechanism of autoclaved wood fiber reinforced cements and mortars under flexural loads. The composites were prepared by Coutts et al. (1982) [25] from P. Radiata kraft with different degrees of beating (703 and 442 CSF) using the slurry-dewatering process followed by autoclaving. The specimens were conditioned at 50 $\pm$ 5% relative humidity and 22 $\pm$ 2 deg. C (72 $\pm$ 3 deg. F), and were then tested in flexure on a span of 100 mm (3.94 in). The composite specimens of this study had relatively low fiber contents to facilitate microstructural studies by the Scanning Electron Microscope.

Typical micrographs of the fracture surfaces of composites incorporating 1% weight fraction of unrefined (703 CSF) and refined (442 CSF) kraft pulps are shown in Figures 4.23 (a) and (b), respectively. Some fiber pullout is evident in Figure 4.23 (a) for unrefined fibers although fiber fracture has predominated, and Figure 4.23 (b) clearly shows more fiber fracture with minor fiber pullout in the case of refined fibers. A more critical examination of the fracture surface for the two matching sides of the composite containing beaten fibers in Figure 4.23 (c) indicates that considerable damage has been rendered to the fibers that have been pulled out. Fiber A in Figure 4.23 (c) is firmly attached to the walls of the hole in the matrix from which it has been pulled out. Fiber B is encrusted with the matrix and this suggests that the heterogenous matrix failed in shear at a flaw before sufficient stress could be exerted on the fiber to cause debonding at the interface or fiber fracture. Fiber C was lying at an angle to the plane of the advancing crack and has been subjected to shear stresses which cause fracture between different layers of the fiber. It should be noted that the composites discussed here had 1% fiber weight fraction, which is not sufficient for achieving desirable toughness characteristics.



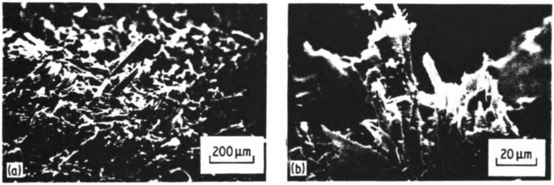
(a) Unbeaten Fiber (b) Beaten Fiber



(c) Two Matching Surfaces with Unbeaten Fibers

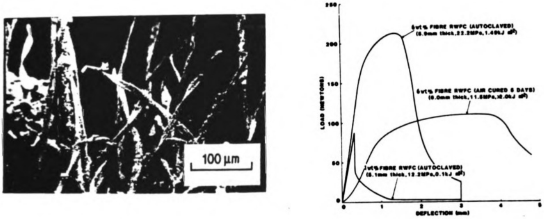
Figure 4.23 Typical SEM Micrographs of the Fracture Surfaces for Autoclaved Composites Reinforced with 1% Weight Fraction of P. Radiata Kraft Pulp [25].

Coutts et al. (1982) [25] have also performed microstructural studies on autoclaved cement composites having a more typical fiber content of 6% by weight. Refined P. Radiata kraft pulp was used in this study and, as shown in Figure 4.24 (a), fiber fracture dominated the failure mechanism. The fractured fiber ends are shown at a higher magnification in Figure 4.24 (b). Coutts et al. (1982) [25] have also performed an investigation on air cured composites rather than autoclaved ones), noting that air curing gives a weaker matrix with 11.5 MPa (1656 psi) flexural strength when compared with the 22.3 MPa (3211 psi) flexural strength obtained after autoclaving. The air cured composites showed almost total pullout and very few fractured fibers, as shown in Figure 4.25 (a). The air cured composites showed low flexural strengths but relatively desirable toughness characteristics associated with fiber pullout (see Figure 4.25 b).



(a) Lower Magnification (b) Higher Magnification

Figure 4.24 Typical SEM Micrographs of Autoclaved Cement Composites Incorporating 6% Mass Fraction of P. Radiata Kraft Pulp [25].



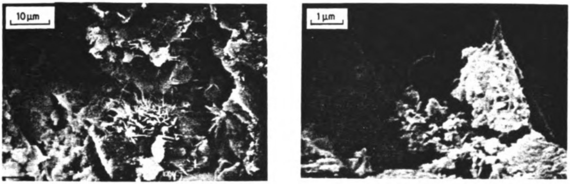
(a) Fracture Surface (b) Flexural Load Deflection Curve

Figure 4.25 Fracture Surface and Flexural Performance of Air Cured Cement Composites Reinforced with 6% Mass Fraction of P. Radiata Kraft Pulp [25].

Coutts et al. (1982) [25] have also hinted at the possibility of damage to fibers during fabrication (which could cause some pulled out fibers to look like fractured ones), and have concluded that the dual mechanisms of fiber pullout and fracture take place in cement composites reinforced with wood fibers. The dominance of fiber fracture or pullout would depend on the curing condition and moisture content of specimens. Curing in autoclave and reducing the moisture content led to increased possibility of fiber fracture [18, 24, 25].

Coutts (1987) [26], based on the examination of the SEM micrographs of wood fiber-cement fractured surfaces, has concluded that the general characteristics normally associated with the interfaces of fiber reinforced cement composites are not applicable to wood fiber cements. Wood fibers have a unique structure which differs substantially from the homogenous, dense and non-compressible glass and steel fibers or aggregates. Wood fibers are hollow and may collapse to varying degrees depending on the fiber wall thickness and the pulping technique used in the manufacture of fibers. They also have a much greater capacity to be deformed by compression. The individual wood fibers are themselves composites composed mainly of cellulose microfibrils which are cemented together by non cellulosic components.

In the case of wood fiber reinforced cement composites, both chemical and mechanical bonds are important [20, 32]. The curing of cement matrices is primarily due to the hydration of tri, di-calcium silicates, which leads to hardening mainly through the formation of calcium silicate hydrate (C-S-H) which renders the hydrating cement paste its strength characteristics. Figure 4.26 (a) shows the C-S-H crystals growing in a void in air cured cement. When wood fibers are present, the hydration products can interlock with the microfibrils exposed at fiber surfaces and produce desirable fiber-matrix mechanical bonding (Figure 4.26 b). This phenomenon would obviously be pronounced in the case of refined fibers with a higher degree of microfibril protrusions [26].

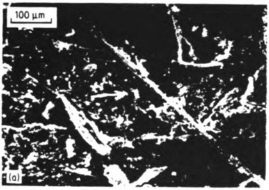


(a) Growth of CSH in a Void in Cement

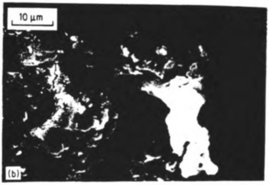
(b) Mechanical Interlocking of Microfibrils and Growing Cement Hydration Products

Figure 4.26 Development of Cement Hydration Product and Their Mechanical Interlocking with Wood Fiber Microfibrils [26].

A fracture surface of an air cured cement composite reinforced with kraft pulp is shown in Figure 4.27 (a), and at a higher magnification in Figure 4.27 (b). The specific fiber under consideration in these micrographs seems to have fractures. Close examination of the matrix in the vicinity of fiber in Figure 4.27 (b) suggests that the interface zone, unlike that around glass and steel fibers or aggregates, is rather dense. Although discontinuity may occur at higher fiber loadings when normal packing of the fibers becomes more difficult (Figure 4.27 c), still no obvious fiber-matrix interface zone can be distinguished from bulk of cement paste (Figure 4.27 d). A possible explanation for this observation is that during fabrication of wood fiber cement composites by the slurry-dewatering technique the material is subjected to pressure for compaction and lowering of its water-cement ratio. The compressible wood fibers would be compressed under pressure, but following the removal of pressure a sponge like fiber draws the surrounding water into itself. This would lower the porosity of the interface by reducing its water content, and would lead to the formation of a homogenous and dense interface zone [26].

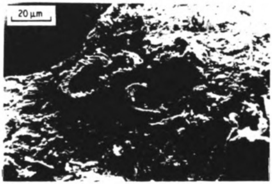


(a) Fracture Surface at Low Magnification



(b) Higher Magnification Presentation of the Interface

(c) Interface with Some Discontinuity



(d) Dense Structure of the Interface

Figure 4.27 Interface Zone Characteristics in Air-Cured Cement Composites Reinforced with Kraft Pulps [26].

4.4 EXPERIMENTAL DESIGN

The main emphasis in this phase of the research was to establish the reinforcing action of wood fibers in cement matrix. In order to achieve this objective, the following steps were taken: (a) selection and characterization of different wood fiber types; (b) assessment of the mechanical and physical properties of wood fiber-cement composites; (c) optimization of the fiber mass fraction in different manufacturing conditions; (d) modification of the matrix with pozzolanic admixtures and latex; (e) Investigation of the bleaching effects; (f) modification of the processing (manufacturing) parameters; (g) combination of wood fibers with synthetic fibers; and (h) comprehensive statistical investigation of the effects of different parameters specific to wood fiber reinforced composites.

Replicated test specimens were manufactured from each mix in order to derive reliable conclusions through statistical analyses of results. The dimensions and the number of specimens depend on the specific tests performed. In case of panels, the test specimen had to be cut using a diamond saw to the required dimensions.

4.4.1 Characterization of Different Wood Fiber Types

A variety of wood fiber types were selected and characterized for cement applications. An attempt was made to cover a large variety of commercially available wood fiber types to make the final results as conclusive as possible. The wood fibers selected for this investigation were: Southern Softwood Kraft (SSK) [41], Northern Hardwood Kraft (NHK) [42], and Mechanical Pulp (1000L) [43]. Some key properties of these wood fibers are presented in Table 4.1. A series of experiments were then performed on the selected wood fiber types to assess their length distribution, moisture content and regain (ASTM D 1348), water solubility (TAPPI T 207), and durability in alkaline environment.

Table 4.1 Properties of Wood Fibers [41, 42, 43]

Brand Name	Type	Species	Average Length (mm)	Canadian Standard Freeness
1000L	Mechanical	Softwood	8.0	-
SSK	Kraft	Softwood	3.0	700
NHK	Kraft	Hardwood	0.9	500

4.4.2 Mechanical and Physical Properties of Molded Wood Fiber-Cement Composites

An experimental program was designed to establish the reinforcing ability of wood fibers in cement-based matrices processed by the molding technique. It should be noted that the molding is applicable only at relatively low fiber contents. The wood fibers used in this investigation were: Southern Softwood Kraft (SSK) [41], Northern Hardwood Kraft (NHK) [42], and Mechanical Pulp (1000L) [43]. The cementitious matrices used in this study were neat cement paste consisting simply of regular Portland cement Type I and tap water. The fiber mass fractions and matrix mix proportions are given in Table 4.2. The water content was adjusted (increased with fiber content) in order to maintain the fresh mix workability at a reasonable practical level represented by a flow (ASTM C 230) of 65 ± 5% at one minute after mixing. The values of flow at 1 minute are also presented in Table 4.2. Three replicated flexural, compression and impact test specimens were manufactured from each mix using molding method. The flexural specimens were prisms with 38.1 mm (1.5 in) square cross section and total length of 152.4 mm (6 in), tested by 4-point loading on a span of 114.3 mm (4.5 in). The compression test specimens were cylinders 76.2 mm (3 in) in diameter and 152.4 mm (6 in) high. The cylindrical impact specimens were 152.4 mm (6 in) in diameter and 63.5 mm (2.5 in) high.

Table 4.2 Fiber Mass Fractions and Matrix Mix Proportions - Wood Fiber-Cement Composites

Fiber Type	Fiber Mass Fraction (%)	Water-Cement Ratio	Flow (%)
-	0	0.28	66
Softwood Kraft Pulp (SSK)	1	0.35	65
	2	0.40	62
Hardwood Kraft Pulp (NHK)	1	0.35	63
	2	0.40	62
Mechanical Pulp (1000L)	1	0.35	74
	2	0.40	66

4.4.3 Optimization of Fiber Content in Molding and Slurry-Dewatering Processes

The wood fibers used in this investigation were Southern Softwood Kraft (SSK) [41] and Mechanical Pulp (1000L) [43]. Optimization of fiber mass content was done in two stages: (a) for composites containing low fiber content ($\leq 2\%$) manufactured through molding method; and (b) for composites containing high fiber content ($\geq 4\%$) manufactured through slurry-dewatering. The matrix contained equal amounts of cement and silica sand (particle size 0.15 to 0.6 mm, 0.006 to 0.024 in). The fiber mass fractions and matrix mix proportions used in this phase of the study are introduced in Table 4.3. In the molding method of manufacture, water and superplasticizer [44] contents were varied in order to achieve reasonable fresh mix workability characteristics represented by a flow (ASTM C-230) of 55% to 65% at 1 minute after mixing. Fibrous mixtures also contained non-chloride set accelerator [45], which was essential to keep the setting time of the composites within acceptable limits. In the slurry-dewatering method of manufacture, thin-sheet specimens were formed from a dilute slurry of approximately 20% solids. A relatively small dosage of 1% diluted flocculent (flocculent/cement=0.001) [46] was added to achieve agglomeration of cement solids in the slurry, which helps in reducing the amount of cement particles lost through the filtering screens during dewatering. Fiber mass fraction, in the slurry-dewatering method of manufacture is defined as the ratio of fibers to the dry constituents of the matrix by weight. From each mix wood fiber reinforced cement composites were manufactured for flexural testing in the hardened state. Molded flexural specimens were prisms with 38.1 mm (1.5 in) square cross sections and total length of 152.4 mm (6 in), tested by 4-point loading on a span of 114.3 mm (4.5 in). An average of 10 specimens with a specific mix design were manufactured and tested from two different batches in order to accurately measure the variability of results. Thin sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method at higher fiber contents. Flexural specimens (38.1 x 125 x 10 mm, 1.5 x 5.0 x 0.4 in) were then cut out from each panel using a diamond saw, and an average of 3 specimens were tested for flexural performance.

Table 4.3 Fiber Mass Fractions and Matrix Mix Proportions - Optimization of Wood Fiber Content

(a) Molding Method

Fiber Type	Fiber Mass Fraction (%)	Sand-Cement Ratio	Water-Cement Ratio	Set Accelerator-Cement Ratio	Superplasticizer-Cement Ratio	Flow (%)
-	0	1	0.30	-	-	58
Kraft (SSK)	1	1	0.35	0.02	0.01	58
	2	1	0.43	0.02	0.02	48
Mech. (1000L)	1	1	0.30	0.02	0.01	64
	2	1	0.30	0.02	0.02	59

(b) Slurry-Dewatering Method

Fiber Type	Fiber Mass Fraction (%)	Sand-Cement Ratio	Flocculent-Cement Ratio	Water
Kraft (SSK)	4	1	0.001	80% of total quantity of mix ingredients by weight
	6	1	0.001	
	8	1	0.001	
	10	1	0.001	
	12	1	0.001	
	14	1	0.001	

4.4.4 Matrix Modification

The fiber used in this study was Southern Softwood Kraft (SSK) [41]. The samples contained an optimum fiber content (2% for molding method and 8% for slurry dewatering method). The matrix modification was achieved through partial substitution of cement with pozzolanic admixtures (15% silica fume or 30% fly ash). In case of molding technique it was also considered to modify the matrix through latex polymer [47]. The fiber mass fraction and matrix mix proportions are introduced in Table 4.4. From each mix wood fiber reinforced cement composites were manufactured for flexural testing in the hardened state. Molded flexural specimens were prisms with 38.1 mm (1.5 in) square cross sections and total length of 152.4 mm (6 in), tested by 4-point loading on a span of 114.3 mm (4.5 in). An average of 10 specimens with a specific mix design were manufactured and tested from two different batches in order to accurately measure the variability of results. Thin-sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method at higher fiber contents. Flexural specimens (38.1 x 125 x 10 mm, 1.5 x 5.0 x 0.4) were then cut out from each panel using a diamond saw, and an average of 3 specimens were tested for flexural performance.

Table 4.4 Fiber Mass Fractions and Matrix Mix Proportions - Matrix Modification

(a) Molding Method

Fiber Type & Content	Binder	Sand-Binder Ratio	Water-Binder Ratio	Superplasticizer-Binder Ratio	Set Accelerator-Cement Ratio	Latex-Binder Ratio	Flow (%)
Kraft (SSK) 2% by Weight	Cement : Silica Fume = 85 : 15	1	0.43	0.03	0.02	-	55
	Cement : Fly Ash = 70 : 30	1	0.35	0.02	0.02	-	55
	Cement	1	0.4	-	0.02	0.1	61

(b) Slurry-Dewatering Method

Fiber Type & Content	Binder	Sand-Binder Ratio	Flocculent-Binder Ratio	Water
Kraft (SSK) 8% by Weight	Cement : Silica Fume = 85 : 15	1	0.001	80% of total quantity of mix ingredients by weight
	Cement : Fly Ash = 70 : 30	1	0.001	

4.4.5 Effect of Bleaching

The fibers used in this study were unbleached and bleached Southern Softwood Kraft (SSK) [41]. The composites were manufactured using molding technique and the fiber content was 2% by mass. The matrix mix proportions used in this study are given in Table 4.5. From each mix wood fiber reinforced cement composites were manufactured for flexural testing in the hardened state. Molded flexural specimens were prisms with 38.1 mm (1.5 in) square cross sections and total length of 152.4 mm (6 in), tested by 4-point loading on a span of 114.3 mm (4.5 in). An average of 10 specimens with a specific mix design were manufactured and tested from two different batches in order to accurately measure the variability of results.

Table 4.5 Fiber Mass Fractions and Matrix Mix Proportions - Effect of Bleaching

Fiber Type	Fiber Mass Fraction (%)	Sand-Cement Ratio	Water-Cement Ratio	Set Accelerator-Cement Ratio	Superplasticizer-Cement Ratio	Flow (%)
2% Kraft (SSK) Bleached	2	1	0.43	0.02	0.02	48
2% Kraft (SSK) Unbleached	2	1	0.43	0.02	0.02	51

4.4.6 Modification of Processing Parameters in Slurry-Dewatering Technique

The fiber used in this study was Southern Softwood Kraft (SSK) [41]. Two different fiber contents (8% and 16%) were used in this study. The matrix contained equal amounts of cement and silica sand. The processing parameters considered in this study were casting pressure (1.6 and 3.2 MPa, 232 and 464 psi) and pressing time (1 hour and 24 hours). The matrix mix proportions used in this study are presented in Table 4.6. Two replicated thin-sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method. Specimens for flexural testing (38.1 x 125 x 10 mm, 1.5 x 5.0 x 0.4 in) were then cut using a diamond saw. An average of 6 specimens with specific mix design were selected from two different batches in order to accurately measure the variability of results.

Table 4.6 Fiber Mass Fractions and Matrix Mix Proportions - Modification of Slurry-Dewatering Processing Parameters

Fiber Type	Fiber Mass Fraction (%)	Sand-Cement Ratio	Flocculent-Cement Ratio	Water	Casting Pressure (MPa)	Pressing Time (hr)
Kraft (SSK)	8	1	.001	80% of total quantity of mix ingredients by weight	1.6 1.6 3.2 3.2	1 24 1 24
	16	1	.001		1.6 1.6 3.2 3.2	1 24 1 24

4.4.7 Combination with Synthetic Fibers

The fibers used in this study were Southern Softwood Kraft (SSK) [41] and Polyethylene Pulp (PulPlus) [48]. The composites were manufactured using slurry-dewatering technique, and the combined fiber content was kept at an optimum value of 8% by mass. The matrix mix proportions used in this study are presented in Table 4.7. Two replicated thin-sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method. Specimens for flexural testing (38.1 x 125 x 10 mm, 1.5 x 5.0 x 0.4 in) were then cut using a diamond saw. An average of 6 specimens with specific mix design were selected from two different batches in order to accurately measure the variability of results.

Table 4.7 Fiber Mass Fractions and Matrix Mix Proportions - Combination with Synthetic Fibers

Fiber Mass Fraction (%)		Sand - Cement Ratio	Flocculent - Cement Ratio	Water
Kraft Pulp (SSK)	Polyethylene Pulp (PulPlus)			
8	0	1	0.001	80% of total quantity of mix ingredients by weight
4	4	1	0.001	
0	8	1	0.001	

4.4.8 Comprehensive Statistical Study of Different Parameters and their Effects

An experimental program was developed based on the statistical method of fractional factorial design. The composites were manufactured using slurry-dewatering technique. The variables of the experimental study were: (1) wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash & 15% silica fume); and (4) silica sand content (silica sand-cement ratio = 0.5 & 1.0). The fiber mass fractions and matrix mix proportions are given in Table 4.8. Two replicated thin-sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method. The panel specimens were then tested for specific gravity, water absorption and moisture movement

Table 4.8 Fiber Mass Fractions and Matrix Mix Proportions - Comprehensive Statistical Study (see Appendix B for notation)

Mix	1	2	3	4	5	6	7	8
Fiber Type	SSK	NHK	NHK	NHK	NHK	NHK	NHK	SSK
Fiber Content (%)	8	8	8	4	8	4	8	4
Binder	SF	FA	SF	FA	SF	FA	FA	FA
Batch	1	2	1	1	2	2	1	2
Sand Content (S/B)	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0

Mix	9	10	11	12	13	14	15	16
Fiber Type	SSK	SSK	NHK	NHK	SSK	SSK	SSK	SSK
Fiber Content (%)	8	4	4	4	8	8	4	4
Binder	FA	SF	SF	SF	FA	SF	SF	FA
Batch	1	1	1	2	2	2	2	1
Sand Content (S/B)	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5

4.5 MANUFACTURING PROCEDURE

Wood fiber reinforced cement composites at low fiber contents ($\leq$ 2%) were manufactured through molding method, and at high fiber contents (> 2%) through slurry-dewatering method. In the molding method, mixing was performed in a regular mortar mixer. A batch-type slurry-dewatering equipment (simulation of the Hatschek process) was developed for use in the laboratory. The mixing procedure adopted for the two different techniques are described below.

4.5.1 Molding Method

This method of wood fiber-cement manufacture involves mixing of mix constituents in a mortar mixer and compacting inside molds through external vibration. The water content should be kept low in order to ensure desirable hardened material properties. The kraft pulps (SSK and NHK) are generally shipped in the form of relatively compact sheets, and have to be disintegrated in water using a mortar mixer (at 450 revolutions per minute) before being added to the mixture; otherwise, a uniform dispersion of fibers inside the cementitious paste can not be achieved conveniently. No disintegration prior to mixing was necessary for the 1000L mechanical pulp.

The mixing procedure for the manufacture of wood fiber reinforced cement in a regular mortar mixer was as follows: (1) Add cement, sand and 70% of water and mix at low speed (140 RPM) for about 1 minute or until a uniform mixture is achieved; (2) turn the mixer to medium speed (285 RPM) and gradually add the fibers and the remainder of water and superplasticizer (if used) and mix for 2-5 minutes depending on the fiber content, taking care that no fiber balls are formed; (3) Add the set accelerator (if used) and mix for 1 minute at medium speed; and (4) Stop the mixer and wait for 1 minute, and then finalize the process by mixing at high speed (450 RPM) for 2 minutes.

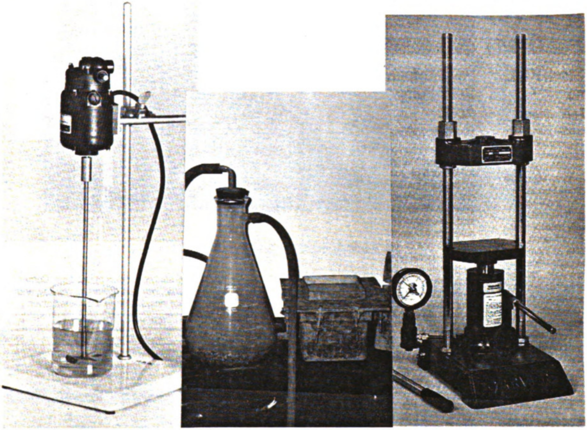
All the fibrous specimens were compacted through external vibration, and were kept inside their molds underneath a wet burlap covered with plastic sheet for 24 hours. They were then demolded and moist cured for 5 days before being air cured in a regular laboratory environment (40 - 50% RH and 23 deg. C, 73 deg. F, temperature) until the test age of 28 days.

4.5.2 Slurry-Dewatering

This method of wood fiber-cement manufacture involves mixing the constituents in a dilute slurry (about 20% solids of fiber-cement or fiber-mortar). The excess water was removed from the slurry through the application of suction and pressure.

The mixing procedure for the manufacture of wood fiber reinforced cement through slurry-dewatering (Figure 4.28) was as follows: (1) soak fibers in water for 24 hours and then disperse them using a high-speed mixer (1400 RPM) for 5 minutes; (2) add other mix constituents and continue mixing for 5 more minutes; (3) add small quantity of 1% diluted flocculent (flocculent/cement=0.01) to achieve agglomeration of cement solids in the slurry; this reduces the amount of cement particles lost through the filtering screens during slurry-dewatering; (4) pour the mixture into an evacuable casting box (125 mm x 125 mm, 5 x 5 x 0.4 in, in size) and distribute over the screen (with mild tamping) and apply vacuum of 60 KPag (8.7 psig) for 5 minutes; and (5) remove the sheet from the filter screen, store between two steel plates and apply a constant pressure of 3.2 MPa (464 psi) for 5 minutes or until all the remaining water was removed.

The sheets were covered with plastic for 24 hours and then moist cured for 5 days before being air cured in a regular laboratory environment until the test age of 28 days.



(a) Stirrer (b) Vacuum Box (c) Press

Figure 4.28 Laboratory Set-Up for the Manufacture of Wood fiber Reinforced Cement Composites.

(d) Photograph of the Set-Up

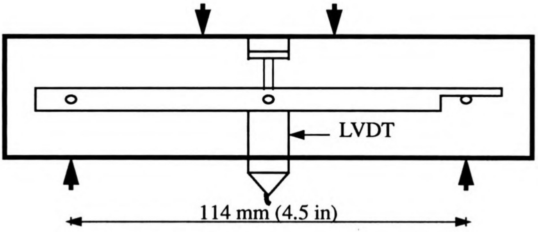
Figure 4.28 (cont'd) Laboratory Set-Up for the Manufacture of Wood fiber Reinforced Cement Composites.

4.6 TEST PROCEDURES

The fresh fibrous cement mixtures were tested for: (1) flow (ASTM C-230); (2) air content (ASTM C-185); and (3) setting time (ASTM C-403).

The flexural tests were performed according to the Japanese Standard Specification JCI-SF [49]. The Japanese method of measuring flexural deflections (Figure 4.29) is particularly effective in reducing errors associated with rigid body movements of the specimen and local deformations at the supports and loading points, which could be recorded as flexural deflections if measurements were performed with respect to reference points outside the specimen.

An important consideration in flexural tests performed on fiber reinforced cement composites is the measurement of energy absorption capacity, defined as the area underneath the load-deflection curve. The Japanese fixtures which monitor flexural deflections during the test give accurate results for energy absorption calculations. Flexural toughness according to the Japanese code JCI-SF4, is defined as the area underneath the flexural load-deflection curve up to a deflection equal to the span length divided by 150 (0.76 mm, 0.03 in, in this case).



(a) Japanese Standard Flexural Test Set-Up

(b) Photograph of Flexural Testing

Figure 4.29 Flexural Testing.

The compression tests were performed according to the Japanese code JCI-SF [49]; in this approach compressive toughness is defined as the area underneath the compressive load-deflection curve up to a strain at 0.0075.

In the flexural and compression tests, both load and deflection were monitored throughout the test in order to obtain complete load-deformation relationship.

The impact test was conducted following the procedure recommended by the ACI committee 544 [50]. In this test, a cylindrical specimen is subjected to repeated blows from a 4.54 Kg (10 lb) compaction hammer with a 457 mm (18 in) drop on a 63.5 mm (2.5 in) diameter hardened steel ball resting on the specimen. The number of blows required to cause the first visible crack on the top and to cause ultimate failure are both recorded.

The void content, specific gravity and water absorption of the hardened materials were also assessed using the broken flexure specimens (ASTM C-642 and ASTM C 1185).

Moisture movement test (ASTM C 1185) is used to determine the serviceability of composites in areas subjected to moisture changes. This test involves measuring the change in length of specimen (gage length of 100 mm, 4 in), subjected to a change in relative humidity from $30 \pm 2\%$ to $90 \pm 5\%$ (Figure 4.30). The dial gage comparator used for measuring length changes should be capable of taking the reading to the nearest 0.02 mm (0.001 in). Moisture movement is reported as percent change in length based on the lengths at 30 and 90% relative humidity.

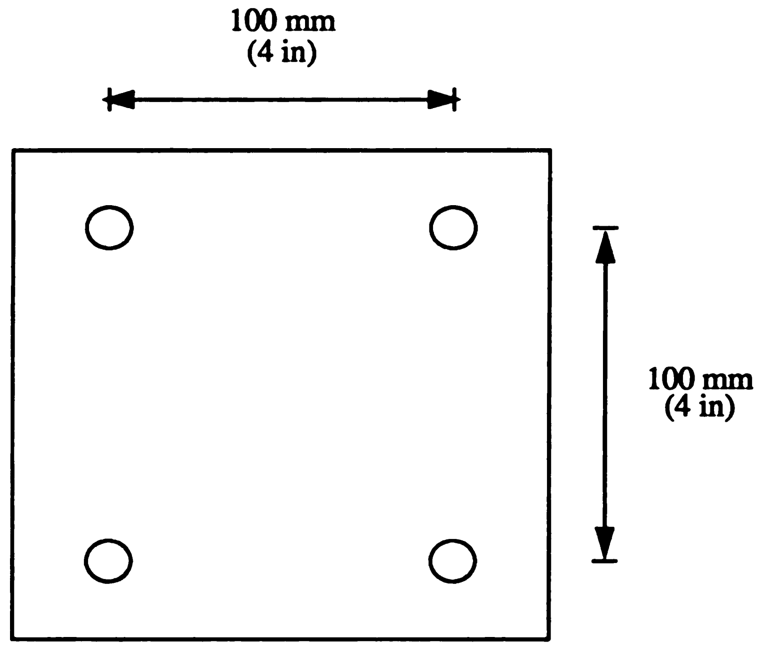


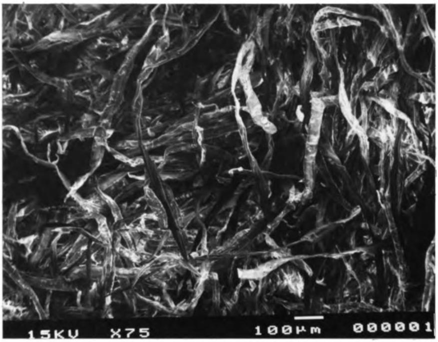
Figure 4.30 Moisture Movement Testing.

4.7 TEST RESULTS AND DISCUSSIONS

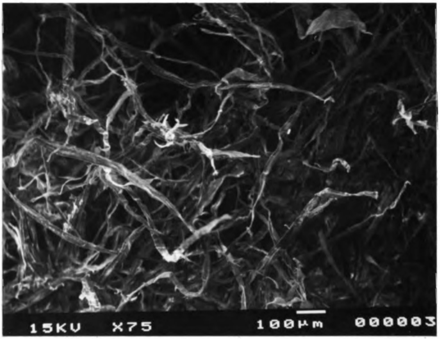
4.7.1 Characterization of Different Wood Fiber Types

Wood fiber length and diameter vary considerably even within the same tree species. Such variability can be easily matched by variability within a single tree. In order to make the final results as conclusive as possible, a variety of commercially available wood fibers were selected and characterized for cement applications. The wood fibers selected for this investigation were: Southern Softwood Kraft (SSK) [41], Northern Hardwood Kraft (NHK) [42], and Mechanical Pulp (1000L) [43].

Figure 4.31 presents typical micrographs of Southern Softwood Kraft Pulp (SSK), Northern Hardwood Kraft Pulp (NHK) and Mechanical Pulp (1000L) in conditions they were received. Surface characteristics of softwood and hardwood kraft pulps are similar and show clear separation of individual fibers due to the pulping process involved. Mechanical pulps, on the other hand, show no clear separation of individual fibers.



(a) Kraft Pulp (SSK)



(b) Kraft Pulp (NHK)

Figure 4.31 SEM Micrographs of Mechanical and Kraft Pulps.

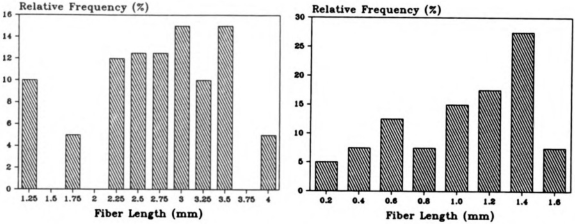
(c) Mechanical Pulp (1000L)

Figure 4.31 (cont'd) SEM Micrographs of Mechanical and Kraft Pulps.

Fiber length has important effects on the composite material properties. Fiber lengths were measured in this investigation using a stereo microscope and were statistically analyzed for their distribution. Table 4.9 presents average lengths, and corresponding standard deviations and coefficients of variation; Figure 4.32 shows fiber length distribution for Kraft (SSK) and Mechanical pulp (1000L). Softwood fibers used in this investigation were found to be much longer than hardwood fibers. The relatively large variation in fiber lengths observed for different fiber types is a particularity of wood fibers. This may actually be an advantage in the sense that different fiber lengths are more effective in enhancing specific aspects of cement material properties (e.g. shorter fibers may enhance strength better than the longer fibers which could be more effective in improving ductility).

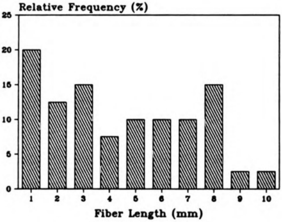
Table 4.9 Average Values and the Variations in Fiber Lengths

Fiber Type	Average Length (mm)	Standard Deviation (mm)	Coefficient of Variation (%)
Kraft (SSK)	2.89	0.73	25
Kraft (NHK)	1.06	0.43	41
Mechanical (1000L)	4.6	2.9	63



(a) Kraft Pulp (SSK)

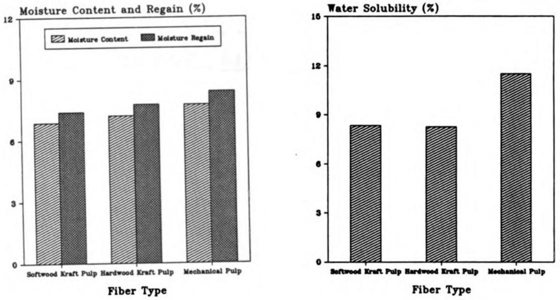
(b) Kraft Pulp (NHK)



(c) Mechanical Pulp (1000L)

Figure 4.32 Fiber Length Distribution of Mechanical and Kraft Pulps.

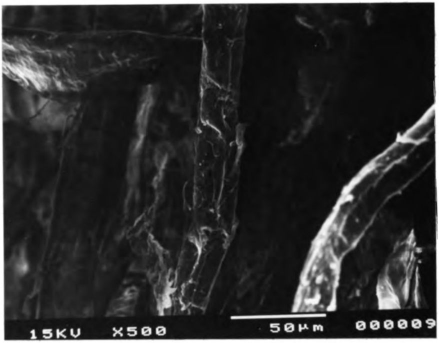
The moisture content and regain (ASTM C 1348) and water solubility (TAPPI T 207) test results for different wood fiber types are presented in Figure 4.33. High moisture content and regain values (of the order of 8%) were observed for all the fiber types. Affinity of wood fibers to moisture plays an important role in influencing fresh mix and hardened material properties of wood fiber-cement composites, noting that water plays a central role in deciding all these aspects of cementitious material properties. Water solubility of wood fibers is a concern during the addition of fibers to fresh cementitious matrices. High water solubility of mechanical pulps (1000L) damages the hydration process of cementitious matrix.



(a) Moisture Content and Regain (b) Water Solubility

Figure 4.33 Moisture Content and Water Solubility of Different Wood Fiber Types.

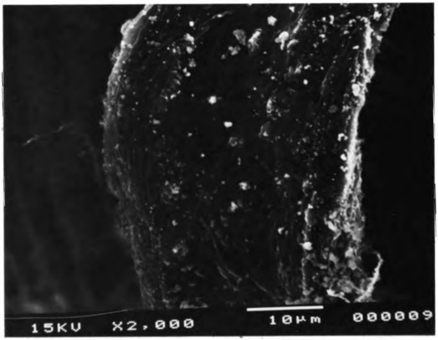
The pore water in cementitious matrix is highly alkaline. The durability of wood fiber-cement composite would thus partly depend on the strength loss of wood fibers following alkaline exposure. In order to study the durability of wood fibers in alkaline environment, Kraft pulp (SSK) was immersed in solutions of different alkalinity for one year and the change in surface characteristics were then observed using Scanning Electron Microscope (Figure 4.34). The alkaline solutions used in this study were water (pH = 8.3), lime solution (pH = 12.5), concrete pore water (pH = 13.1) and concentrated sodium hydroxide (pH = 13.0). Figure 4.34 presents micrographs of softwood kraft fiber (SSK) conditioned in different alkaline solutions. Fibers immersed in water did not show any deterioration. Wood fibers immersed in saturated lime solution and concrete pore water showed small deposits of salts on their surfaces. Fibers immersed in concentrated sodium hydroxide showed small damage to the surface characteristics. It can be concluded from this investigation that kraft fibers withstand alkali attack without severe damage to the surface.



(a) As Received

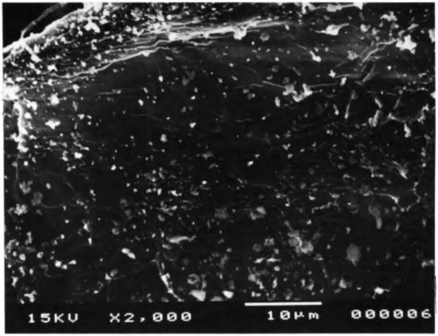
Figure 4.34 Typical SEM Micrographs of Softwood Kraft Pulp (SSK) Conditioned in Different Alkaline Solutions.

(b) Conditioned in Water for One Year

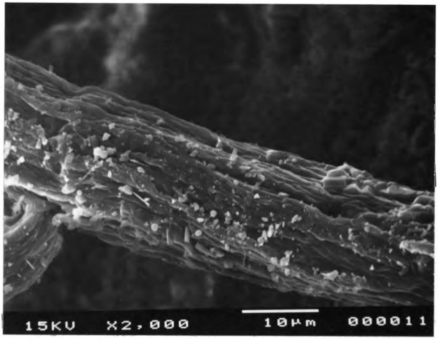


(c) Conditioned in Saturated Lime Solution for One Year

Figure 4.34 (cont'd) Typical SEM Micrographs of Softwood Kraft Pulp (SSK) Conditioned in Different Alkaline Solutions.



(d) Conditioned in Concrete Pore Water for One Year



(e) Conditioned in Concentrated Sodium Hydroxide Solution for One Year

Figure 4.34 (cont'd) Typical SEM Micrographs of Softwood Kraft Pulp (SSK) Conditioned in Different Alkaline Solutions.

4.7.2 Mechanical and Physical Properties of Molded Wood Fiber-Cement Composites

This section presents the effects of wood fiber reinforcement on the fresh mix and hardened material properties of cement using the test data generated in this investigation.

4.7.2.1 Fresh Mix Properties

Test data on water requirements (for achieving comparable levels of workability), flow, setting time and air content of cement matrices reinforced with different wood fiber types and mass fractions are presented in Table 4.10. Water-cement ratios were varied in order to obtain comparable workability levels represented by a flow (ASTM C-230) of 55% to 65%. The water requirement is observed in Table 4.10 to increase with increasing fiber content (from 0.28 for plain cement to 0.40 for the mix containing 2% mass fraction of wood fibers). The need for higher amounts of water during mixing is typical to all fiber reinforced cement composites, as higher fiber content requires more water to wet the surface area of fibers. Also, the fact that wood fibers themselves absorb part of the mixing water creates the need for higher amounts of water during mixing.

Table 4.10 Fresh Mix Properties of Molded Wood Fiber-Cement Composites

Fiber Mass Content & Type	Water-Cement Ratio	Flow (%)	Setting Time (minutes)		Air Content (%)
			Initial	Final	
Plain	0.28	66	190	210	15.3
1% Kraft (SSK)	0.35	65	190	270	23.15
2% Kraft (SSK)	0.40	62	195	315	27.6
1% Kraft (NHK)	0.35	63	195	280	23.0
2% Kraft (NHK)	0.40	62	200	350	26.08
1% Mech. (1000L)	0.35	74	270	345	22.0
2% Mech. (1000L)	0.40	66	495	690	26.0

The effects of wood fiber reinforcement on the initial and final setting times of cementitious matrices are also presented in Table 4.10. There is a tendency in setting time to increase in the presence of mechanical pulp. The final setting of the matrix containing 2% mass fraction of mechanical pulp was as much as 3 times that of plain matrix. Kraft pulps only slightly increase the final setting time (50% for SSK and 64% for NHK, at 2% fiber mass fraction) of the matrix. Mechanical pulps retard setting time more than kraft pulps possibly because mechanical pulps still carry the extractives with retarding effects, and also because their porous and hollow structure absorbs the water available in fresh mix and thus make it difficult for cement to access the water for hydration purposes. Mechanical pulps also contain higher amounts of lignin which dissolve in water and interfere with the process of cement hydration, thereby retarding the setting of fibrous cement composites more than kraft pulps. It should be emphasized that fibrous mixtures had higher water contents than the plain matrix.

The fresh mix entrapped air content is observed in Table 4.10 to increase when wood fibers are added to the mix. The increase in fresh mix air content was 80% for kraft pulps (SSK), 70% for kraft pulp (NHK), and 70% for mechanical pulps at 2% fiber mass fraction. The increase in entrapped air content could be attributed to the difficulty of compacting cement composites incorporating higher fiber mass fractions.

4.7.2.2 Mechanical Properties

Mechanical properties of wood fiber reinforced cement composites studied in this investigation were flexural performance, compressive behavior and impact resistance. The effects of wood fiber reinforcement on these aspects of mechanical properties are presented in Table 4.11.

Table 4.11 Mechanical Properties of Molded Wood Fiber-Cement Composites

Fiber Mass Content & Type	Flexural		Compressive		Impact Resistance	
	Strength (MPa)	Toughness (N-mm)	Strength (MPa)	Toughness (KN-mm)	Initial (Blows)	Failure (Blows)
Plain	2.710	6.214	60.65	116.22	1	2
	2.279	3.118	73.85	154.66	1	1
	1.542	3.718	72.35	153.68	1	2
Mean	2.177	4.350	68.95	141.52	1	1.67
1% Kraft (SSK)	8.042	52.87	61.95	137.61	40	41
	7.054	38.98	51.16	138.36	53	56
	6.544	27.57	59.19	135.33	130	148
Mean	7.213	38.81	57.44	137.10	74.3	81.7
2% Kraft (SSK)	11.62	63.73	47.55	77.364	76	79
	11.25	92.20	53.54	148.05	117	154
	9.875	82.60	53.29	134.59	101	121
Mean	10.92	79.51	51.46	120.00	98	118
1% Kraft (NHK)	6.712	30.51	63.63	149.66	137	138
	6.818	44.18	62.50	173.95	110	110
	8.261	44.97	54.98	127.80	16	18
Mean	7.263	39.89	60.37	150.47	87.7	88.7
2% Kraft (NHK)	8.914	82.93	53.41	123.60	108	118
	9.499	83.84	50.82	123.46	125	135
	8.779	52.77	49.78	123.50	98	105
Mean	9.064	73.18	51.33	123.52	110.3	119.3
1% Mech. (1000L)	3.993	23.62	51.30	124.20	4	5
	3.732	23.05	52.91	107.03	4	5
	4.398	35.03	52.40	116.99	6	6
Mean	4.041	27.23	52.20	116.07	4.67	5.33
2% Mech. (1000L)	4.278	25.65	39.90	102.13	5	6
	5.463	15.93	38.55	92.032	8	9
	4.633	24.63	41.20	77.205	11	12
Mean	4.791	22.07	39.89	90.455	8	9

The effects of wood fiber reinforcement on the flexural load-deflection behavior of cement-based materials are shown in Figure 4.35 for different fiber types. The effects of fiber content and type on flexural strength and toughness are presented in Table 4.11 and Figures 4.36 (a) and (b), respectively. Japanese standard JCI-SF [49] was used for performing the flexural test. Flexural toughness according to JCI-SF4 is defined as the area under the flexural load-deflection curve up to a deflection of 0.762 mm (0.03 in), which is the span length divided by 150. There are major improvements in the flexural strength and toughness of cement in the presence of wood fibers. Kraft pulps (SSK softwood and NHK hardwood) seem to be more effective than the mechanical pulp (1000L) in enhancing the flexural performance of cement. The increase in flexural strength at 2% fiber mass fraction was about 5 times for kraft pulp (SSK), 4 times for kraft pulp (NHK), and 2 times for mechanical pulp (1000L) when compared with that of plain matrix. Improvements in flexural toughness were even more significant (about 18 times for SSK kraft pulp, 17 times for NHK kraft pulp, and 5 times for 1000L mechanical pulp at 2% fiber mass fraction). The effects of fiber content and fiber type were found to be statistically significant at 95% level of confidence.

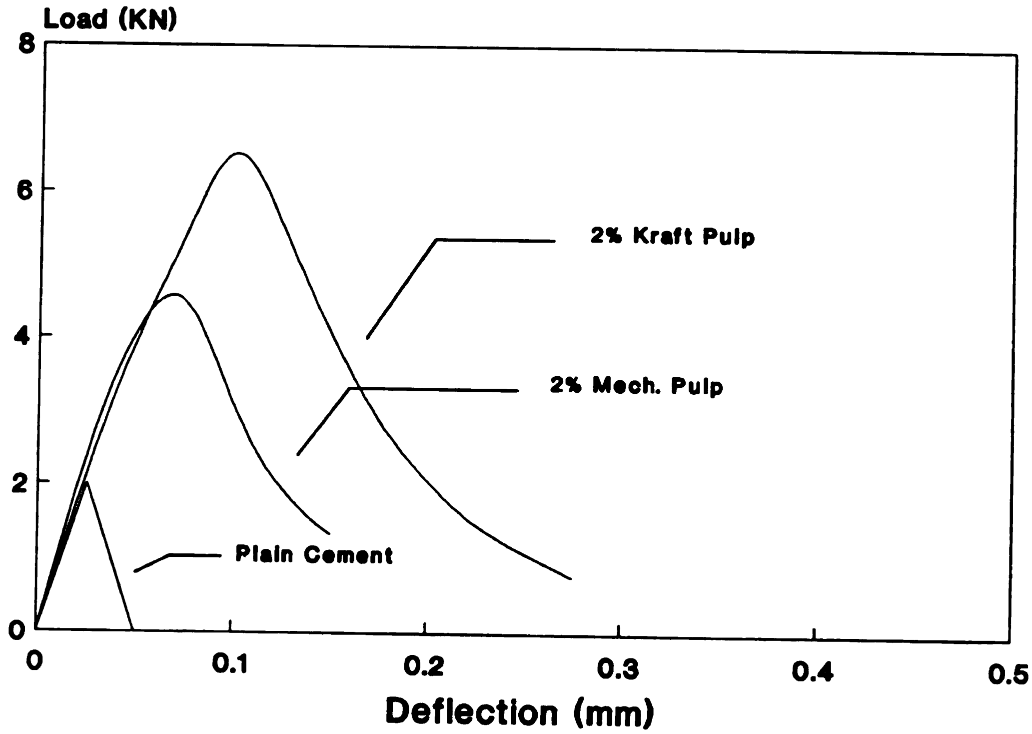
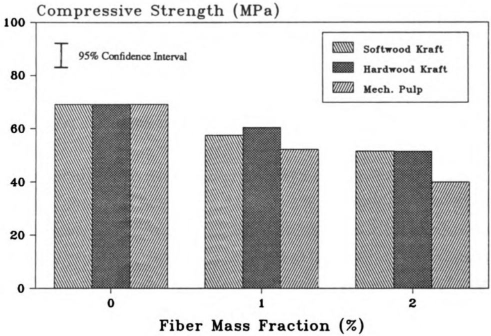


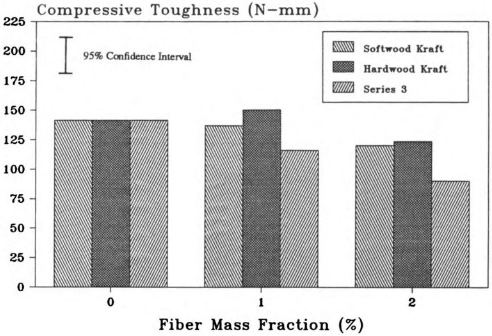
Figure 4.35 Flexural Load-Deflection Behavior of Molded Wood Fiber-Cement Composites.

The compressive strength and toughness test results are shown in Table 4.11 and also in Figures 4.37 (a) and (b), respectively. The Japanese standard JCI-SF [49] was used for performing this test. According to JCI-SF5, compressive toughness is defined as the area underneath the compressive load-deflection curve up to a strain of 0.0075. Wood fibers are observed to reduce the compressive strength and toughness of cementitious materials. This effect is relatively small and, considering the major improvements in flexural performance, it is not a major factor in application of wood fiber reinforced cement to thin-sheet products where flexure and impact loads dominate the behavior and compressive behavior is of little consequence.



(a) Compressive Strength

Figure 4.37 Compressive Behavior of Molded Wood Fiber-Cement Composites.



(b) Compressive Toughness

Figure 4.37 (cont'd) Compressive Behavior of Molded Wood Fiber-Cement Composites.

Effects of wood fiber reinforcement on the first crack and ultimate impact strengths of cement are presented in Table 4.11 and Figures 4.38 (a) and (b), respectively. Impact resistance represents the number of blows by a standard hammer (10 lb. mass with a drop height of 457.2 mm, 18 in) required for cracking and failure of the test specimen[17]. Figure 4.37 indicates that tremendous improvements in the impact resistance of cement can be achieved through wood fiber reinforcement. Kraft pulps are much more effective (about 71 times impact resistance for both SSK and NHK at 2% fiber mass fraction when compared with plain matrix) than the mechanical pulp (about 5 times impact resistance at 2% fiber mass fraction) in this regard.

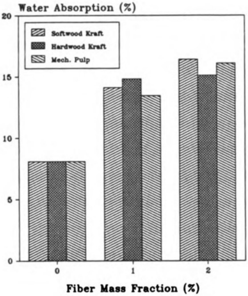
4.7.2.3 Physical Properties

The water absorption capacity of cement-based materials are observed in Table 4.12 and Figure 4.39 (a) to increase with increasing fiber mass fraction. The increase in water absorption over that of plain cement was 100% for kraft pulp (SSK), 86% for kraft pulp (NHK) and 99% for mechanical pulp (1000L) at 2% mass fraction. High water absorption values observed are partly due to the increased void content of the composite due to poor compactibility and partly due to the affinity of wood fibers to moisture.

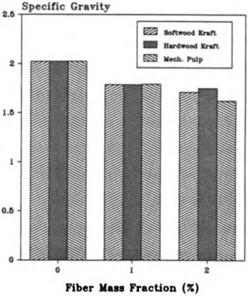
The specific gravity of hardened cement-based materials is observed in Table 4.12 and Figure 4.38 (b) to decrease with increasing wood fiber content. At 2% fiber mass fraction, kraft fiber reinforced composites showed a reduction in specific gravity of about 16% for SSK and 13% for NHK when compared with plain cement, while mechanical pulps produced a decrease of 20%; similar trends were observed in the fresh mix unit weight. Increased void content due to poor compactibility is the main cause for reductions in the specific gravity of composites.

Table 4.12 Physical Properties of Molded Wood Fiber-Cement Composites

Fiber Mass Content & Type	Water Absorption (%)	Specific Gravity
Plain	8.1	2.022
1% Kraft (SSK)	14.1	1.787
2% Kraft (SSK)	16.4	1.71
1% Kraft (NHK)	14.8	1.785
2% Kraft (NHK)	15.1	1.75
1% Mech. (1000L)	13.46	1.791
2% Mech. (1000L)	16.10	1.622



(a) Water Absorption



(b) Specific Gravity

Figure 4.39 Water Absorption and Specific Gravity of Molded Wood Fiber-Cement Composites.

4.7.3 Optimization of Fiber Content in Molding and Slurry-Dewatering Processes

Optimization of fiber mass content was done in two stages: (a) for composites containing low fiber content ($\leq$ 2%) manufactured through molding method; and (b) for composites containing high fiber content ($\geq$ 4%) manufactured through slurry-dewatering.

4.7.3.1 Molding Method

This section presents the effects of wood fiber reinforcement on the fresh mix and hardened material properties of cement-based materials using the test data generated in this investigation. The wood fibers used were Southern Softwood Kraft (SSK) [41] and Mechanical Pulp (1000L) [43]. The fiber mass fractions and matrix mix proportions used in this phase of the study are introduced in Table 4.3 (a). Water and superplasticizer contents were varied in order to achieve reasonable fresh mix workability characteristics represented by a flow (ASTM C-230) of 55% to 65% at 1 minute after mixing. Fibrous mixtures also contained a non-chloride set accelerator, which was essential to keep their setting times within acceptable limits.

Fresh Mix Properties: Table 4.13 presents the test data on water requirements (for achieving comparable levels of workability), air content, water absorption and setting time of composites with different mass fractions of different fiber types. The results presented are average of two values obtained from two different batches for a specific mix, with information given on the range covered by the two replicated test points. The variations between batches are observed to be relatively small. Water-cement ratios were varied in order to obtain comparable workability levels represented by a flow (ASTM C-230) of 55% to 65%. The water requirement is observed in Table 4.13 to increase with increasing fiber content (from 0.3 for plain mortar to 0.425 for the mix containing 2% mass fraction of kraft fibers). Kraft fibers require more water than mechanical fibers. A possible explanation for this is that kraft fibers, being smaller in diameter, have more surface area at the same mass fraction, and thus require more water to wet their surfaces.

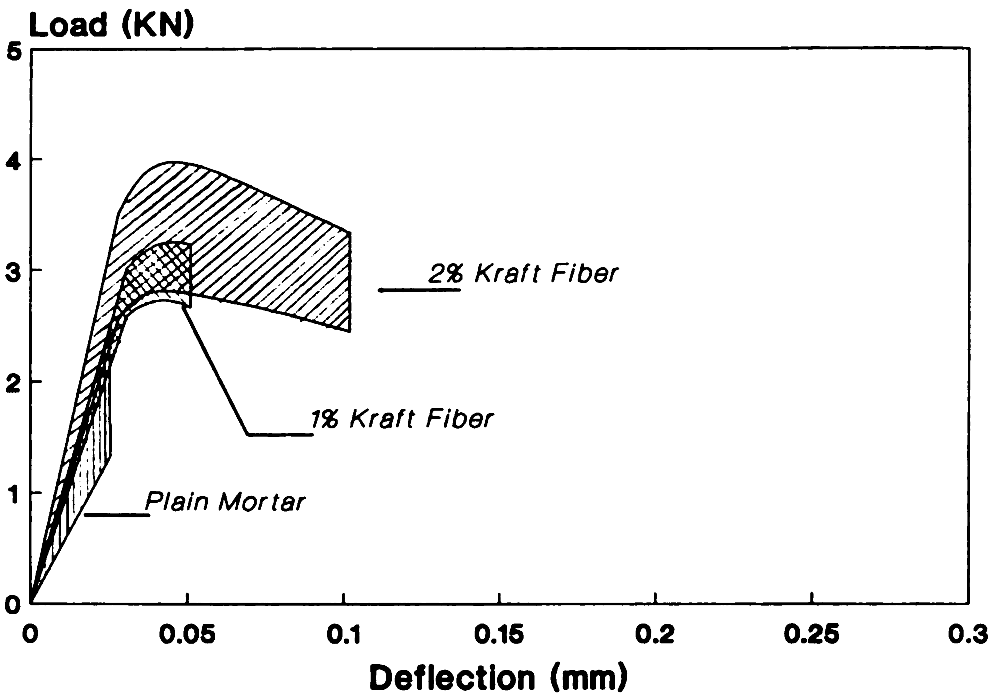
Table 4.13 Fresh Mix Properties of Molded Wood Fiber Reinforced Cement Composites (average ± half the range)

Fiber Mass Content & Type	Water-Cement Ratio	Flow (%)	Setting Time (minutes)		Air Content (%)
			Initial	Final	
Plain	0.30	58	186 ±3	210 ±3	21.07 ±0.25
1% Kraft (SSK)	0.35	58	211 ±4	253 ±2	21.38 ±0.13
2% Kraft (SSK)	0.43	48	233 ±3	293 ±4	22.50 ±0.26
1% Mech. (1000L)	0.30	64	272 ±4	354 ±3	20.86 ±0.27
2% Mech. (1000L)	0.30	59	292 ±4	387 ±3	23.94 ±0.41

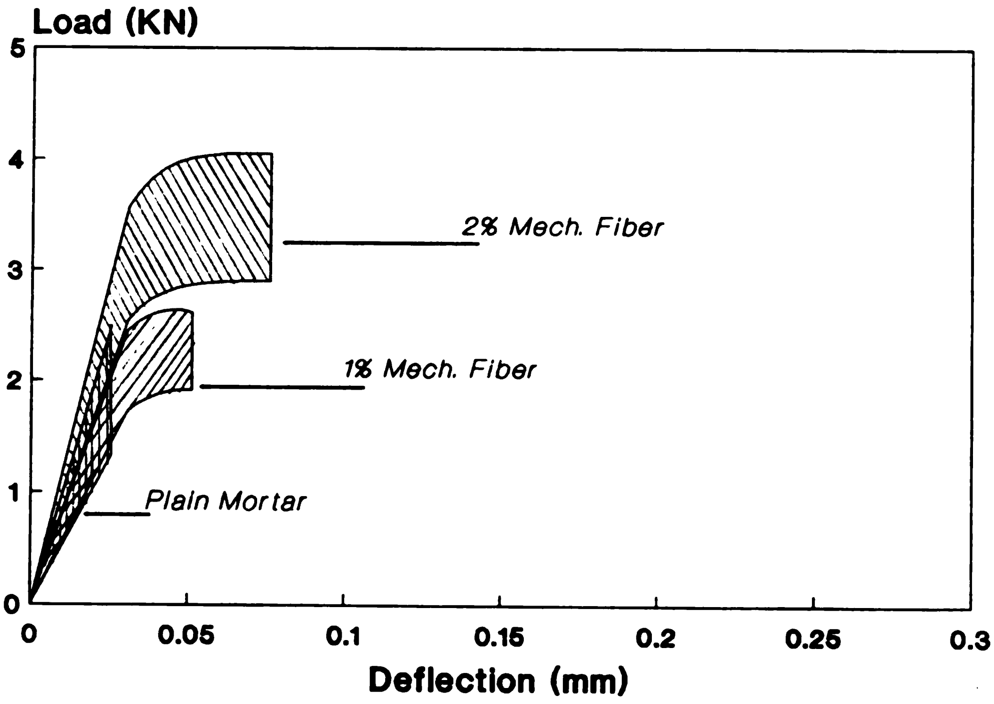
Setting time of mixtures containing fibers increased as fiber mass content was increased (see Table 4.13). The initial setting time increased by as much as 25% and 58% for mixes containing 2% mass fraction of kraft and mechanical fibers, respectively; this increase was even more for the final setting time (39% for kraft fibers and 84% for mechanical fibers). Mechanical pulps retard the setting time more than kraft pulps possibly because mechanical pulps still carry the extractives with retarding effects, and also because their porous and hollow structure absorbs the water available in fresh mix and thus make it difficult for cement to access the water for hydration purposes. Mechanical pulps also contain higher amounts of lignin which dissolve in water and interfere with the process of cement hydration, thereby retarding the setting of fibrous cement composites more than kraft pulps. It should be noted here that fibrous mixtures contained higher amounts of water as well as a small dosage of non-chloride set accelerator [45]. Thus an accurate comparison of setting time for plain and fibrous mixtures could not be made.

The fresh mix air content is observed in Table 4.13 to increase when wood fibers are added to the mix. The increase in fresh mix air content was 7% for the kraft pulp and 14% for the mechanical pulp at 2% mass fraction. The increase in entrapped air content could be attributed to the difficulty of compacting cement composites incorporating higher fiber mass fractions.

Mechanical Properties: Wood fiber reinforced cement composites were tested for their flexural performance. The effects of wood fiber reinforcement on the flexural load-deflection behavior of cement-based materials are shown in Figure 4.40 for different fiber types. The effects of fiber content and type on flexural strength and toughness are presented in Table 4.14 and Figures 4. 41 (a) and (b), respectively. Japanese standard JCI-SF [49] was used for performing the flexural tests. Flexural toughness according to JCI-SF4 is defined as the area underneath the flexural load-deflection curve up to a deflection of 0.762 mm (0.03 in), which is the span length divided by 150.



(a) Kraft Pulp (SSK)



(b) Mechanical Pulp (1000L)

Figure 4.40 Flexural Load-Deflection Behavior of Molded Wood Fiber Reinforced Cement Composites (Range for 10 Curves).

Table 4.14 Flexural Performance of Molded Wood Fiber Reinforced Cement Composites

Fiber Mass Content & Type	Flexural Strength (MPa)			Flexural Toughness (N-mm)		
	Batch 1	Batch 2	Mean (St. Dev.)	Batch 1	Batch 2	Mean (St. Dev.)
Plain	3.7799 5.7557 4.9466 3.9167 3.0181	4.1222 3.6159 4.4956 3.8610 2.6266	3.9146 (0.9989)	51.975 36.156 35.026 41.806 39.546	33.897 41.806 40.902 46.326 32.767	40.021 (5.9658)
1% Kraft (SSK)	9.3878 9.3686 9.1754 7.6484 6.8372	8.5965 5.7523 6.4618 8.3731 6.3511	7.7949 (1.3688)	87.001 91.521 114.12 75.929 97.171	97.171 75.703 87.002 91.521 87.002	90.414 (9.9317)
2% Kraft (SSK)	6.7155 6.6509 6.6921 7.8581 6.4350	6.5306 4.9809 7.2799 6.9451 6.7402	6.6825 (0.7729)	182.59 177.62 170.95 192.31 165.76	169.82 145.76 189.03 114.12 185.42	169.269 (23.26)
1% Mech. (1000L)	4.3390 4.9147 5.4340 5.2188 3.9577	5.1871 4.8624 4.6245 4.3307 4.5162	4.7245 (0.4654)	61.014 71.183 83.612 82.482 51.975	94.011 70.053 76.042 61.353 70.392	72.302 (1.4011)
2% Mech. (1000L)	6.3048 8.3320 7.7079 7.7210 7.6562	6.9667 5.8345 6.8398 6.4572 6.3813	6.9994 (0.0928)	90.391 98.300 91.521 87.002 94.911	80.222 74.573 79.092 77.962 81.352	85.533 (0.5649)

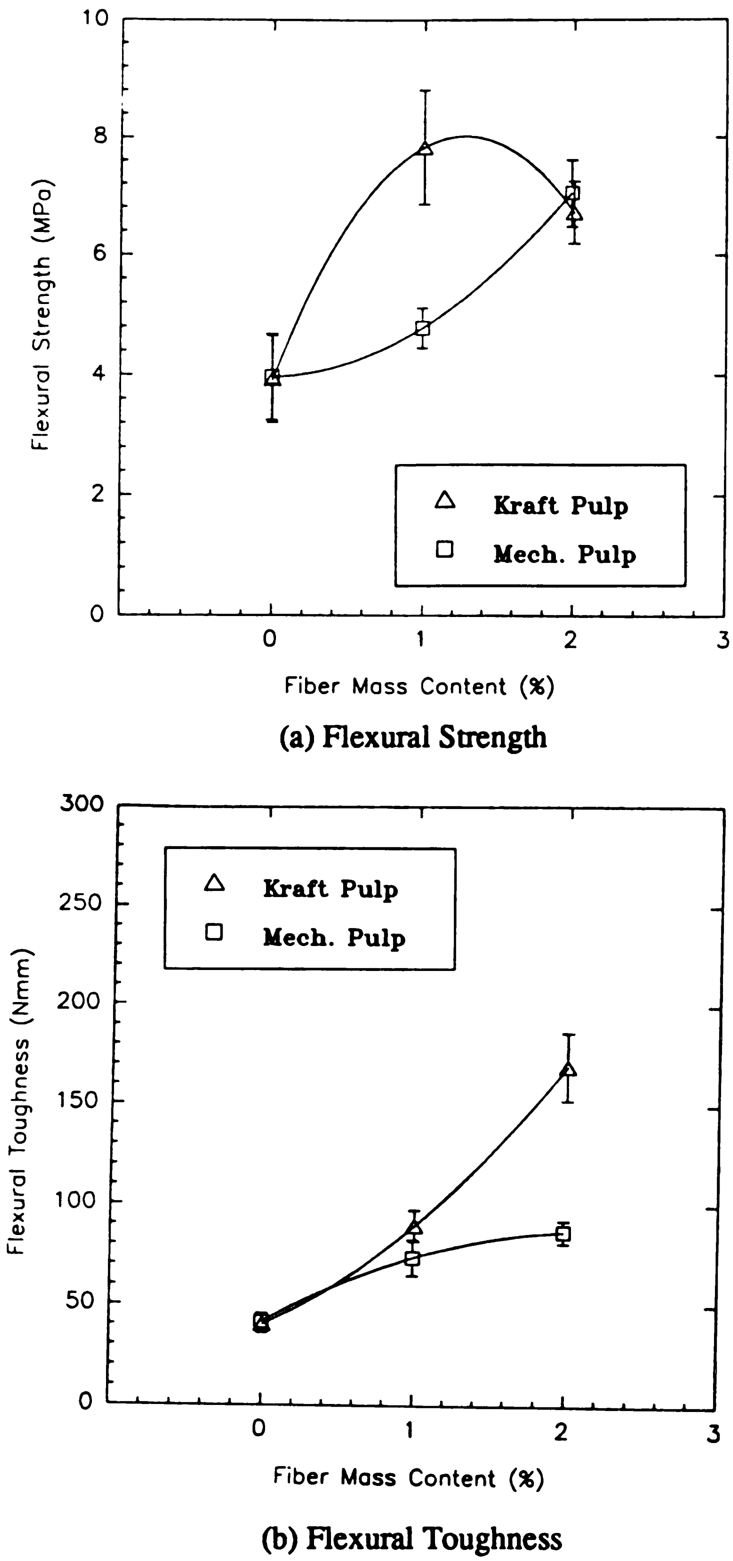


Figure 4.41 Effects of Fiber Mass Content on Flexural Performance of Molded Wood Fiber Reinforced Cement Composites (Regression Analysis with 95% Confidence Interval).

The following conclusions could be derived from the test data regarding the effects of fiber mass fraction and type on flexural performance.

Flexural strength and toughness of composites incorporating mechanical pulp continue to increase with increasing fiber mass fraction up to 2%. The composite with 2% mechanical fibers had a 79% increase in flexural strength and a 114% increase in flexural toughness over the plain matrix. Flexural strength of composites incorporating kraft fibers increased at 1% fiber content and then decreased when fiber content was increased to 2%; fracture toughness, however, increased continuously with increasing fiber content. The composite with 1% kraft fibers had, on the average, 99% increase in flexural strength and 126% increase in flexural toughness over the plain matrix. The increase in flexural toughness at 2% fiber mass fraction was even more significant (an average of 323%), where the average increase in flexural strength was 71% over that of plain matrix.

Statistical analysis of the generated test data were performed using the analysis of variance and multiple comparison techniques. A significant effect represents a confidence level between 99 and 95%, and a highly significant effect represents confidence levels higher than 99%. The addition of 1% mass fraction of fibers to plain cement matrix had a highly significant effect on flexural strength. However, fiber content, changing from 1% to 2% mass fraction did not show any significant effect on flexural strength. The effect of fiber content on flexural toughness was highly significant. Fiber type (kraft vs. mechanical pulp) had a highly significant effect on flexural strength at 1% fiber content (with kraft fibers giving higher strength), while at 2% fiber content the effect of fiber type on flexural strength was not significant. Effect of fiber type on flexural toughness was highly significant at all fiber contents (with kraft fibers producing higher toughness values).

Physical Properties: The water absorption capacity of cement-based materials is observed in Table 4.15 to increase with increasing fiber mass fraction. The increase in water absorption over that of plain cementitious matrix was 23% for kraft pulp and 13% for mechanical pulp at 2% fiber mass fraction.

Table 4.15 Physical Properties of Molded Wood Fiber Reinforced Cement Composites (average ± half the range)

Fiber Mass Content & Type	Water Absorption (%)	Specific Gravity
Plain	11.07 ± 0.12	2.00 ± 0.001
1% Kraft (SSK)	11.95 ± 0.12	1.91 ± 0.013
2% Kraft (SSK)	13.66 ± 0.06	1.75 ± 0.041
1% Mech. (1000L)	11.45 ± 0.02	1.86 ± 0.064
2% Mech. (1000L)	12.48 ± 0.18	1.65 ± 0.055

The specific gravity of hardened cement-based materials is observed in Table 4.15 to decrease with increasing wood fiber content. At 2% fiber mass content, kraft fiber reinforced composites showed a reduction in specific gravity of about 13% below that of plain matrix, while mechanical pulps produced a decrease of 17%; similar trends were observed in the fresh mix unit weight.

In order to see if there is any relationship between air content, specific gravity and water absorption, correlation coefficients were calculated for the generated test data. The results showed that the correlation is significant at a confidence level of 95% for all the two combinations of properties for both mechanical and kraft pulps.

4.7.3.2 Slurry-Dewatering

This section presents the optimization of wood fiber content for composites containing relatively high fiber contents (≥ 4%) manufactured through slurry-dewatering. The wood fibers used in this investigation were Southern Softwood Kraft (SSK) [41]. Optimization was achieved through flexural testing of the composite containing different fiber contents. The fiber mass fractions and matrix mix proportions used in this phase of the study are introduced in Table 4.3 (b). Thin-sheet specimens were formed from a dilute slurry of approximately 20% solids. A relatively small dosage of 1% diluted flocculent (flocculent/cement=0.001) [46] was added to achieve agglomeration of cement solids in the slurry, which helps in reducing the amount of cement particles lost through the filtering screens during dewatering. Fiber mass fraction, in the slurry-dewatering method of manufacture, is defined as the ratio of fibers to the dry constituents of the matrix by weight.

Mechanical Properties: The effects of wood fiber mass fraction on flexural load-deflection behavior of cement-based materials are shown in Figure 4.42. The effects of fiber content and type on flexural strength and toughness are presented in Table 4.15 and Figures 4. 43 (a) and (b), respectively. Each test point in this figure represents the average of three experiments; regression lines with 95% confidence intervals are also presented. Japanese standard JCI-SF [49] was used for performing the flexural test. Flexural toughness in this study was defined as the total area under the full load-deflection curve to account for large deflection capacity of the composites.

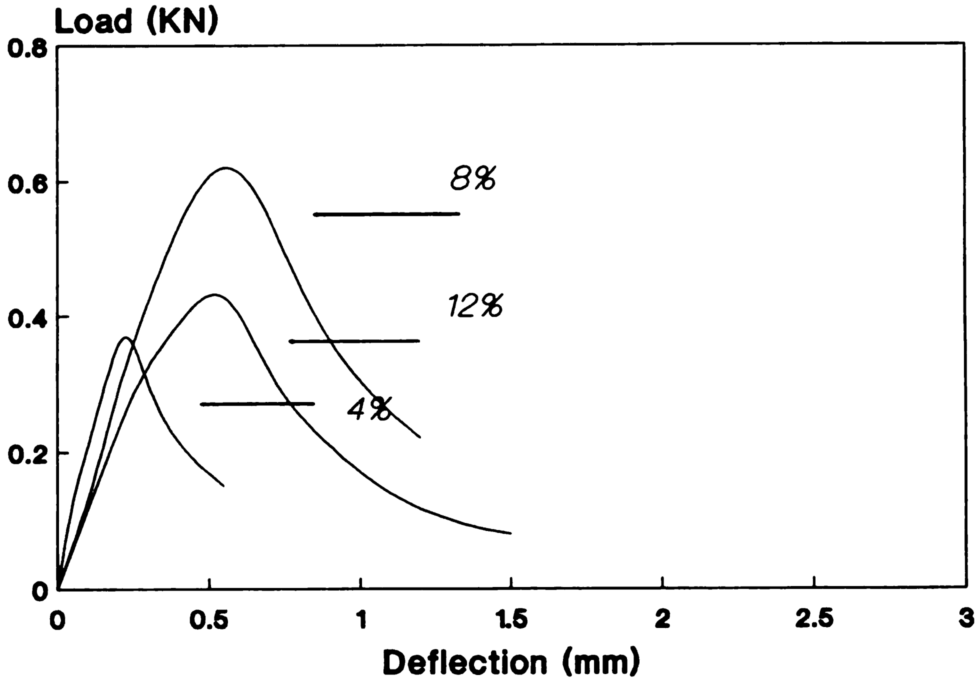
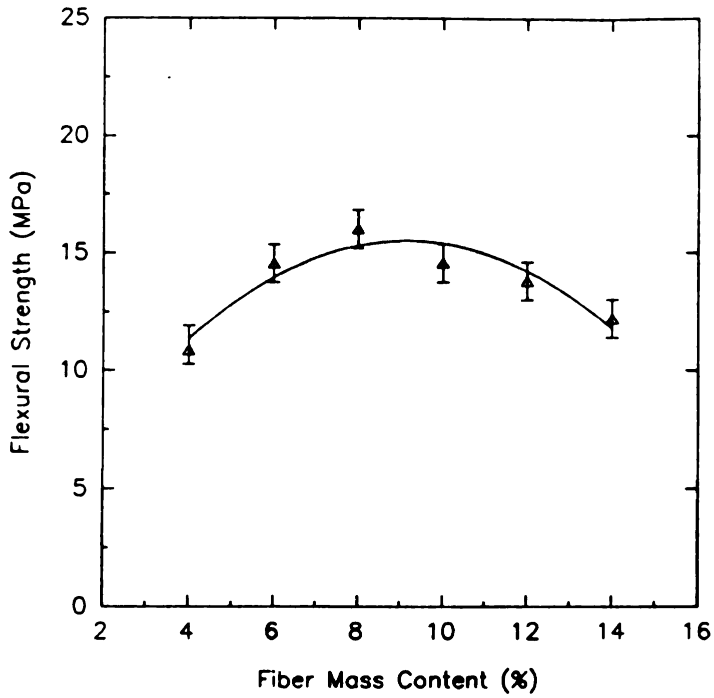


Figure 4.42 Flexural Load-Deflection Behavior of Slurry-Dewatered Wood Fiber Reinforced Cement Composites.

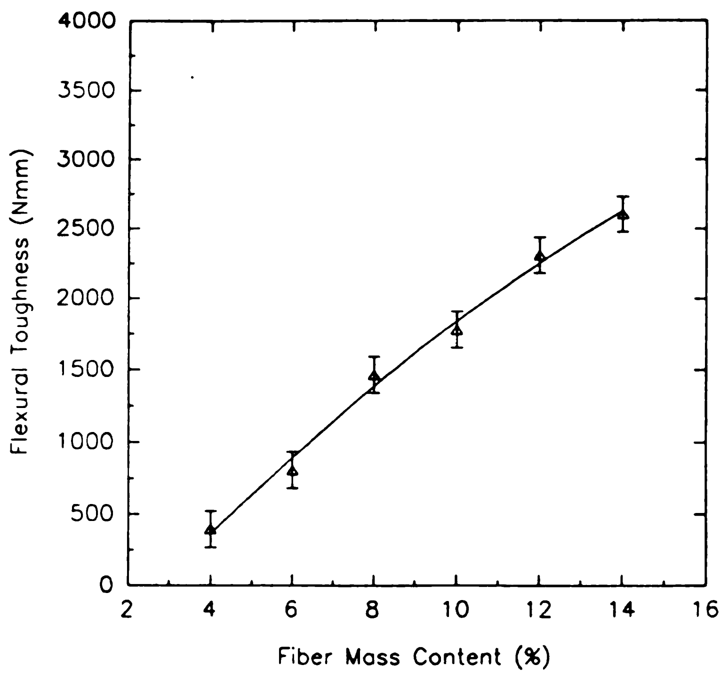
Table 4.16 Flexural Performance of Slurry-Dewatered Wood Fiber Reinforced Cement Composites

Flexural Performance	Fiber Mass Fraction (%)					
	4	6	8	10	12	14
Flexural Strength (MPa)	10.710 10.841 11.045	14.514 13.804 15.314	15.865 15.410 16.706	13.796 15.176 14.638	13.027 13.758 14.551	11.632 12.364 12.555
Mean	11.095	14.544	15.994	14.537	13.778	12.184
Flexural Toughness (N-mm)	398.08 378.74 465.85	740.75 815.55 866.40	1354.5 1468.4 1570.4	1864.3 1756.3 1720.0	2471.9 2322.3 2134.2	2547.9 2560.9 2696.6
Mean	394.56	807.57	1464.4	1780.2	2309.5	2601.8



(a) Flexural Strength

Figure 4.43 Effects of Fiber Mass Content on the Flexural Performance of Slurry-Dewatered Wood Fiber Reinforced Cement Composites (Regression Analysis with 95% Confidence Interval).



(b) Flexural Toughness

Figure 4.43 (cont'd) Effects of Fiber Mass Content on the Flexural Performance of Slurry-Dewatered Wood Fiber Reinforced Cement Composites (Regression Analysis with 95% Confidence Interval).

The following conclusions could be derived from the test data regarding the effects of fiber mass fraction on flexural strength and toughness.

Flexural strength of composites incorporating kraft fibers increased with increasing fiber content up to 8% by mass and then decreased when fiber content was increased further. Fracture toughness, however, increased continuously with increasing fiber content. The composite with 8% kraft fibers had, on the average, 44% increase in flexural strength and 4 times increase in flexural toughness over the composite containing 4% fiber content. The increase in flexural toughness at 14% fiber mass fraction was even more significant (6 times), while the average increase in flexural strength was 9% at 14% fiber content over the composite containing 4% fiber content.

Statistical analysis of the generated test data using analysis of variance and multiple comparison techniques indicated that fiber content has a significant effect (at 99% level of confidence) on flexural strength and toughness.

Physical Properties: The water absorption and specific gravity of slurry-dewatered wood fiber reinforced cement composites are presented in Table 4.17. The following conclusions could be derived from the test data regarding the effects of fiber mass fraction on water absorption and density.

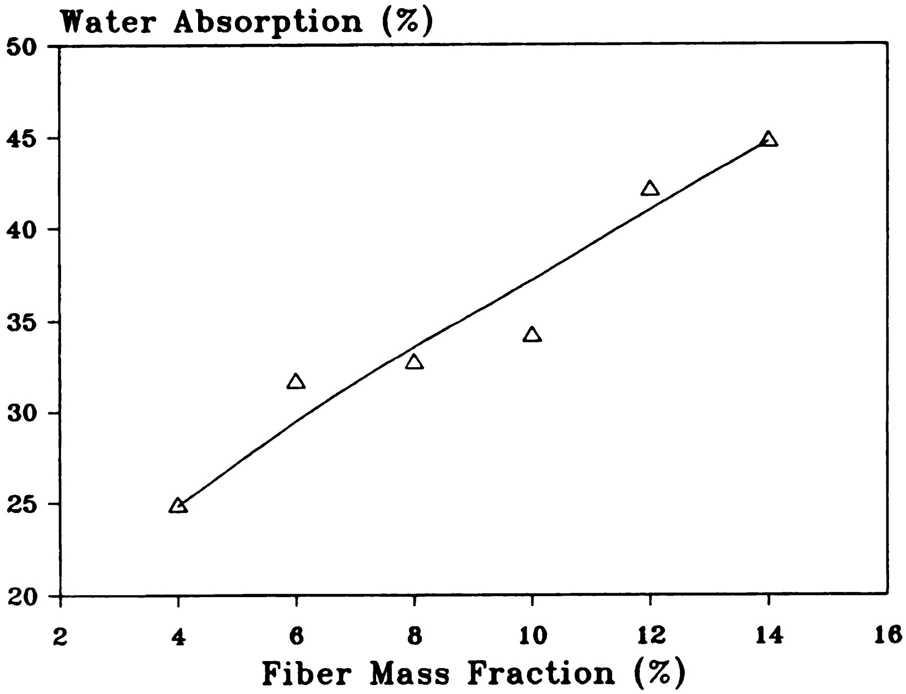
The water absorption capacity of slurry-dewatered cement composites is observed in Figure 4.44 (a) to increase with increasing fiber mass fraction. The increase in water absorption was as much as 30% when the fiber content was increased from 4 to 8%, by mass. An even higher water absorption value was observed at 14% fiber mass content (65% more than the composite containing 4% fibers by mass). The effect of fiber content on water absorption was found to be statistically significant at 95% level of confidence.

The specific gravity of wood fiber reinforced cement composites is observed in Figure 4.44 (b) to decrease with increasing fiber content. The reduction in specific gravity was as much as 12% when the fiber content was increased from 4 to 8%, by mass. An even lower value of specific gravity was observed at 14% fiber mass content (30% reduction when compared with the composite containing 4% by mass). The effect of fiber content on specific gravity was found to be statistically significant at 95% confidence level.

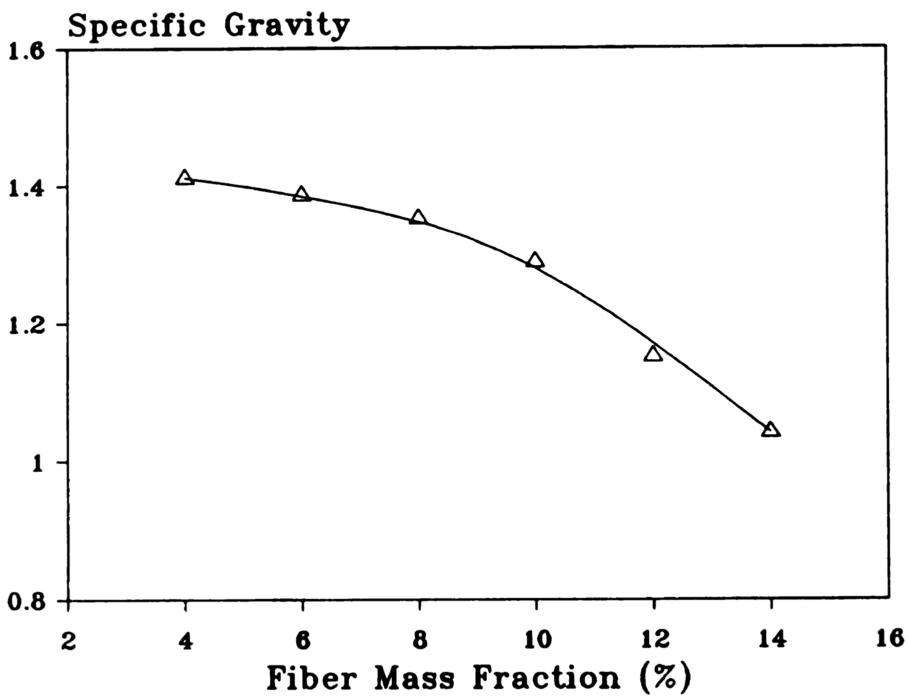
It may be concluded from the above discussion that specific gravity and water absorption of the composite are related. The water absorption of the composite increases as its specific gravity is reduced with the addition of wood fibers.

Table 4.17 Physical Properties of Slurry-Dewatered Wood Fiber Reinforced Cement Composites

Physical Property	Fiber Mass Fraction (%)					
	4	6	8	10	12	14
Water Absorption (%)	24.81	31.62	32.67	34.12	42.05	44.71
Specific Gravity	1.412	1.387	1.352	1.289	1.152	1.041



(a) Water Absorption



(b) Specific Gravity

Figure 4.44 Water Absorption and Specific Gravity of Slurry-Dewatered Wood Fiber Reinforced Cement Composites.

4.7.4 Matrix Modification

This section presents test results on the modification of matrix mix constituents through pozzolanic admixtures and latex in wood fiber reinforced cement composites. The fiber used in this study was Southern Softwood Kraft (SSK) [41]. The samples contained an optimum fiber contents (2% for molding method and 8% for slurry dewatering method). The matrix modification was achieved through partial substitution of cement with pozzolanic admixtures (15% for silica fume or 30% for fly ash by weight). In the case, the matrix was also modified by the addition by the addition of a latex polymer [47]. The fiber mass fraction and matrix mix proportions are introduced in Table 4.4.

4.7.4.1 Mechanical Properties

The effects of matrix modification on flexural strength and toughness are presented in Table 4.18, and in Figures 4. 45 and 4.46. Each test point in the figures represents the average values of the test data; 95% confidence intervals are also presented. Japanese standard JCI-SF [49] was used for performing the flexural tests.

Table 4.18 Effects of Matrix Modification on the Flexural Performance of Wood Fiber Reinforced Cement Composites

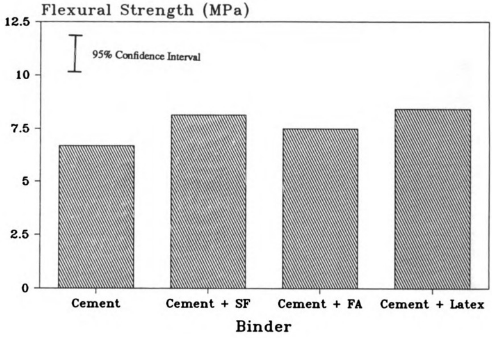
(a) Molded Composites

Matrix	Flexural Strength (MPa)			Flexural Toughness (N-mm)		
	Batch 1	Batch 2	Mean (St. Dev.)	Batch 1	Batch 2	Mean (St. Dev.)
Pure Cement	6.7155 6.6509 6.6921 7.8581 6.4350	6.5306 4.9809 7.2799 6.9451 6.7402	6.6825 (0.7729)	182.59 177.62 170.95 192.31 165.76	169.82 145.76 189.03 114.12 185.42	169.269 (23.26)
Cement & 15% Silica Fume	9.1120 8.0213 9.2636 8.7521 8.8512	7.9921 7.1152 8.0253 7.1102 7.0120	8.1255 (0.8510)	161.72 114.12 153.11 140.26 120.42	120.37 148.55 138.78 145.23 144.75	138.731 (15.60)
Cement & 30% Fly Ash	8.0122 6.5122 7.8900 6.8132 6.0012	8.1205 7.1121 8.0126 8.4531 7.8925	7.4819 (0.8142)	145.29 169.17 169.12 162.00 158.11	179.32 106.91 172.98 158.23 147.21	156.834 (20.596)
Cement & 10% Latex	9.3317 8.4412 9.4561 9.0167 7.8911	8.1149 7.2261 8.2514 7.5571 8.7521	8.4038 (0.7409)	946.31 1002.1 956.12 875.31 899.19	935.23 976.32 910.98 990.23 970.12	946.193 (41.15)

Table 4.18 (cont'd) Effects of Matrix Modification on the Flexural Performance of Wood Fiber Reinforced Cement Composites

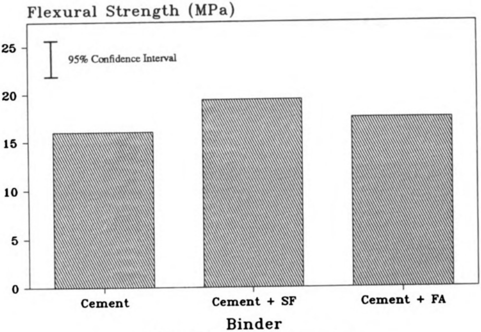
(b) Slurry-Dewatered Composites

Flexural Performance	Matrix		
	Pure Cement	Cement & 15% Silica Fume	Cement & 30% Fly Ash
Flexural Strength (MPa)	15.865 15.410 16.706	18.623 19.292 20.229	17.913 18.596 17.444
Mean	15.994	19.382	17.984
Flexural Toughness (N-mm)	1354.5 1468.4 1570.4	1129.0 1355.0 1242.6	1142.3 1356.0 1318.9
Mean	1464.4	1242.2	1272.4



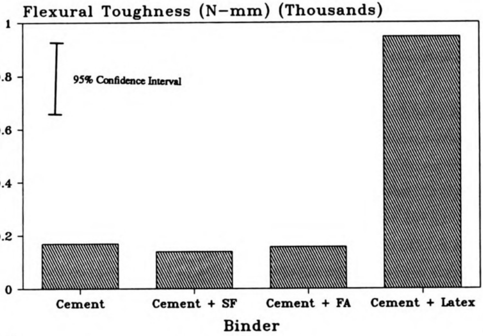
(a) Molded Composites

Figure 4.45 Effects of Matrix Modification on the Flexural Strength of Wood Fiber Reinforced Cement Composites.



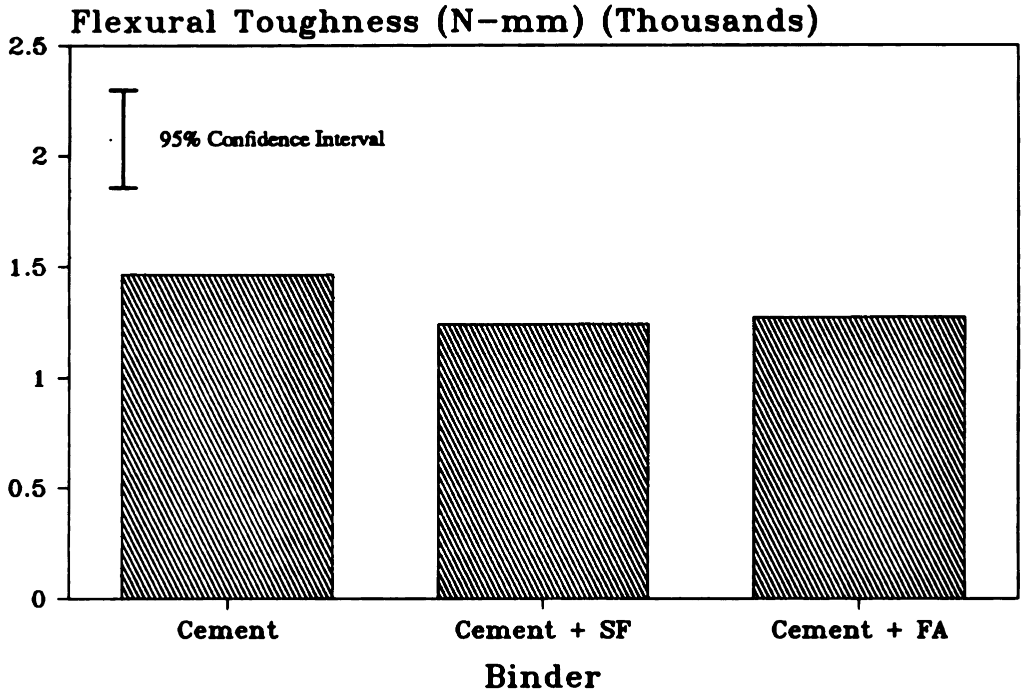
(b) Slurry-Dewatered Composites

Figure 4.45 (cont'd) Effects of Matrix Modification on the Flexural Strength of Wood Fiber Reinforced Cement Composites.



(a) Molded Composites

Figure 4.46 Effects of Matrix Modification on the Flexural Toughness of Wood Fiber Reinforced Cement Composites.



(b) Slurry-Dewatered Composites

Figure 4.46 (cont'd) Effects of Matrix Modification on the Flexural Toughness of Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived from the test data regarding the effects of matrix modification on flexural performance.

Pozzolans (30% Silica fume and 15% Fly ash) are observed to increase the flexural strength of the composite while slightly reducing toughness. These observations were confirmed through statistical analyses of results at 95% level of confidence; the effects are more pronounced with silica fume. Silica fume and fly ash increased flexural strength on the average by about 20% and 12%, respectively, for both molded and slurry-dewatered composites. The reduction in flexural toughness in the presence of silica fume was about 20% for molded composites and 15% for slurry-dewatered composites. Composites containing fly ash showed relatively small reductions in flexural strength (about 10%). Pozzolanic reaction helps in improving the fiber-to-matrix bond, and hence improved strength and reduced toughness values are observed.

Modification of matrix by latex polymer (10% Styrene Butadiene by weight of cement) in molded wood fiber reinforced cement composites substantially improved the flexural performance. The increase in flexural strength (Figure 4.45 a) due to polymer modification was significant (26%), and the increase in flexural toughness (Figure 4.46 a) was highly significant (about 5 times). Formation of a thin layer of polymeric film around the fiber in the presence of latex, which enhances the fiber-to-matrix bonding, seems to be the mechanisms which improve the flexural performance of latex modified wood fiber reinforced cement composites significantly

4.7.4.2 Physical properties

The water absorption and specific gravity of wood fiber reinforced cement composites are presented in Table 4.19. It can be concluded from the test data that the addition of pozzolans slightly reduces the water absorption and density of composites (by about 6%), while the specific gravity values are comparable. The reduced water absorption values are indicative of reduced permeability and reduced access of fibers to moisture in composites incorporating pozzolanic admixtures.

The reduction in water absorption of latex modified composites was 10%, when compared to composites with pure cement-based matrix. The specific gravity of these composites were comparable. Reduced absorption may be again related to reduced permeability and limited access of fibers to moisture in composites incorporating latex polymers.

Table 4.19 Effects of Matrix Modification on the Physical Properties of Wood Fiber Reinforced Cement Composites

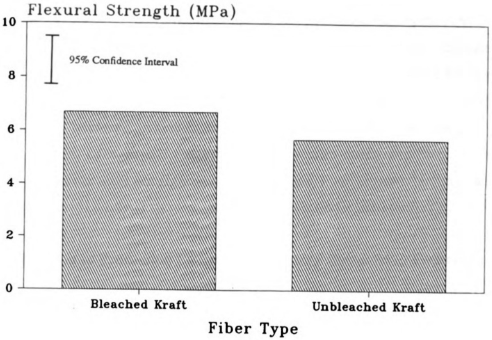
Matrix Modification	Molded Composites		Slurry-Dewatered Composites	
	Water Absorption (%)	Specific Gravity	Water Absorption (%)	Specific Gravity
Pure Cement	13.66	1.75	32.67	1.35
Cement & 15% Silica Fume	12.78	1.70	31.27	1.27
Cement & 30% Fly Ash	12.81	1.61	30.31	1.21
Cement & 10% Latex	12.54	1.78	-	-

4.7.5 Effect of Bleaching

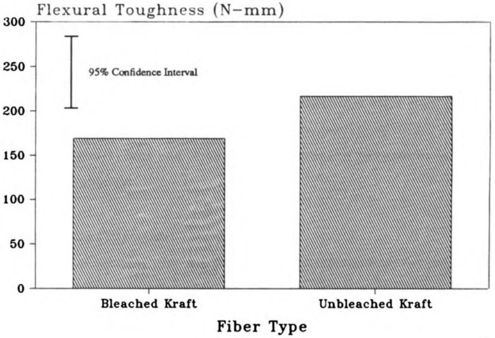
This section presents test results on the flexural performance of bleached and unbleached wood fiber reinforced cement composites. The fibers used in this study were unbleached and bleached Southern Softwood Kraft Pulp (SSK) [41]. The composites were manufactured using the molding technique, and the fiber content was 2% by mass. The matrix mix proportions used in this study are given in Table 4.5. A comparison of the test results on flexural performance of bleached and unbleached wood fiber reinforced cement composites is presented in Table 4.20 and Figure 4.47.

Table 4.20 Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers

Fiber Mass Content & Type	Flexural Strength (MPa)			Flexural Toughness (N-mm)		
	Batch 1	Batch 2	Mean (St. Dev.)	Batch 1	Batch 2	Mean (St. Dev.)
2% Kraft (SSK) Bleached	6.7155 6.6509 6.6921 7.8581 6.4350	6.5306 4.9809 7.2799 6.9451 6.7402	6.6825 (0.7729)	182.59 177.62 170.95 192.31 165.76	169.82 145.76 189.03 114.12 185.42	169.269 (23.26)
2% Kraft (SSK) Unbleached	6.4520 5.8210 5.2894 6.1324 5.8812	5.1190 4.6632 6.1813 6.3267 4.8875	5.6754 (0.6377)	198.48 199.36 230.12 241.30 179.13	185.40 236.78 220.45 235.13 240.55	216.67 (23.886)



(a) Flexural Strength



(b) Flexural Toughness

Figure 4.47 Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers.

Cement Composites containing bleached wood fibers show higher flexural strengths when compared with unbleached wood fiber reinforced cement composites; the increase in flexural strength was 15%. However, composites containing bleached wood fibers showed a drop in flexural toughness (by about 30%). Analysis of variance of test results at 95% level of confidence, however, indicated that, considering the random experimental errors, changes in flexural strength and toughness of composites containing bleached and unbleached wood fibers were not significant. Unbleached wood fibers which contain small amounts of lignin [51] did not show any adverse effects on flexural performance.

4.7.6 Modification of Processing Parameters in Slurry-Dewatering Technique

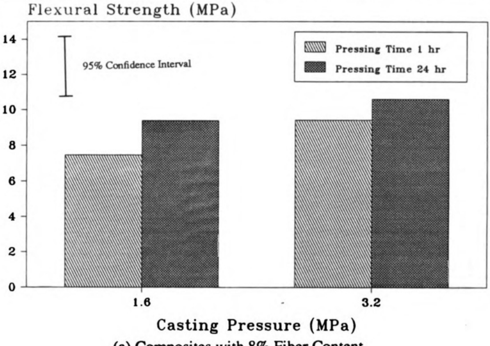
This section presents test results on the effects of processing parameters in slurry-dewatering on flexural performance of wood fiber reinforced cement composites. It is often stated that the use of pressure in the manufacture of fiber reinforced cements increases the strength of the composite but reduced the fracture toughness [35, 36, 37]. The fiber used in this study was Southern Softwood Kraft (SSK) [41]. Two different fiber contents (8% and 16%) were used in this study, noting that higher fiber contents make compaction more difficult and thus potentially reveals any positive effects of increased compaction pressure and duration. The matrix contained equal amounts of cement and silica sand. The processing parameters considered in this study were casting pressure (1.6 and 3.2 MPa, 232 and 464 psi) and pressing time (1 hour and 24 hours). The matrix mix proportions used in this study are presented in Table 4.6.

4.7.6.1 Mechanical Properties

The effects of pressing time and pressure on flexural strength and toughness are presented in Table 4.21, and in Figures 4.48 and 4.49. Japanese standard JCI-SF [49] was used for performing the flexure tests. Flexural toughness in this study was defined as the total area under the full load-deflection curve to account for large deflection capacity of the composites.

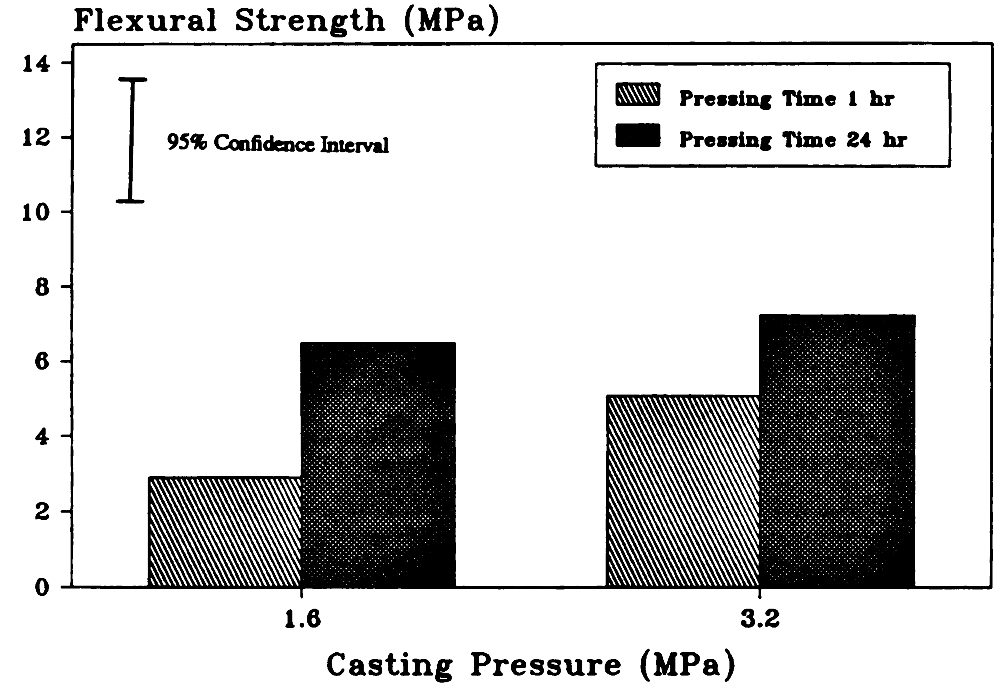
Table 4.21 Effects of Slurry-Dewatering Processing Parameters on the Flexural Performance of Wood Fiber Reinforced Cement Composites (average ± half the range of two replications)

Fiber Type and Content	Casting Pressure (MPa)	Pressing Time (hr)	Flexural Strength (MPa)	Flexural Toughness (N-mm)
8% Kraft (SSK)	1.6	1	7.4708 ± 0.241	557.60 ± 80.31
	1.6	24	9.5345 ± 0.962	460.68 ± 90.28
	3.2	1	9.3938 ± 1.202	521.31 ± 76.34
	3.2	24	10.596 ± 0.481	504.61 ± 103.2
16% Kraft (SSK)	1.6	1	2.8849 ± 0.481	808.38 ± 145.6
	1.6	24	6.4903 ± 0.721	925.08 ± 151.2
	3.2	1	5.0471 ± 0.722	831.19 ± 146.1
	3.2	24	7.2115 ± 1.442	900.01 ± 138.1



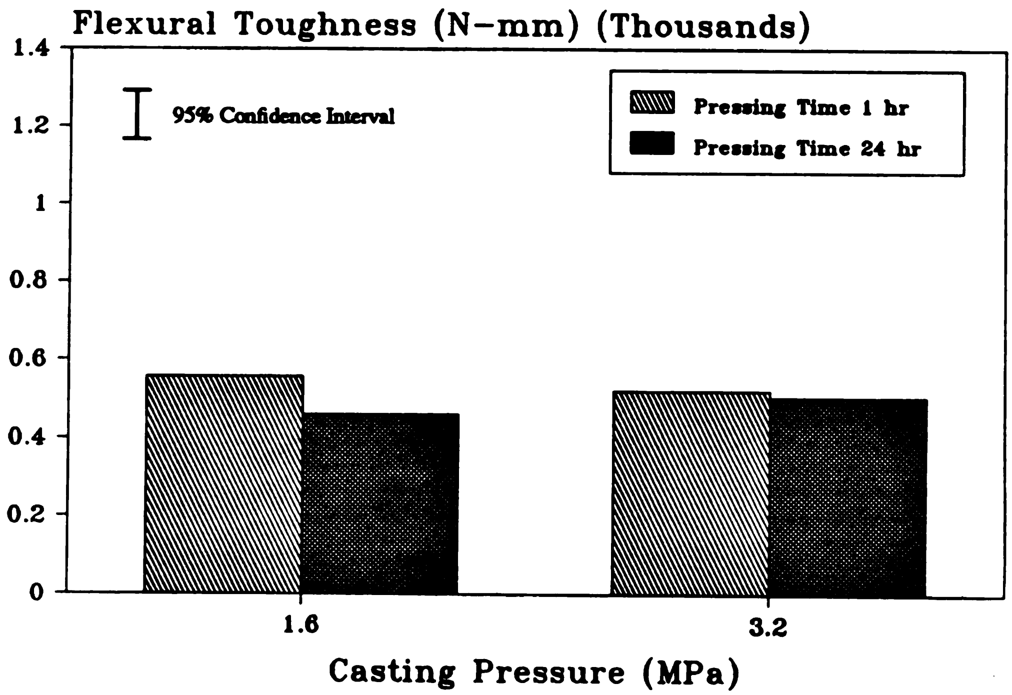
(a) Composites with 8% Fiber Content

Figure 4.48 Effects of Slurry-Dewatering Processing Parameters on the Flexural Strength of Wood Fiber Reinforced Cement Composites.



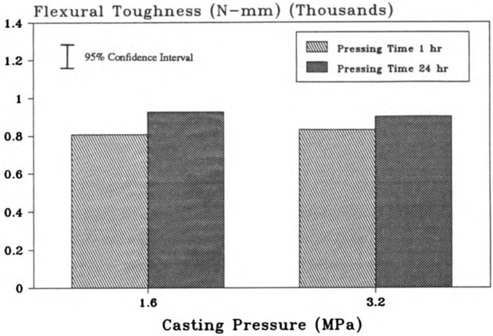
(b) Composites with 16% Fiber Content

Figure 4.48 (cont'd) Effects of Slurry-Dewatering Processing Parameters on the Flexural Strength of Wood Fiber Reinforced Cement Composites.



(a) Composites with 8% Fiber Content

Figure 4.49 Effects of Slurry-Dewatering Processing Parameters on the Flexural Toughness of Wood Fiber Reinforced Cement Composites.



(b) Composites with 16% Fiber Content

Figure 4.49 (cont'd) Effects of Slurry-Dewatering Processing Parameters on the Flexural Toughness of Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived based on the analysis of variance of test data regarding the effects of processing parameters on the flexural performance.

Flexural strength of composites dropped significantly when fiber mass fraction was increased from 8% to 16%. Flexural strength of composites containing 8% fiber mass fraction increased with increased casting pressure and pressing time (45% increase at the maximum pressure and pressing time considered). However, statistical analysis of the test data did not show any significant effect of casting pressure or pressing time at 8% fiber mass fraction on flexural strength (at 95% level of confidence). The effects of casting pressure and pressing time were more pronounced in composites containing 16% fiber content, where flexural strength increased (by more than 2 times) at the maximum casting pressure and pressing time. However, statistical analysis of the test data showed only significant effect of pressing time on flexural strength of composites with 16% fiber content at 95% level of confidence.

Flexural toughness of composites increased significantly (by about 65%) when fiber mass fraction was increased from 8% to 16%. However, flexural toughness of composites at all fiber contents remained virtually constant with increased casting pressure and pressing time. These results were confirmed statistically at 95% confidence level.

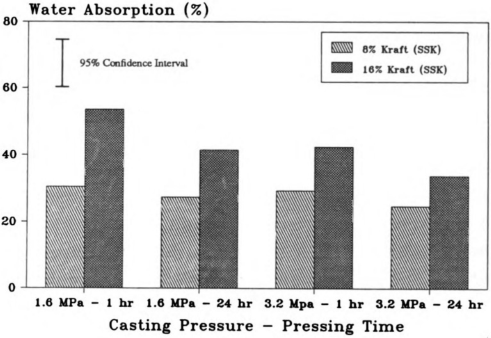
This study suggests that higher casting pressure over a sufficiently long period is essential to obtain better composites at higher fiber contents (with the period of pressing being the key variable).

4.7.6.2 Physical Properties

The effects of pressing time and pressure on water absorption and specific gravity are presented in Table 4.22 and Figure 4.50. It can be concluded from the test data that higher fiber contents (16% when compared to 8%) significantly increase water absorption and reduce specific gravity of the composite. There is a clear reduction in water absorption and increase in specific gravity of the composite with the increase in casting pressure and pressing time at all fiber contents. Composites containing 8% fiber content showed 19% reduction in water absorption and 7% increase in specific gravity when the pressing time and pressure were increased from the minimum to maximum levels. These reduction in specific gravity and increase in specific gravity were more pronounced in composites containing 16% fiber content (37% and 26%, respectively). Statistical study of the test results at 95% level of confidence confirmed the significant effects of casting pressure and pressing time on specific gravity and water absorption for composites containing 16% fiber content, while only the effect of pressing time was significant for composites containing 8% fiber content.

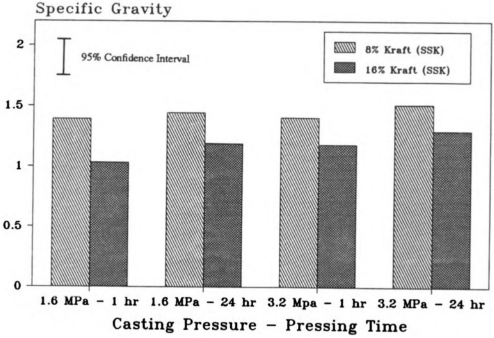
Table 4.22 Effects of Slurry-Dewatering Processing Parameters on the Physical Properties of Wood Fiber Reinforced Cement Composites (average ± half the range)

Fiber Type and Content	Casting Pressure (MPa)	Pressing Time (hr)	Water Absorption (%)	Specific Gravity
8% Kraft (SSK)	1.6	1	30.49 ± 1.21	1.391 ± 0.015
	1.6	24	27.36 ± 0.89	1.440 ± 0.021
	3.2	1	29.30 ± 0.93	1.403 ± 0.019
	3.2	24	24.72 ± 0.54	1.512 ± 0.026
16% Kraft (SSK)	1.6	1	53.56 ± 1.78	1.032 ± 0.011
	1.6	24	41.49 ± 1.27	1.189 ± 0.013
	3.2	1	42.36 ± 1.43	1.181 ± 0.018
	3.2	24	33.76 ± 1.02	1.297 ± 0.020



(a) Water Absorption

Figure 4.50 Effects of Slurry-Dewatering Processing Parameters on Water Absorption and Specific Gravity of Wood Fiber Reinforced Cement Composites.



(b) Specific Gravity

Figure 4.50 (cont'd) Effects of Slurry-Dewatering Processing Parameters on Water Absorption and Specific Gravity of Wood Fiber Reinforced Cement Composites.

4.7.7 Combination with Synthetic Fibers

The fibers used in this study were Southern Softwood Kraft (SSK) [41] and Polyethylene Pulp (PulPlus) [48]. The composites were manufactured using the slurry-dewatering technique, and the combined (total) fiber content was kept constant 8% by mass. The matrix mix proportions used in this study are presented in Table 4.7. The effects of wood and synthetic fiber reinforcement on the flexural load-deflection behavior of cement-based materials are shown in Figure 4.51. A comparison of the test results on flexural performance of composites containing different combinations of wood and synthetic fibers are presented in Table 4.23 and Figure 4.52.

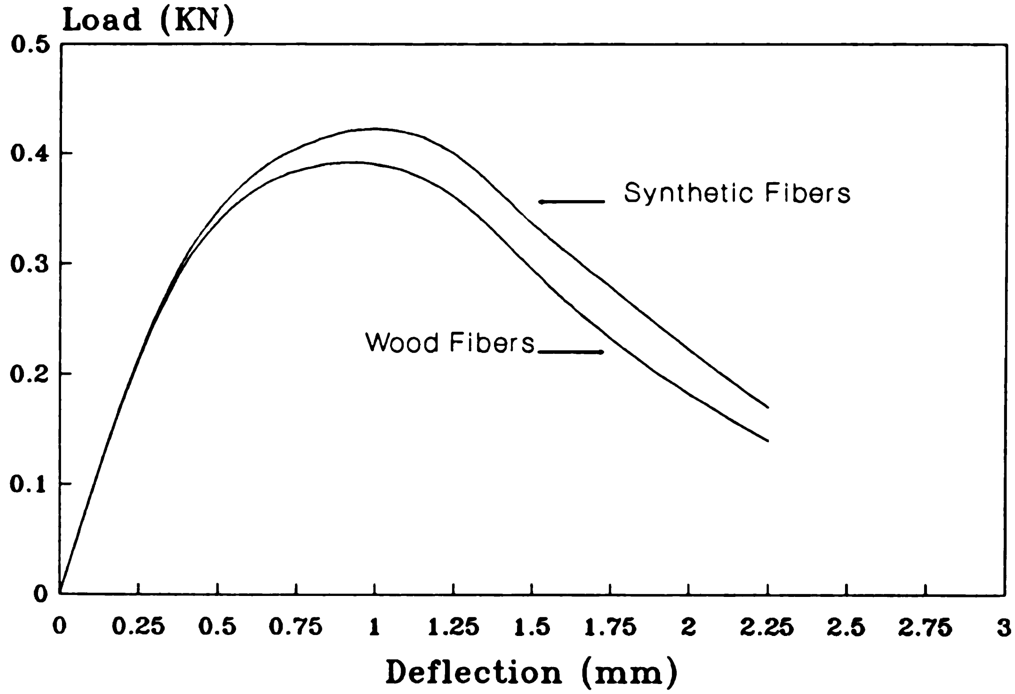
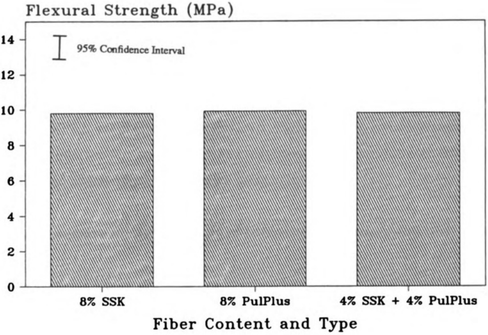


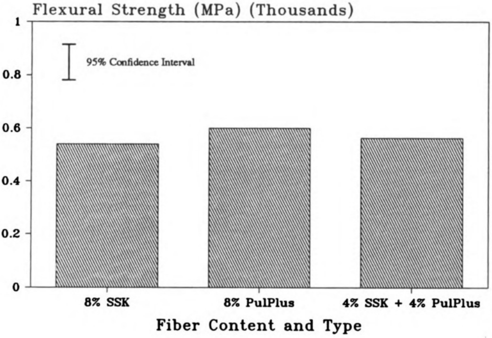
Figure 4.51 Flexural Load-Deflection of Composites Containing Synthetic and Wood Fibers.

Table 4.23 Flexural Performance of Composites Containing Synthetic and Wood Fibers (average ± half the range of two replications)

Fiber Type and Content	Flexural Strength (MPa)	Flexural Toughness (N-mm)
8% Kraft Pulp (SSK)	9.8051 ± 0.968	540.01 ± 80.62
8% Polyethylene Pulp (PulPlus)	9.9237 ± 0.535	600.05 ± 93.89
4% Kraft Pulp (SSK) & 4% Polyethylene Pulp (PulPlus)	9.8137± 0.574	562.90 ± 105.1



(a) Flexural Strength



(b) Flexural Toughness

Figure 4.52 Flexural Performance of Composites Containing Synthetic and Wood Fibers.

Cement composites containing synthetic and wood fibers show comparable flexural strengths. However, composites containing synthetic fibers showed a slight increase in flexural toughness (by about 10%). Composites containing equal quantities of synthetic and wood fibers also showed slightly better flexural toughness. Statistical analysis of the test results at 95% level of confidence, however, indicated that, considering random experimental variations, the flexural strength and toughness of composites with different combinations of wood and synthetic fibers were comparable.

4.7.8 Comprehensive Statistical Study of Different Parameters and their Effects

This section presents the results of a comprehensive statistical investigation of different parameters and their effects on water absorption, specific gravity and moisture movement. An experimental program was developed based on the statistical method of fractional factorial design. The composites were manufactured using the slurry-dewatering technique. The variables of the experimental study were: (1) wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash or 15% silica fume); and (4) silica sand content (silica sand-cement ratio = 0.5 & 1.0). Test results on specific gravity, water absorption and moisture movement are presented in Table 4.24.

Table 4.24 Specific Gravity, Water Absorption and Moisture Movement of Wood Fiber Reinforced Cement Composites - Comprehensive Statistical Study (average ± half the range)*

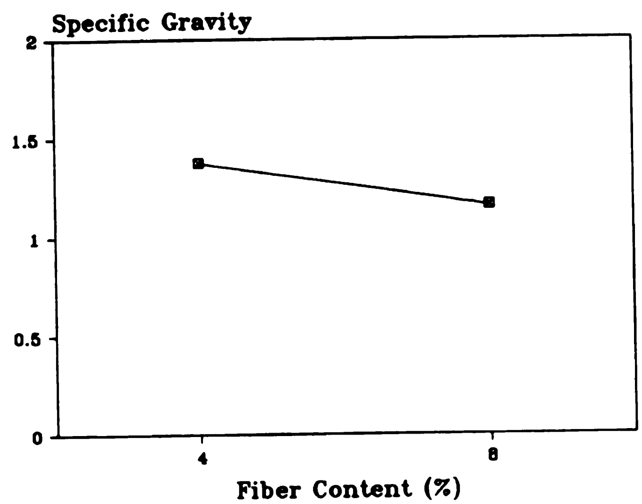
Mix	1	2	3	4	5	6	7	8
Fiber Type	SSK	NHK	NHK	NHK	NHK	NHK	NHK	SSK
Fiber Content (%)	8	8	8	4	8	4	8	4
Binder	SF	FA	SF	FA	SF	FA	FA	FA
Batch	1	2	1	1	2	2	1	2
Sand Content (S/B)	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0
Specific Gravity	1.251 ±0.02	0.925 ±0.03	1.233 ±0.01	1.377 ±0.00	1.221 ±0.01	1.338 ±0.01	1.055 ±0.01	1.401 ±0.03
Water Absorption (%)	33.15 ±1.32	53.87 ±2.16	32.52 ±1.17	26.37 ±0.83	33.53 ±1.02	29.14 ±0.47	45.40 ±0.84	25.95 ±0.25
Moisture Movement (%)	0.242 ±0.04	0.410 ±0.05	0.137 ±0.03	0.198 ±0.03	0.344 ±0.00	0.372 ±0.04	0.312 ±0.04	0.108 ±0.01
Mix	9	10	11	12	13	14	15	16
Fiber Type	SSK	SSK	NHK	NHK	SSK	SSK	SSK	SSK
Fiber Content (%)	8	4	4	4	8	8	4	4
Binder	FA	SF	SF	SF	FA	SF	SF	FA
Batch	1	1	1	2	2	2	2	1
Sand Content (S/B)	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5
Specific Gravity	1.21 ±0.00	1.306 ±0.02	1.342 ±0.01	1.412 ±0.01	1.10 ±0.04	1.27 ±0.00	1.435 ±0.01	1.389 ±0.04
Water Absorption (%)	30.31 ±4.98	31.28 ±1.38	29.35 ±1.46	26.04 ±1.37	42.64 ±2.34	31.27 ±0.27	26.28 ±0.10	27.37 ±1.85
Moisture Movement (%)	0.373 ±0.02	0.167 ±0.03	0.261 ±0.05	0.316 ±0.01	0.283 ±0.03	0.402 ±0.00	0.256 ±0.02	0.278 ±0.03

* see Appendix B for notation

The following conclusions could be derived from statistical fractional factorial analysis of the test data regarding the effects of different parameters considered in this study.

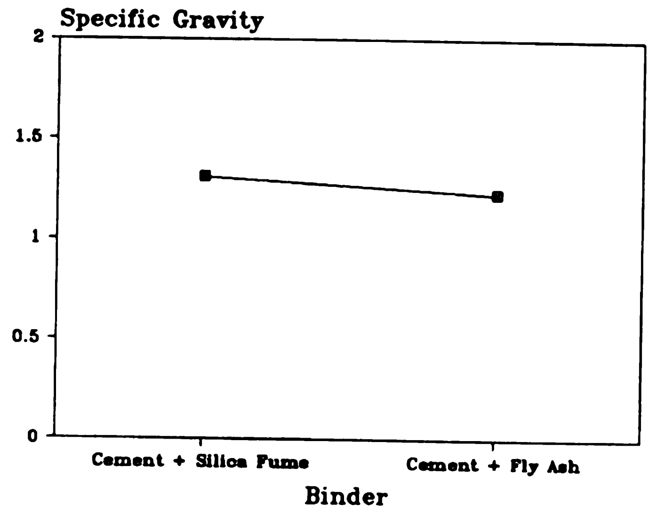
4.7.8.1 Specific Gravity

Addition of wood fibers to cementitious matrix reduces the specific gravity of the composite. Fiber content had a statistically significant effect on the specific gravity of the composite (at 95% level of confidence); increasing the fiber content from 4% to 8% mass fraction produced composites with lower specific gravity (Figure 4.53 a). Type of binder (partial substitution of cement with 15% silica fume or 30% fly ash) also had statistically significant effects on the specific gravity of the composites (at 95% confidence level). Composites containing silica fume showed higher values of specific gravity when compared to those containing fly ash (Figure 4.53 b). There was also a strong interaction between fiber content and binder, indicating that the binder type modifies the effects of fibers on specific gravity. The other parameters considered in this study (fiber type or sand content) did not show any significant effects on specific gravity.



(a) Fiber Content

Figure 4.53 Effects of Fiber Content and Binder on Specific Gravity of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

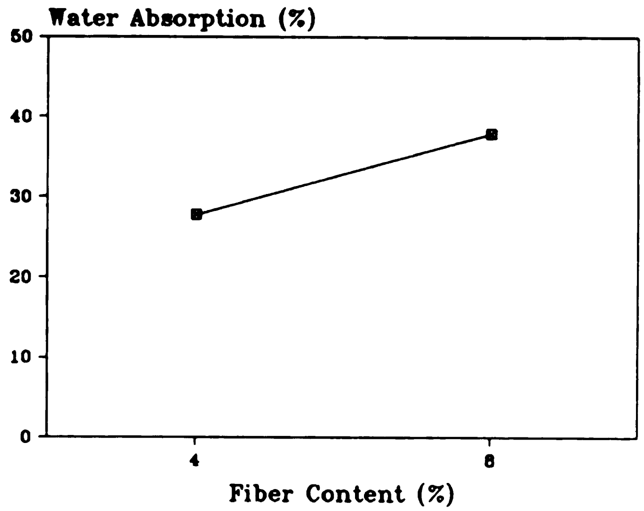


(b) Binder Type

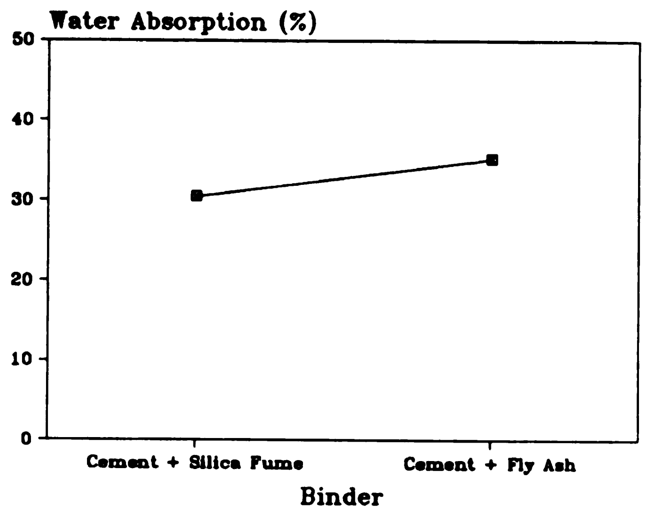
Figure 4.53 (cont'd) Effects of Fiber Content and Binder on Specific Gravity of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

4.7.8.2 Water Absorption

Fiber content and binder type both had statistically significant effects (at 95% level of confidence) on the water absorption capacity of wood fiber reinforced cement composites (Figure 4.54). The increase in fiber content from 4% to 8% led to an increase in the water absorption of the composites. Partial substitution of cement with silica fume produced composites with lower water absorption when compared to those containing fly ash. There was also a strong interaction between fiber content and binder type. The other parameters considered in this study (fiber type or sand content) did not show any significant effects on water absorption.



(a) Fiber Content



(b) Binder Type

Figure 4.54 Effects of Fiber Content and Binder on Water Absorption of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

Figure 4.55 presents the relationship between specific gravity and water absorption. A correlation coefficient of -0.968 was obtained for the results, indicating a very strong negative correlation between specific gravity and water absorption. Composites with a higher specific gravity tend to have a lower water absorption capacity.

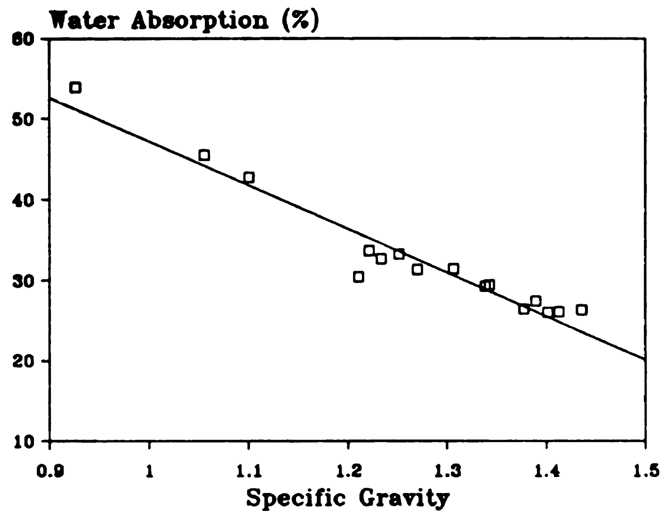


Figure 4.55 Relationship between Specific Gravity and Water Absorption.

4.7.8.3 Moisture Movement

Moisture movement is a serviceability requirement of composites in areas subjected to moisture changes. Moisture movement is reported as percent change in length based on the lengths at 30% and 90% relative humidity.

Fiber content had statistically significant (adverse) effects, at 95% level of confidence, on moisture movement of wood fiber reinforced cement composites (Figure 4.56). An increase in fiber content from 4% to 8% increased the moisture movements. There was also a strong interaction between fiber content and sand content; the increase in moisture movement with increasing fiber content was less pronounced at higher sand content. Partial substitution of cement with pozzolan (15% silica fume or 30% fly ash), fiber type (softwood kraft or hardwood kraft), and sand content did not show any significant effects on moisture movements.

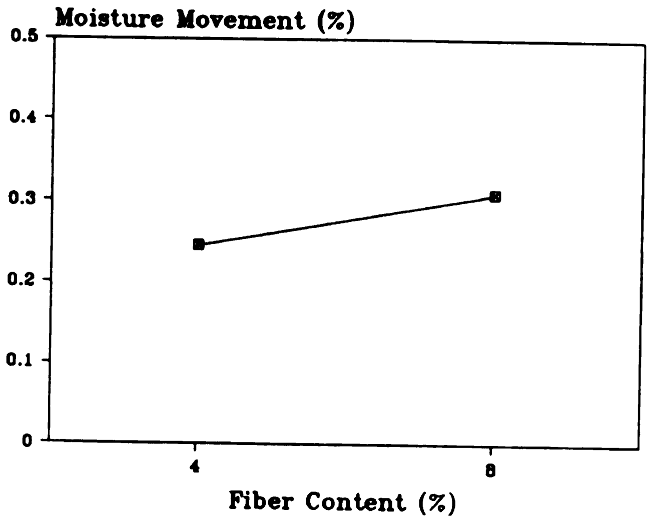


Figure 4.56 Effects of Fiber Content on Moisture Movement of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

MOISTURE-SENSITIVITY AND LONG-TERM DURABILITY CHARACTERISTICS OF WOOD FIBER REINFORCED CEMENT COMPOSITES

Volume II

By

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DOCTOR OF PHILOSOPHY

Department of Civil & Environmental Engineering

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CHAPTER 5

MOISTURE-SENSITIVITY OF WOOD FIBER REINFORCED CEMENT COMPOSITES

5.1 INTRODUCTION

Rapid drying of cement-based materials may induce tensile cracks due to non-uniform drying (and hence differences in drying shrinkage) of the specimen. The cracks do not have much effect on compressive strength but will lower the flexural and tensile strengths [52, 53]. If drying takes place very slowly, so that internal stresses can be redistributed and alleviated by creep, an increase in strength may result from drying.

Wetting of concrete may lead to losses in compressive strength as a result of the dilation of cement gel by adsorbed water and also breaking of Si-O-Si bonds, which lead to reduction of the cohesion between solid particles. Conversely, when the wedge-action of water upon drying ceases, an apparent increase in strength of the specimen is recorded. Resoaking of oven-dried specimens in water reduces their strength to the value of continuously wet-cured specimens, provided they have been hydrated to the same degree. The variation in strength due to drying is thus a reversible phenomenon.

Wood fiber reinforced cement composites are much more sensitive to moisture variations than would be expected from the above moisture effects. Considerable differences in flexural strength and fracture toughness values are observed when the specimens are tested at different moisture contents. There is a general tendency in flexural strength to decrease and flexural toughness to increase with increasing moisture content in wood fiber reinforced cement composites [13, 24]. This has been attributed to moisture effects on the interface zones and wood fibers [20, 40].

5.2 OBJECTIVES

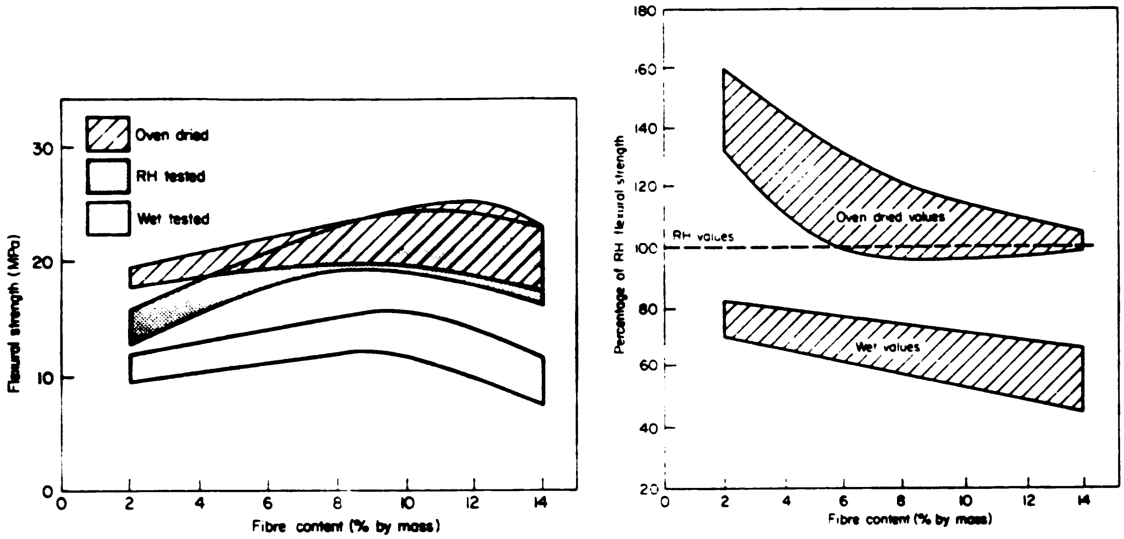
The main thrust in this phase of research was to assess the moisture sensitivity of wood fiber reinforced cement composites. Flexural behavior of the composites subjected to different moisture conditions were studied and the fracture surfaces were observed under a Scanning Electron Microscope in order to assess the failure mechanisms. For this purpose, three different moisture conditions were selected: the specimens after normal air curing for 28 days were air-dried, oven-dried or saturated before being tested for flexural performance. An effort was also made to modify the matrix through partial substitution of cement with pozzolans (fly ash or silica fume) and latex in order to reduce the moisture-sensitivity of composites. The results obtained in this study were analyzed statistically using the analysis of variance and multiple comparison techniques in order to derive statistically reliable conclusions.

5.3 BACKGROUND

Wood fiber reinforced cement composites are highly sensitive to moisture variations. Considerable differences in flexural strength and fracture toughness values are observed when the specimens are tested at different moisture contents. There is a general tendency in flexural strength to decrease and in flexural toughness to increase with increasing moisture content in wood fiber reinforced cement composites.

Coutts (1984) [13] reports flexural test results for wood fiber reinforced cement at different moisture contents. The composites were manufactured by slurry-dewatering and contained various amounts of softwood P. Radiata kraft fibers. The composites (silica sand-cement ratio = 1) were either air cured in an atmosphere with 50 $\pm$ 5% relative humidity or autoclaved for 8 hours at 0.86 MPa (124 psi) under steam pressure, and then exposed to air until the test age. Standard pretesting conditions were established in Coutts (1984) [13] in order to study the moisture effects. The samples were stored: (a) in the laboratory with relative humidity of 50 $\pm$ 5% and temperature of 22 $\pm$ 2 deg. C (72 $\pm$ 3 deg. F); (b) in an oven at 116 deg. C (241 deg. F) for 24 hours and then cooled in the atmosphere; and (c) in water for 48 hours, with excess water removed with a cloth prior to testing.

Test results indicated that wet fiber reinforced cement mortar samples showed about 50% reduction in flexural strength over that of specimens tested at 50% relative humidity. On the other hand, oven drying has been observed to slightly increase the flexural strength of wood fiber cement composites. Figures 5.1 (a) and (b) show the variations in flexural strength at various fiber loadings with moisture content. Figure 5.1 (b) is an alternative representation of Figure 5.1 (a) in which the flexural strength of oven dried and wet tested samples are given as a percentage of the flexural strength of the same composites when tested at ambient relative humidity and temperature. Relatively large variations in test results of Figure 5.1 partly result from the fact that these tests cover fibers with different degrees of beating (e.g. Freeness ranged from 700-60 CSF). From Figure 5.1 it may be concluded that the oven dried specimens have higher strengths than the relative humidity specimens only at fiber contents below 6% by mass. The oven dried and relative humidity specimens give comparable flexural strengths at higher fiber contents. This observation is justified by Coutts (1984) [13] who notes that at low fiber contents (<6%), the number of bonds between fibers is small by comparison with the number of fiber-to-matrix bonds. It could be implied from Figure 5.1 that greater loads are needed to break the oven-dried fiber-to-matrix bond than the same bond at relative humidity. As the fiber content is increased (>6%) there is an increase in void content and greater number of fiber-to-fiber bonds are formed. The increase in fiber to fiber bonds uses up more of the fiber surface area and reduces fiber-to-matrix bonding. The increase in void content also reduces the interfacial area of contact between fiber and matrix and so diminishes the potential for a given fiber to be able to bond to the matrix. Hence, at increasing fiber contents there is a general overlap of flexural strength for oven dried and relative humidity samples. The wet tested samples continue to decrease in flexural strength due to the increasing role of fiber-to-fiber bond (hydrogen bonds, which could be destroyed in the presence of moisture) in carrying an increased component of the load in the composite.



(a) Flexural Strength

(b) Percentage of RH Tested Flexural Strengths

Figure 5.1 Effects of Moisture Content on the Flexural Strength of Mortars Reinforced with Different Mass Fractions of P. Radiata Kraft Pulp [13].

The effects of moisture content on the fracture toughness of fiber reinforced mortars are shown in Figure 5.2. At lower fiber contents (<6% by mass) the wet and relative humidity (50%) tested specimens give comparable fracture toughness values, while oven dried samples generally give very low fracture toughness (noting that flexural strengths is usually high for oven dried samples). This has been attributed by Coutts et al. (1984) [20] and Coutts et al. (1982) [25] to the dominance of fiber fracture in deciding the failure mechanism of oven dried samples while a combination of fiber pullout and fiber fracture tends to occur as moisture contents increases (as indicated by scanning electron microscope examination).

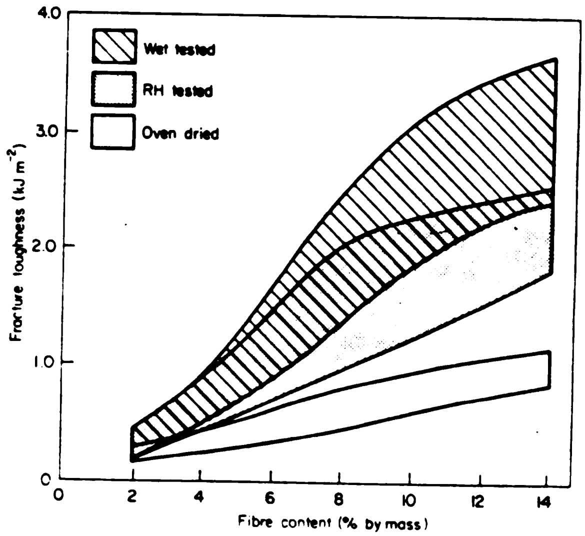
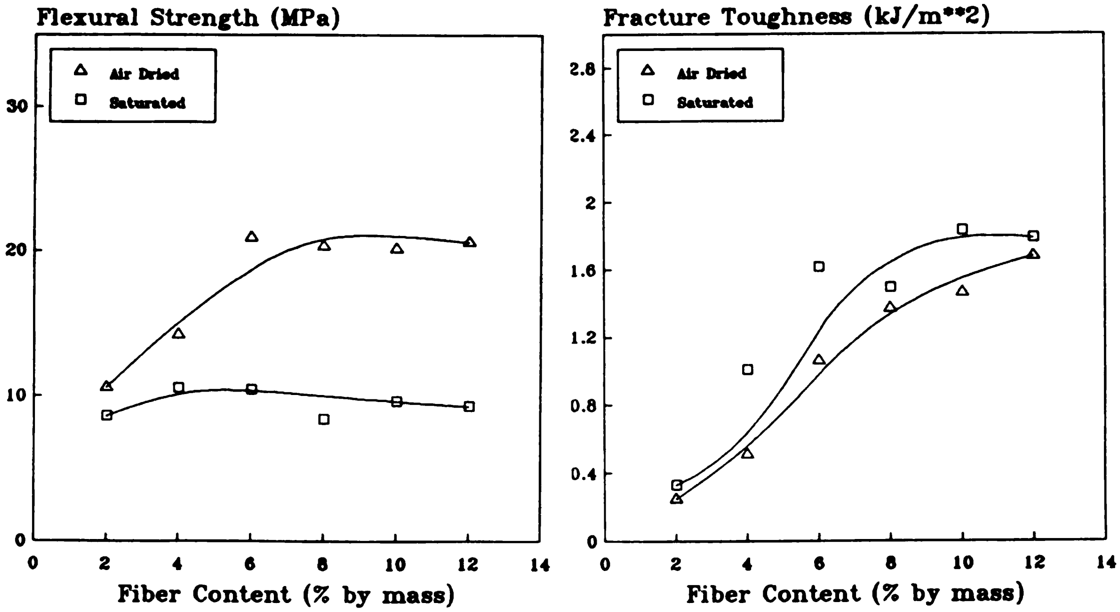


Figure 5.2 Effects of Moisture Content on the Fracture Toughness of Mortars Reinforced with Different Mass Fractions of P. Radiata Kraft Pulp [13].

Coutts (1987) [29] has reported the effects of moisture content on composites containing E. Regnans (hardwood) fiber. The effects of moisture content on flexural strength and toughness are shown in Figure 5.3. When tested wet, the flexural strength of composites containing E. Regnans drops to approximately 50% of the dry tested specimens. It is interesting to note that wetting of cement composites incorporating hardwood fibers does not produce as much increase in fracture toughness as obtained through wetting of composites incorporating softwood fibers (compare Figure 5.3 b for E. Regnans hardwood fibers with Figure 5.2 for P. Radiata softwood).

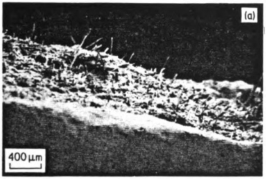


(a) Flexural Strength (b) Fracture Toughness

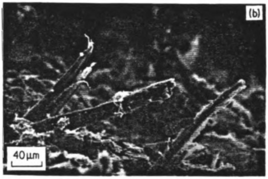
Figure 5.3 Effects of Moisture Content on the Flexural Performance of Autoclaved Cement Composites Incorporating Different Mass Fractions of E. Regnans (Eucalyptus) Hardwood [29].

Microstructural studies on the effects of moisture content on the failure mechanism of wood fiber reinforced cement composites have been reported by Coutts et al. (1984) [20]. The cement composites in this reference were reinforced with P. Radiata kraft pulp. The specimens were manufactured by slurry-dewatering technique and were cured in an autoclave. They were conditioned in 3 different environments prior to the flexure tests: (1) at 50 $\pm$ 5% relative humidity and 22 $\pm$ 2 deg. C (72 $\pm$ 3 deg. F); (2) at 100 to 105 deg. C (212 to 221 deg. F) for 24 hours and then cooled in a desiccator; (3) under water for 48 hours with excess water removed with a cloth prior to testing. A relatively low fiber content (2% by mass) was used in this study in order to reduce the potential problems with SEM analysis of surfaces with high fiber contents.

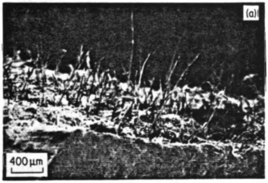
The failure mechanism of the oven dried specimens was dominated by the fracture of fibers (Figure 5.4 a), and the matrix attached to the exposed part of the fiber surfaces was indicative of a strong bonding between the fibers and the matrix Figure 5.4 b). The water saturated specimens showed failure mechanisms dominated by fiber pullout, with some twisting of the pulled out fibers (Figure 5.4 c). The twisting of fibers under tension has also been reported by Page et al. (1971) [22] due to the collapse of hollow wood fibers under tension. As shown in Figure 5.4 d, the protruding parts of fibers at the fracture surface of water saturated specimens were largely devoid of the adhering matrix, which is indicative of weak fiber-matrix bonding. This Figure also shows that many of the fibers were broken, even the ones with long protruding segments. It also seems that the collapsed kraft fibers remain collapsed in cement composite and do not swell open during fabrication. In the case of composites conditioned at 50 ± 5% relative humidity (Figure 5.4 e), both fiber fracture and fiber pullout are observed to have taken place. At a higher magnification in Figure 5.4 f, considerable damage to some fibers of relatively short protruding length and some pulling out of fibers can be observed.



(a) Oven Dried-Lower Magnification



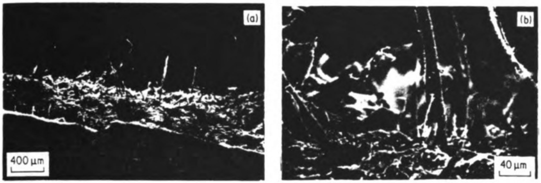
(b) Oven Dried-Higher Magnification



(c) Water Saturated-Lower Magnification

(d) Water Saturated-Higher Magnification

Figure 5.4 Typical SEM Micrographs of Fracture Surfaces of Cement Composites Reinforced with 2% Mass Fraction of P. Radiata Kraft Pulp [20].



(e) Preconditioned at 50 ± 5% RH-
Lower Magnification

(f) Preconditioned at 50 ± 5% RH-
Higher Magnification

Figure 5.4 (cont'd) Typical SEM Micrographs of Fracture Surfaces of Cement Composites Reinforced with 2% Mass Fraction of P. Radiata Kraft Pulp [20].

5.4 EXPERIMENTAL DESIGN

In this phase of the research, the moisture-sensitivity of wood fiber reinforced cement composites was assessed. For this purpose, the following tasks were performed regarding the moisture effects on the flexural performance of wood fiber-cement composites: (a) assess the effect of fiber type and content on moisture-sensitivity; (b) modify the matrix with pozzolanic admixtures and latex to enhance stability under moisture effects; (c) study the effects of bleaching on moisture-sensitivity; (d) modify the processing variables in manufacturing to induce stability under moisture effects; (e) combine wood fibers with synthetic fibers to reduce moisture-sensitivity; and (h) comprehensive statistical study of the effects of different parameters specific to wood fiber reinforced composites with emphasis on moisture resistance.

Replicated test specimens were manufactured from each mix in order to derive reliable conclusions through statistical analyses of results. The dimensions and the number of specimens depend on the specific tests performed. In case of panels, the test specimen had to be cut using a diamond saw to the required dimensions.

5.4.1 Effects of Fiber Type and Content

The wood fibers used in this investigation were Southern Softwood Kraft (SSK) [41] and Mechanical Pulp (1000L) [43]. The effects of wood fiber type and content on moisture resistance were investigated in two stages: (a) with composites containing lower fiber contents (≤ 2%) manufactured through molding method; and (b) with composites containing higher fiber contents (≥ 4%) manufactured through slurry-dewatering. The fiber mass fractions and matrix mix proportions used in this phase of the study are introduced in Table 4.3. The experimental design used in this study is presented in Table 5.1. In the molding method of manufacture, water and superplasticizer contents were varied in order to achieve reasonable fresh mix workability characteristics represented by a flow (ASTM C-230) of 55% to 65% at 1 minute after mixing. Fibrous mixtures also contained a non-chloride set accelerator [45], which was essential to keep the setting time of composites within acceptable limits. In the slurry-dewatering method of manufacture, thin-sheet specimens were formed from a dilute slurry of approximately 20% solids. A relatively small dosage of 1% diluted flocculent (flocculent/cement=0.01) [46] was added to achieve agglomeration of cement solids in the slurry, which helps in reducing the amount of cement particles lost through the filtering screens during dewatering. Fiber mass fraction in slurry-dewatered composites is defined as the ratio of weight of fibers to that of the dry constituents of the matrix. From each mix wood fiber reinforced cement composites were manufactured for flexural testing in the hardened state. Molded flexural specimens were prisms with 38.1 mm (1.5 in) square cross sections and total length of 152.4 mm (6 in), tested by 4-point loading on a span of 114.3 mm (4.5 in). An average of 10 specimens with a specific mix design were manufactured for tests at each moisture condition. The specimens were selected from two different batches in order to accurately measure variability of the results. Thin sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method at higher fiber contents. Flexural specimens (38.1 x 125 x 10 mm, 1.5 x 5.0

x 0.4 in) were then cut out from each panel using a diamond saw, and an average of 3 specimens were tested for each moisture condition.

Table 5.1 Experimental Design for Moisture-Sensitivity - Effect of Wood Fiber Type and Content

(a) Molding Method

Fiber Type	Fiber Content	Moisture Condition		
		Air Dried	Oven Dried	Saturated
-	0	*	*	*
Kraft (SSK)	1	*	*	*
	2	*	*	*
Mech. (1000L)	1	*	*	*
	2	*	*	*

(b) Slurry-Dewatering Method

Fiber Type	Fiber Content	Moisture Condition		
		Air Dried	Oven Dried	Saturated
Kraft (SSK)	4	*	*	*
	6	*	*	*
	8	*	*	*
	10	*	*	*
	12	*	*	*
	14	*	*	*

5.4.2 Matrix Modification

The fiber used in this study was Southern Softwood Kraft (SSK) [41]. The samples contained an optimum fiber content (2% for molding method and 8% for slurry-dewatering). The matrix modification was achieved through partial substitution of cement with pozzolanic admixtures (15% silica fume or 30% fly ash). In case of molding technique it was also considered to modify the matrix by a Styrene Butadiene latex polymer. The fiber mass fraction and matrix mix proportions are introduced in Table 4.4. From each mix wood fiber reinforced cement composites were manufactured for flexural testing in the hardened state. Molded flexural specimens were prisms with 38.1 (1.5 in) square cross sections and total length of 152.4 mm (6 in), tested by 4-point loading on a span of 114.3 mm (4.5 in). An average of 10 specimens with a specific mix design were manufactured for tests at each moisture condition. The specimens were selected from two different batches in order to accurately measure variability of the results. Thin sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method at higher fiber contents. Flexural specimens (38.1 x 125 x 10 mm, 1.5 x 5 x 0.4 in) were then cut out from each panel using a diamond saw, and an average of 3 specimens were tested for each moisture condition.

Table 5.2 Experimental Design for Moisture-Sensitivity - Effect of Matrix Modification

(a) Molding Method

Fiber Type & Content	Matrix Modification	Moisture Condition		
		Air Dried	Oven Dried	Saturated
Kraft (SSK) 2% by Weight	-	*	*	*
	15% Silica Fume	*	*	*
	30% Fly Ash	*	*	*
	10% Latex	*	*	*

(b) Slurry-Dewatering Method

Fiber Type & Content	Matrix Modification	Moisture Condition		
		Air Dried	Oven Dried	Saturated
Kraft (SSK) 8% by Weight	-	*	*	*
	15% Silica Fume	*	*	*
	30% Fly Ash	*	*	*

5.4.3 Effect of Bleaching

The fibers used in this study were unbleached and bleached Southern Softwood Kraft (SSK) [41]. The composites were manufactured using the molding technique, and the fiber content was 2% by mass. The matrix mix proportions used in this study are given in Table 4.5. The experimental design is presented in Table 5.3. Molded flexural specimens were prisms with 38.1 square cross sections and total length of 152.4 mm, tested by 4-point loading on a span of 114.3 mm. An average of 10 specimens with a specific mix design were manufactured for tests at each moisture condition. The specimens were selected from two different batches in order to accurately measure variability of the results.

Table 5.3 Experimental Design for Moisture-Sensitivity - Effect of Bleaching

Fiber Type & Content	Moisture Condition	
	Air Dried	Saturated
Kraft (SSK) Bleached 2% by Weight	*	*
Kraft (SSK) Unbleached 2% by Weight	*	*

5.4.4 Modification of Processing Parameters in Slurry-Dewatering Technique

The fiber used in this study was Southern Softwood Kraft (SSK) [41]. Two different fiber contents (8% and 16%) were used in this study. The matrix contained equal amounts of cement and silica sand. The processing parameters considered in this study were the casting pressure (1.6 and 3.2 MPa, 232 and 464 psi) and pressing time (1 hour and 24 hours). The matrix mix proportions used in this study are given in Table 4.6. The experimental design is presented in Table 5.4. Two replicated thin-sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method. Three specimens for flexural testing (38.1 x 125 x 10 mm, 1.5 x 5.0 x 0.4 in) were then cut using a diamond saw. An average of 6 specimens with specific mix design were selected from two different batches and tested for each moisture condition.

Table 5.4 Experimental Design for Moisture-Sensitivity - Effect of Modification of Processing Parameters in Slurry-Dewatering

Fiber Type & Content	Casting Pressure (MPa)	Pressing Time (hr)	Moisture Condition	
			Air Dried	Saturated
Kraft (SSK) 8% by Weight	1.6	1	*	*
		24	*	*
	3.2	1	*	*
		24	*	*
Kraft (SSK) 16% by Weight	1.6	1	*	*
		24	*	*
	3.2	1	*	*
		24	*	*

5.4.5 Combination with Synthetic Fibers

The fibers used in this study were Southern Softwood Kraft (SSK) [41] and Polyethylene Pulp (PulPlus) [48]. The composites were manufactured by slurry-dewatering, and the combined fiber content was kept at an optimum value of 8% by mass. The matrix mix proportions used in this study are given in Table 4.7. The experimental program is presented in Table 5.5. Two replicated thin-sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method. Three specimens for flexural testing (38.1 x 125 x 10 mm, 1.5 x 5.0 x 0.4 in) were then cut using a diamond saw. An average of 6 specimens with specific mix design were selected from two different batches and tested for each moisture condition.

Table 5.5 Experimental Design for Moisture-Sensitivity - Effect of Combination with Synthetic Fibers

Fiber Type and Content	Moisture Condition	
	Air Dried	Saturated
8% Kraft Pulp (SSK)	*	*
4% Kraft Pulp (SSK) + 4% Polyethylene Pulp (PulPlus)	*	*
8% Polyethylene Pulp (PulPlus)	*	*

5.4.6 Comprehensive Statistical Study of Different Parameters and their Effects

An experimental program was developed based on the statistical method of fractional factorial design. The composites were manufactured by slurry-dewatering. The variables of the experimental study were: (1) wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash & 15% silica fume); (4) moisture conditions (air dried & saturated); and (5) silica sand content (silica sand-cement ratio = 0.5 & 1.0). The experimental program is presented in Table 5.6. Two replicated thin-sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufactured from each mix using slurry-dewatering method. Three specimens for flexural testing (38.1 x 125 x 10 mm, 1.5 x 5.0 x 0.4 in) were then cut using a diamond saw. An average of 6 specimens with specific mix design were selected from two different batches and tested for each moisture condition.

Table 5.6 Experimental Design for Moisture-Sensitivity - Comprehensive Statistical Study (see Appendix B for notation)

Mix	1	2	3	4	5	6	7	8
Fiber Type	SSK	NHK	NHK	NHK	NHK	NHK	NHK	SSK
Fiber Content (%)	8	8	8	4	8	4	8	4
Binder	SF	FA	SF	FA	SF	FA	FA	FA
Moisture Condition	AD	SAT	AD	AD	SAT	SAT	AD	SAT
Sand Content (S/B)	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0
Mix	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Fiber Type	SSK	SSK	NHK	NHK	SSK	SSK	SSK	SSK
Fiber Content (%)	8	4	4	4	8	8	4	4
Binder	FA	SF	SF	SF	FA	SF	SF	FA
Moisture Condition	AD	AD	AD	SAT	SAT	SAT	SAT	AD
Sand Content (S/B)	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5

5.5 MANUFACTURING PROCEDURE

Wood fiber reinforced cement composites at low fiber mass fractions (≤ 2%) were manufactured through the molding technique, and at high fiber contents (> 2%) through slurry-dewatering. Molding method of mixing was performed in a regular mortar mixer. A batch-type slurry-dewatering equipment (simulation of the Hatschek process) was developed for use in laboratory. The mixing procedure adopted for the two different techniques are described in Chapter 4.

5.6 TEST PROCEDURES

A series of standard moisture conditions for flexural testing were established for the 28 day old specimens in order to investigate the effects of moisture content. Samples were conditioned in the following environments: (a) in laboratory with Relative Humidity of 50

$\pm$ 10% and temperature of 22 $\pm$ 2 deg. C (72 $\pm$ 3 deg. F); (b) in an oven at 116 deg. C (241 deg. F) for 24 hours and then cooled in the laboratory; and (c) in water for 48 hours with excess water removed by a cloth prior to testing. Flexural tests were performed according to the Japanese Specification JCI-SF [49].

5.7 TEST RESULTS AND DISCUSSIONS

5.7.1 Effects of Fiber Type and Content

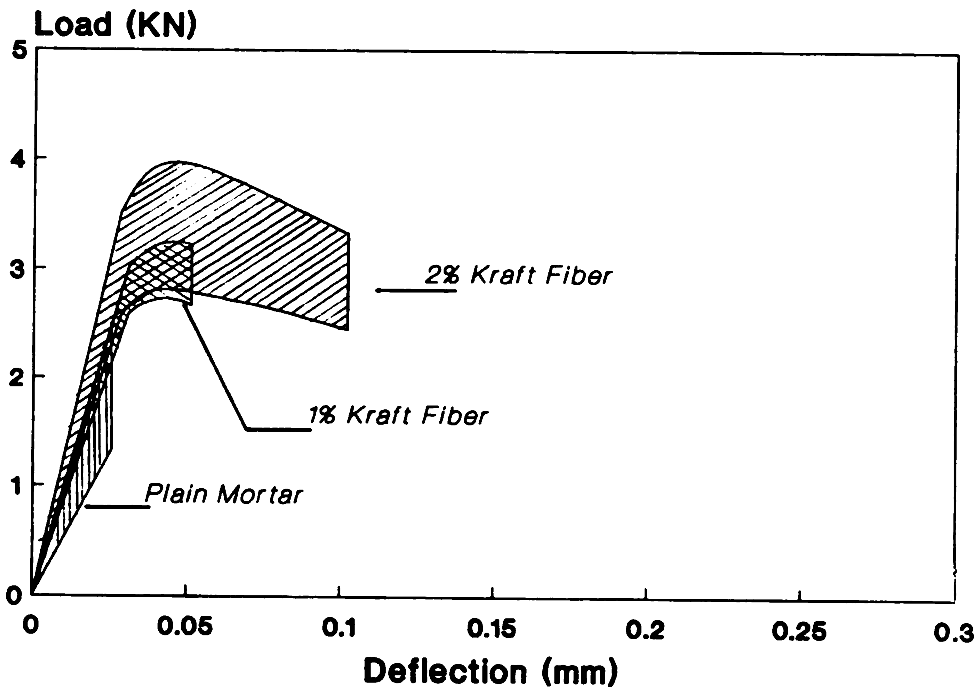
The effects of fiber content and moisture condition on the flexural behavior of composites with different wood fiber types were investigated in two stages: (a) for composites containing low fiber contents (< 2%) manufactured through molding method; and (b) for composites containing high fiber contents (> 4%) manufactured through slurry-dewatering.

Wood fiber reinforced cement composites were tested for their flexural performance in this investigation. A series of standard moisture conditions for flexural testing were established for the 28 days old specimens in order to investigate the effects of moisture content. Samples were conditioned in the following environments: (a) in laboratory with Relative Humidity of 50 $\pm$ 10% and temperature of 22 $\pm$ 2 deg. C (72 $\pm$ 3 deg. F); (b) in an oven at 116 deg. C (241 deg. F) for 24 hours and then cooled in the laboratory; and (c) in water for 48 hours with excess water removed by a cloth prior to testing. Flexural tests were performed according to the Japanese Specification JCI-SF4.

5.7.1.1 Molding Method

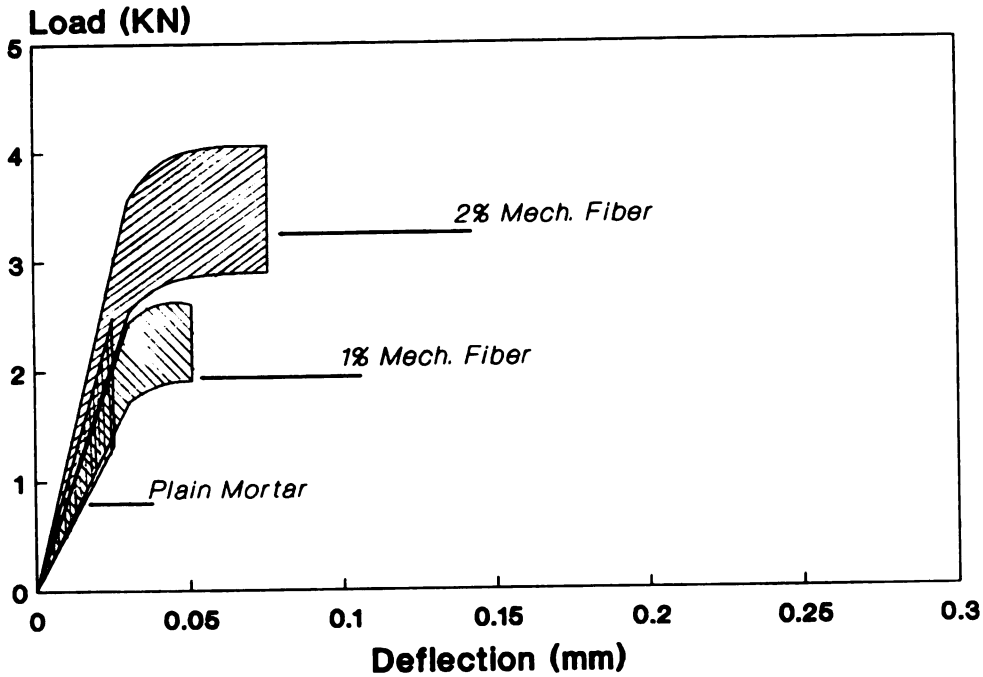
This section presents the effects of wood fiber content and type, and the composite moisture condition on the flexural performance of cement based materials using the test data generated in this investigation. The wood fibers used were Southern Softwood Kraft Pulp (SSK) [41] and Mechanical Pulp (1000L) [43]. The fiber mass fractions and matrix mix proportions used in this phase of the study are introduced in Table 4.3 (a), and the experimental design is presented in Table 5.1. Water and superplasticizer contents were varied in order to achieve reasonable fresh mix workability characteristics represented by a flow (ASTM C-230) of 55% to 65% at 1 minute after mixing. Fibrous mixtures also contained non-chloride set accelerator, which was essential to keep the setting time of the composites within acceptable limits. The results of tests on fresh mix properties, mechanical properties and physical properties are discussed in section 4.7.3.1.

The effects of wood fiber reinforcement on the flexural load-deflection behavior of cement-based materials are shown in Figure 5.5 for different fiber types and moisture conditions. The effects of fiber mass fraction on flexural strength and toughness for different fiber types and moisture conditions are presented in Tables 5.8 and 5.9, and Figures 5.6 and 5.7, respectively.

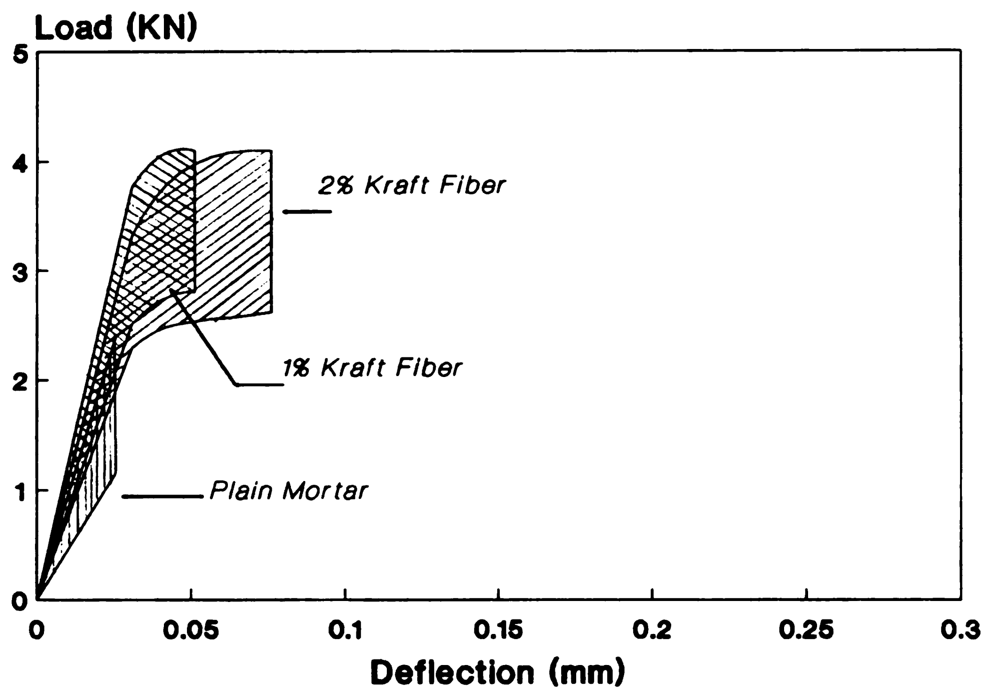


(a) Air Dried Kraft Pulp

Figure 5.5 Effects of Moisture Condition on the Flexural Load-Deflection Behavior of Molded Wood Fiber Reinforced Cement Composites (Range for 10 Curves).

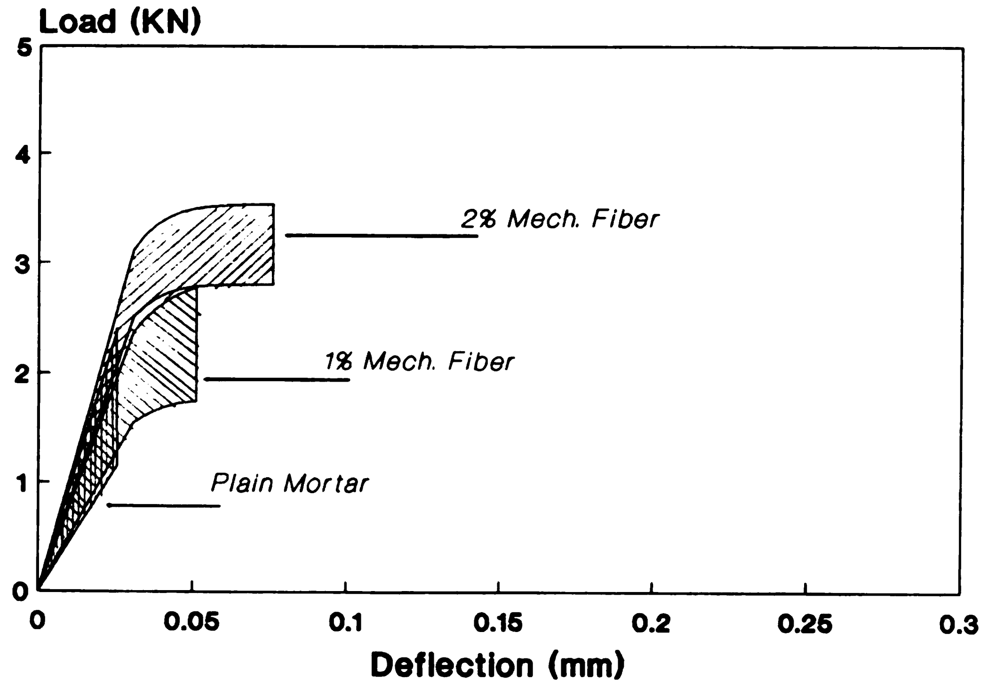


(b) Air Dried Mechanical Pulp

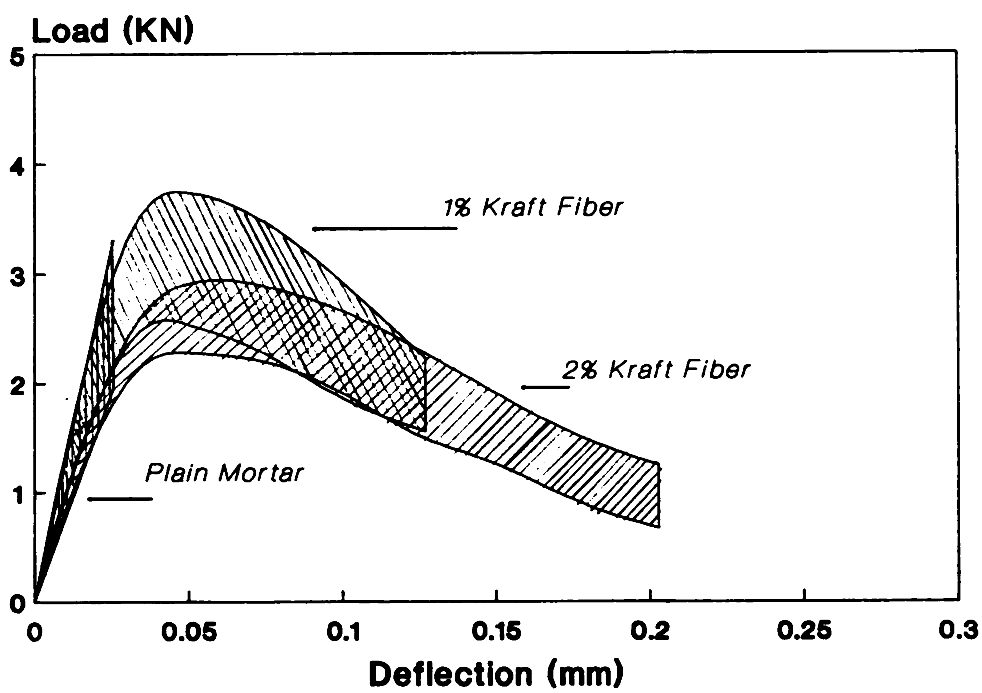


(c) Oven Dried Kraft Pulp

Figure 5.5 (cont'd) Effects of Moisture Condition on the Flexural Load-Deflection Behavior of Molded Wood Fiber Reinforced Cement Composites (Range for 10 Curves).

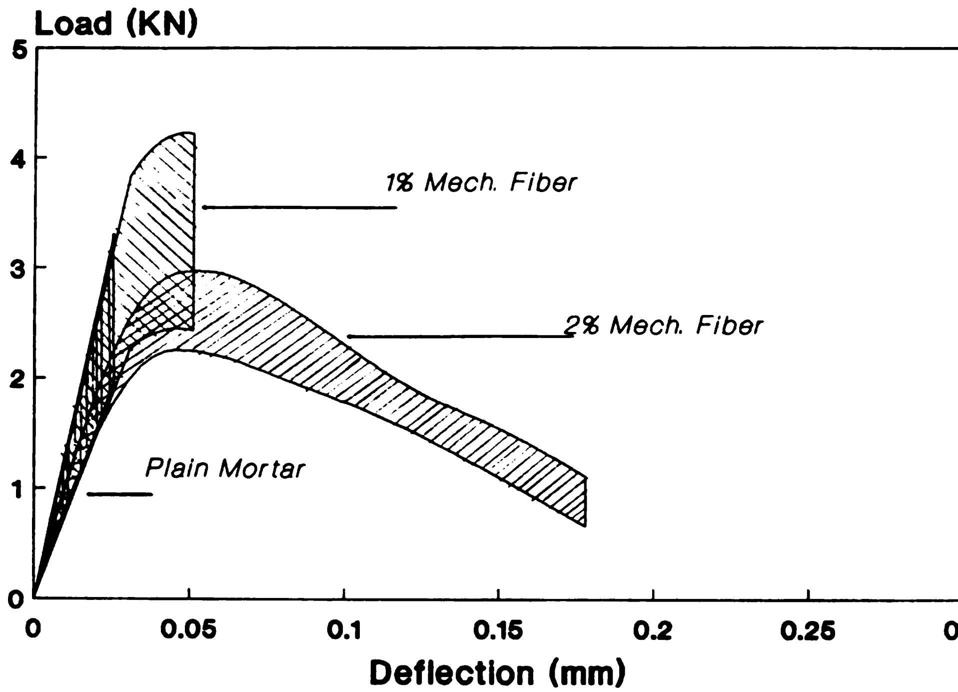


(d) Oven Dried Mechanical Pulp



(e) Saturated Kraft Pulp

Figure 5.5 (cont'd) Effects of Moisture Condition on the Flexural Load-Deflection Behavior of Molded Wood Fiber Reinforced Cement Composites (Range for 10 Curves).



(f) Saturated Mechanical Pulp

Figure 5.5 (cont'd) Effects of Moisture Condition on the Flexural Load-Deflection Behavior of Molded Wood Fiber Reinforced Cement Composites (Range for 10 Curves).

Table 5.8 Effects of Moisture Condition on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites (MPa)

Fiber Mass Content & Type	Moisture Condition					
	Air Dried		Oven Dried		Saturated	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Plain	3.7799 5.7557 4.9466 3.9167 3.0181	4.1222 3.6159 4.4956 3.8610 2.6266	4.1099 2.1299 4.1367 4.5616 4.2446	5.6251 4.2315 4.6619 4.1367 4.4818	4.9940 6.0500 6.9664 5.6354 4.1353	6.6048 5.9675 5.8224 5.5687 5.1700
Mean (St. Dev.)	3.9146 (0.9989)		4.2322 (0.8662)		5.6918 (0.8098)	

Table 5.8 (cont'd) Effects of Moisture Condition on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites (MPa)

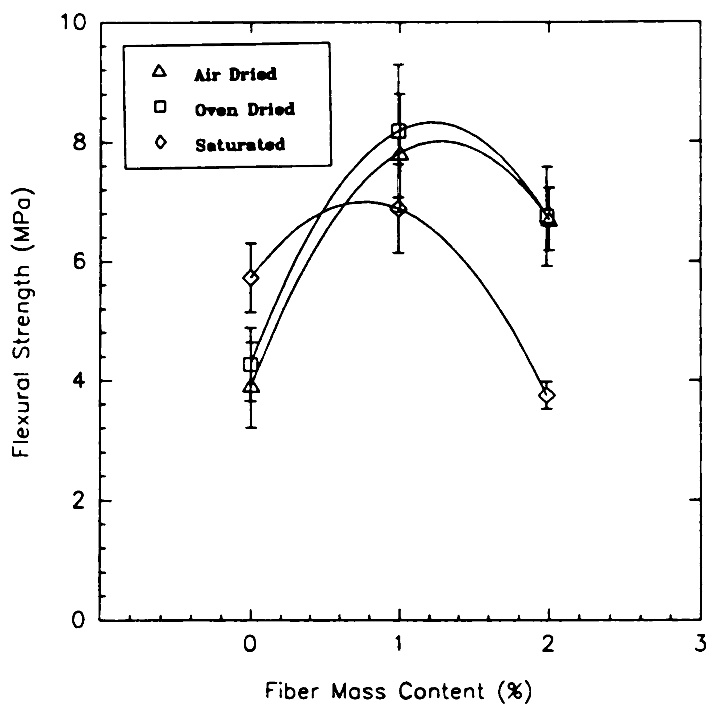
Fiber Mass Content & Type	Moisture Condition					
	Air Dried		Oven Dried		Saturated	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
1% Mech. (1000L)	4.3390 4.9147 5.4340 5.2188 3.9577	5.1871 4.8624 4.6245 4.3307 4.5162	5.6401 4.0053 3.0014 4.9734 4.9733	5.6842 5.8566 4.7506 3.8025 4.8079	2.7422 5.7539 4.4038 5.2499 4.4018	7.8237 9.6296 8.5774 5.7552 4.5245
Mean (St. Dev.)	4.7245 (0.4654)		4.7706 (0.9261)		5.8939 (2.1429)	
2% Mech. (1000L)	6.3048 8.3320 7.7079 7.7210 7.6562	6.9667 5.8345 6.8398 6.4572 6.3813	7.3687 7.4860 7.3832 8.1526 8.2471	5.5781 6.0862 7.3445 6.5971 5.5663	4.7596 3.9191 3.7502 4.4300 4.6328	4.2011 3.7819 4.6969 2.1885 4.2328
Mean (St. Dev.)	6.9994 (0.0928)		6.9609 (0.1382)		4.0473 (0.0818)	
1% Kraft (SSK)	9.3878 9.3686 9.1754 7.6484 6.8372	8.5965 5.7523 6.4618 8.3731 6.3511	9.1988 8.8433 9.3665 8.9512 9.9550	6.6454 5.0703 9.1245 7.3102 6.9713	8.3669 6.2865 7.5061 8.1469 8.3112	5.6801 6.3903 6.2714 6.2411 5.6726
Mean (St. Dev.)	7.7949 (1.3688)		8.1434 (1.5544)		6.8489 (1.0381)	
2% Kraft (SSK)	6.7155 6.6509 6.6921 7.8581 6.4350	6.5306 4.9809 7.2799 6.9451 6.7402	5.0881 6.0637 6.2700 8.1991 5.4395	6.6887 8.5243 7.1802 7.6883 5.9785	3.8672 3.3949 3.8733 3.0813 3.4554	4.1381 3.7242 3.9641 3.5929 3.9352
Mean (St. Dev.)	6.6825 (0.7729)		6.7121 (1.1584)		3.7029 (0.3204)	

Table 5.9 Effects of Moisture Condition on the Flexural Toughness of Molded Wood Fiber Reinforced Cement Composites (N-mm)

Fiber Mass Content & Type	Moisture Condition					
	Air Dried		Oven Dried		Saturated	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Plain	51.975 36.156 35.026 41.806 39.546	33.897 41.806 40.902 46.326 32.767	35.391 22.711 27.004 53.783 29.716	71.974 38.982 54.574 33.106 34.236	22.034 34.123 23.728 36.157 36.608	59.884 29.377 36.157 34.010 34.914
Mean (St. Dev.)	40.021 (5.9658)		40.190 (15.265)		34.699 (10.282)	
1% Mech. (1000L)	61.014 71.183 83.612 82.482 51.975	94.011 70.053 76.042 61.353 70.392	55.365 41.467 72.539 49.602 59.545	56.834 56.155 39.207 24.293 43.614	65.647 80.222 87.115 68.019 85.420	94.459 97.849 97.849 80.222 87.115
Mean (St. Dev.)	72.302 (1.4011)		49.862 (1.5818)		84.392 (1.1186)	
2% Mech. (1000L)	90.391 98.300 91.521 87.002 94.911	80.222 74.573 79.092 77.962 81.352	73.443 48.585 91.521 129.94 65.534	89.261 72.313 48.585 94.459 91.521	310.72 362.70 215.81 249.71 372.86	112.99 350.27 370.60 282.47 310.72
Mean (St. Dev.)	85.533 (0.5649)		80.516 (5.2427)		293.88 (60.483)	
1% Kraft (SSK)	87.001 91.521 114.12 75.929 97.171	97.171 75.703 87.002 91.521 87.002	73.443 66.664 77.963 67.793 81.352	63.274 54.235 81.352 64.404 64.404	456.47 531.05 536.70 457.61 525.40	515.23 259.88 259.88 406.76 384.16
Mean (St. Dev.)	90.414 (9.9317)		72.878 (12.011)		433.31 (105.32)	

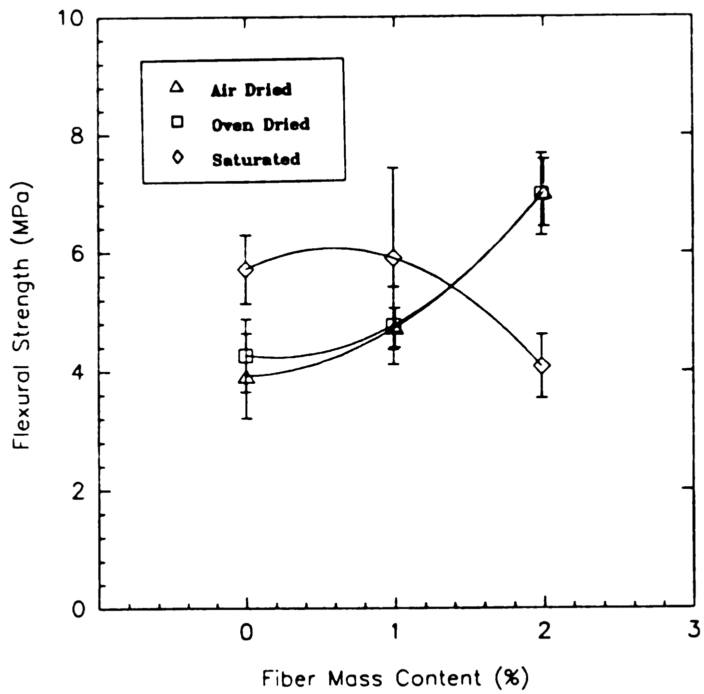
Table 5.9 (cont'd) Effects of Moisture Condition on the Flexural Toughness of Molded Wood Fiber Reinforced Cement Composites (N-mm)

Fiber Mass Content & Type	Moisture Condition					
	Air Dried		Oven Dried		Saturated	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
2% Kraft (SSK)	182.59 177.62 170.95 192.31 165.76	169.82 145.76 189.03 114.12 185.42	35.027 77.398 39.659 123.38 65.986	84.741 144.97 98.526 107.90 78.414	509.58 580.76 552.53 440.66 512.97	536.70 576.24 463.25 514.10 598.84
Mean (St. Dev.)	169.269 (23.26)		85.600 (34.620)		528.56 (50.969)	



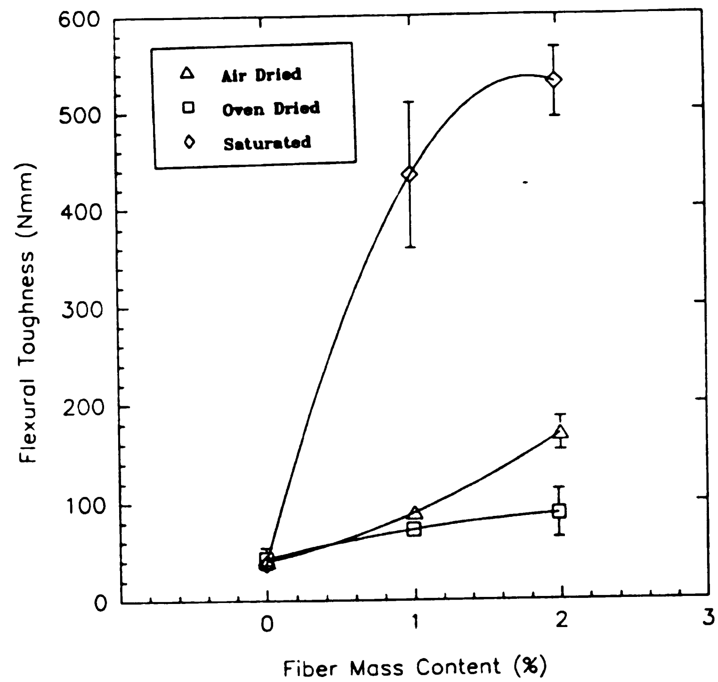
(a) Kraft Pulp (SSK)

Figure 5.6 Effects of Moisture Condition on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites (Regression Analysis with 95% Confidence Interval).

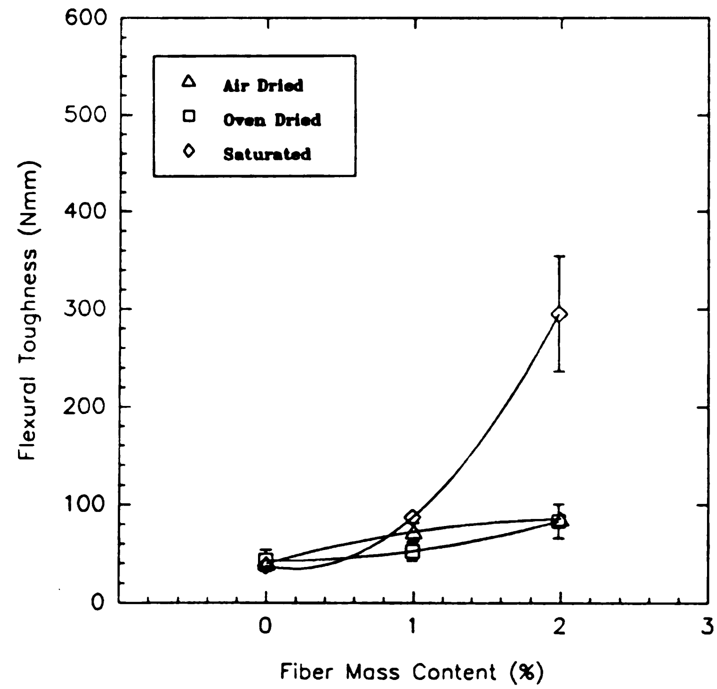


(b) Mechanical Pulp (1000L)

Figure 5.6 (cont'd) Effects of Moisture Condition on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites (Regression Analysis with 95% Confidence Interval).



(a) Kraft Pulp (SSK)



(b) Mechanical Pulp (1000L)

Figure 5.7 Effects of Moisture Condition on the Flexural Toughness of Molded Wood Fiber Reinforced Cement Composites (Regression Analysis with 95% Confidence Interval).

The following conclusions could be derived from the test data regarding the effects of fiber type, mass fraction and moisture condition on flexural performance.

For the mechanical fibers, the flexural strength and toughness in air-dried condition continue to increase with increasing fiber mass content up to 2%. The composite with 2% mechanical fibers had 79% increase in flexural strength and 114% increase in flexural toughness over the plain matrix.

For the kraft fibers, the flexural strength in air-dried condition increased at 1% fiber content and then decreased when fiber content was increased to 2%; fracture toughness, however, increased continuously with increasing fiber content. The composite with 1% kraft fibers had, on the average, 99% increase in flexural strength and 126% increase in flexural toughness over the plain matrix. The increase in flexural toughness at 2% fiber mass fraction was even more significant (an average of 323%).

Oven drying of the composite caused only a slight increase in the flexural strength of wood fiber-cement composites; plain oven dried mortar specimens showed approximately 8% increase in flexural strength over the air dried ones. Wetting, on the average, reduced the flexural strength by 42% for mechanical pulp and by 45% for kraft pulp at 2% fiber mass content when compared with air dried ones.

Oven drying of the composites reduced their flexural toughness by about 50% for kraft pulp and 6% for mechanical pulp at 2% fiber mass content, while wetting of produced a considerable increase in fracture toughness values (by 212% above that for air-dried specimens in the case of kraft pulp and 244% in the case of mechanical pulp at 2% fiber mass content).

Factorial analyses and multiple comparisons were performed on the test data generated for plain and fibrous composites in order to distinguish the effects of different factors involved. In the discussion presented below, a significant effect represents a confidence level between 95 to 99%, and a highly significant effect represents confidence levels higher than 99%.

The results of one-way analysis of variance performed on flexural strength and toughness of plain mortar indicated that oven drying produced results statistically comparable to those obtained with air drying, while wetting by immersion in water had highly significant effects, leading to increased flexural strength in plain mortars.

Effect of Fiber Content: Fiber content, changing from 1% to 2% mass fraction, was observed to have highly significant effect on the flexural strength of wet specimens where strength was reduced with increasing fiber content. Fiber content (1% vs. 2%) did not have any significant effect on the flexural strength of air or oven dried specimens. The effect of fiber content on flexural toughness was highly significant for both the kraft and mechanical pulps at all moisture contents.

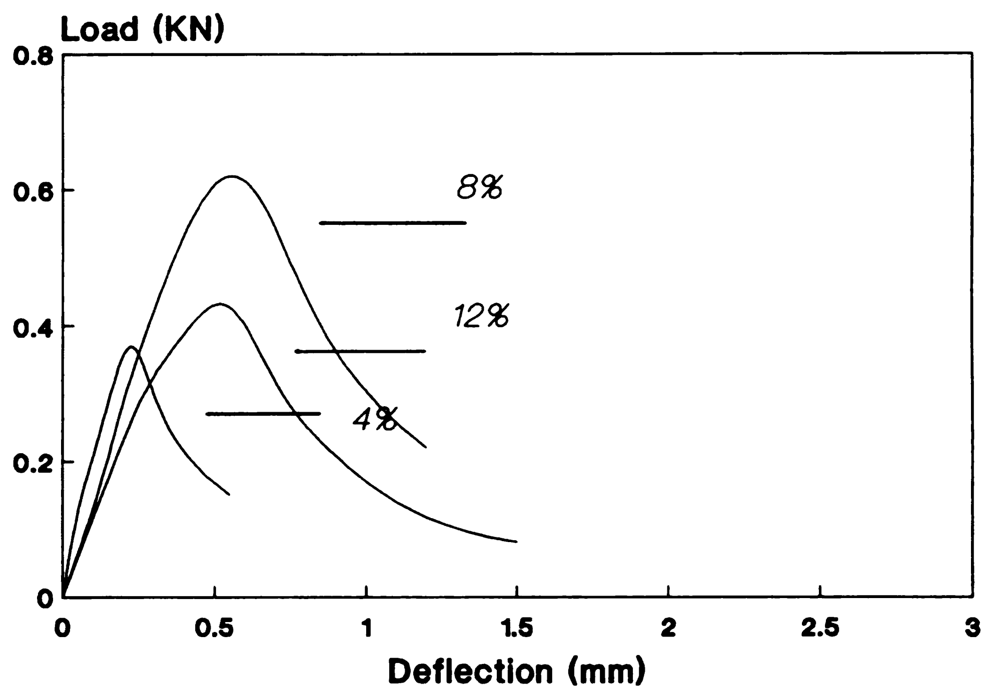
Effect of Moisture Condition: Wetting of the specimens incorporating 2% fiber content was observed to have highly significant effects on flexural strength (where strength was reduced); at 1% fiber content, however, the effect of wetting was not significant. Oven drying of the specimens did not have any significant effect at all fiber contents. The effect of moisture condition on flexural toughness was highly significant for both the kraft and mechanical pulps at all fiber contents (where toughness was increased with wetting and reduced with oven drying).

Effect of Fiber Type: Fiber type (kraft vs. mechanical pulp) was observed to have highly significant effect on flexural strength at 1% fiber content for all moisture conditions (with kraft fibers giving higher strength), while at 2% fiber content the effect of fiber type on flexural strength was not significant. Effect of fiber type on flexural toughness was highly significant at all fiber contents and for all moisture conditions.

5.7.1.2 Slurry-Dewatering

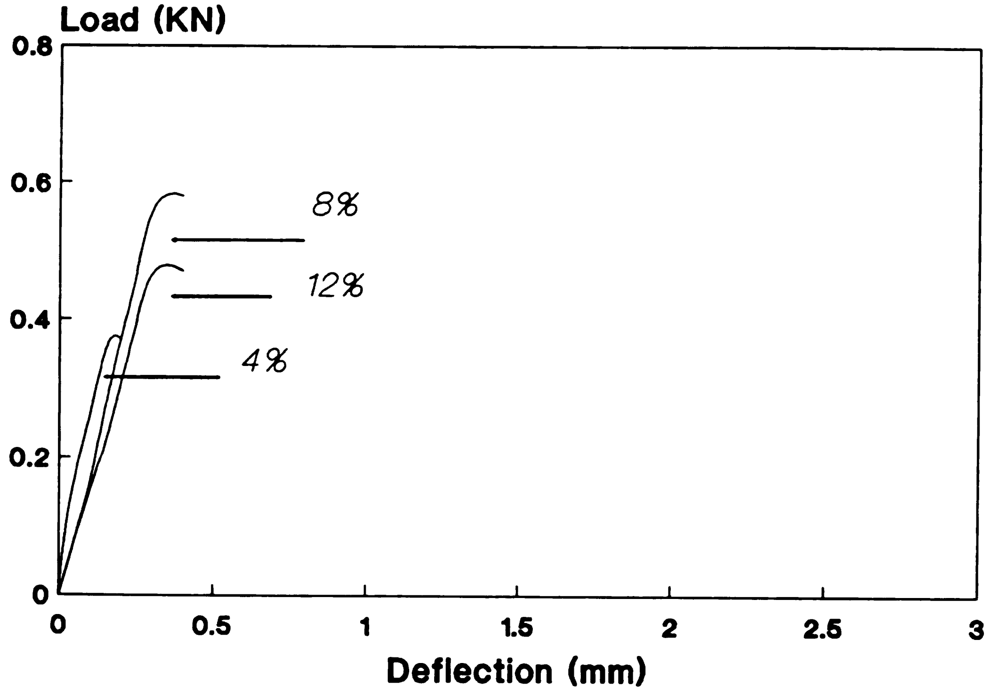
This section presents the effects of wood fiber content and moisture condition on the flexural performance of composites containing high fiber contents ($\geq$ 4%) manufactured through slurry-dewatering. The wood fibers used in this investigation were Southern Softwood Kraft (SSK) [41]. Optimization was achieved through flexural testing of the composite containing different fiber contents. The fiber mass fractions and matrix mix proportions used in this phase of the study are introduced in Table 4.3 (b) and the experimental design used in this study is presented in Table 5.1. Thin-sheet specimens were formed from a dilute slurry of approximately 20% solids. A relatively small dosage of 1% diluted flocculent (flocculent/cement=0.001) [46] was added to achieve agglomeration of cement solids in the slurry, which helps in reducing the amount of cement particles lost through the filtering screens during dewatering. Fiber mass fraction, in the slurry-dewatering method of manufacture, is defined as the ratio of fibers to the dry constituents of the matrix by weight. The results of tests on fresh mix properties, and hardened material mechanical and physical properties are discussed in section 4.7.3.2.

The effects of wood fiber reinforcement on the flexural load-deflection behavior of cement-based materials are shown in Figure 5.8 for different fiber contents and moisture conditions. The effects of fiber mass fraction and moisture condition on flexural strength and toughness are presented in Table 5.10, and also in Figure 5.9. Each test point in this figure represents the average of three experiments; regression lines with 95% confidence intervals are also presented.

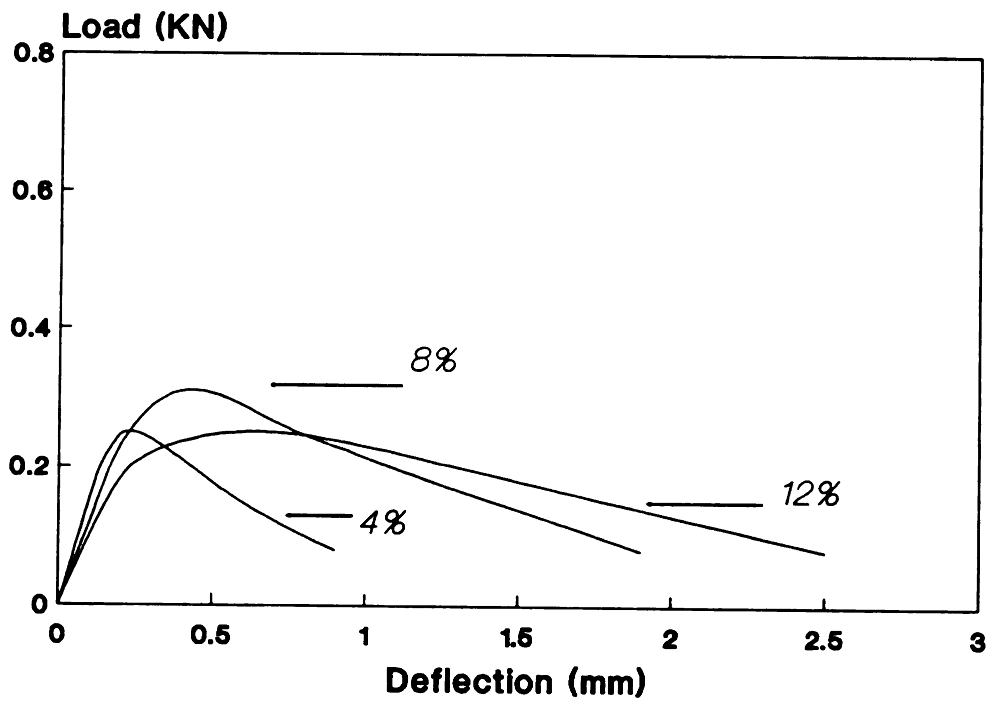


(a) Air Dried

Figure 5.8 Effects of Moisture Condition on the Flexural Load-Deflection Behavior of Slurry-Dewatered Wood Fiber Reinforced Cement Composites.



(b) Oven Dried



(c) Saturated

Figure 5.8 (cont'd) Effects of Moisture Condition on the Flexural Load-Deflection Behavior of Slurry-Dewatered Wood Fiber Reinforced Cement Composites.

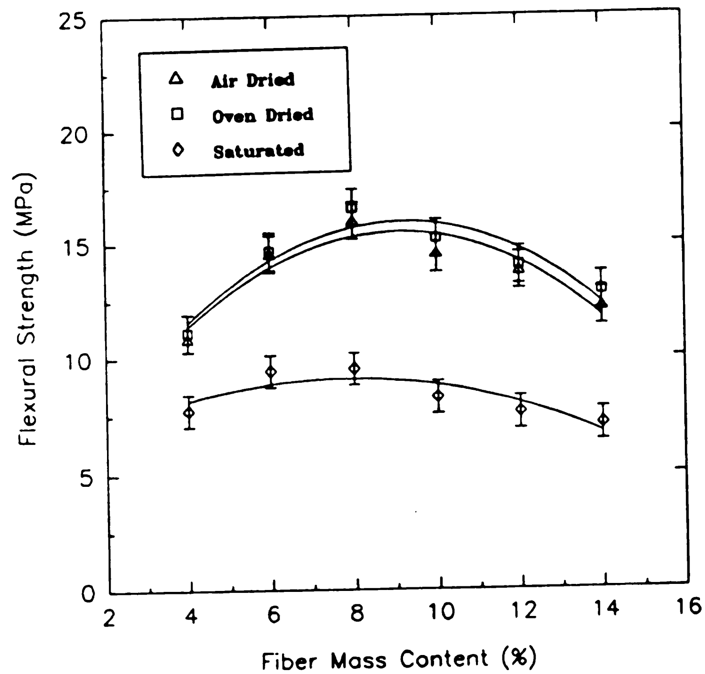
Table 5.10 Effects of Moisture Condition on the Flexural Performance of Slurry-Dewatered Wood Fiber Reinforced Cement Composites

(a) Flexural Strength (MPa)

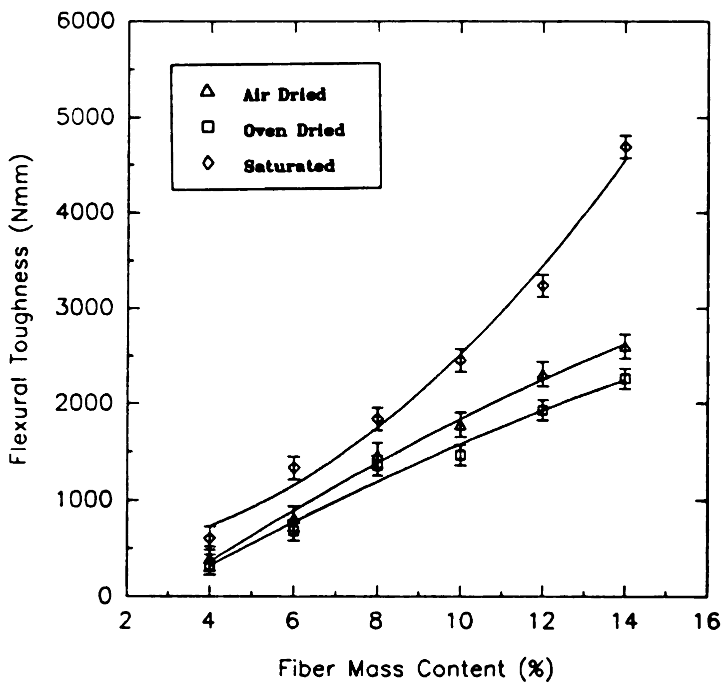
Moisture Condition	Fiber Mass Fraction (%)					
	4	6	8	10	12	14
Air Dried	10.710 10.841 11.045	14.514 13.804 15.314	15.865 15.410 16.706	13.796 15.176 14.638	13.027 13.758 14.551	11.632 12.364 12.555
Mean	11.095	14.544	15.994	14.537	13.778	12.184
Oven Dried	10.811 11.122 11.411	15.445 14.011 14.493	17.244 16.569 15.872	14.638 14.859 16.114	13.852 14.679 13.514	12.121 13.052 13.487
Mean	11.115	14.650	16.562	15.203	14.013	12.886
Saturated	6.9777 8.4877 7.7817	9.9219 8.7429 9.6737	9.4255 9.4324 9.7426	8.1223 8.5705 8.1361	8.4050 7.6052 6.8812	6.8660 6.8398 7.6534
Mean	7.7492	9.4461	9.5337	8.2761	7.6307	7.1198

(b) Flexural Toughness (N-mm)

Moisture Condition	Fiber Mass Fraction (%)					
	4	6	8	10	12	14
Air Dried	398.08 378.74 465.85	740.75 815.55 866.40	1354.5 1468.4 1570.4	1864.3 1756.3 1720.0	2471.9 2322.3 2134.2	2547.9 2560.9 2696.6
Mean	394.56	807.57	1464.4	1780.2	2309.5	2601.8
Oven Dried	289.13 385.07 313.88	640.53 675.22 740.42	1292.9 1341.2 1443.5	1373.4 1571.9 1458.9	2033.9 1920.5 1845.1	2145.9 2357.5 2290.1
Mean	329.36	685.39	1359.2	1468.1	1933.2	2264.5
Saturated	563.48 601.21 652.51	1421.1 1328.7 1254.2	1800.0 1954.8 1768.3	2455.5 2334.6 2568.7	3161.4 3272.8 3277.8	4594.5 4645.2 4836.9
Mean	605.73	1334.9	1841.0	2452.9	3237.4	4692.2



(a) Flexural Strength



(b) Flexural Toughness

Figure 5.9 Effects of Moisture Condition on the Flexural Performance of Slurry-Dewatered Wood Fiber Reinforced Cement Composites (Regression Analysis with 95% Confidence Interval).

The following conclusions could be derived from the test data regarding the effects of fiber mass fraction and moisture condition on flexural performance.

Flexural strength of air-dried composites increased with increasing fiber content up to 8% by mass, and then decreased when fiber content was further increased. Fracture toughness, however, increased continuously with increasing fiber content. The composite with 8% kraft fibers had, on the average, 44% increase in flexural strength and 4 times increase in flexural toughness over the composite containing 4% fiber content. The increase in flexural toughness at 14% fiber mass fraction was even more significant (6 times), where the average increase in flexural strength was 9% over the composite containing 4% fiber content.

Oven drying of the composite caused only a slight increase in the flexural strength over the air dried ones. Wetting, on the average, reduced the flexural strength by 45% at 8% fiber mass content when compared with the air dried composites.

Oven drying of the composites reduced their flexural toughness by about 15%, while wetting produced a considerable increase in fracture toughness values (25%) over air dried composites at 8% fiber mass fraction. Maximum flexural strengths for different moisture conditions were obtained at 8% fiber mass fraction.

Factorial analyses and multiple comparisons were performed on the test data generated for plain and fibrous composites in order to statistically confirm the effects of different factors involved. In the discussion presented below, a significant effect represents a confidence level between 95 to 99%, and a highly significant effect represents confidence levels higher than 99%.

Effect of Fiber Content: Fiber mass content has highly significant effect on flexural strength and toughness at all moisture conditions. Maximum flexural strengths for different moisture conditions were obtained at 8% fiber mass fraction. Flexural toughness at all moisture conditions continues to increase with increasing fiber mass fraction; maximum toughness values were obtained at the maximum fiber mass fraction considered (14%).

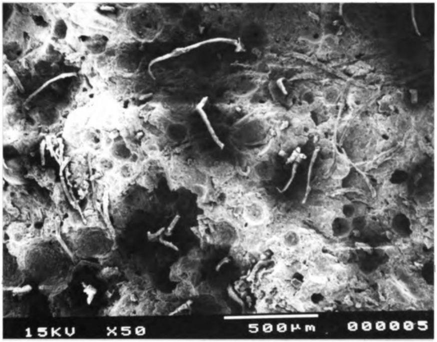
Effect of Moisture Condition: Oven-drying of the composites, when compared with air-drying, has no statistically significant effect on flexural strength, but has significant (adverse) effects on flexural toughness. Wetting of the composites, when compared to air-drying, has highly significant effects on flexural strength and toughness (where strength is reduced and toughness is increased). There were also strong interactions between fiber content and moisture condition on flexural strength and toughness. In other words, the effects of moisture on composites are dependent on their fiber content.

5.7.1.3 Microstructural Investigation

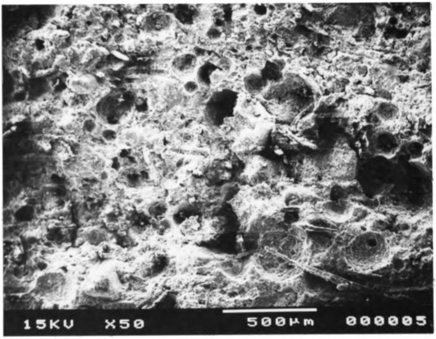
The fiber-to-matrix interfacial bond in fiber reinforced cement-based composites can be mechanical or chemical, or a combination of both. In the case of wood fiber reinforced cement composites, both mechanical bonds and chemical bonds play important roles.

Scanning Electron Microscopic studies of the fractured surfaces of wood fiber reinforced cement composites containing 2% kraft pulp were conducted with emphasis placed on the interface zone behavior. The results showed that failure occurs by the dual mechanisms of fiber fracture and fiber pullout in air-dried specimens (Figure 5.10 a). Figure 5.10 (b) shows that fiber fracture dominates the failure mechanism of oven-dried samples while, as shown in Figure 5.10 (c), fiber pullout dominates failure in wet samples. Hence, oven-dried samples are expected to be relatively strong but brittle because the dissipation of energy through pullout is lost by oven-drying; wet specimens, on the other hand, are relatively weak but tough with considerable energy absorption capacity associated with fiber pullout.

At the pH of the cement (>12.5) C-OH, Si-OH, and Ca-OH bonds are present in the composite which contribute to hydrogen bonds taking place between wood fibers and matrix or between wood fibers themselves. Wet and dry wood fibers have about the same tensile strength, but the stiffness is ten times greater in dry condition [20]. Thus, an oven-dried composite has stiff, contorted fibers locked into the cement matrix and held together by a number of hydrogen bonds. This system when stressed can load the fibers until failure occurs. A wet sample on the other hand has swollen conformable fibers. The hydrogen bonds between fibers and matrix or between the fibers themselves are broken by insertion of water molecules. Under stress this system allows the fibers to pull out of the matrix. However, due to swelling, considerable frictional forces may be present and over sufficient fiber lengths, longer than those used in this investigation, they could result in the fibers being loaded to failure.

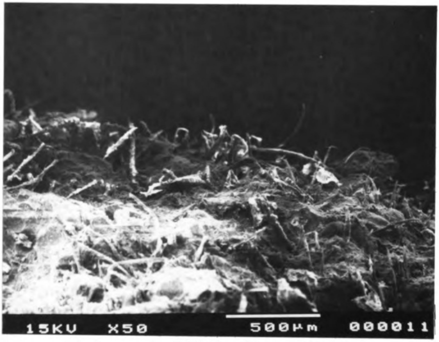


(a) Air Dried



(b) Oven-Dried

Figure 5.10 Fracture Surface of Molded Wood Fiber Reinforced Cement Composites Containing 2% Kraft Pulp (SSK).



(c) Saturated

Figure 5.10 (cont'd) Fracture Surface of Molded Wood Fiber Reinforced Cement Composites Containing 2% Kraft Pulp (SSK).

5.7.2 Matrix Modification

This section presents test results concerned with the effects of matrix modification and moisture condition on the flexural performance of wood fiber reinforced cement composites. The fiber used in this study was Southern Softwood Kraft (SSK). The samples contained optimum fiber contents (2% for molding method and 8% for slurry dewatering method). The matrix modification was achieved through partial substitution of cement with pozzolanic admixtures (15% silica fume or 30% fly ash). In the case of molding technique, the matrix was also modified through the addition of a latex polymer. The fiber mass fraction and matrix mix proportions are introduced in Table 4.4, and the experimental program is presented in Table 5.2. The effects of matrix modification and moisture condition on flexural strength and toughness are presented in Tables 5.11 and 5.12, and also in Figures 5.11 and 5.12, respectively. Each test point in these figures represents the average of three experiments; 95% confidence intervals are also presented.

Table 5.11 Effects of Matrix Modification and Moisture Condition on the Flexural Strength of Wood Fiber Reinforced Cement Composites (MPa)

(a) Molded Composites

Matrix	Moisture Condition					
	Air Dried		Oven Dried		Saturated	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Pure Cement	6.7155 6.6509 6.6921 7.8581 6.4350	6.5306 4.9809 7.2799 6.9451 6.7402	5.0881 6.0637 6.2700 8.1991 5.4395	6.6887 8.5243 7.1802 7.6883 5.9785	3.8672 3.3949 3.8733 3.0813 3.4554	4.1381 3.7242 3.9641 3.5929 3.9352
Mean (St. Dev.)	6.6825 (0.7729)		6.7121 (1.1584)		3.7029 (0.3204)	
Cement & 15% Silica Fume	9.1120 8.0213 9.2636 8.7521 8.8512	7.9921 7.1152 8.0253 7.1102 7.0120	9.1021 8.2233 9.1121 8.4210 8.6740	8.1011 7.1052 8.8711 7.2203 7.1189	6.1021 6.9925 6.0341 5.0231 4.3425	5.6678 4.5587 4.5523 3.9912 4.0123
Mean (St. Dev.)	8.1255 (0.8510)		8.1949 (0.7963)		5.1277 (1.0197)	
Cement & 30% Fly Ash	8.0122 6.5122 7.8900 6.8132 6.0012	8.1205 7.1121 8.0126 8.4531 7.8925	8.0122 6.8865 7.9873 6.8132 6.7631	8.1104 7.1173 8.1021 8.6731 7.7925	5.5222 4.8765 3.9717 4.9931 5.5213	5.5587 5.3201 4.1165 3.6789 4.0124
Mean (St. Dev.)	7.4819 (0.8142)		7.6258 (0.6729)		4.7271 (0.7122)	
Cement & 10% Latex	9.3317 8.4412 9.4561 9.0167 7.8911	8.1149 7.2261 8.2514 7.5571 8.7521	9.4521 8.4325 9.4021 9.2218 7.9921	8.3232 7.3371 8.8867 7.4459 8.8871	7.0231 6.3500 5.8839 6.8946 5.9982	5.9937 5.3982 5.1650 5.9987 6.3044
Mean (St. Dev.)	8.4038 (0.7409)		8.5380 (0.7661)		6.1009 (0.5805)	

Table 5.11 (cont'd) Effects of Matrix Modification and Moisture Condition on the Flexural Strength of Wood Fiber Reinforced Cement Composites (MPa)

(b) Slurry-Dewatered Composites

Moisture Condition	Matrix		
	Pure Cement	Cement & 15% Silica Fume	Cement & 30% Fly Ash
Air Dried	15.865 15.410 16.706	18.623 19.292 20.229	17.913 18.596 17.444
Mean	15.994	19.382	17.984
Oven Dried	17.244 16.569 15.872	19.740 19.685 20.837	17.582 18.768 17.575
Mean	16.562	20.087	17.975
Saturated	9.4255 9.4324 9.7426	13.321 13.555 14.493	12.225 13.252 12.487
Mean	9.5337	13.790	12.654

Table 5.12 Effects of Matrix Modification and Moisture Condition on the Flexural Toughness of Wood Fiber Reinforced Cement Composites (N-mm)

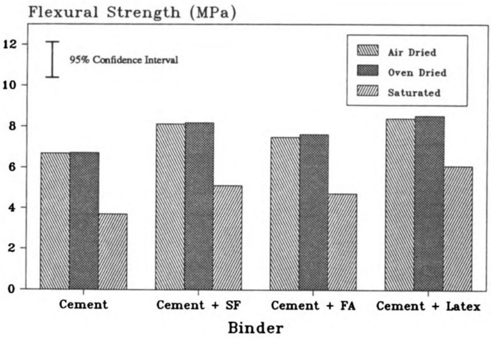
(a) Molded Composites

Matrix	Moisture Condition					
	Air Dried		Oven Dried		Saturated	
	Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2
Pure Cement	182.59 177.62 170.95 192.31 165.76	169.82 145.76 189.03 114.12 185.42	35.027 77.398 39.659 123.38 65.986	84.741 144.97 98.526 107.90 78.414	509.58 580.76 552.53 440.66 512.97	536.70 576.24 463.25 514.10 598.84
Mean (St. Dev.)	169.269 (23.26)		85.600 (34.620)		528.56 (50.969)	
Cement & 15% Silica Fume	161.72 114.12 153.11 140.26 120.42	120.37 148.55 138.78 145.23 144.75	102.13 101.28 87.470 92.080 103.12	83.120 78.610 89.430 106.13 98.140	413.92 444.57 365.93 354.38 450.37	365.48 456.48 389.14 451.92 411.20
Mean (St. Dev.)	138.731 (15.60)		94.151 (9.3616)		410.20 (39.691)	
Cement & 30% Fly Ash	145.29 169.17 169.12 162.00 158.11	179.32 106.91 172.98 158.23 147.21	115.12 78.350 93.120 105.10 100.20	120.64 102.19 98.210 89.330 110.46	377.12 460.14 346.25 470.18 426.10	456.24 493.12 375.14 390.13 460.25
Mean (St. Dev.)	156.834 (20.596)		101.27 (12.525)		425.46 (49.810)	
Cement & 10% Latex	946.31 1002.1 956.12 875.31 899.19	935.23 976.32 910.98 990.23 970.12	754.24 812.11 724.12 687.65 697.30	780.64 726.15 704.37 770.34 748.65	1603.1 1676.3 1544.9 1404.3 1530.5	1466.3 1509.1 1555.5 1403.5 1522.4
Mean (St. Dev.)	946.193 (41.149)		740.55 (39.894)		1521.6 (83.843)	

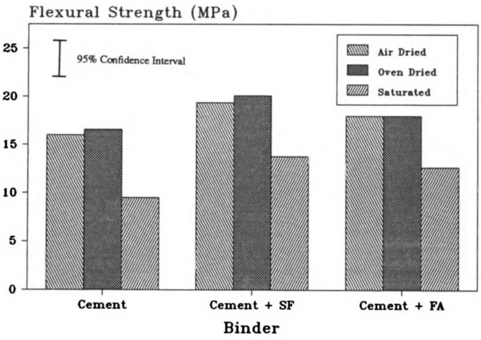
Table 5.12 (cont'd) Effects of Matrix Modification and Moisture Condition on the Flexural Toughness of Wood Fiber Reinforced Cement Composites (N-mm)

(b) Slurry-Dewatered Composites

Moisture Condition	Matrix		
	Pure Cement	Cement & 15% Silica Fume	Cement & 30% Fly Ash
Air Dried	1354.5 1468.4 1570.4	1129.0 1355.0 1242.6	1142.3 1356.0 1318.9
Mean	1464.4	1242.2	1272.4
Oven Dried	1292.9 1341.2 1443.5	1016.3 874.87 1128.2	1016.1 1154.9 1241.9
Mean	1359.2	1006.5	1137.6
Saturated	1800.0 1954.8 1768.3	1356.1 1481.6 1593.3	1468.9 1456.0 1594.5
Mean	1841.0	1477.0	1506.5

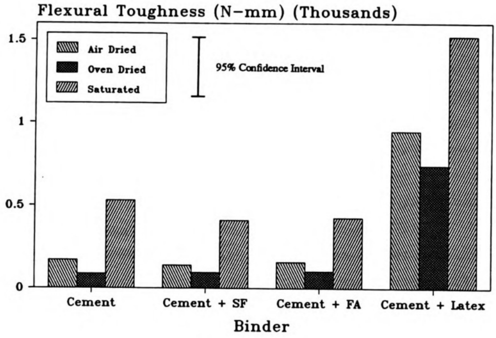


(a) Molded Composites

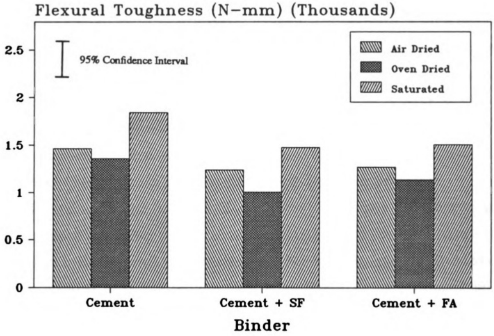


(b) Slurry-Dewatered Composites

Figure 5.11 Effects of Matrix Modification and Moisture Condition on the Flexural Strength of Wood Fiber Reinforced Cement Composites.



(a) Molded Composites



(b) Slurry-Dewatered Composites

Figure 5.12 Effects of Matrix Modification and Moisture Condition on the Flexural Toughness of Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived from the test data regarding the effects of matrix modification and moisture condition on flexural performance.

Pozzolans (30% Silica fume and 15% Fly ash) are observed to increase the flexural strength of air dried composite while slightly reducing toughness. These effects are more pronounced with silica fume. Silica fume and fly ash increased flexural strength on the average by about 20% and 12%, respectively, for both molded and slurry-dewatered composites. The reduction in flexural toughness in the presence of silica fume was about 20% for molded composites and 15% for slurry-dewatered composites. Composites containing fly ash showed only marginal reduction in flexural toughness (about 10%).

In the presence of pozzolans no statistically significant difference was observed between the flexural behavior of air dried and oven dried composites; wetting still had highly significant effects on flexural performance (adverse effects on flexural strength and positive effects on flexural toughness). However, the reduction of flexural strength in the presence of pozzolans was much lower when compared to that of the pure cement-based matrix. Pozzolans reduced the moisture sensitivity of wood fiber reinforced cement composites; while without pozzolans wetting reduced flexural strength by an average of 40% below that in air-dried composites, in the presence of silica fume or fly ash there was a drop of only 30% in flexural strength upon wetting. The average increase in flexural toughness with wetting of different composites were comparable. Thus the presence of pozzolans helped in improving the flexural strength and moisture sensitivity of the composites without losing ductility. The improved flexural performance and moisture sensitivity are associated with improved fiber-to-matrix bond and reduced permeability of the composite.

Modification of matrix through latex polymer (10% Styrene Butadiene by weight of cement) in molded wood fiber reinforced cement composites showed superior flexural performance at all moisture conditions. The increase in flexural strength of air-dried composites due to polymer modification was significant (26%), and the increase in flexural toughness was highly significant (about 5 times). In the presence of latex no statistically significant difference was observed between the flexural behavior of air-dried and oven-dried composites; wetting still had highly significant effects on flexural performance (adverse effects on flexural strength and positive effects on flexural toughness). However, the reduction of flexural strength in the presence of latex was much lower (25%) when compared to corresponding reduction with the pure cement based matrix (40%) or even with pozzolans (30%). Highly improved moisture resistance characteristics of wood fiber reinforced composites in the presence of latex are mainly due to the coating of wood fibers with latex polymers, development of strong and stable bonding between fibers and matrix, and substantially reduced permeability of the composite itself.

5.7.3 Effect of Bleaching

This section presents test results on moisture-sensitivity of bleached and unbleached wood fiber reinforced cement composites. The fibers used in this study were unbleached and bleached Southern Softwood Kraft (SSK) [41]. The composites were manufactured using molding technique and the fiber content was 2% by mass. The matrix mix proportions used in this study are given in Table 4.5. A comparison of the test results on moisture sensitivity of bleached and unbleached wood fiber reinforced cement composites is presented in Table 5.12 and Figure 5.13.

Table 5.13 Effects of Moisture Condition on the Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers

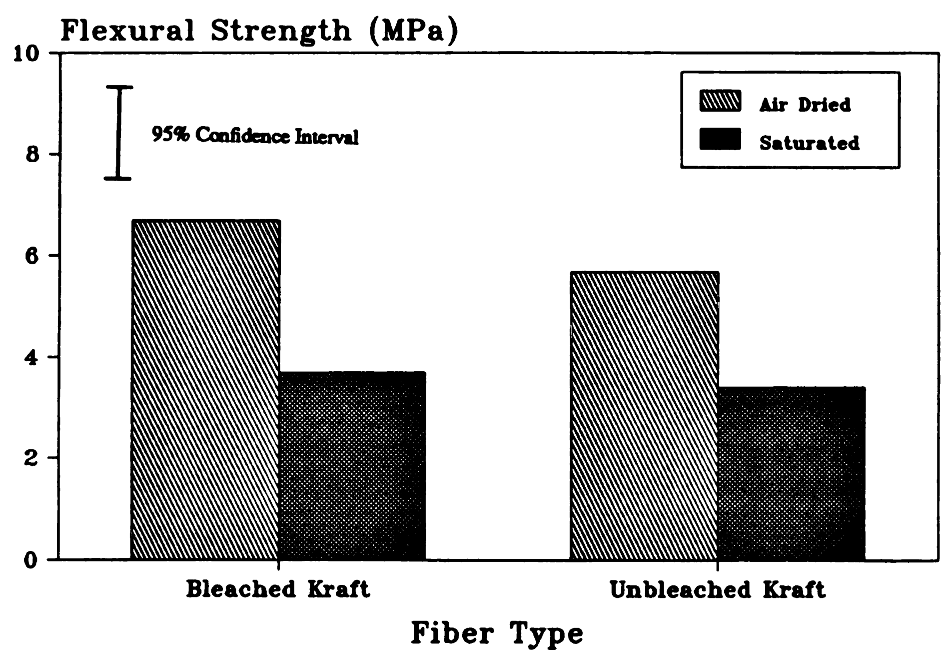
(a) Flexural Strength (MPa)

Fiber Mass Content & Type	Moisture Condition					
	Air Dried			Saturated		
	Batch 1	Batch 2	Mean (St. Dev.)	Batch 1	Batch 2	Mean (St. Dev.)
2% Kraft (SSK) Bleached	6.7155 6.6509 6.6921 7.8581 6.4350	6.5306 4.9809 7.2799 6.9451 6.7402	6.6825 (0.7729)	3.8672 3.3949 3.8733 3.0813 3.4554	4.1381 3.7242 3.9641 3.5929 3.9352	3.7029 (0.3204)
2% Kraft (SSK) Unbleached	6.4520 5.8210 5.2894 6.1324 5.8812	5.1190 4.6632 6.1813 6.3267 4.8875	5.6754 (0.6377)	3.4672 3.1104 2.9856 2.6798 3.1010	3.9822 3.5581 4.1020 3.6614 3.3050	3.3953 (0.4475)

Table 5.13 (cont'd) Effects of Moisture Condition on the Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers

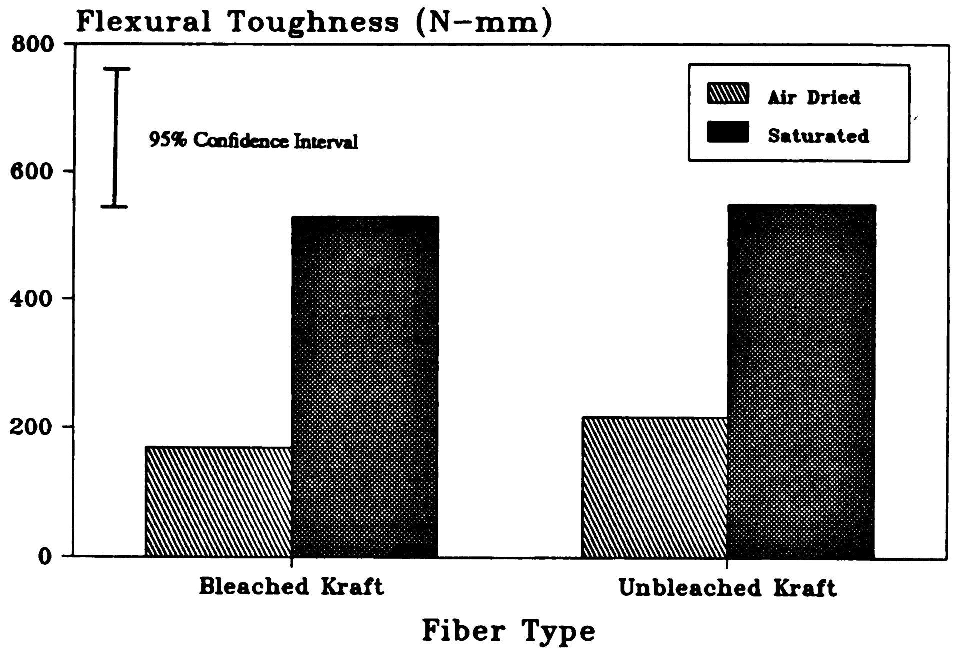
(b) Flexural Toughness (N-mm)

Fiber Mass Content & Type	Moisture Condition					
	Air Dried			Saturated		
	Batch 1	Batch 2	Mean (St. Dev.)	Batch 1	Batch 2	Mean (St. Dev.)
2% Kraft (SSK) Bleached	182.59 177.62 170.95 192.31 165.76	169.82 145.76 189.03 114.12 185.42	169.269 (23.260)	509.58 580.76 552.53 440.66 512.97	536.70 576.24 463.25 514.10 598.84	528.56 (50.969)
2% Kraft (SSK) Unbleached	198.48 199.36 230.12 241.30 179.13	185.40 236.78 220.45 235.13 240.55	216.67 (23.886)	580.31 581.32 552.14 480.27 525.18	570.87 590.16 497.58 550.36 560.18	548.87 (36.922)



(a) Flexural Strength

Figure 5.13 Effects of Moisture Condition on the Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers.



(b) Flexural Toughness

Figure 5.13 (cont'd) Effects of Moisture Condition on the Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers.

The following conclusions could be derived from the test data regarding the effects of bleaching and moisture condition on flexural performance.

Air-dried Cement composites containing bleached wood fiber show higher flexural strength and lower toughness than unbleached wood fiber reinforced cement composites. The increase in flexural strength and reduction in flexural toughness were 15% and 30%, respectively, for bleached wood fiber reinforced cement composites. However, they were not statistically significant at 95% confidence level.

Wetting has adverse effects on flexural strength and positive effects on flexural toughness for both composites. Wetting, on the average, reduced the flexural strength by 40% and increased flexural toughness by 3 times for both composites. Moisture had highly significant effect on the flexural performance of bleached and unbleached wood fiber reinforced cement composites. The flexural strength and toughness values of composites containing bleached and unbleached composites in the wet state were comparable. Unbleached wood fibers which contain small amounts of lignin did not show any significant change in behavior over that of composites containing bleached fibers at all moisture conditions.

5.7.4 Modification of Processing Parameters in Slurry-Dewatering Technique

This section presents test results on the effects of slurry-dewatering processing parameters and moisture content on the flexural performance of wood fiber reinforced cement composite. It is often stated that the use of pressure in the manufacture of fiber reinforced cements increases the strength of the composite but reduces the fracture toughness [35, 36, 37]. The fiber used in this study was Southern Softwood Kraft (SSK). Two different fiber contents (8% and 16%) were used in this study. The matrix contained equal amounts of cement and silica sand. The processing parameters considered in this study were casting pressure (1.6 and 3.2 MPa, 232 and 464 psi) and pressing time (1 hour and 24 hours). The matrix mix proportions are presented in Table 4.6. The effects of moisture content, and pressing time and pressure on flexural strength and toughness are presented in Table 5.14, and in Figures 5.14 and 5.15.

Table 5.14 Effects of Slurry-Dewatering Processing Parameters on the Moisture-Sensitivity of Wood Fiber Reinforced Cement Composites (average ± half the range of two replications)

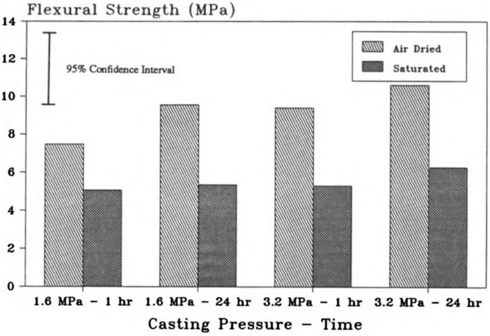
(a) Flexural Strength (MPa)

Fiber Type & Content	Casting Pressure (MPa)	Pressing Time (hr)	Moisture Condition	
			Air Dried	Saturated
Kraft (SSK) 8% by Weight	1.6	1	7.4708 ± 0.241	5.0672 ± 0.240
		24	9.5345 ± 0.962	5.3460 ± 0.480
	3.2	1	9.3938 ± 1.202	5.3079 ± 0.481
		24	10.596 ± 0.481	6.2690 ± 0.493
Kraft (SSK) 16% by Weight	1.6	1	2.8849 ± 0.481	1.4424 ± 0.123
		24	6.4903 ± 0.721	2.9230 ± 0.465
	3.2	1	5.0471 ± 0.722	2.4036 ± 0.193
		24	7.2115 ± 1.442	3.1248 ± 0.241

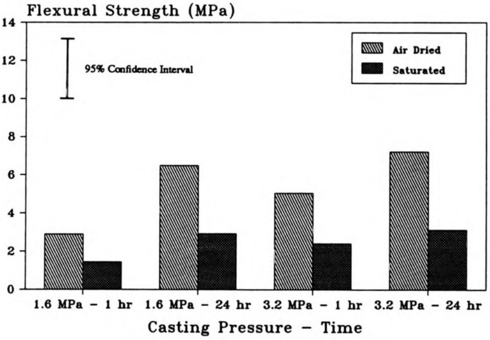
Table 5.14 (cont'd) Effects of Slurry-Dewatering Processing Parameters on the Moisture-Sensitivity of Wood Fiber Reinforced Cement Composites (average ± half the range of two replications)

(b) Flexural Toughness (N-mm)

Fiber Type & Content	Casting Pressure (MPa)	Pressing Time (hr)	Moisture Condition	
			Air Dried	Saturated
Kraft (SSK) 8% by Weight	1.6	1	557.60 ± 80.31	690.17 ± 91.36
		24	460.68 ± 90.28	501.72 ± 88.14
	3.2	1	521.31 ± 76.34	645.76 ± 148.4
		24	504.61 ± 103.2	587.44 ± 101.3
Kraft (SSK) 16% by Weight	1.6	1	808.38 ± 145.6	977.5 ± 169.75
		24	925.08 ± 151.2	1175.0 ±170.2
	3.2	1	831.19 ± 146.1	1081.4 ± 175.2
		24	900.01 ± 138.1	1158.2 ± 159.2

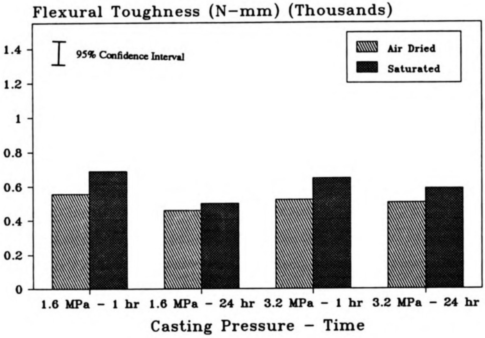


(a) Composites with 8% Fiber Content

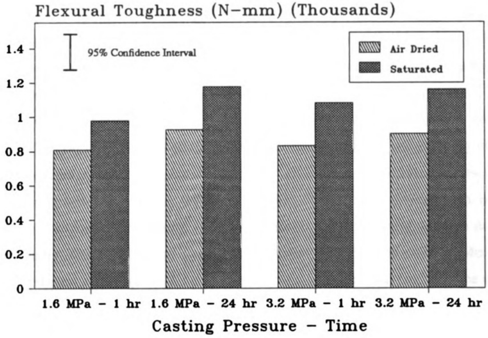


(b) Composites with 16% Fiber Content

Figure 5.14 Effects of Slurry-Dewatering Processing Parameters and Moisture Condition on Flexural Strength of Wood Fiber Reinforced Cement Composites.



(a) Composites with 8% Fiber Content



(b) Composites with 16% Fiber Content

Figure 5.15 Effects of Slurry-Dewatering Processing Parameters and Moisture Condition on the Flexural Toughness of Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived from the test data regarding the effects of moisture conditions and processing parameters on the flexural performance of wood fiber reinforced cement composites.

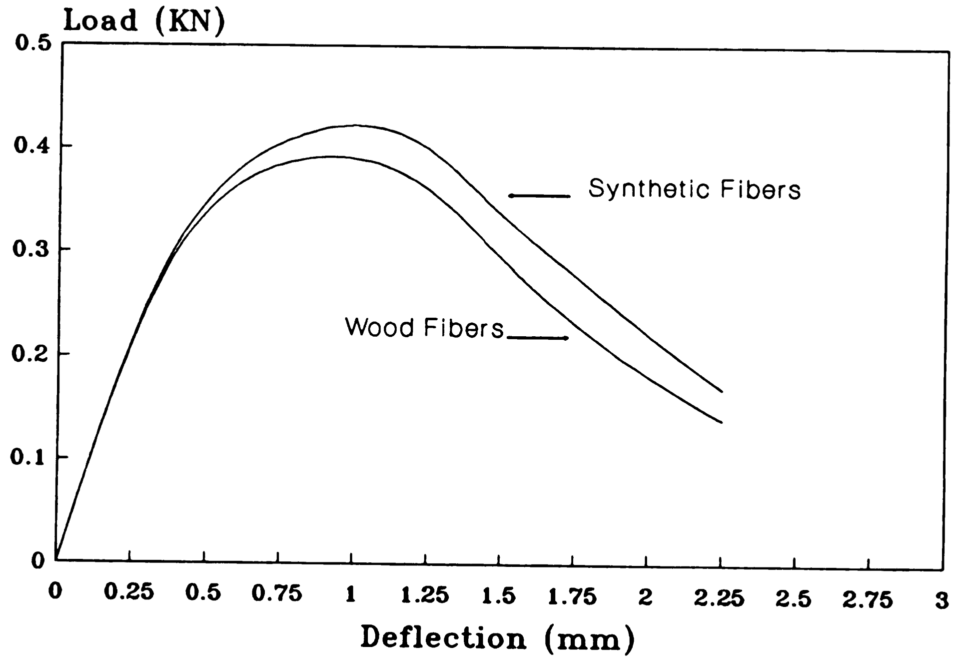
Flexural strength of air dried and saturated composites dropped significantly when fiber mass fraction was increased from 8% to 16%. Flexural strength of composites containing 8% fiber mass fraction slightly increased with increasing casting pressure and pressing time (45% in air dried condition and 26% in saturated condition at maximum levels of pressing time and pressure). However, statistical analysis of the test data did not show any significant effect of casting pressure or pressing time at 8% fiber mass fraction on flexural strength (at 95% level of confidence). The effects of casting pressure and pressing time were more pronounced in composites containing 16% fiber content, where flexural strength increased (by more than 2 times for air dried and saturated condition) with increased casting pressure and pressing time. However, statistical analysis of the test data showed only significant effect of pressing time on flexural strength of composites with 16% fiber content at 95% level of confidence.

Flexural toughness of composites increased significantly when fiber mass fraction was increased from 8% to 16%. However, flexural toughness of composites at all fiber contents remained virtually constant with increased casting pressure and pressing time. These results were confirmed statistically at 95% confidence level.

Wetting had adverse effects on flexural strength and positive effects on flexural toughness for composites at all combinations of casting pressure and pressing time. Wetting, on the average, reduced flexural strength by 45% and increased flexural toughness by 25% for composites containing 8% fiber content. These effects were even more pronounced in composites containing 16% fiber content, where flexural strength reduced on the average by 50% and flexural toughness increased by 27% with wetting. Moisture had highly significant effects (at 95% confidence level) on the flexural performance of cement composites reinforced with wood fibers. There were also strong interactions between pressing time and moisture condition on flexural toughness. In other words, the effects of moisture on composites were influenced by pressing time where increased pressing time produced better stable composites.

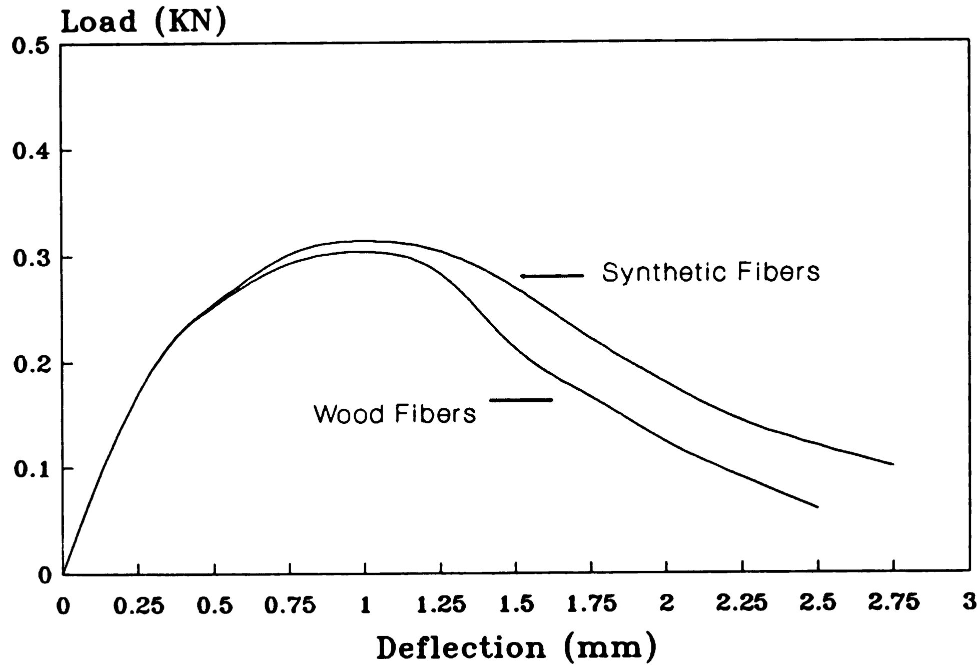
5.7.5 Combination with Synthetic Fibers

The fibers used in this study were Southern Softwood Kraft (SSK) [41] and Polyethylene Pulp (PulPlus) [48]. The composites were manufactured using the slurry-dewatering technique, and the combined fiber content was kept constant at 8% by mass. The matrix mix proportions used in this study are presented in Table 4.7. The effects of wood and synthetic fiber reinforcement on the flexural load-deflection behavior are shown in Figure 5.16 for different moisture conditions. A comparison of the test results on flexural performance of composites containing different combinations of wood and synthetic fibers are presented in Table 5.15 and Figure 5.17.



(a) Air Dried Condition

Figure 5.16 Effects of Moisture Condition on the Flexural Load-Deflection Behavior of Composites Containing Synthetic and Wood Fibers.

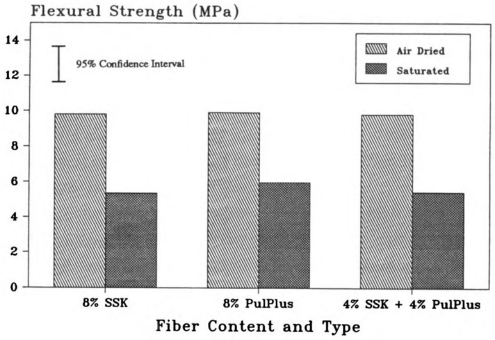


(a) Saturated Condition

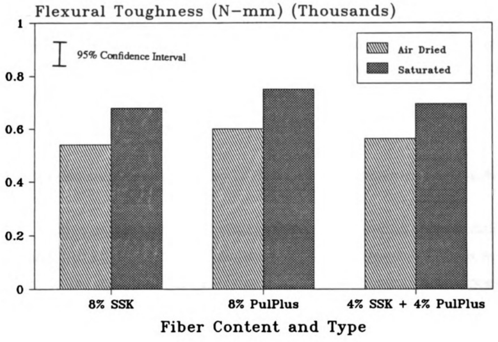
Figure 5.16 (cont'd) Effects of Moisture Condition on the Flexural Load-Deflection Behavior of Composites Containing Synthetic and Wood Fibers.

Table 5.15 Effects of Moisture Condition on the Flexural Performance of Composites Containing Synthetic and Wood Fibers (average ± half the range of two replications)

Fiber Type and Content	Flexural Strength (MPa)		Flexural Toughness (N-mm)	
	Air Dried	Saturated	Air Dried	Saturated
8% Kraft Pulp (SSK)	9.8052 ± 0.968	5.358 ± 1.0858	540.01 ± 80.62	679.77 ± 150.4
8% Polyethylene Pulp (PulPlus)	9.9236 ± 0.535	5.9634 ± 0.841	600.05 ± 93.89	750.15 ± 155.2
4% Kraft Pulp (SSK) & 4% Polyethylene Pulp (PulPlus)	9.8136 ± 0.574	5.4253 ± 0.574	562.90 ± 105.1	695.18 ± 148.7



(a) Flexural Strength



(b) Flexural Toughness

Figure 5.17 Effects of Moisture Condition on the Flexural Performance of Composites Containing Synthetic and Wood Fibers.

The following conclusions could be derived from the test data regarding the effects of moisture condition on the flexural performance of composites containing synthetic and wood fibers.

Cement composites containing synthetic and wood fibers showed comparable flexural strength and toughness in air dried condition. However, in saturated condition, composites containing synthetic fibers when compared to wood fibers showed slightly higher flexural strength (12%) and toughness (7%).

Wetting of the composites had adverse effects on flexural strength and positive effects on flexural toughness for all fiber combinations. Wetting, on the average, reduced the flexural strength (on the average by 50% for wood fiber reinforced composites, by 40% for synthetic fiber reinforced cement composites, and by 45% for composites containing equal amounts of synthetic and wood fibers) and increased the flexural toughness (on the average by 25% for all the composites). Moisture had highly significant effects (at 95% confidence level) on the flexural performance of composites reinforced with combinations of wood and synthetic fibers.

It is interesting to note that the synthetic fibers used in this study (specifically made for slurry-dewatering method of manufacturing cement composites) were also sensitive to moisture effects (although to a slightly smaller extent than wood fibers). Partial or full substitution of wood fibers with synthetic fibers can slightly reduce the sensitivity of the flexural strength and toughness of composites to moisture effects.

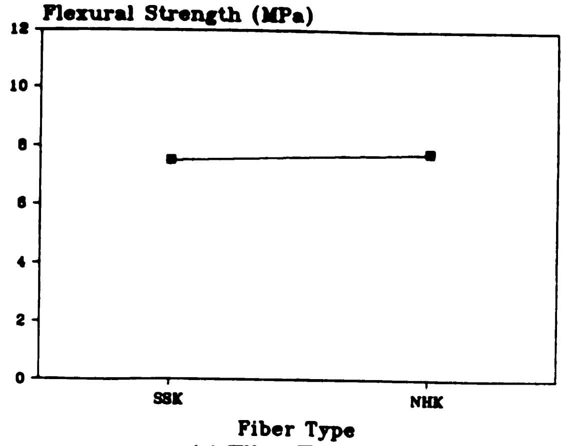
5.7.6 Comprehensive Statistical Study of Different Parameters and their Effects

This section presents the results of a comprehensive statistical study of different parameters and their effects on flexural performance. An experimental program was developed based on the statistical method of fractional factorial design. The composites were manufactured using the slurry-dewatering technique. The variables of the experimental study were: (1) wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash or 15% silica fume); (4) moisture conditions (air dried & saturated); and (5) silica sand content (silica sand-cement ratio = 0.5 & 1.0). Table 5.6 and Figures 5.18 and 5.19 present the effects of different parameters on the flexural strength and toughness (defined here as the total area underneath the flexural load-deflection curve) of wood fiber reinforced cement composites.

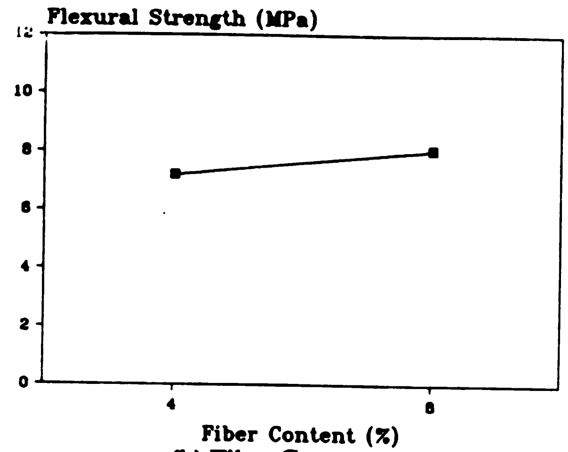
Table 5.16 Effects of Moisture Condition on the Flexural Performance of Wood Fiber Reinforced Cement Composites - Comprehensive Statistical Study (average ± half the range of two replications)*

Mix	1	2	3	4	5	6	7	8
Fiber Type	SSK	NHK	NHK	NHK	NHK	NHK	NHK	SSK
Fiber Content (%)	8	8	8	4	8	4	8	4
Binder	SF	FA	SF	FA	SF	FA	FA	FA
Moisture Condition	AD	SAT	AD	AD	SAT	SAT	AD	SAT
Sand Content (S/B)	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0
Flexural Strength (MPa)	9.643 ±0.54	4.728 ±0.47	8.777 ±0.65	7.059 ±0.53	7.776 ±0.48	6.177 ±0.51	8.154 ±0.62	5.471 ±0.38
Flexural Toughness (N-mm)	642.0 ±50.3	862.3 ±63.1	684.5 ±58.9	402.8 ±30.5	842.7 ±72.3	501.2 ±58.4	642.1 ±59.1	567.7 ±49.2
Mix	9	10	11	12	13	14	15	16
Fiber Type	SSK	SSK	NHK	NHK	SSK	SSK	SSK	SSK
Fiber Content (%)	8	4	4	4	8	8	4	4
Binder	FA	SF	SF	SF	FA	SF	SF	FA
Moisture Condition	AD	AD	AD	SAT	SAT	SAT	SAT	AD
Sand Content (S/B)	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5
Flexural Strength (MPa)	8.154 ±0.72	6.323 ±0.57	7.765 ±0.46	5.647 ±0.47	6.221 ±0.51	4.977 ±0.35	6.883 ±0.59	6.882 ±0.52
Flexural Toughness (N-mm)	673.1 ±72.2	392.9 ±47.9	372.2 ±49.5	499.9 ±50.3	828.2 ±60.1	873.6 ±80.5	492.8 ±53.1	422.7 ±48.2

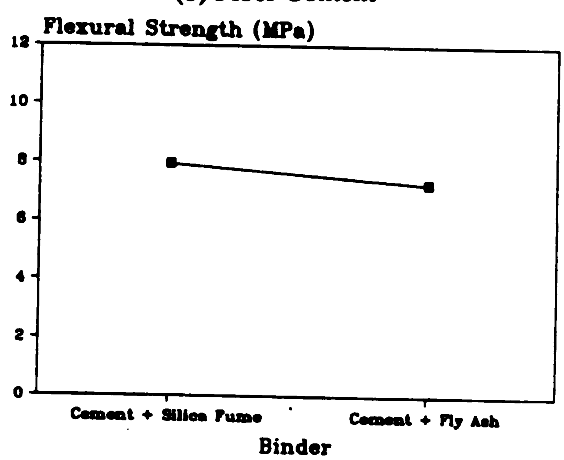
* see Appendix B for notation



(a) Fiber Type

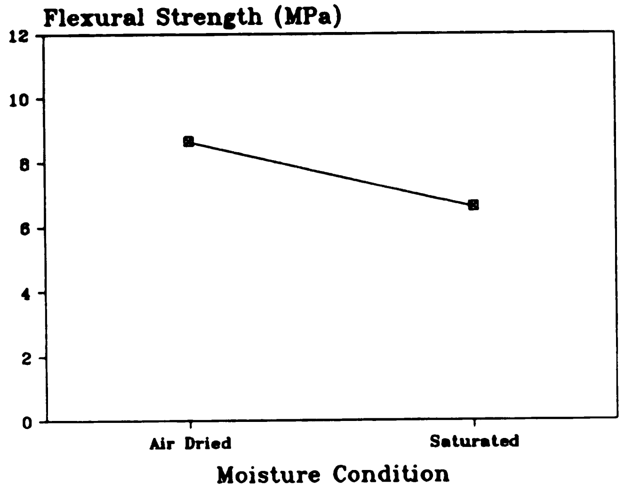


(b) Fiber Content

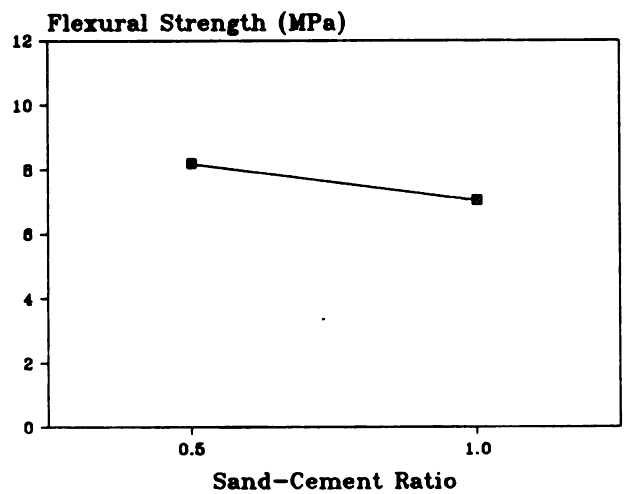


(c) Binder

Figure 5.18 Effects of Fiber Type, Fiber Content, Binder, Moisture Condition and Sand Content on Flexural Strength of Wood Fiber Reinforced Cement Composites Based on Factorial Analysis of Variance.

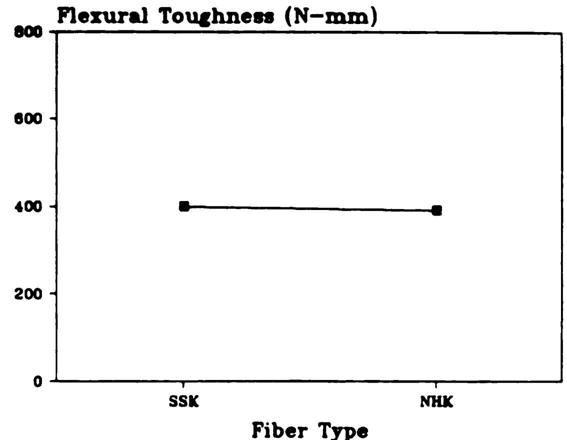


(d) Moisture Condition

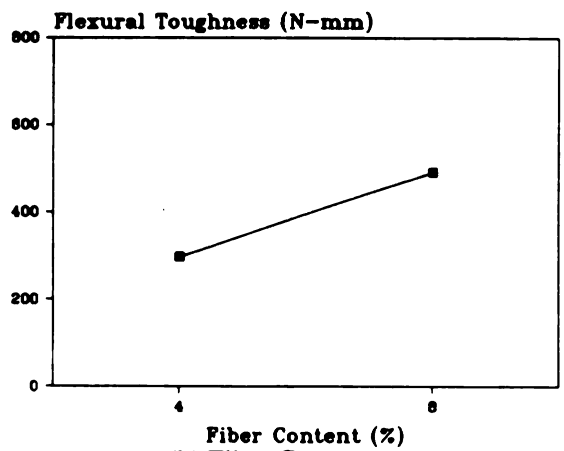


(e) Sand Content

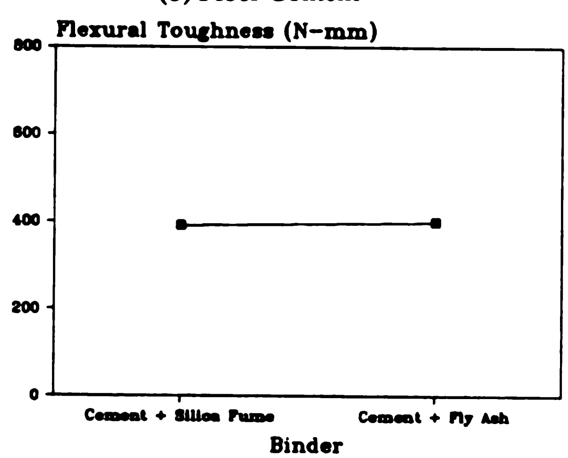
Figure 5.18 (cont'd) Effects of Fiber Type, Fiber Content, Binder, Moisture Condition and Sand Content on Flexural Strength of Wood Fiber Reinforced Cement Composites Based on Factorial Analysis of Variance.



(a) Fiber Type

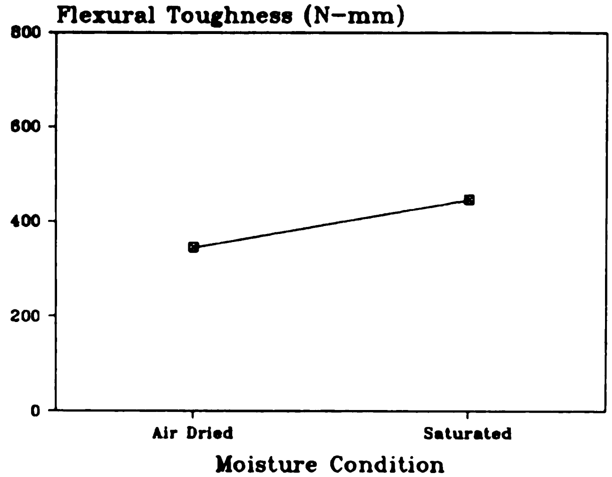


(b) Fiber Content

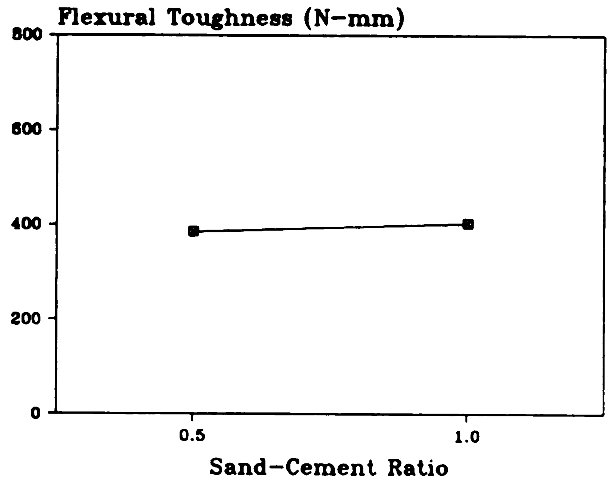


(c) Binder

Figure 5.19 Effects of Fiber Type, Fiber Content, Binder, Moisture Condition and Sand Content on Flexural Toughness of Wood Fiber Reinforced Cement Composites Based on Factorial Analysis of Variance.



(d) Moisture Condition



(e) Sand Content

Figure 5.19 (cont'd) Effects of Fiber Type, Fiber Content, Binder, Moisture Condition and Sand Content on Flexural Toughness of Wood Fiber Reinforced Cement Composites Based on Factorial Analysis of Variance.

The following conclusions could be derived from the test data regarding the effects of fiber type, fiber mass fraction, binder type, sand content, and moisture condition on flexural performance. Statistical fractional factorial analysis was performed on the generated test data in order to evaluate the effects of different factors involved (Figures 5.18 and 5.19).

Fiber Type: Composites containing softwood kraft pulp (SSK) and hardwood kraft pulp (NHK) produced comparable flexural strength and toughness values at all fiber contents and moisture conditions. Slight improvements in flexural strength and toughness with softwood fibers (SSK) were not statistically significant at 95% level of confidence.

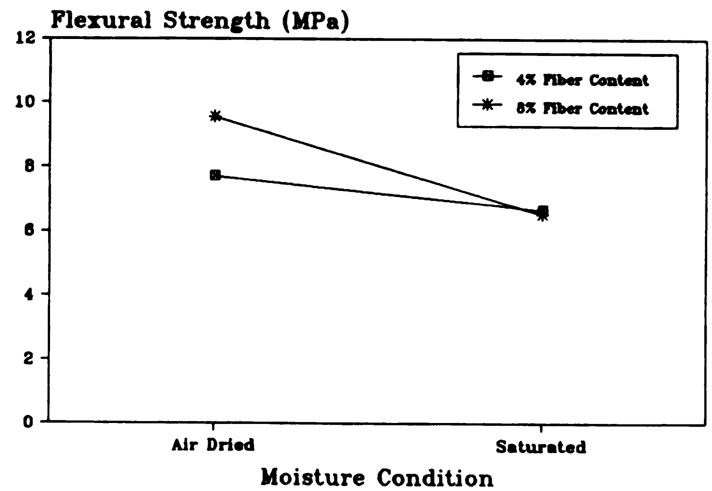
Fiber Content: Increasing the fiber mass fraction from 4% to 8% had statistically significant effects on the flexural strength of composites; strength increased with increasing fiber content. The effect of fiber content on flexural toughness was even more significant, where composites with 8% fiber content produced substantially higher flexural toughness values.

Binder Type: Partial substitution of cement with 15% silica fume when compared to 30% fly ash produced significantly higher flexural strengths. However, the toughness values were comparable. Improved fiber-to-matrix bonding and reduced permeability of the composite due to the addition of pozzolans help improve the flexural performance and moisture-sensitivity of wood fiber reinforced cement composites.

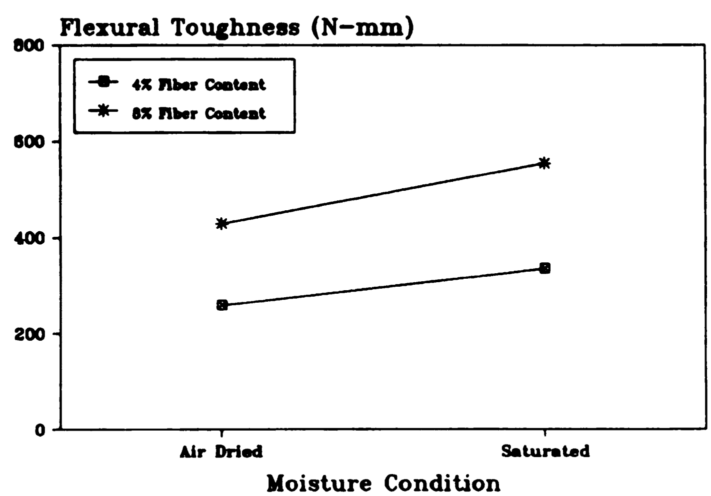
Sand Content: Reducing silica sand-cement ratio (i.e. increasing cement content) improves the flexural strength of wood fiber reinforced composites, at 95% level of confidence, at all fiber contents and moisture conditions. However, lower sand contents reduce the flexural toughness of composites.

Moisture Condition: Wood fiber reinforced cement composites are sensitive to moisture effects. Wetting of the composite had statistically significant effects, at 95% level of confidence, on flexural strength, which dropped sharply upon wetting. On the other hand, there were statistically significant improvements in flexural toughness of wood fiber reinforced cement composites upon wetting. These effects were more pronounced in composites containing 8% fiber mass fraction.

The interaction curves obtained through fractional factorial analysis of variance of the results (Figure 5.20) indicated strong interaction between fiber content and moisture condition on flexural strength; composites containing 8% fiber content showed higher strength loss due to wetting. The improvements in flexural toughness due to wetting of the composites were comparable. Improved flexural toughness and reduced flexural strength of composites upon wetting can be attributed to the weakening of fiber-to-matrix bond in the presence of moisture, and reduced stiffness and expansion of wet fibers.



(a) Flexural Strength



(b) Flexural Toughness

Figure 5.20 Interaction of Fiber Content and Moisture Condition on the Flexural Performance of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

CHAPTER 6

LONG-TERM DURABITY CHARACTERISTICS OF WOOD FIBER REINFORCED CEMENT COMPOSITES

6.1 INTRODUCTION

It is important to ensure that the improvements achieved in the properties of cement-based material through wood fiber reinforcement would be retained over a long period of time in the actual exposure conditions. In particular, one should be careful about the affinity of wood fibers for moisture, their durability in the alkaline environment of cement, and the possibility of biological attacks on woods. As far as the biological attacks are concerned, it is worth mentioning that no evidence is available to indicate that natural fibers can be decomposed biologically when used in cement materials [14].

Various durability test methods that deal with the particularities of wood fibers used in cement-based materials have not been used by past investigators. This makes it difficult to compare the results reported by different investigators and to arrive at general conclusions.

6.2 OBJECTIVES

The main thrust in this phase of the research was to assess the long-term durability of wood fiber reinforced cement composites. The specimens were subjected to repeated cycles of freezing and thawing, wetting and drying, and also to hot water immersion, and outdoor exposure in Michigan. After ageing, the specimens were tested for flexural performance, except for freeze-thaw durability tests in which case the specimens were subjected to non-destructive testing to obtain their relative dynamic modulus of elasticity. The results obtained in this study were analyzed statistically using analysis of variance and multiple comparison techniques in order to derive statistically reliable conclusions. Statistical time-series analysis were also used to predict the behavior of the composite beyond the testing period.

6.3 BACKGROUND

6.3.1 Mechanisms of Deterioration

Kraft pulp is the dominant wood fiber used in cement-based materials. These fibers have minimum lignin content and, noting the susceptibility of lignin to alkaline attack, have been used in applications involving outside exposure. Different weathering conditions actually increase the flexural strength and modulus of elasticity of the composite. However, the weathered wood fiber reinforced composites are more brittle than the original composites [38, 39, 54].

Mechanical pulps which contain higher lignin and hemicellulose contents than kraft pulps may require attention as far as potential dissolving of lignin in the alkaline cement environment is concerned. Much of the available test data on long-term durability of wood fiber cement composites deals with the use of natural fibers (e.g. sisal) in cement-based materials. In this case, unless measures are taken to reduce the alkalinity of cement matrix or to protect the natural fibers, the repeated action of wetting and drying results in the transport of alkaline pore water to the fibers and the removal of neutralized pore water (which would be produced in the vicinity of fibers) as well as the decomposed products from the fibers, causing decomposition of some natural fibers like sisal [14]. This can lead to the embrittlement of natural fiber reinforced cement composites. Repeated wetting and drying is a key factor accelerating this deterioration process of natural fibers, and it depends on the temperature and humidity history in the vicinity of the cement product. Interior exposure conditions or continuous immersion in water at ambient temperatures cannot produce cycles of wetting and drying. Two years of exposure in such conditions did not lead to any embrittlement of sisal reinforced cement composites in test results reported by Gram (1983) [14].

A description of the mechanisms leading to the embrittlement of natural fiber reinforced concrete under the action of repeated wetting and drying (rain-heat) is presented in Gram (1983) [14]. According to this description, the alkaline pore water in concrete reacts with the lignin and hemicellulose existing in the middle lamellae causing decomposition of these constituents of fibers. This leads to the weakening of the link between individual fiber cells in natural fibers (Figure 6.1). External changes in moisture and temperature which can provide a supply of water to and removal of water from concrete pores generate the moisture movements needed for alkaline pore water to reach and progressively decompose the natural fibers, leading to the embrittlement of the composite material.

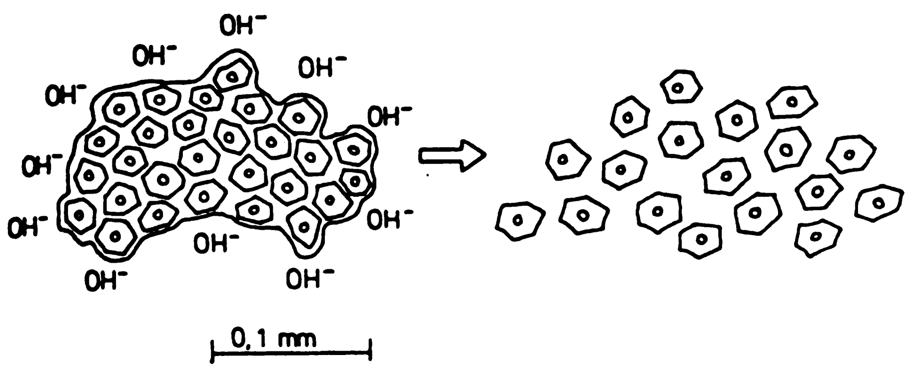


Figure 6.1 Schematic Sketch of the Decomposition of Natural (Sisal) Fibers in the Alkaline Pore Water of Concrete [14].

Wood fibers, especially kraft fibers, contain negligible amounts of lignin and thus they can withstand the alkaline pore water attack better than natural fibers. The reduced toughness accompanied with the strength gain in these composites with ageing may be associated with the petrification process (filling of the core of the fiber with hydration products) and the consequent changes in fiber failure mode [55, 56, 57, 58, 59]. The filling of fiber cores and possibly cell wall pores with hydration products is expected to result in an increase in the strength and stiffness. In addition to that, it seems that the petrified fibers are more stable dimensionally and no separation and debonding between the fibers and the matrix could be observed. In short, this petrification process increases the stiffness, strength and bond strengths of fibers, but reduces their ductility; these conditions lead to improved stiffness and strength of increased brittleness of the composite.

6.3.2 Experimental Results - Natural Fibers

Gram (1983) [14] has reported test results on the durability characteristics of sisal and coir reinforced mortars, in which a typical matrix had 1:2:0.5, binder : aggregate : water proportions. Fiber content ranged from 0.5-4% by volume. Tests were performed for natural ageing and also for accelerated ageing. In order to reproduce environmental conditions simulating the alkaline pore water attack on natural fibers (e.g. tropical conditions involving repeated exposure to rain and sun shine), an accelerated wetting-drying test equipment was developed (Figure 6.2). The panel specimens used in this "climate box" measure 10 mm in thickness and are subjected to half-cycles of moistening and cooling by spraying them with water, followed by half cycles of heating with the temperature reaching 105 deg. C (221 deg. F) and maintained at this level for a sufficiently long period so that the capillary pore system in the specimen dries out.

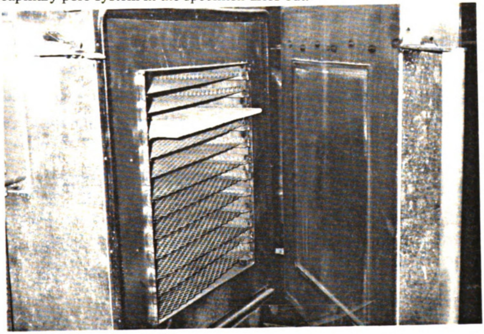
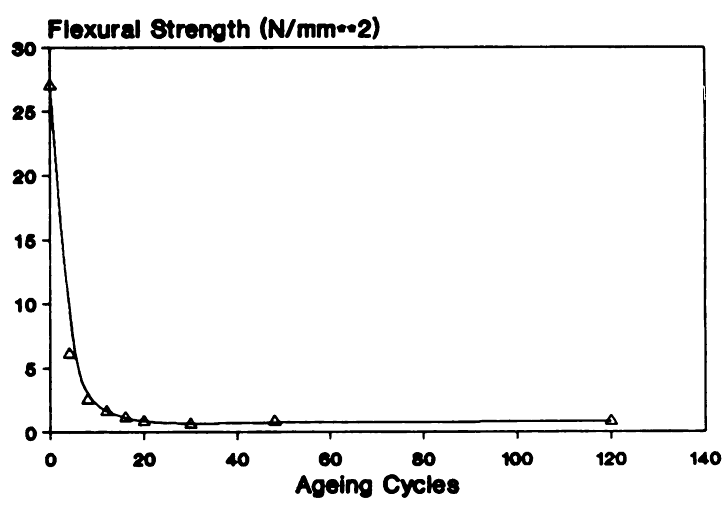


Figure 6.2 CBI Climate Box [14].

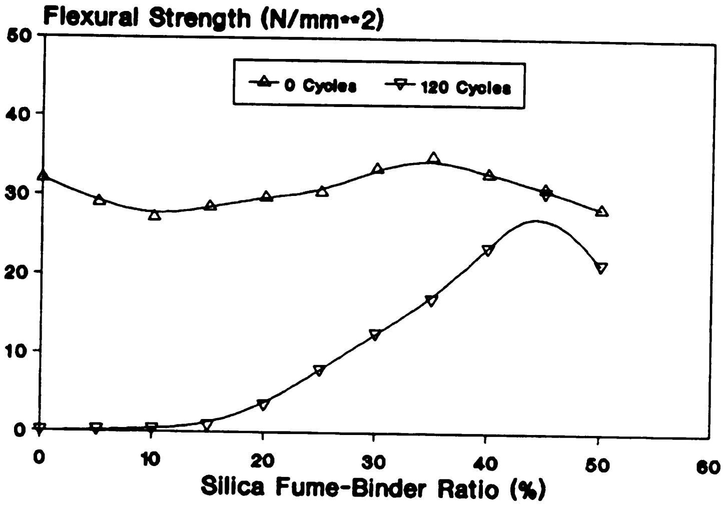
As a result of the above wetting-drying cycle, the capillary pore system of specimens is both filled with and emptied of water during the conditioning cycle that lasts about 6 hours. This means that the fibers embedded in specimens come in contact with the alkaline pore water of the concrete during the moistening phase, and that any decomposition products which are formed as a result of the reaction between the fiber components and the pore water can be transported away from the fiber during the drying phase. Figure 6.3 (a) presents the reduction in flexural strength of specimens incorporating sisal fibers due to ageing under repeated wetting-drying cycles. Considerable decrease in flexural strength is observed as the number of cycles increases. This can be attributed to the attack on natural fibers by the alkaline pore water of concrete.

The alkalinity of pore water in the matrix can be reduced and the strength of the composite can be improved by replacing part of the cement with silica fume. The pH value for the pore water reduces from 13.2 for a matrix with ordinary Portland cement to 12.0 for a matrix in which 33% of Portland cement by weight is substituted with silica fume. Figure 6.3 (b) shows the flexural strength of specimens reinforced with sisal fibers after 0 and 120 cycles of wetting and drying as a function of the percentage of cement by weight substituted with silica fume. Specimens in which up to 20% of Portland cement was replaced with silica fume show comparatively insignificant drops in strength after 120 wetting drying cycles when compared with specimens without silica fume. A dramatic improvement is obtained when 30-50% of the cement is replaced with silica fume. Hence, an effective approach to reducing the alkaline attack and thus enhancing the durability of natural fiber-cement composites is through reducing the alkalinity of concrete pore water by the use of silica fume [14, 60, 61].



(a) Pure Cement

Figure 6.3 Flexural Strength of Composite Reinforced with Sisal Fibers After Wetting-Drying Cycles [14].



(b) With Silica Fume

Figure 6.3 (cont'd) Flexural Strength of Composite Reinforced with Sisal Fibers After Wetting-Drying Cycles [14].

6.3.3 Experimental Results - Processed Fibers

Earlier durability test results with processed wood fibers (paper pulp) suggest that wood fiber-cement composites may be prone to degradation in certain exposure conditions. Four potential ageing mechanisms were investigated by Sharman (1983) [39] and Sharman, et al. (1986) [38] for autoclaved wood fiber reinforced cement sheets. The ageing mechanisms considered were carbonation, microbiological attack, moisture stressing of wood fibers, and increase in fiber-to-matrix bond, acting independently or together.

Carbonation is an important ageing mechanism in asbestos cement, causing embrittlement. In the case of wood fibers, however, carbonation may increase susceptibility to microbiological attack by reducing the alkalinity of the cement pore water, and/or increasing the bonding of cementitious matrices to wood fibers. The rate and extent of carbonation depends on the physical conditions of the sheet (e.g. porosity) and local climatic conditions (relative humidity and temperature). Microbiological attack on wood fibers in cement products was studied by Mansur and Aziz (1982) [62], who found it to be unlikely in the highly alkaline environment of cementitious matrices. Long-term drop in the pH of cement products after weathering and carbonation effects, however, may have adverse effects on resistance to biological attack.

Under natural weathering, wood fibers may be exposed to moisture cycling, carbonation, and fungal attack. The behavior of wood fiber reinforced cement composites has been investigated under various accelerated ageing effects, including (1) hot water soak, (2) moisture cycling, (3) carbonation, and (4) fungal cellar exposure. Comprehensive ageing test data have been reported by Sharman et al. (1986) [38] for autoclaved cement sheets consisting of 8% kraft pulp (P. Radiata), 46% cement, and 46% silica sand, and also by other investigators. The results are presented in the following.

6.3.3.1 Hot Water Soak

Hot water soak tests have been used to accelerate the ageing process and the subsequent strength loss of glass fiber reinforced cement composites. In the case of wood fiber reinforced cement composites, this test has been used to investigate any ageing effects on fibers or their bond to cementitious matrices. Effects of 350 days of immersion in 50 deg. C (122 deg. F) water on various aspects of the engineering properties of wood fiber reinforced cement composites are presented in Table 6.1. It should be noted that changes in material properties in warm water soak occurred dominantly in the first 20 days of immersion; thereafter, the material properties stayed practically constant. These test results indicate that warm water immersion, as an accelerated weathering condition, causes an increase in elastic modulus of wood fiber reinforced cement composites; other effects of accelerated ageing under warm water do not seem to be significant.

Table 6.1 Wood Fiber-Cement Composites - Hot Water (50 deg. C, 122 deg. F) Soak Test (see Appendix B for notation [38]

Number of Days Immersed	Mechanical Test Method	Modulus of Rupture (MPa)		Tensile Strength (MPa)		Internal Bond Strength (MPa)
		MD	CD	MD	CD	
0	Mean S.D.	18.6 0.6	10.3 0.2	4.38 0.16	7.98 0.14	0.204 0.056
350	Mean S.D.	19.2 0.9	12.1 1.2	5.30 0.29	9.06 0.20	0.314 0.140

Number of Days Immersed	Mechanical Test Method	Impact Strength (kJ/m^2)		Moisture Movement (%)		Modulus of Elasticity (GPa)	
		MD	CD	MD	CD	MD	CD
0	Mean S.D.	3.97 0.53	2.46 0.12	0.302 0.008	0.283 0.005	7.92 0.33	3.88 0.70
350	Mean S.D.	3.50 0.50	3.45 0.88	0.235 0.009	0.224 0.012	9.79 0.33	8.15 0.35

Harper (1982) [6] has observed similar effects of warm water immersion on wood fiber-cement composites, implying that degradation of wood fibers under weathering effects is unlikely. This can be explained by the fact that lignin, which is the wood fiber constituent most susceptible to alkali attack, is totally removed during the kraft pulping process (noting that kraft pulp is the main wood fiber used in cement composites). The fact that mechanical properties of wood fiber reinforced cement sheets remained much the same throughout exposure indicated that there was no major change in the nature of fiber-to-cement bond. Failure in mechanical testing was predominantly by fiber pullout.

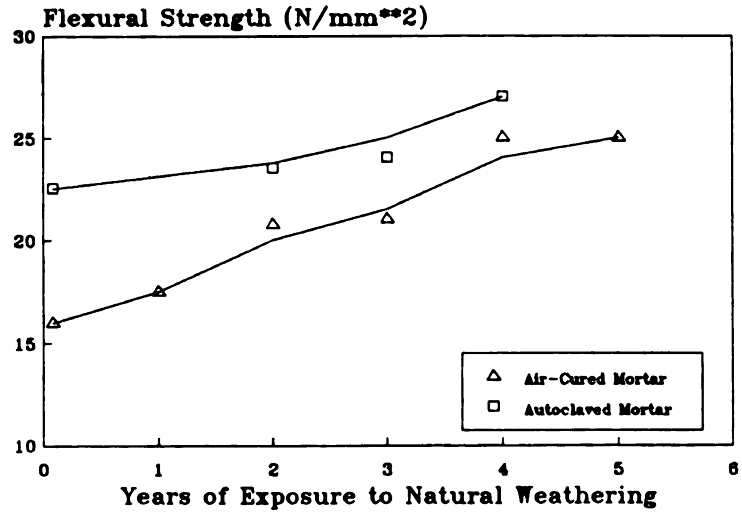
6.3.3.2 Accelerated Wetting and Drying

Repeated wetting-drying tests are widely used for accelerated weathering of particle boards. Sharman et. al (1986) [38] have reported test results on wood fiber reinforced cement sheets subjected to 10, 20, 35 and 50 cycles of wetting and drying. The test results showed only a small increase in modulus of elasticity up to 10 cycles with no further changes after 10 cycles. A slight reduction in impact resistance was also observed.

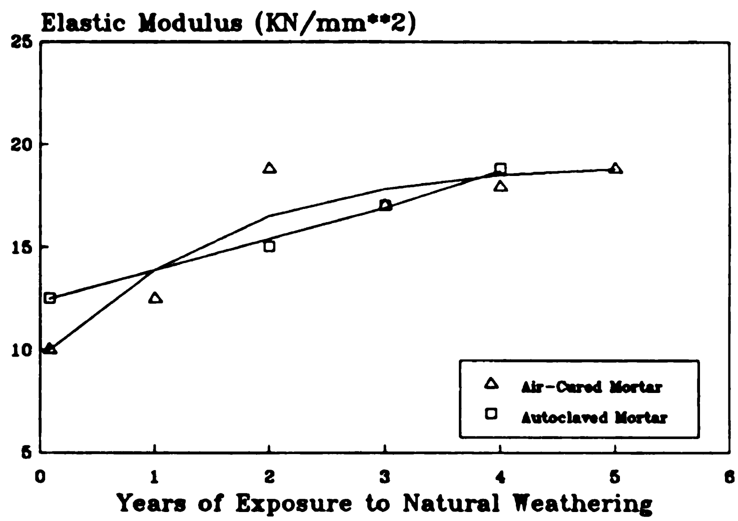
Recent studies on repeated wetting and drying are reported by Akers et al. [54]. In this study effects of natural versus accelerated weathering conditions on the ageing behavior of wood fiber reinforced cement composites were also investigated. Two products manufactured on a standard Hatschek machine were used in this study. They were: (1) 8% wood fibers in a Portland cement-based matrix and cured at ambient temperature and relative humidity; and (2) 8% wood fibers in a Portland cement and silica based matrix and autoclaved. The dimensions of the flat sheet products were 600 x 400 x 6 mm (24 x 16 in x 0.23 in) for natural weathering and 200 x 100 x 6 mm (8 x 4 x 0.23 in) for accelerated ageing tests. The Portland cement-based and Portland silica-based products were exposed to natural weathering for 5 and 4 years, respectively. Similar products were also subjected to accelerated tests.

The accelerated test involved repeated cycles of wetting and drying, with each cycle consisting of the following steps over a 24-hour time period: (a) 9 hours submersion under water at 20 deg. C (68 deg. F); (b) 3 hours in air at 20 deg. C (68 deg. F); (c) 9 hour infrared radiation at 80 deg. C (176 deg. F) in air; and (d) 3 hours cooling down to 20 deg. C (68 deg. F) in air. The natural and accelerated ageing effects on wood fiber-cement composites are discussed in the following.

The test results on specimens exposed to natural weathering (Figure 6.4) showed a general increase in strength and stiffness. This increase in strength is associated with an increase in density from 1750 to 1870 kg/m^3 (109 to 117 lb/ft^3) over a period of 5 years for Portland-based (air cured) specimens and from 1610 to 1790 kg/m^3 (100 112 lb/ft^3) over a period of 4 years for Portland cement/silica-based (autoclaved) specimens. The products were found to be well carbonated at the end of the natural weathering test period.



(a) Flexural Strength



(b) Elastic Modulus

Figure 6.4 Flexural Strength and Young's Modulus of Air Cured and Autoclaved Products Exposed to Natural Weathering [54].

The degree of polymerization of wood fibers in the naturally aged products was found to decrease with age by about 20% for air cured products and 35% for autoclaved products. This is in contrast to the tendency in strength to increase with age. Thus, the weakening effects which might have been expected upon reduction in the degree of polymerization are apparently more than compensated for by other processes, including the improvement in fiber-to-matrix bonding and overall densification of the composite under ageing effects.

The naturally aged specimens were found to be brittle. The embrittlement of these composites may have been due to the increase in fiber-to-matrix bond, which results in fiber rupture rather than pullout dominating failure at fracture surfaces; this ageing effect reduces the frictional energy absorption associated with fiber pullout. The specimens subjected to accelerated ageing (up to 3 months) in ambient environment (with minimal carbonation effects) showed drops in flexural strength (16.4 to 12.3 MPa, 2.38 to 1.78 ksi) and tensile strength (7 to 2.6 MPa, 1.02 to 0.38 ksi). This is in contrast to the increase in flexural strength shown by naturally aged composites. The increase in elastic modulus and the drop in degree of polymerization were, however, comparable.

Observation of the fractured surfaces of composites after accelerated ageing in ambient environment indicated invariably broken fibers with their hollow nature clearly shown [55]. In most cases the matrix around the fibers was quite dense (Figure 6.5). It was typical to observe debonding between wood fibers and the surrounding matrix.

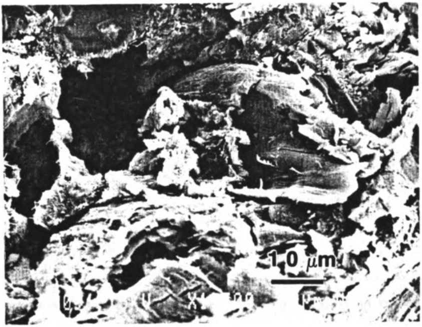
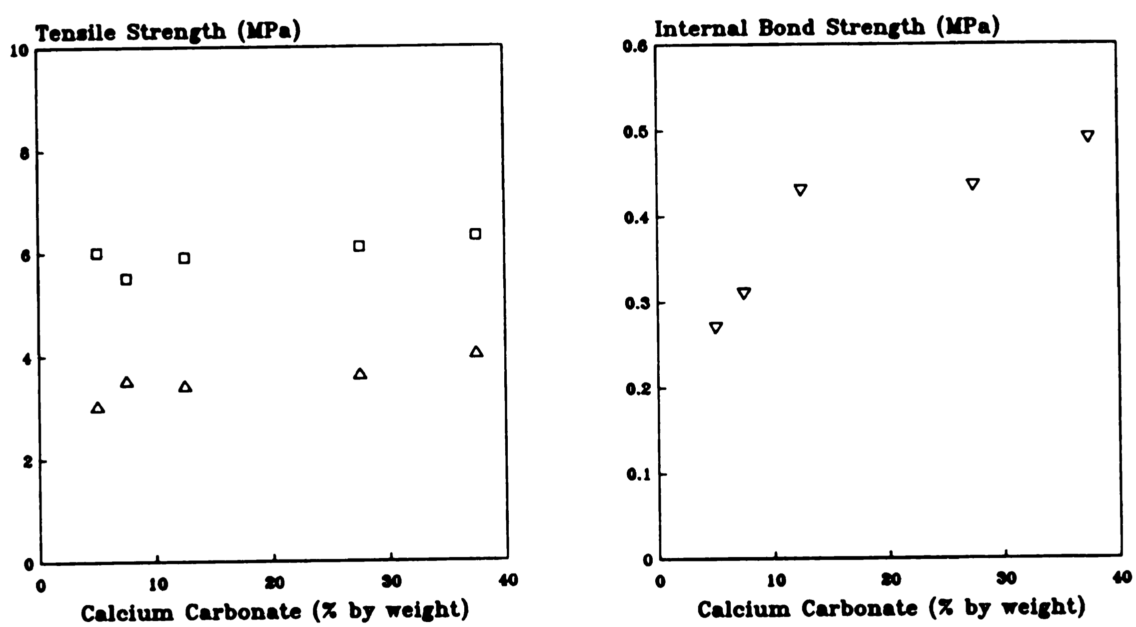


Figure 6.5 Scanning Electron Micrographs of Fractured Surfaces After Accelerated Weathering in Ambient Environment [55].

6.3.3.3 Carbonation

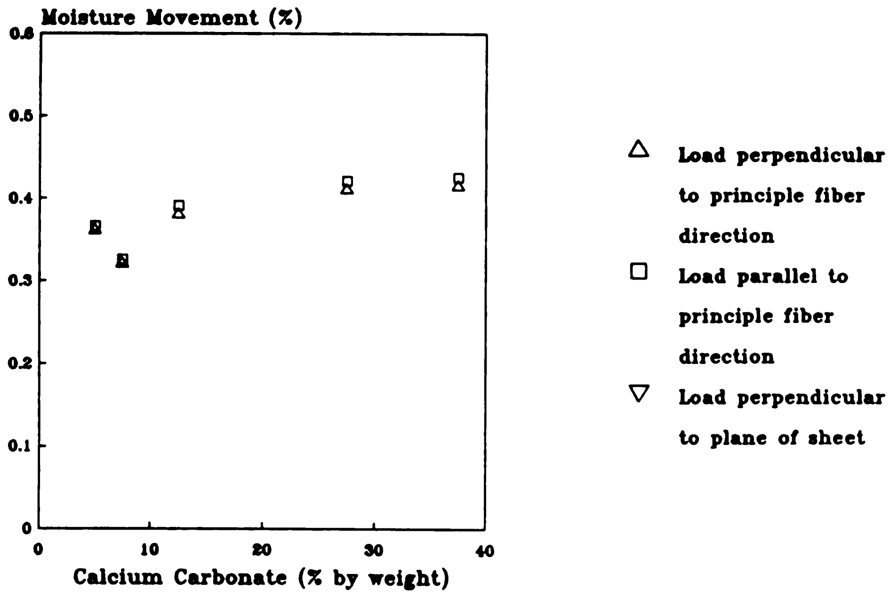
Carbonation of the matrix by atmospheric carbon dioxide has been observed to cause loss of strength in asbestos cement composites. Since wood fiber cement sheets will also undergo carbonation in everyday use, it is desirable to account for this process in any accelerated ageing tests on wood fiber-cement composites.

Sharman et al. (1986) [38] have conducted carbonation tests on autoclaved wood fiber reinforced cement composites. The specimens were stored in a tank (RH 65% and temperature 20 deg. C, 68 deg. F) which was supplied with carbon dioxide at a rate of 40 cm^3/min (2.5 in^3/min). The extent of carbonation was assessed by the measurement of $CaCO_3$ content, which reached levels ranging from 36 to 41%, when the absorption of CO_2 virtually ceased. The significant changes noted in the properties of carbonated wood fiber reinforced cement sheets were increased tensile strength, internal bond and moisture movement (Figure 6.6). An increase in modulus of rupture was also observed, and the flexural stiffness showed a similar increase. It is worth mentioning that the increase in moisture movement seems to be the only potentially deleterious effect of carbonation observed in this investigation.



(a) Tensile Strength (b) Internal Bond Strength

Figure 6.6 Effects of Carbonation on Wood Fiber Reinforced Cement Sheets [38].



(c) Moisture Movement

Figure 6.6 (cont'd) Effects of Carbonation on Wood Fiber Reinforced Cement Sheets [38].

Akers et al. [54] in more recent studies on carbonation effects, subjected wood fiber-cement composites to accelerated weathering conditions which also involved exposure to a carbon dioxide rich environment. Two composites (air cured cement-based and autoclaved Portland cement and silica based matrices) were subjected to the following accelerated weathering cycles.

(a) 8 hours submersion under water at 20 deg. C (68 deg. F)
(b) 1 hour in oven at 80 deg. C (176 deg. F)
(c) 5 hours in oven at 20 deg. C (68 deg. F) in a saturated CO_2 environment
(d) 9 hour in oven at 80 deg. C (176 deg. F)
(e) 1 hour cooling down from 80 deg. C to 20 deg. C (176 to 68 deg. F)

The test cycles chosen were optimized by trial and error experiments based on the degree of carbonation and water penetration into the products. Table 6.2 shows the test results on the ageing of composites subjected to natural weathering and accelerated ageing tests. The results suggest that the development of mechanical properties of wood fiber reinforced cement composites when exposed to CO_2 rich accelerated test simulates more closely the behavior in natural weathering. Accelerated ageing in a CO_2 rich environment and natural weathering both led to an increase in strength and elastic modulus. Also, the increase in the degree of carbonation in a CO_2 environment compares favorably with the naturally weathered products. The increase in density of the product with age may be associated with carbonation of the matrix.

Table 6.2 Properties of Wood Fiber-Cement Products Exposed to Different Ageing Conditions [54]

(a) Air Cured Cement Based Matrix

Type of ageing	Flexural strength N/mm^2	E-modulus kN/mm^2	Tensile strength N/mm^2	Strain at failure %	CO_2 content %	DP (fibre)	Density kg/m^3
Non-aged	16.4 ±0.9	10.9 ±1.3	7.0 ±0.2	2.80 ±0.70	1.65 ±0.12	581 ±60	1770 ±20
Accelerated aged 3 months ambient environment	12.3 ±1.1	14.8 ±1.2	2.6 ±0.9	0.04 ±0.01	4.85 ±0.16	430 ±50	1780 ±10
Accelerated aged 3 months CO_2 rich environment	23.9 ±2.2	18.9 ±1.4	7.2 ±1.3	0.05 ±0.01	6.71 ±0.05	435 ±80	1800 ±10
Natural weathering	25.1 ±1.6	18.0 ±0.9	7.4 ±0.9	0.05 ±0.01	9.72 ±0.10	491 ±50	1830 ±40

(b) Autoclaved Cement and Silica Based Matrix

Type of ageing	Flexural strength N/mm^2	E-modulus kN/mm^2	Tensile strength N/mm^2	Strain at failure %	CO_2 content %	DP (fibre)	Density kg/m^3
Non-aged	23.0 ±1.3	13.2 ±1.6	10.1 ±1.3	0.07 ±0.02	1.30 ±0.06	730 ±50	1610 ±20
Accelerated aged 3 months ambient environment	20.2 ±1.8	13.5 ±1.8	7.8 ±1.2	0.05 ±0.01	1.62 ±0.21	530 ±20	1700 ±30
Accelerated aged 3 months CO_2 rich environment	25.6 ±1.3	13.1 ±1.1	11.2 ±1.3	0.05 ±0.02	10.7 ±0.22	504 ±60	1790 ±10
Natural weathering	27.2 ±1.4	18.6 ±0.3	12.2 ±1.1	0.04 ±0.01	11.8 ±0.08	475 ±40	1790 ±20

With respect to wood fiber properties, there is a breakdown in the molecular chain of the fibers with age, which may be directly correlated with the decrease in degree of polymerization (see Table 6.2). The drop in degree of polymerization should logically result in a drop in tensile strength of the wood fibers; however, other factors such as carbonation, which tend to increase the strength and elastic modulus of the composite overshadow any negative effects of the damage to wood fibers.

The mode of fracture after ageing was brittle with most of the fibers being broken at the fractured plane (Figure 6.7). Very frequently, the circular cross section of the broken fiber was filled up with dense hydration products and there was no perimeter debonding. This microstructure is referred to as "brittle petrified."

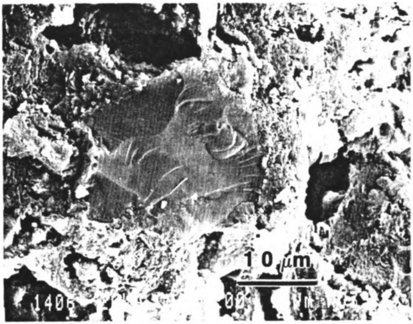


Figure 6.7 Brittle Fracture in a Composite After Accelerated Ageing in a CO_2 Rich Environment. [55]

It is suggested that the increase in strength and rigidity of the petrified fibers, and the increase in their bond strength (due to matrix densification and elimination of shrinkage-debonding from the surrounding matrix) can account for the increase in strength and elastic modulus of the composite upon ageing.

Naturally aged composites produced microstructural features at failure surfaces similar to those of composites subjected to accelerated ageing in a carbon dioxide rich environment. This suggests that petrification takes place more readily under carbonating conditions, probably due to the lower pH and greater solubility of the hydration products.

6.4 EXPERIMENTAL DESIGN

In this phase of the research, the long-term durability of wood fiber reinforced cement composites was assessed. The specimens were subjected to repeated cycles of freezing and thawing, wetting and drying, hot water immersion, and outdoor exposure. After ageing, the specimens were tested for flexural performance, except for freeze-thaw durability in which case the specimens were subjected to non-destructive testing to obtain their relative dynamic modulus of elasticity. The following steps were taken at this stage to study the long-term durability of wood fiber-cement composites: (a) assess the effect of fiber type and content on durability characteristics; (b) study the effect of bleaching on durability; and (c) perform a comprehensive statistical study on the effects of different parameters specific to wood fiber reinforced cement composites on long-term durability.

Replicated test specimens were manufactured from each mix in order to derive reliable conclusions through statistical analysis of results. The dimensions and the number of specimens depend on the specific test performed. In case of panels, the test specimen has to be cut using a diamond saw to the required dimension.

6.4.1 Effects of Fiber Type and Content

The wood fibers used in this investigation were Southern Softwood Kraft (SSK) [41], Northern Hardwood Kraft (NHK) [42] and Mechanical Pulps (1000L) [43]. Wood fiber reinforced cement composites containing lower fiber contents ($\leq$ 2%) were manufactured through the molding method. The fiber mass fractions and matrix mix proportions used in this phase of the study are introduced in Table 4.3 (a). The experimental design used in this study is presented in Table 6.3. In the molding method of manufacture, water and superplasticizer contents were varied in order to achieve reasonable fresh mix workability characteristics represented by a flow (ASTM C-230) of 55% to 65% at 1 minute after mixing. Fibrous mixtures also contained a non-chloride set accelerator, which was essential to keep the setting time of the composites within acceptable limits. Molded thin-sheet panel specimens (280 x 400 x 10 mm, 11 x 16 x 0.4 in) were manufactured from each mix for accelerated wetting-drying and natural ageing tests. Flexural specimens (38.1 x 152.4 x 10 mm, 1.5 x 6.0 x 0.4 in) were then cut out from each panel using a diamond saw for flexural testing. An average of 10 flexural specimens were tested for each ageing cycle. The specimens for freeze-thaw testing were prisms with 76.2 x 101.6 mm (3 x 4 in) cross section and length of 406.4 mm (16 in). An average of 2 specimens from each mix were subjected to repeated freezing and thawing cycles, and were tested for fundamental transverse frequency over a span of 196.3 mm (7.728 in) at regular intervals.

Table 6.3 Experimental Design for Long-Term Durability - Effect of Fiber Type and Content

(a) Repeated Wetting and Drying

Fiber Type	Fiber Mass Fraction (%)	Number of Wetting-Drying Cycles					
		0	12	24	30	60	120
-	0	*	*	*	*	*	*
Kraft (NHK)	1	*	*	*	*	*	*
	2	*	*	*	*	*	*
Kraft (SSK)	2	*	*	*	*	*	*
Mech. (1000L)	2	*	*	*	*	*	*

(b) Outdoor Exposure to Natural Weathering

Fiber Type	Fiber Mass Fraction (%)	Outdoor Exposure (Number of Months)				
		0	3	6	9	12
-	0	*	*	*	*	*
Kraft (NHK)	1	*	*	*	*	*
	2	*	*	*	*	*
Kraft (SSK)	2	*	*	*	*	*
Mech. (1000L)	2	*	*	*	*	*

Table 6.3 (cont'd) Experimental Design for Long-Term Durability - Effect of Fiber Type and Content

(c) Repeated Freezing and Thawing

Fiber Type	Fiber Mass Fraction (%)	Number of Freezing-Thawing Cycles							
		0	20	40	60	80	100	120	140
		160	180	200	220	240	260	280	300
-	0	* *	* *	* *	* *	* *	* *	* *	* *
Kraft (NHK)	1	* *	* *	* *	* *	* *	* *	* *	* *
	2	* *	* *	* *	* *	* *	* *	* *	* *
Kraft (SSK)	2	* *	* *	* *	* *	* *	* *	* *	* *
Mech. (1000L)	2	* *	* *	* *	* *	* *	* *	* *	* *

6.4.2 Effect of Bleaching

The fibers used in this study were unbleached and bleached Southern Softwood Kraft (SSK) [41]. The composites were manufactured by the molding technique, and the fiber content was 2% by mass. The matrix mix proportions used in this study are given in Table 4.5. The experimental design is presented in Table 6.4. Molded thin-sheet panel specimens (280 x 400 x 10 mm, 11 x 16 x 0.4 in) were manufactured from each mix for accelerated wetting-drying and natural ageing tests. Flexural specimens (38.1 x 152.4 x 10 mm, 1.5 x 6 x 0.4 in) were then cut out from each panel using a diamond saw for flexural testing. An average of 10 flexural specimens were tested for each ageing cycle. The specimens for freeze-thaw testing were prisms with 76.2 x 101.6 mm (3 x 4 in) cross sections and a length of 406.4 mm (16 in). Two specimens from each mix were subjected to repeated freezing and thawing cycles, and were tested for fundamental transverse frequency over a span of 196.3 mm (7.728 in) at regular intervals.

Table 6.4 Experimental Design for Long-Term Durability - Effect of Bleaching

(a) Accelerated Wetting and Drying

Fiber Type	Fiber Mass Fraction (%)	Number of Wetting-Drying Cycles					
		0	12	24	30	60	120
Kraft (SSK) Bleached	2	*	*	*	*	*	*
Kraft (SSK) Unbleached	2	*	*	*	*	*	*

(b) Outdoor Exposure to Natural Weathering

Fiber Type	Fiber Mass Fraction (%)	Outdoor Exposure (Number of Months)				
		0	3	6	9	12
Kraft (SSK) Bleached	2	*	*	*	*	*
Kraft (SSK) Unbleached	2	*	*	*	*	*

(c) Repeated Freezing and Thawing

Fiber Type	Fiber Mass Fraction (%)	Number of Freezing-Thawing Cycles							
		0	20	40	60	80	100	120	140
		160	180	200	220	240	260	280	300
Kraft (SSK) Bleached	2	* *	* *	* *	* *	* *	* *	* *	* *
Kraft (SSK) Unbleached	2	* *	* *	* *	* *	* *	* *	* *	* *

6.4.3 Comprehensive Statistical Study of Different Parameters and their Effects

An experimental program was developed based on the statistical method of fractional factorial design. The composites were manufactured by slurry-dewatering. The variables of the experimental study were: (1) wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash & 15% silica fume); (4) ageing condition (aged & unaged); and (5) silica sand content (silica sand-cement ratio = 0.5 & 1.0). The experimental program is presented in Table 6.5. In slurry-dewatering method of manufacture, thin-sheet specimens were formed from a dilute slurry of approximately 20% solids. A relatively small dosage of 1% diluted flocculent (flocculent/cement=0.01) was added to achieve agglomeration of cement solids in the slurry, which helps in reducing the amount of cement particles lost through the filtering screens during dewatering. Fiber mass fraction in the slurry-dewatering method of manufacture is defined as the ratio of fibers to the dry constituents of the matrix by weight. Thin sheet panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were manufacture by slurry-dewatering for accelerated wetting-drying and hot water immersion tests. Two replicated panel specimens were manufactured from each mix. Specimens for flexural testing (38.1 x 125 x 10 mm, 1.5 x 5.0 x 0.4 in) were then cut using a diamond saw. An average of 6 specimens with specific mix design were selected from two different batches in order to accurately measure the variability of results.

Table 6.5 Experimental Design for Long-Term Durability - Comprehensive Statistical Study (see Appendix B for notation)

(a) Wetting-Drying

Mix	1	2	3	4	5	6	7	8
Fiber Type	SSK	NHK	NHK	NHK	NHK	NHK	NHK	SSK
Fiber Content (%)	8	8	8	4	8	4	8	4
Binder	SF	FA	SF	FA	SF	FA	FA	FA
Wet-Dry Cycles	0	25	0	0	25	25	0	25
Sand Content (S/B)	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0

Mix	9	10	11	12	13	14	15	16
Fiber Type	SSK	SSK	NHK	NHK	SSK	SSK	SSK	SSK
Fiber Content (%)	8	4	4	4	8	8	4	4
Binder	FA	SF	SF	SF	FA	SF	SF	FA
Wet-Dry Cycles	0	0	0	25	25	25	25	0
Sand Content (S/B)	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5

Table 6.5 (cont'd) Experimental Design for Long-Term Durability - Comprehensive Statistical Study (see Appendix B for notation)

(b) Hot Water Soak

Mix	1	2	3	4	5	6	7	8
Fiber Type	SSK	NHK	NHK	NHK	NHK	NHK	NHK	SSK
Fiber Content (%)	8	8	8	4	8	4	8	4
Binder	SF	FA	SF	FA	SF	FA	FA	FA
Hot Water (days)	55	0	55	55	0	0	55	0
Sand Content (S/B)	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0
Mix	9	10	11	12	13	14	15	16
Fiber Type	SSK	SSK	NHK	NHK	SSK	SSK	SSK	SSK
Fiber Content (%)	8	4	4	4	8	8	4	4
Binder	FA	SF	SF	SF	FA	SF	SF	FA
Hot Water (days)	55	55	55	0	0	0	0	55
Sand Content (S/B)	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5

6.5 MANUFACTURING PROCEDURE

Wood fiber reinforced cement composites at lower fiber contents ($\leq 2\%$) were manufactured through the molding technique, and at higher fiber contents ($> 2\%$) through slurry-dewatering. In the molding method, mixing was performed in a regular mortar mixer. A batch-type slurry-dewatering equipment (simulation of the Hatschek process) was developed for use in laboratory. The manufacturing procedures adopted for the two different techniques are described in Chapter 4.

6.6 TEST PROCEDURES

6.6.1 Accelerated Wetting and Drying

An accelerated wetting-drying test procedure was developed in order to study the ageing behavior of wood fibers under the environmental effects stimulating the alkaline pore water attack on wood fibers (e.g., conditions involving repeated exposure to rain and sun shine). For this purpose, an accelerated wetting-drying test chamber (Figure 6.8) was developed. The 10 mm (0.4 in) thick panel specimens are subjected in the climate box to moisture by spraying for 1/2 hour until the capillary pores are filled with pore water; the panels are then heated to reach 82 deg. C (180 deg. F) and the temperature is maintained at this level for a sufficiently long period (5 1/2 hours) to dry out the capillary pore system. Under these conditions, the fibers come into contact with the alkaline pore water of cement during the moistening phase; the decomposition products which are formed as a result of the reaction between the fiber components and the pore water are then transported away from the fiber during the drying phase.

Figure 6.8 Accelerated Wetting-Drying Test Equipment.

Six panel specimens were subjected to this accelerated ageing test. After 0, 12, 24, 30, 60 and 120 cycles, a panel specimen was taken out and a minimum of ten flexural specimens (38.1 x 152.4 x 10 mm, 1.5 x 6.0 x 0.4 in) were cut out using a diamond saw. Flexural tests were then performed according to the Japanese Specification JCI-SF (Japanese Concrete Institute, 1984) [49].

Recently ASTM has developed a standard test method for accelerated wetting and drying on thin cement products (ASTM C 1185). This test method suggests a spraying cycle of 2 hours and 55 minutes at 30 deg. C (86 deg. F), and a heating cycle of 2 hours and 55 minutes at 60 ± 5 deg. C (140 ± 9 deg. F), with a pause of 5 minutes between each cycle. This testing method was adopted for a comprehensive statistical study of various parameters involved in slurry-dewatered composites. Two replicated panel specimens (125 x 125 x 10 mm, 5 x 5 x 0.4 in) were subjected to 25 cycles of accelerated wetting and drying. Specimens for flexural testing (38.1 x 125 x 10 mm, 1.5 x 5 x 0.4 in) were then cut using a diamond saw. An average of 6 specimens for each mix design were selected from two different batches in order to accurately measure the variability of results. Flexural tests were performed according to the Japanese Specification JCI-SF (Japanese Concrete Institute, 1984) [49]. Test results on aged specimens were compared with those on unaged specimens.

6.6.2 Freezing and Thawing

In order to assess the resistance of wood fiber reinforced cement composites to freezing and thawing the specimens were subjected to repeated cycles of freezing and thawing in water (ASTM C-666). An average of two specimens for each mix were subjected to a maximum of 300 cycles and tested for fundamental transverse frequency over a span of 196.3 mm (7.728 in) at a regular interval of 20 freeze-thaw cycles (Figure 6.9). Each freezing and thawing cycle consists of alternately lowering the temperature of the specimens from 4.4 deg. C to -17.8 deg. C (40 to 0 deg. F) in 3 3/4 hour and raising it from -17.8 deg. C to 4.4 deg. C (0 to 40 deg. F) in 1 1/4 hour. One freeze-thaw cycle requires 5 hours for completion, in which 25% of the time is used for thawing. The freeze-thaw damage was assessed through measurement of the fundamental transverse frequency of specimens when simply supported on a span of 196.3 mm (7.728 in), from which the relative dynamic modulus of elasticity (P_t) was derived using the following equation:

$$P_k = (n_1)^2 / (n)^2 \times 100$$

Where n = fundamental transverse frequency at 0 freeze-thaw cycles;

n_1 = fundamental transverse frequency at k freeze-thaw cycles

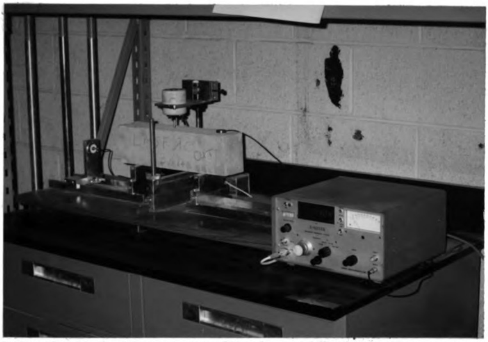


Figure 6.9 Test Set-Up for Measurement of Fundamental Transverse Frequency.

6.6.3 Hot Water Soak

Hot water soak test (ASTM C 1185) investigates the long-term chemical interaction of constituent materials. In this method of testing wet and elevated temperature conditions are used to accelerate the results. The test specimens are saturated in water with an excess of lime and maintained at 60 ± 2 deg. C (140 ± 4 deg. F) for 56 ± 2 days and are tested for flexural performance. Two replicated panel specimens (125 x 125 x 10 mm, 0.4 mm) were soaked in hot water. Specimens for flexural testing (38.1 x 125 x 10 mm, 1.5 x 5 x 0.4 in) were then cut using a diamond saw. An average of 6 specimens for each mix design were selected from two different batches in order to accurately measure the variability of results. Flexural tests were performed according to the Japanese Specification JCI-SF (Japanese Concrete Institute, 1984) [49]. The test results on aged specimens were compared with those of saturated unaged specimens.

6.6.4 Natural Weathering

In order to assess the effect of natural weathering on wood fiber reinforced cement composites, the specimens were exposed to the relatively harsh natural environment of

Michigan. Five panel specimens were exposed to Michigan climate, and after each exposure period of 0, 3, 6, 9 and 12 months a panel specimen was taken out and minimum of ten flexural specimens (38.1 x 152.4 x 10 mm, 1.5 x 5 x 0.4 in) were cut out using a diamond saw. Flexural tests were then performed according to the Japanese Specification JCI-SF (Japanese Concrete Institute, 1984).

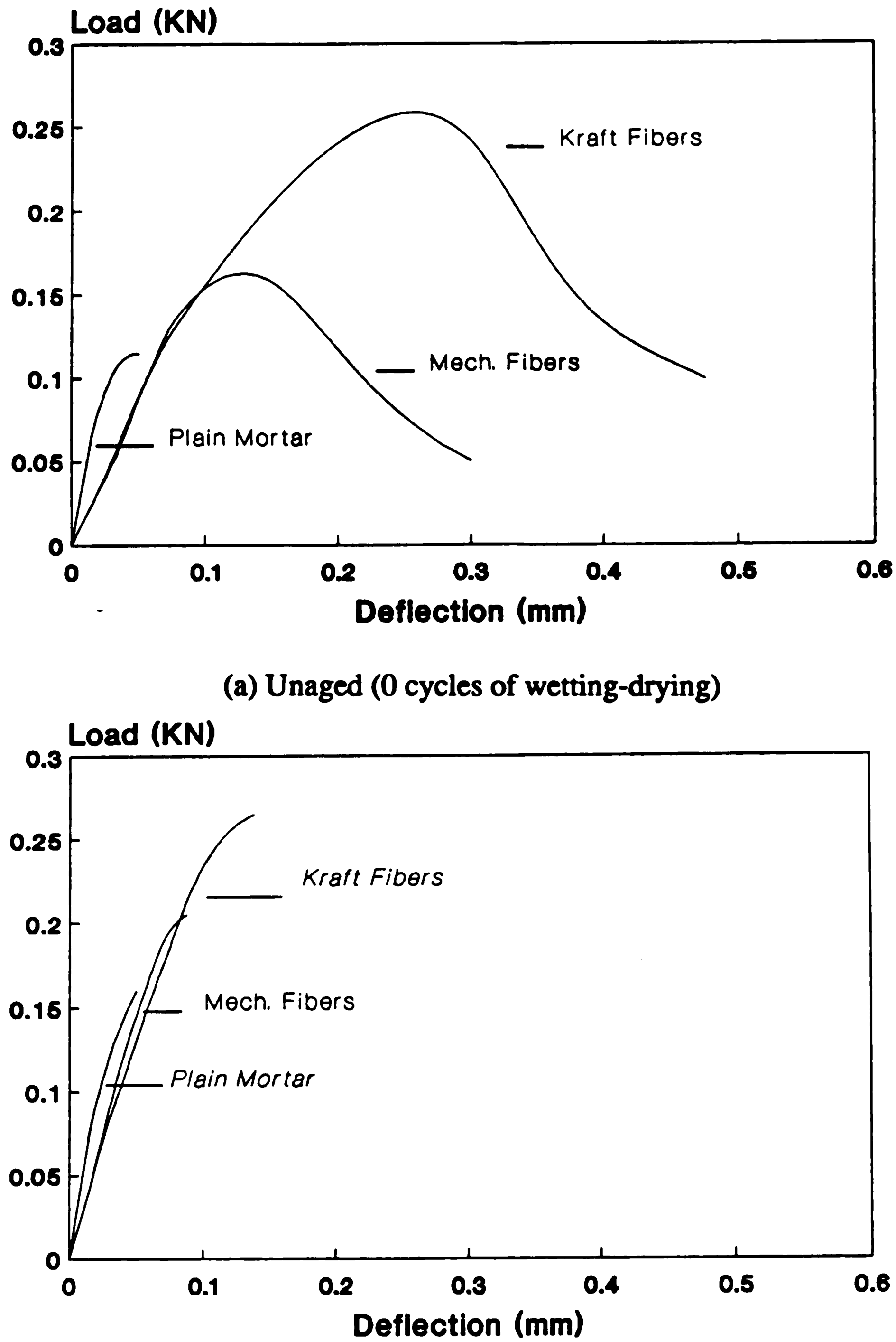
6.7 TEST RESULTS AND DISCUSSIONS

6.7.1 Effects of Fiber Type and Content

This section presents the test results on long-term durability characteristics of wood fiber reinforced cement composites containing different wood fiber types and contents. Wood fiber reinforced cement composites were subjected to repeated cycles of wetting-drying, freezing-thawing, and also to outdoor exposure. The wood fibers used in this investigation were Southern Softwood Kraft (SSK) [41], Northern Hardwood Kraft (NHK) [42], and Mechanical Pulp (1000L) [43]. Wood fiber reinforced cement composites containing lower fiber contents (≤ 2%) were manufactured through the molding method. The fiber mass fractions and matrix mix proportions used in this phase of the study are introduced in Table 4.3 (a). The experimental design used in this study is presented in Table 6.3. Statistical analyses of the test data were performed in two stages. Analysis of variance and multiple comparison techniques were used in order to derive reliable conclusions regarding the differences in composite material properties at different ageing stages. Statistical time-series techniques were then used to predict the trends in the behavior of the composite beyond the testing period.

6.7.1.1 Accelerated Wetting-Drying

Accelerated wetting-drying tests were performed to study the ageing behavior of thin-sheet wood fiber-cement composites. Flexural tests were performed on composites subjected to 0, 12, 24, 30, 60 and 120 cycles of accelerated wetting and drying. The effects of wood fiber reinforcement on the flexural load-deflection behavior of cement-based materials are shown in Figures 6.10 (a) and (b) before and after accelerated wetting-drying tests, respectively. Test results on flexural strength for plain matrix and wood fiber reinforced composites after different wetting-drying cycles are presented in Table 6.6 and Figure 6.11.



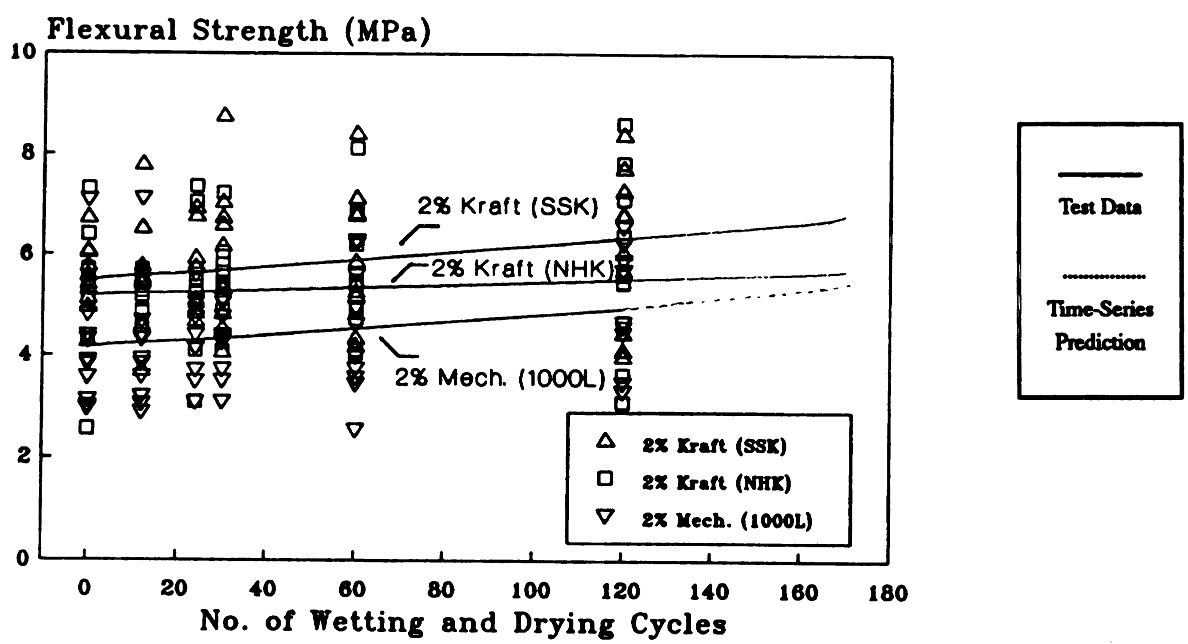
(a) Unaged (0 cycles of wetting-drying)

(b) Aged (120 cycles of wetting-drying)

Figure 6.10 Effects of Accelerated Weathering on the Flexural Load-Deflection Behavior of Molded Wood Fiber Reinforced Cement Composites.

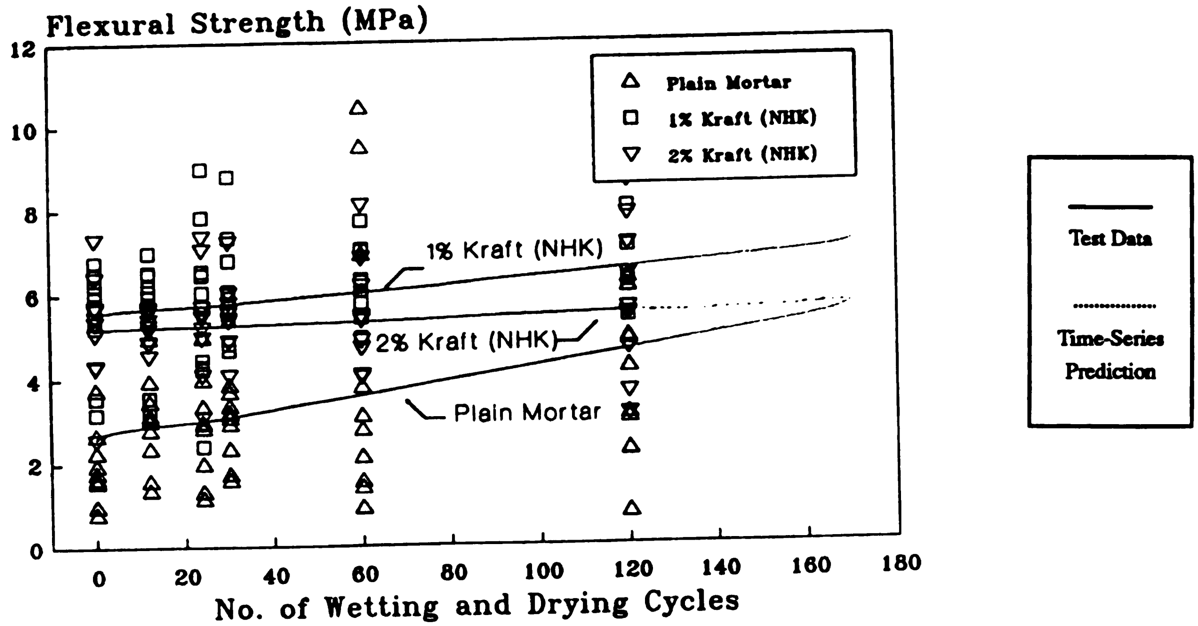
Table 6.6 Effects of Accelerated Weathering on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites (MPa, average of 10 tests ± standard deviation)

Fiber Type & Content	Wetting-Drying Cycles					
	0	12	24	30	60	120
Plain	1.8692 ±0.851	2.7752 ±1.027	2.9221 ±1.212	2.9462 ±0.875	4.2211 ±4.142	3.8260 ±1.911
1% Kraft (NHK)	5.5656 ±1.243	5.6036 ±1.266	5.6878 ±1.924	6.1186 ±1.225	6.1041 ±0.963	6.3351 ±0.727
2% Kraft (NHK)	5.2112 ±1.293	5.2698 ±0.412	5.4015 ±1.243	5.4050 ±0.866	5.5181 ±1.256	5.7869 ±1.753
2% Kraft (SSK)	5.4726 ±0.609	5.5767 ±1.080	5.5525 ±0.801	5.7780 ±1.448	5.9304 ±1.329	6.1028 ±1.546
2% Mech. (1000L)	4.0977 ±1.222	4.0936 ±1.215	4.2004 ±0.650	4.2439 ±0.652	4.4955 ±1.255	5.0127 ±1.292



(a) Effect of Fiber Type

Figure 6.11 Effects of Accelerated Weathering on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites.



(b) Effect of Fiber Content

Figure 6.11 (cont'd) Effects of Accelerated Weathering on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived from the test data regarding the effects of fiber type and content on flexural strength of the composite under repeated cycles of wetting and drying.

The flexural strength of unaged and aged fiber reinforced cement composites were significantly higher than the corresponding strengths of plain mortar. The improvement in strength due to fiber addition was more pronounced in composites containing kraft fibers at all ageing conditions. The flexural strength of unaged fibrous composites at 2% fiber mass fraction, when compared with the unaged strength of plain mortar, were about 3 times higher for kraft pulp (SSK and NHK) and 2 times higher for mechanical pulp (1000L). After accelerated weathering (120 cycles of wetting and drying) fibrous composites still maintained higher strength over plain mortar. The flexural strengths of aged fibrous composites at 2% fiber content, when compared with the plain mortar strength, were 60% higher for kraft pulp (SSK), 50% higher for kraft pulp (NHK), and 30% higher for mechanical pulp (1000L).

Wetting-drying cycles tend to increase the flexural strength and stiffness of both plain and fiber reinforced cement composites. The increase in flexural strength after 120 cycles of wetting and drying was slightly higher for plain cement mortar (100% increase) than wood fiber reinforced cement composites (12% increase for kraft pulp SSK, 11% for kraft pulp NHK and 22% for mechanical pulp 1000L). Analysis of variance of test results at 95% level of confidence, however, indicated that, considering the random experimental variations, the increase in the flexural strength of plain and fibrous cement composites under repeated wetting-drying cycles was not significant.

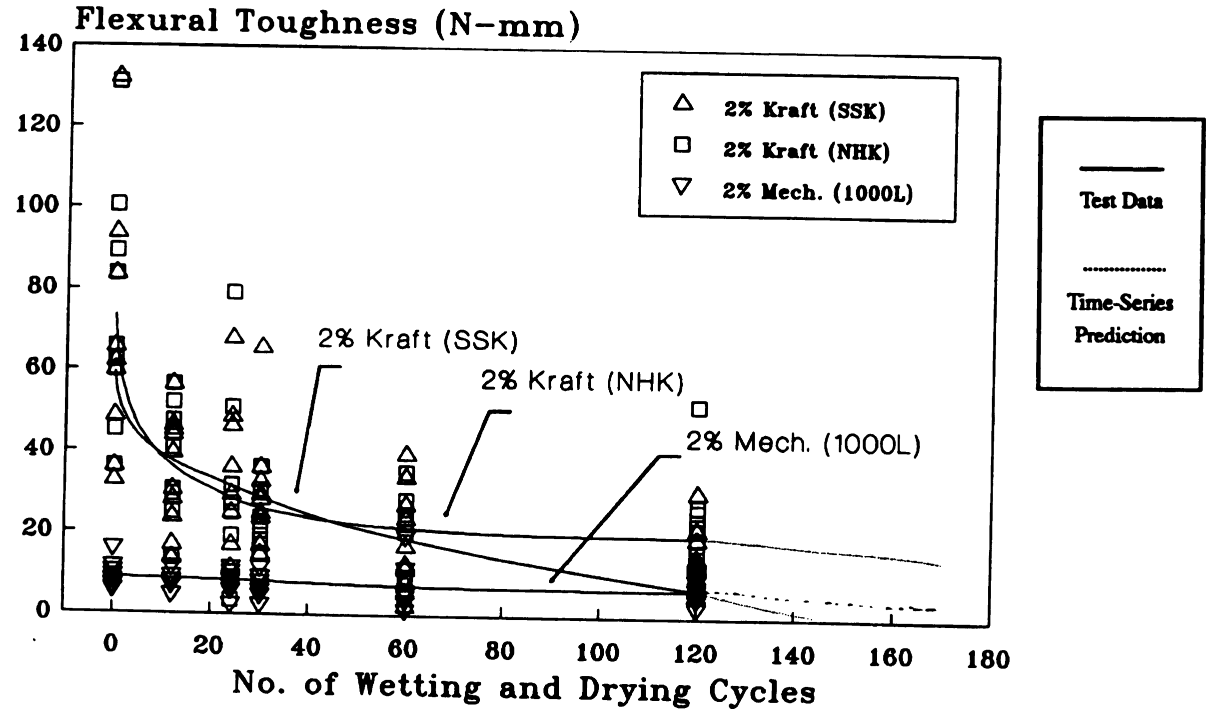
Statistical time-series analysis with regression forecasting predicted continued increase in flexural strength with increased numbers of wetting-drying cycles for plain mortar as well as fibrous composites (see Figure 6.11).

Composites containing 1% mass fraction of kraft pulp (NHK) showed higher average flexural strength at all ages when compared to composites containing 2% fiber mass fraction. Fiber content (1% vs. 2%), however, did not show any statistically significant effect (at 95% level of confidence) on flexural strength when random experimental variations are accounted for.

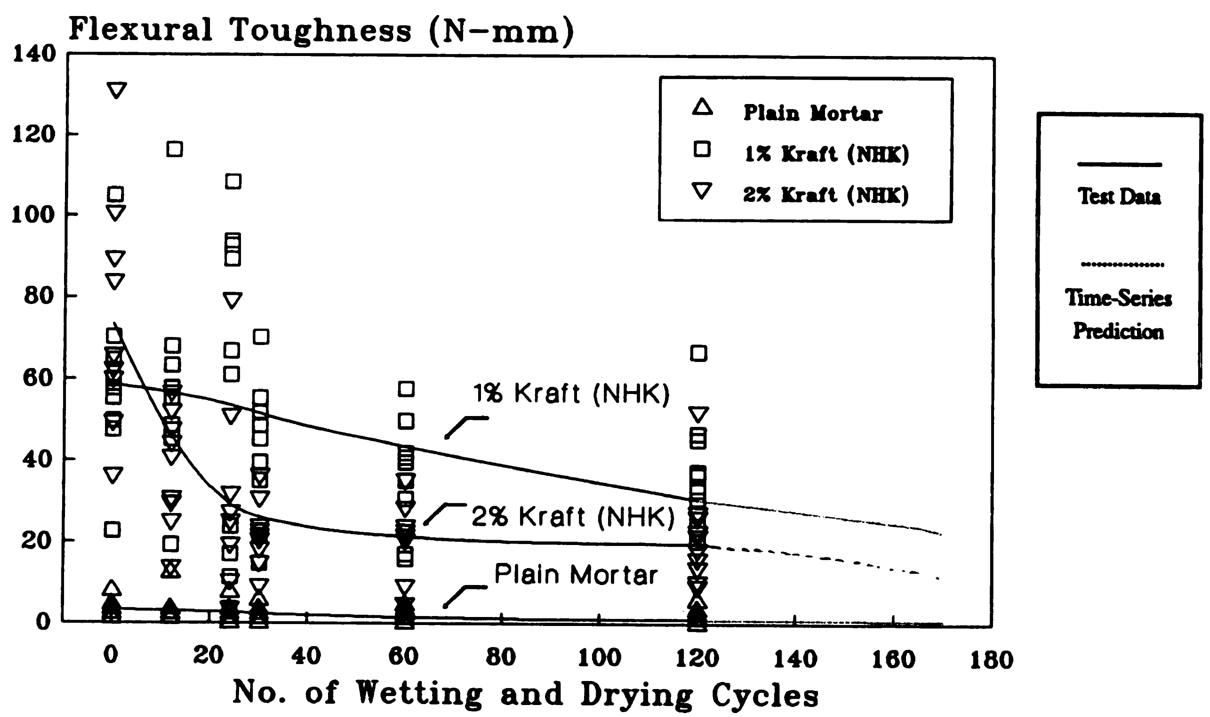
Test results on flexural toughness for plain matrix and wood fiber reinforced composites at different wetting-drying cycles are presented in Table 6.7 and Figure 6.12.

Table 6.7 Effects of Accelerated Weathering on the Flexural Toughness of Molded Wood Fiber Reinforced Cement Composites (N-mm, average of 10 tests ± standard deviation)

Fiber Type & Content	Wetting-Drying Cycles					
	0	12	24	30	60	120
Plain	2.8247 ± 2.147	3.2767 ± 3.344	2.7117 ± 2.926	2.2598 ± 1.921	1.6948 ± 1.706	1.5818 ± 1.864
1% Kraft (NHK)	60.223 ± 20.93	58.641 ± 24.27	56.720 ± 39.58	41.015 ± 17.81	36.947 ± 13.11	36.676 ± 13.51
2% Kraft (NHK)	73.895 ± 27.95	39.094 ± 13.97	30.507 ± 21.37	21.694 ± 7.582	20.903 ± 8.587	21.581 ± 12.35
2% Kraft (SSK)	68.019 ± 29.39	34.462 ± 14.03	34.010 ± 16.55	29.603 ± 14.23	18.078 ± 12.43	14.236 ± 7.683
2% Mech. (1000L)	9.1521 ± 3.085	8.4742 ± 2.339	7.6833 ± 2.859	7.1183 ± 2.870	6.6663 ± 5.310	6.4404 ± 2.870



(a) Effect of Fiber Type



(b) Effect of Fiber Content

Figure 6.12 Effects of Accelerated Weathering on the Flexural Toughness of Molded Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived from the test data regarding the effects of fiber type and content on the flexural toughness of composites due to accelerated wetting and drying.

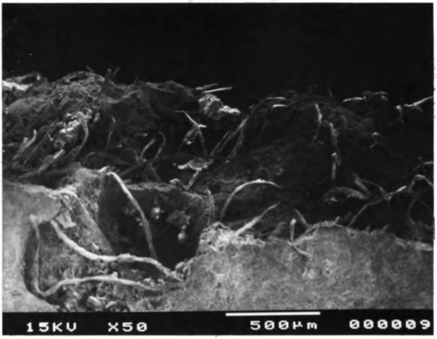
The flexural toughness of unaged and aged fiber reinforced cement composites were significantly higher than those of plain mortar. The improvement in flexural toughness due to fiber addition was more pronounced in composites containing kraft fibers. The flexural toughness of unaged fibrous composites at 2% fiber mass fraction, when compared with the plain mortar, was about 24 times higher for kraft pulp (SSK), 26 times higher for kraft pulp (NHK) and 3 times higher for mechanical pulp (1000L). After ageing (120 cycles of wetting and drying) fibrous composites still had higher flexural toughness values when compared to plain mortar. The flexural toughness of aged fibrous composites (after 120 cycles of wetting and drying) were about 9 times higher for kraft pulp (SSK), 14 times higher for kraft pulp (NHK), and 4 times higher for mechanical pulp (1000L) than that of plain matrix at 2% fiber mass fraction.

Accelerated wetting-drying cycles caused a drop in flexural toughness in both plain and fibrous specimens. The reduction in flexural toughness after 120 cycles of wetting and drying was slightly higher for composites containing 2% kraft pulp (79% for kraft pulp SSK and 71% for kraft pulp NHK, compared to unaged specimens) than plain cement mortar and composites containing 2% mechanical pulp (44% for plain mortar and 30% for mechanical pulp 1000L, compared to unaged specimen). Analysis of variance of the test data at 95% level of confidence confirmed significant drop in flexural toughness only for composites containing kraft fibers. In this case, it was also noted that, at 95% level of confidence, the initial 12 cycles of wetting-drying caused significant drops in flexural toughness; subsequent cycles caused only gradual drops in toughness. It should be noted that accurate values of toughness for plain matrix and composites containing mechanical pulp could not be obtained due to the very low toughness values of these composites. Statistical time-series analysis with regression forecasting predicted continued decrease in flexural toughness with increased numbers of wetting-drying cycles.

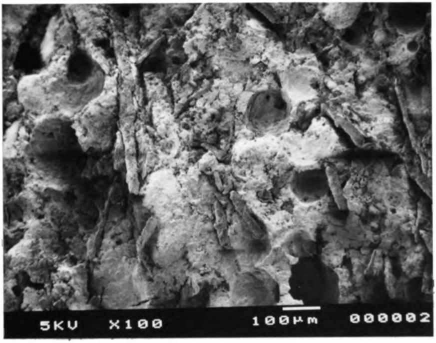
Composite containing 2% mass fraction of kraft pulp (NHK) showed higher flexural toughness when compared to composites containing 1% fiber mass fraction before ageing. However, flexural toughness of composites containing 2% mass fraction dropped severely

(70%) with ageing compared to composites containing 1% fiber mass fraction (40% drop). Fiber content was found to have statistically significant effect on the ageing effects on flexural toughness.

The increase in flexural strength of wood fiber reinforced cement composites with ageing observed in this investigation is in contrast with the ageing behavior of wood fibers themselves. Wood fibers typically show a drop in tensile strength with ageing due to the reduction in the degree of polymerization [54]. However, the increase in strength and reduction in toughness observed in this investigation are due to other properties of the cement composite. In order to study the mechanisms of ageing in wood fiber reinforced cement composites, scanning electron microscopic studies were performed on the fracture surfaces of aged and unaged specimens. The dominant mode of fracture in aged composite was fiber fracture (Figure 6.13 b), while unaged specimens showed a combination of fiber pullout and fiber fracture (Figure 6.13 a), and the matrix around fibers in unaged specimens was relatively porous. After ageing, the hollow fibers were often found to be filled with dense carbonation and hydration products, and showed little or no debonding from the matrix. This microstructure is often referred to as brittle petrified, and carbonation of the matrix has been suggested to accelerate the formation of this microstructure (Bentur et. al. 1989) [55]. Petrification makes fibers stronger and stiffer but more brittle; these changes together with the densening of interface zones and excessive fiber-to-matrix bonding can illustrate the increased strength and embrittlement of the composite with ageing. Petrified fibers with excess bonding tend to rupture rather than pullout at fracture surfaces, thus eliminating the desirable toughness characteristics associated with frictional energy dissipation during fiber pullout.



(a) Unaged (0 cycles of wetting-drying)



(b) Aged (120 cycles of wetting-drying)

Figure 6.13 Scanning Electron Micrographs of the Fractured Surface of Molded Wood Fiber Reinforced Cement Composites Containing 2% Kraft Pulp (SSK).

6.7.1.2 Ageing Under Freeze-Thaw Cycles:

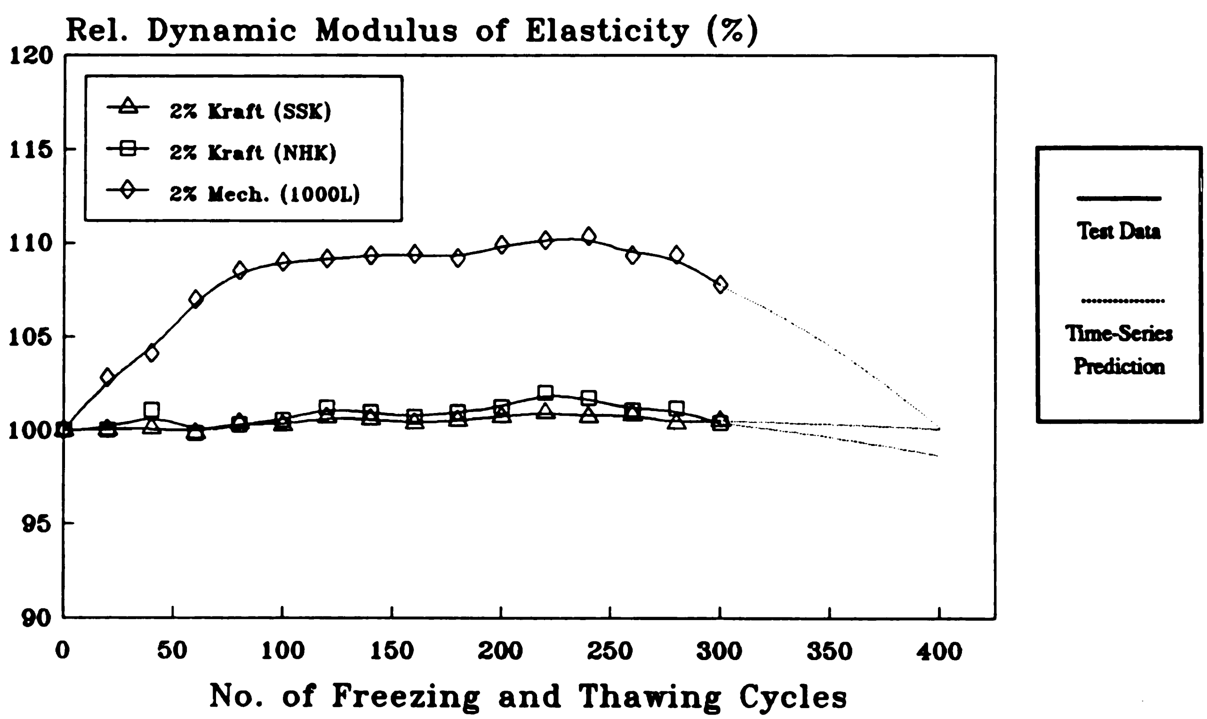
Wood fiber reinforced cement composites were subjected to repeated cycles of freezing and thawing in water, and were tested for their fundamental transverse frequency (to measure dynamic modulus) at regular intervals. The resistance of plain and fibrous specimens to rapidly repeated cycles of freezing and thawing are presented in Table 6.8 and Figure 6.14. The Relative dynamic modulus of elasticity of the material is presented as a function of the number of repeated freeze-thaw cycles. It should be noted that the specimens tested here were not air-entrained.

Table 6.8 Effects of Freezing and Thawing on the Relative Dynamic Modulus of Elasticity of Molded Wood Fiber Reinforced Cement Composites (%, average ± half the range)

Fiber Type & Content	Number of Freezing-Thawing Cycles							
	0	20	40	60	80	100	120	140
	160	180	200	220	240	260	280	300
Plain	100	99.320 ±0.13	98.063 ±0.25	101.07 ±0.65	100.49 ±0.76	97.006 ±1.12	94.530 ±1.39	92.179 ±2.01
	91.898 ±2.41	88.205 ±2.66	84.945 ±2.98	82.501 ±3.22	80.325 ±3.53	78.324 ±4.01	76.552 ±4.15	76.169 ±4.23
1% Kraft (NHK)	100	102.96 ±0.30	103.28 ±0.03	104.99 ±0.18	105.75 ±0.28	107.21 ±0.33	107.32 ±0.11	107.86 ±0.10
	108.41 ±0.01	107.81 ±0.05	109.28 ±0.53	110.82 ±0.41	109.12 ±0.26	109.01 ±0.92	109.06 ±0.42	108.59 ±0.87
2% Kraft (NHK)	100	100.00 ±0.24	101.07 ±0.48	99.826 ±0.41	100.30 ±0.18	100.53 ±0.19	101.19 ±0.25	100.95 ±0.25
	100.71 ±0.12	100.97 ±0.85	102.23 ±0.31	100.99 ±2.62	101.72 ±2.20	100.07 ±2.01	101.17 ±3.67	100.40 ±1.35

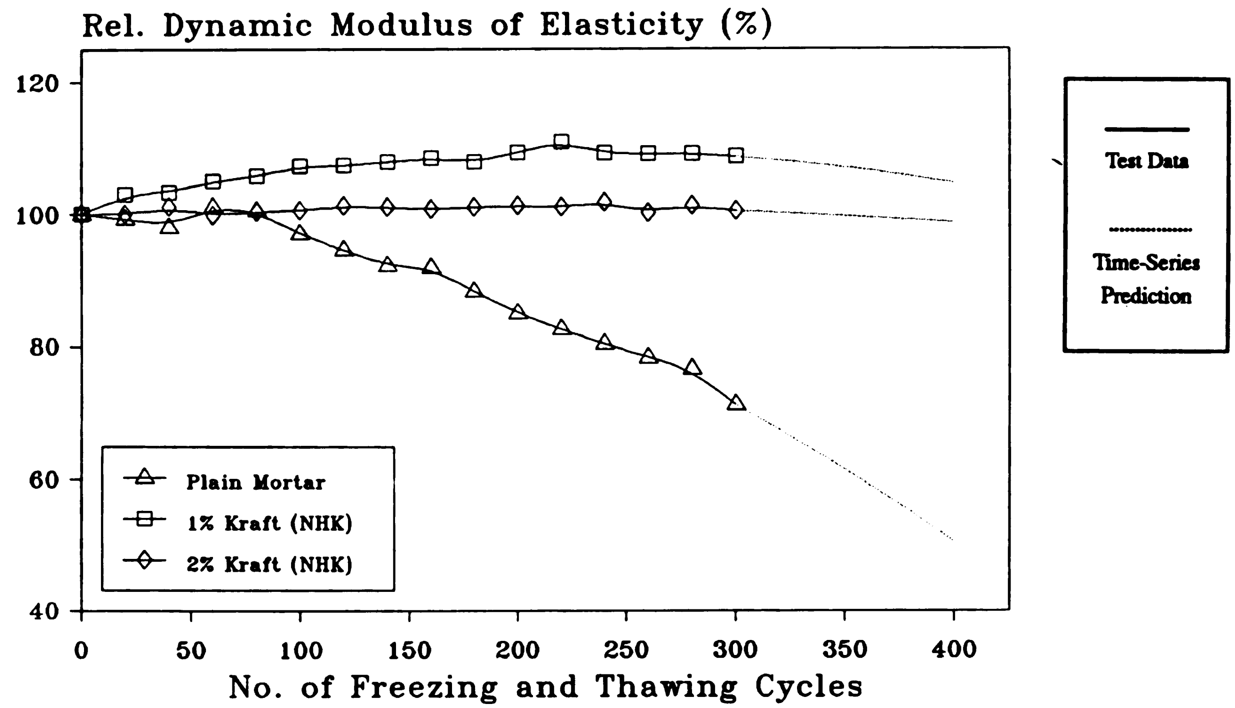
Table 6.8 (cont'd) Effects of Freezing and Thawing on the Relative Dynamic Modulus of Elasticity of Molded Wood Fiber Reinforced Cement Composites (%, average ± half the range)

Fiber Type & Content	Number of Freezing-Thawing Cycles							
	0	20	40	60	80	100	120	140
	160	180	200	220	240	260	280	300
2% Kraft (SSK)	100	100.06 ±0.06	100.12 ±0.47	99.883 ±0.12	100.30 ±0.00	100.29 ±0.29	100.70 ±0.12	100.59 ±0.12
	100.41 ±0.12	100.53 ±0.23	100.75 ±0.24	100.95 ±0.35	100.76 ±0.17	100.86 ±0.70	100.41 ±0.06	100.52 ±0.25
2% Mech. (1000L)	100	102.80 ±0.60	104.12 ±0.35	106.98 ±0.83	108.52 ±0.51	108.98 ±0.86	109.13 ±0.85	109.33 ±0.78
	109.40 ±0.99	109.20 ±0.92	109.87 ±0.79	110.14 ±0.79	110.34 ±0.23	109.33 ±0.65	109.37 ±0.74	107.76 ±0.84



(a) Effect of Fiber Type

Figure 6.14 Effects of Freezing and Thawing on the Relative Dynamic Modulus of Elasticity of Molded Wood Fiber Reinforced Cement Composites.



(b) Effect of Fiber Content

Figure 6.14 (cont'd) Effects of Freezing and Thawing on the Relative Dynamic Modulus of Elasticity of Molded Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived from the test data regarding the effects of fiber addition on resistance to freezing and thawing.

The relative dynamic modulus of elasticity of plain cementitious matrices decreased under repeated cycles of freezing and thawing. The average drop in relative dynamic modulus was 25% after 300 cycles of freezing and thawing, and it was found to be statistically significant at 95% level of confidence. The relative dynamic modulus of fibrous composites increased slightly under repeated freeze-thaw cycles. Composites containing 1% fiber content (Figure 6.14 a) showed higher values of relative dynamic modulus of elasticity at all cycles of freezing and thawing. However, the increase in dynamic modulus of elasticity was not statistically significant at 95% level of confidence.

The relative dynamic modulus of composites containing 2% mass fraction of softwood and hardwood kraft fibers (Figure 6.14 b) showed a slight increase with ageing, which was not statistically significant. However, composites containing 2% mass fraction of mechanical pulp showed significant increase in relative dynamic modulus of elasticity.

Much of the increase was found in earlier cycles of freezing and thawing, while later cycles showed a gradual decrease in relative dynamic modulus of elasticity. The increased relative dynamic modulus of fibrous composites could be partly due to the densification of the composite (i.e. petrification of wood fibers with ageing). In any case, wood fibers at relatively low mass fractions were found to effectively enhance the resistance of non-air-entrained cementitious matrices to freeze-thaw attack.

Statistical time series analysis with regression forecasting predicted an almost constant relative dynamic modulus of elasticity for fibrous composites containing kraft pulp with continued cycles of freezing and thawing. In the case of the plain matrix and fibrous composites containing mechanical pulp, however, the dynamic modulus of elasticity showed a tendency to drop with continued freeze-thaw cycles (see Figure 6.14).

6.7.1.3 Natural Weathering

This section presents test results on the performance of wood fiber reinforced cement composites under natural weathering. The specimens were exposed to the relatively harsh natural environment of Michigan for one year and were tested for their flexural performance at regular intervals of three months. The effects of wood fiber reinforcement on the flexural load-deflection behavior of cement-based materials are shown in Figures 6.15 (a) and (b) before and after exposure to natural weathering, respectively. Test results on flexural strength for plain matrix and wood fiber reinforced composites at different ages of natural weathering are presented in Tables 6.9 and Figure 6.16.

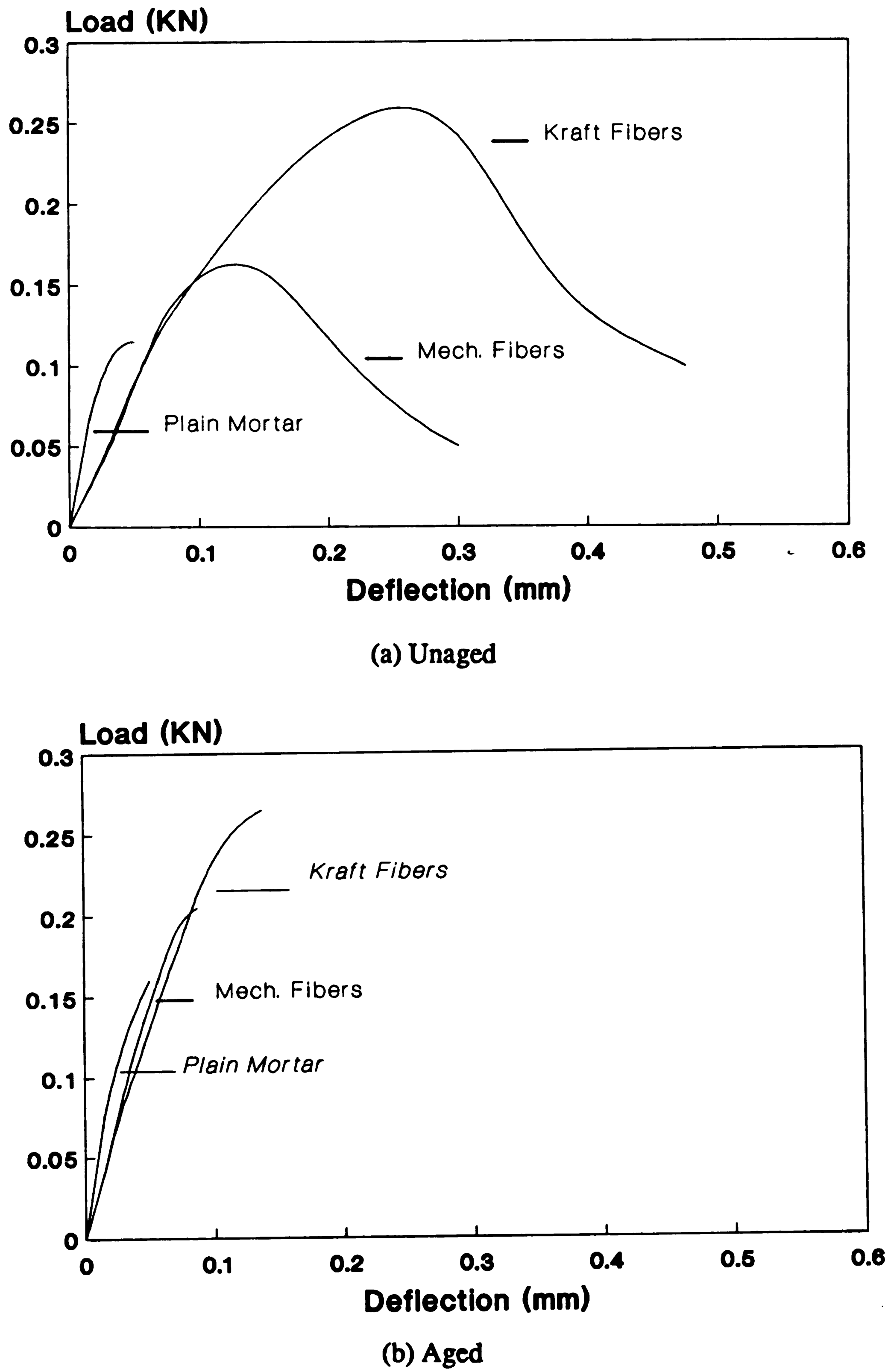
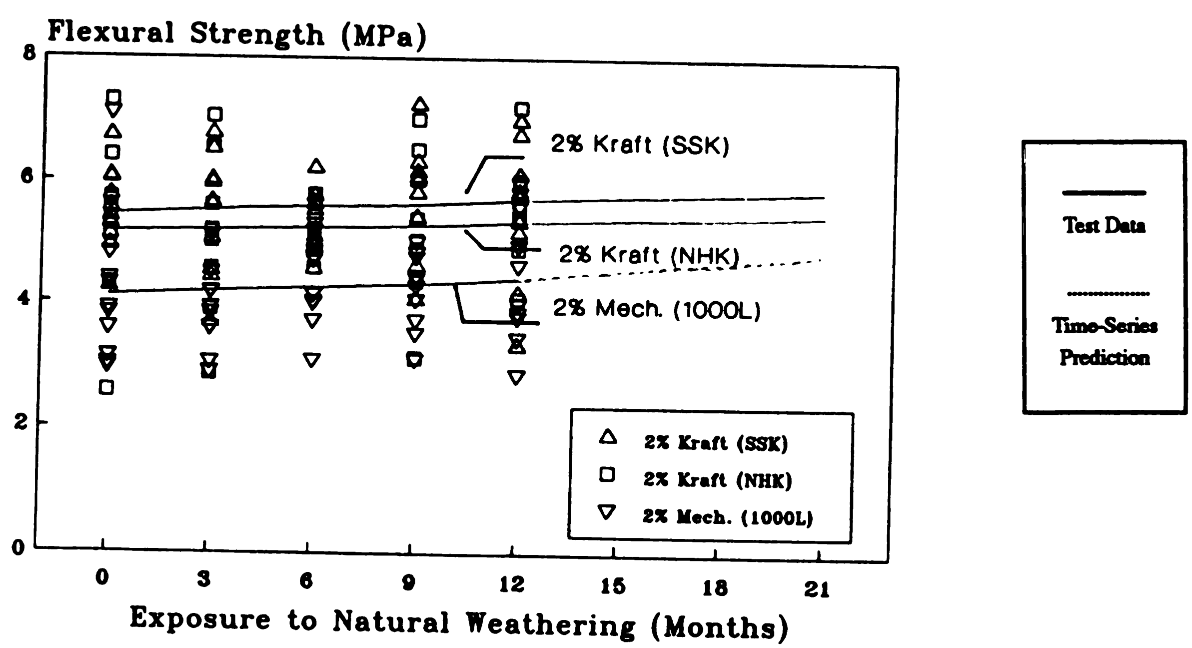


Figure 6.15 Effects of Natural Weathering on the Flexural Load-Deflection Behavior of Molded Wood Fiber Reinforced Cement Composites.

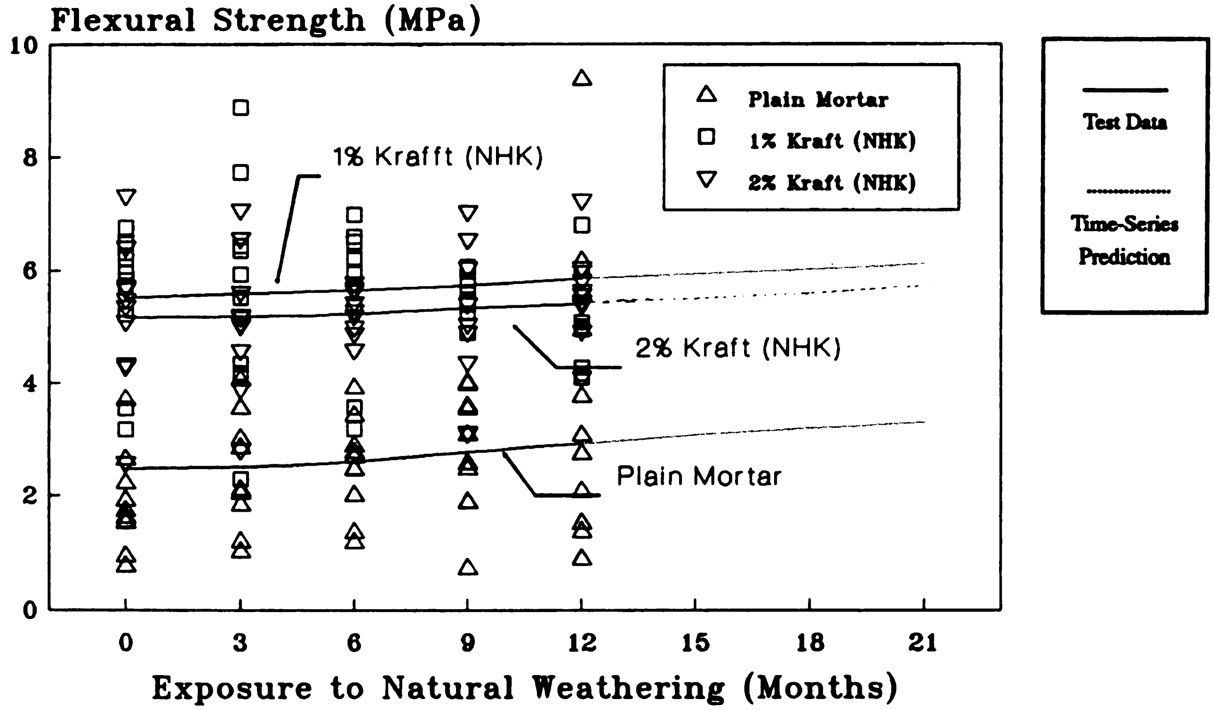
Table 6.9 Effects of Natural Weathering on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites (MPa, average of 10 tests ± standard deviation)

Fiber Type & Content	Outdoor Exposure (Number of Months)				
	0	3	6	9	12
Plain	1.8692 ± 0.851	2.1710 ± 0.901	2.4541 ± 0.908	2.7056 ± 1.351	2.9216 ± 0.867
1% Kraft (NHK)	5.5656 ± 1.243	5.5812 ± 1.888	5.6531 ± 1.277	5.7519 ± 0.660	5.8438 ± 1.170
2% Kraft (NHK)	5.2112 ± 1.293	5.2535 ± 1.209	5.3586 ± 0.419	5.3812 ± 1.630	5.4196 ± 0.868
2% Kraft (SSK)	5.4726 ± 0.609	5.4767 ± 0.790	5.5332 ± 1.072	5.6518 ± 1.432	5.7189 ± 1.433
2% Mech. (1000L)	4.0977 ± 1.222	4.0981 ± 0.6342	4.1808 ± 1.241	4.3576 ± 1.216	4.5074 ± 0.692



(a) Effect of Fiber Type

Figure 6.16 Effects of Natural Weathering on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites.



(b) Effect of Fiber Content

Figure 6.16 (cont'd) Effects of Natural Weathering on the Flexural Strength of Molded Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived from the test data regarding the effects of fiber type and content on the flexural strength of composites subjected to natural weathering.

The flexural strengths of unaged and aged fiber reinforced cement composites were significantly higher than those of plain mortar. The improvement in strength due to fiber addition was more pronounced at all ages in composites containing kraft fibers. The flexural strength of unaged fibrous composites at 2% fiber mass fraction, when compared with that of plain matrix, was about 3 times higher for kraft pulps (SSK and NHK) and 2 times higher for the mechanical pulp (1000L). After one year of exposure to natural weathering, fibrous composites still maintained higher strength over plain mortar. The flexural strength of fibrous composites with 2% fiber contents when compared with that of plain matrix, after one year of exposure to natural weathering were 95% higher for kraft pulp (SSK), 85% higher for kraft pulp (NHK), and 54% higher for mechanical pulp (1000L).

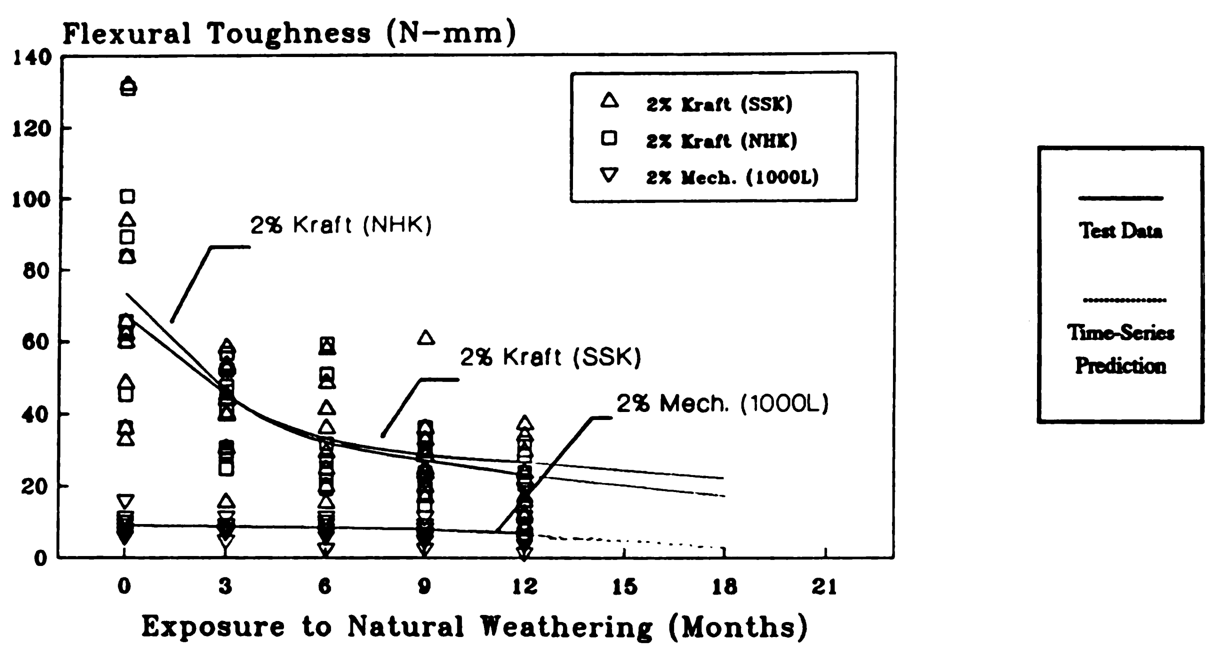
Natural ageing tends to increase the flexural strength and stiffness of both plain and fiber reinforced cement composites. The ageing of composites containing different wood fiber types and contents were similar. The increase in flexural strength after one year of exposure to natural weathering was higher for plain mortar (56% over unaged specimen) than wood fiber reinforced cement composites (4% for kraft pulps NHK and SSK, and 10% for the mechanical pulp 1000L). Analysis of variance and multiple comparison of test results at 95% confidence level, however, indicated that, considering the random experimental errors, changes in flexural strength of plain and fibrous cement composites with exposure to natural weathering were not significant. It should be noted here that exposure to natural weathering for only one year may not be sufficient to derive reliable conclusions; statistical time-series analysis with regression forecasting predicted continued increase in flexural strength with increased exposure to natural weathering for plain mortar as well as fibrous composites.

Composites containing 1% mass fraction of kraft pulp (NHK) showed slightly higher strength at all ages when compared with composites containing 2% fiber mass fraction. However, fiber content did not show any statistically significant effect on flexural strength at different ages.

Test results on flexural toughness for plain matrix and wood fiber reinforced composites exposed to natural weathering are presented in Tables 6.10 and Figure 6.17.

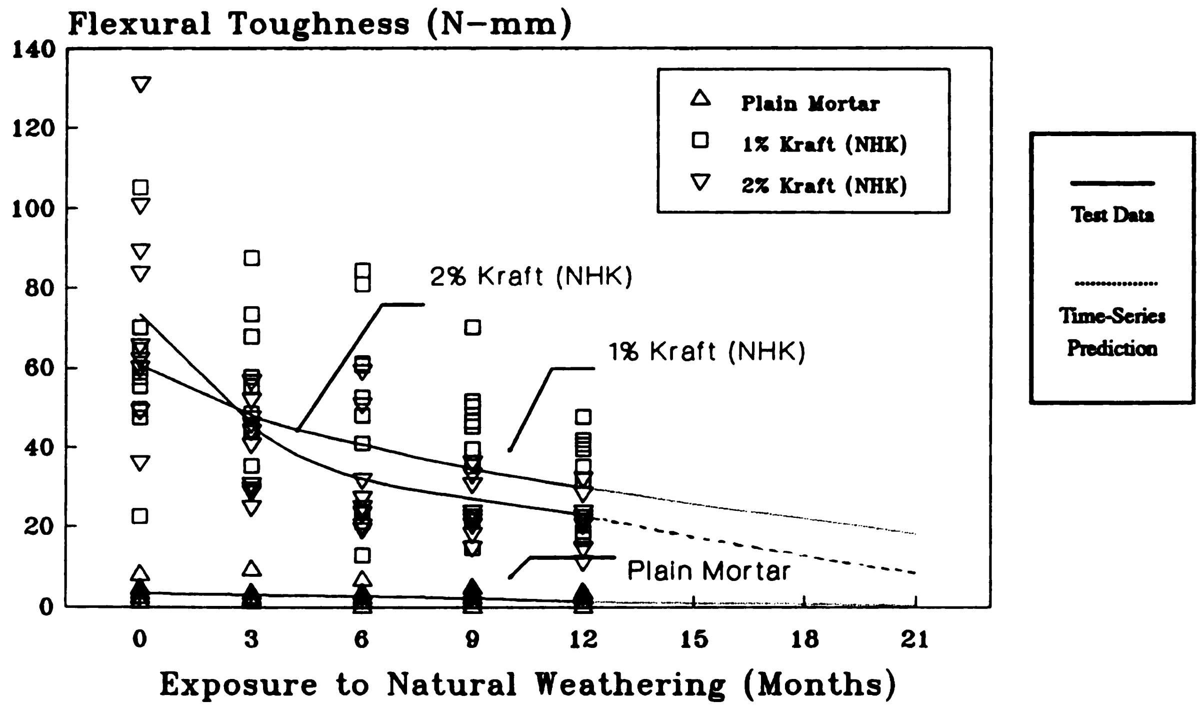
Table 6.10 Effects of Natural Weathering on the Flexural Toughness of Molded Wood Fiber Reinforced Cement Composites (N-mm, average of 10 tests ± standard deviation)

Fiber Type & Content	Outdoor Exposure (Number of Months)				
	0	3	6	9	12
Plain	2.8247 ±2.147	2.8317 ±2.302	2.3051 ±2.352	1.8323 ±1.523	1.6518 ±1.662
1% Kraft (NHK)	60.223 ±20.93	58.705 ±19.11	54.104 ±22.39	45.315 ±16.69	42.104 ±14.94
2% Kraft (NHK)	73.895 ±27.95	53.135 ±18.24	39.123 ±13.98	30.078 ±17.21	29.106 ±11.96
2% Kraft (SSK)	68.019 ±29.39	48.104 ±24.38	40.387 ±16.44	33.123 ±17.88	31.886 ±21.91
2% Mech. (1000L)	9.1521 ±3.085	8.5345 ±3.231	7.7230 ±2.131	6.9623 ±3.102	6.6513 ±5.298



(a) Effect of Fiber Type

Figure 6.17 Effects of Natural Weathering on the Flexural Toughness of Molded Wood Fiber Reinforced Cement Composites.



(b) Effect of Fiber Content

Figure 6.17 (cont'd) Effects of Natural Weathering on the Flexural Toughness of Molded Wood Fiber Reinforced Cement Composites.

The following conclusions could be derived from the test data regarding the effects of fiber type and content on flexural toughness of the composite subjected to natural weathering.

The flexural toughness of unaged fiber reinforced cement composites was significantly higher than that of plane mortar. The improvement in flexural toughness due to fiber addition was more pronounced in composites containing kraft fibers. The flexural toughness of unaged fibrous composites at 2% fiber mass fraction, when compared with that of plain matrix, were about 24 times higher for kraft pulp (SSK), 26 times higher for kraft pulp (NHK) and 3 times higher for mechanical pulp (1000L). After one year of exposure to natural weathering, fibrous composites still had higher flexural toughness values compared to plain mortar. The flexural toughness of composites with 2% fiber content, when compared with that of plain matrix, after one year of exposure to natural weathering was about 19 times for kraft pulp (SSK), 18 times for kraft pulp (NHK), and 4 times for mechanical pulp (1000L).

Exposure to natural weathering caused a major drop in flexural toughness for both plain and fibrous composites. The reduction in flexural toughness after one year of natural exposure was slightly higher for composites containing 2% kraft pulp (53% drop for kraft pulp SSK and 60% for kraft pulp NHK) than plain cement mortar and composites containing 2% mechanical pulp (42% drop for plain cement mortar and 28% for mechanical pulp 1000L). Analysis of variance of test data at 95% level of confidence confirmed significant drop in flexural toughness for plain mortar and fibrous composites. Accurate values of toughness for plain matrix and composites containing mechanical pulp could not be obtained due to very low toughness values of these composites. Statistical time-series analysis with regression forecasting predicted continued decrease in flexural toughness of plain mortar and fibrous composites with increased exposure to natural weathering.

Composite containing 2% mass fraction of kraft pulp (NHK) showed higher flexural toughness values when compared to composites containing 1% fiber mass fraction before ageing. However, flexural toughness of composites containing 2% mass fraction dropped more severely (60%) with ageing compared to composites containing 1% fiber mass fraction (30% drop). Fiber content was found to have significant effects on the ageing effects on flexural toughness.

The trends observed in this study under exposure to natural ageing are in close comparison with the results obtained in accelerated weathering (wetting and drying tests).

6.7.2 Effect of Bleaching

This section presents test results on the long-term durability characteristics of bleached and unbleached wood fiber reinforced cement composites. The fibers used in this study were unbleached and bleached Southern Softwood Kraft (SSK) [41]. Unbleached wood fibers contain small amounts of lignin which are susceptible to alkaline attack. The composites were manufactured using molding technique and the fiber content was 2% by mass. The matrix mix proportions are given in Table 4.5. The experimental design used in this study is presented in Table 6.4. Statistical analyses of the test data were performed in two stages. Analysis of variance and multiple comparison techniques were used in order to derive reliable conclusions regarding the differences in composite material properties at different ageing stages. Statistical time-series techniques were then used to predict the trends in the behavior of the composite beyond the testing period.

6.7.2.1 Accelerated Wetting-Drying

Accelerated wetting-drying tests were performed to study the ageing behavior of thin-sheet wood fiber reinforced cement composites containing unbleached and bleached kraft pulp (SSK). Flexural tests were performed on composites subjected to 0, 12, 24, 30, 60 and 120 cycles of accelerated wetting and drying. The effects of bleaching of fibers on the flexural strength and toughness of wood fiber reinforced composites after different wetting-drying cycles are presented in Tables 6.11 and Figure 6.18.

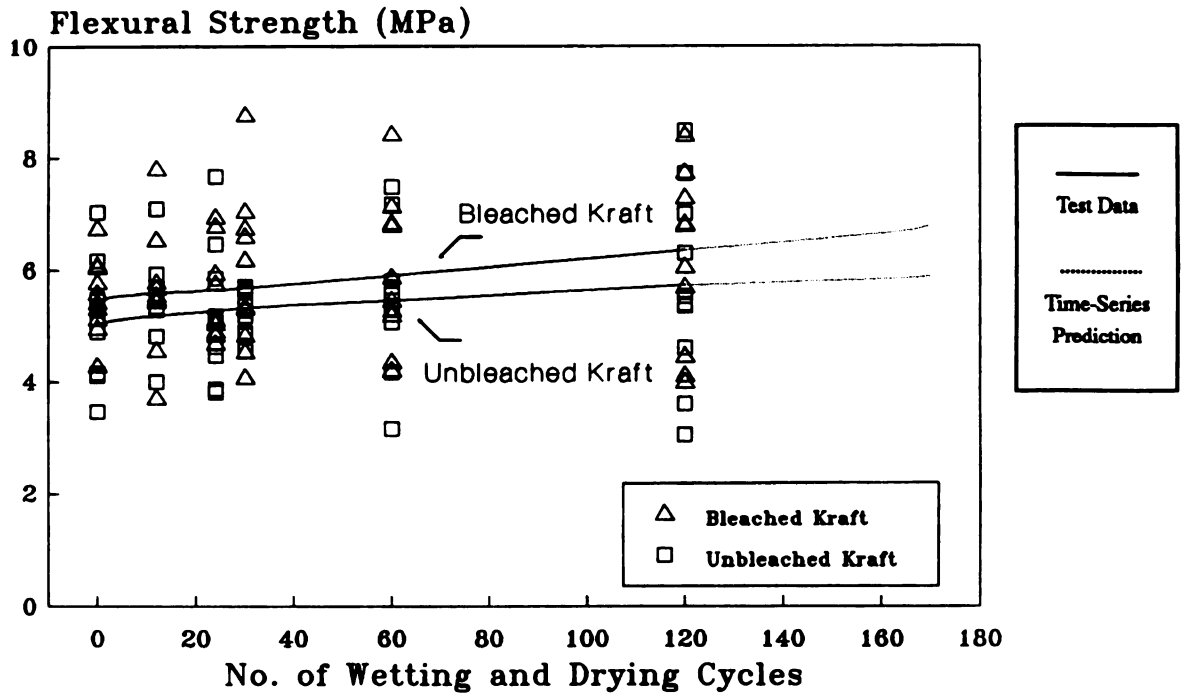
Table 6.11 Effects of Accelerated Weathering on the Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers (average ± standard deviation)

(a) Flexural Strength (MPa)

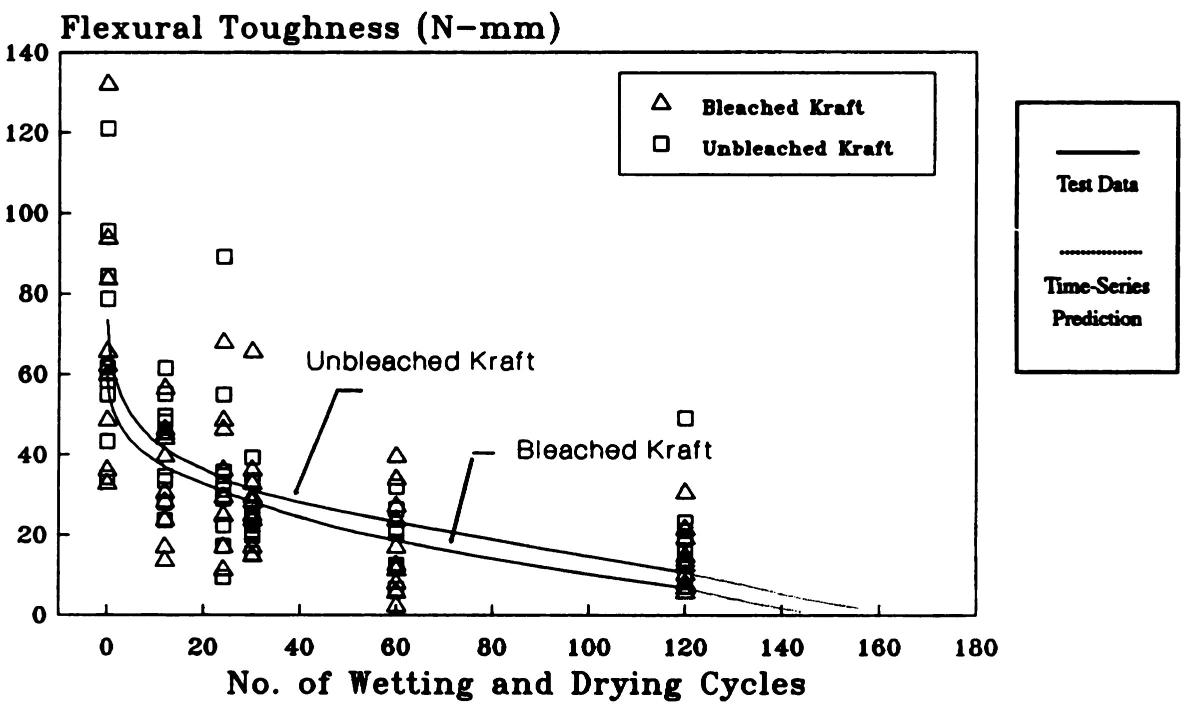
Fiber Type & Content	Wetting-Drying Cycles					
	0	12	24	30	60	120
2% Kraft (SSK) Bleached	5.4726 ± 0.609	5.5767 ± 1.080	5.5525 ± 0.801	5.7780 ± 1.448	5.9304 ± 1.329	6.1028 ± 1.546
2% Kraft (SSK) Unbleached	5.0135 ± 1.244	5.1773 ± 0.405	5.2105 ± 1.278	5.2693 ± 0.844	5.4986 ± 1.251	5.6986 ± 1.726

(b) Flexural Toughness (N-mm)

Fiber Type & Content	Wetting-Drying Cycles					
	0	12	24	30	60	120
2% Kraft (SSK) Bleached	68.019 ± 29.39	34.462 ± 14.03	34.010 ± 16.55	29.603 ± 14.23	18.078 ± 12.43	14.236 ± 7.683
2% Kraft (SSK) Unbleached	78.895 ± 29.84	43.129 ± 15.41	36.507 ± 25.57	30.632 ± 10.71	18.812 ± 7.728	17.484 ± 10.01



(a) Flexural Strength



(b) Flexural Toughness

Figure 6.18 Effects of Accelerated Weathering on the Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers.

The following conclusions could be derived from the test data on the flexural performance of composites containing bleached and unbleached wood fibers due to accelerated weathering.

The flexural strength of unaged and aged cement composites containing bleached wood fibers was higher (by 9% and 7%, respectively) than that of cement composites reinforced with bleached wood fibers at the same age. Wetting-drying cycles tend to increase the flexural strength and stiffness of both bleached and unbleached wood fiber reinforced cement composites. The increase in flexural strength due to ageing (after 120 cycles of accelerated wetting and drying) was 11% and 13% for composites containing bleached and unbleached wood fibers, respectively. Analysis of variance of test results at 95% level of confidence, however, indicated that, considering the random experimental errors, changes in flexural strength of bleached and unbleached wood fiber- cement composites with wetting-drying cycles were not significant. Statistical time-series analysis with regression forecasting predicted continued increase in flexural strength for both composites with increased numbers of wetting-drying cycles.

The flexural toughness of unaged and aged unbleached wood fiber reinforced cement composites were higher (by 16% and 23%, respectively) than those of bleached wood fiber reinforced cement composites. Accelerated wetting-drying cycles caused a severe drop in flexural toughness for both bleached and unbleached fibrous composites. The reduction in flexural toughness due to ageing (120 cycles of accelerated wetting and drying) was 80% and 78%, respectively, for composites containing bleached and unbleached wood fibers. Analysis of variance of test data at 95% level of confidence confirmed significant drops in the flexural toughness of both composites. In this case, it was also noted that, at 95% level of confidence, the initial 12 cycles of wetting-drying caused significant drops in flexural toughness; consequent cycles caused only gradual drops in toughness. Statistical time-series analysis with regression forecasting predicted continued decrease in flexural toughness for both composites with increased numbers of wetting-drying cycles.

Composites reinforced with unbleached wood fibers, which contain small amounts of lignin, produced comparable results with those of composites reinforced with bleached fibers at all ages of wetting and drying. Bleaching of fibers could not mitigate the mechanisms of ageing in wood fiber-cement composites.

6.7.2.2 Ageing Under Freeze-Thaw Cycles

Wood fiber reinforced cement composites were subjected to repeated cycles of freezing and thawing in water, and were tested for their fundamental transverse frequency at regular inter. The resistance of bleached and unbleached fibrous composites to rapidly repeated cycles of freezing and thawing are presented in Table 6.12 and Figure 6.19. The relative dynamic modulus of elasticity of the material is presented as a function of the number of repeated freeze-thaw cycles. It should be noted that the specimens tested here were not air-entrained.

Table 6.12 Effects of Freezing and Thawing on the Relative Dynamic Modulus of Elasticity of Composites Containing Bleached and Unbleached Wood Fibers (%, average ± half the range)

Fiber Type & Content	Number of Freezing-Thawing Cycles							
	0	20	40	60	80	100	120	140
	160	180	200	220	240	260	280	300
2% Kraft (SSK) Bleached	100	100.06 ± 0.06	100.12 ± 0.47	99.883 ± 0.12	100.30 ± 0.00	100.29 ± 0.29	100.70 ± 0.12	100.59 ± 0.12
	100.41 ± 0.12	100.53 ± 0.23	100.75 ± 0.24	100.95 ± 0.35	100.76 ± 0.17	100.86 ± 0.70	100.41 ± 0.06	100.52 ± 0.25
2% Kraft (SSK) Unbleached	100	100.96 ± 0.27	101.28 ± 0.32	101.65 ± 0.29	101.75 ± 0.18	102.01 ± 0.32	101.72 ± 0.26	101.86 ± 0.31
	101.81 ± 0.24	101.41 ± 0.26	100.95 ± 0.30	100.58 ± 0.25	100.25 ± 0.23	100.05 ± 0.19	99.825 ± 0.25	99.595 ± 0.31

The relative dynamic modulus of composites containing bleached and unbleached wood fibers increased slightly under repeated cycles of freezing and thawing. Much of the increase was found at earlier cycles, while later cycles showed gradual decrease in relative dynamic modulus of elasticity. The behavior of composites containing unbleached and bleached fibers due to freezing and thawing were comparable. Statistical time-series analysis with regression forecasting predicted a slight drop in relative dynamic modulus of elasticity for both bleached and unbleached fibrous composites with continued cycles of freezing and thawing. The increased relative dynamic modulus of elasticity of fibrous composites may be partly attributed to the densification of the matrix in the interface zones and petrification of wood fibers with ageing.

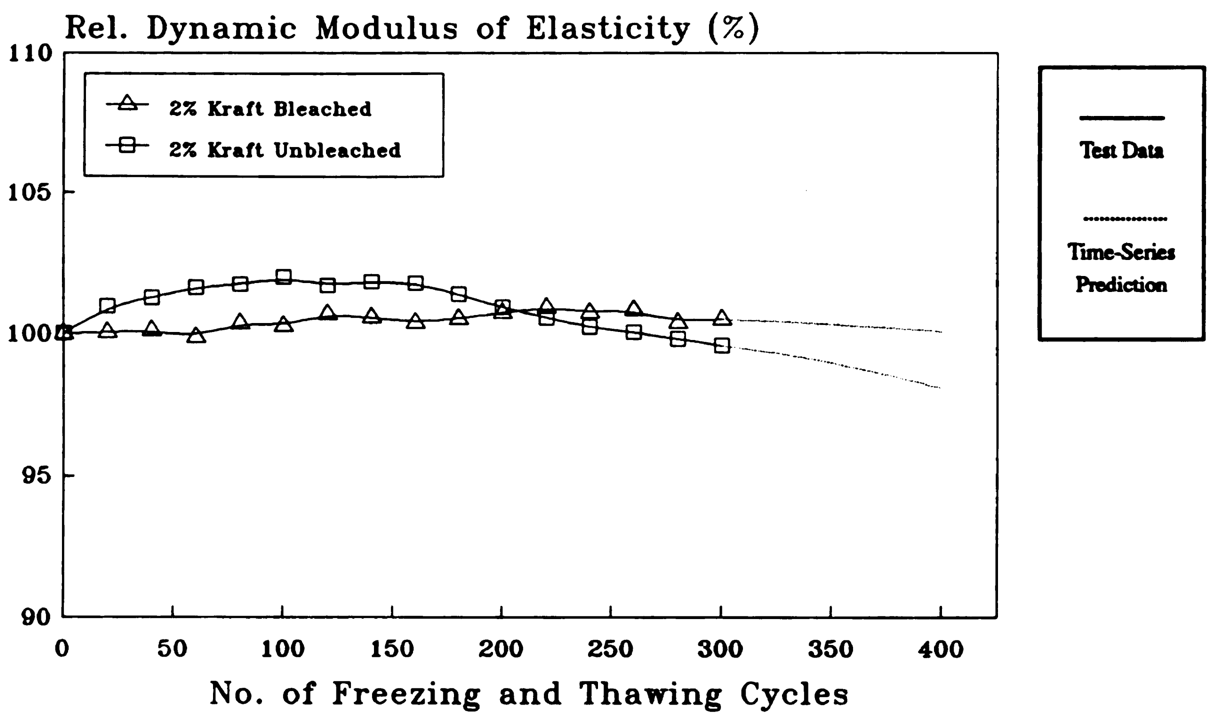


Figure 6.19 Effects of Freezing and Thawing on the Relative Dynamic Modulus of Elasticity of Composites Containing Bleached and Unbleached Wood Fibers.

6.7.2.3 Natural Weathering

This section presents test results on the flexural performance of cement composites containing bleached and unbleached wood fibers under the effects of natural weathering. The composites were exposed to the relatively harsh natural environment of Michigan for one year and were tested for their flexural performance at regular intervals of 3 months. Test results on flexural strength and toughness for composites containing bleached and unbleached wood fibers at different ages of natural weathering are presented in Tables 6.13 and Figure 6.20.

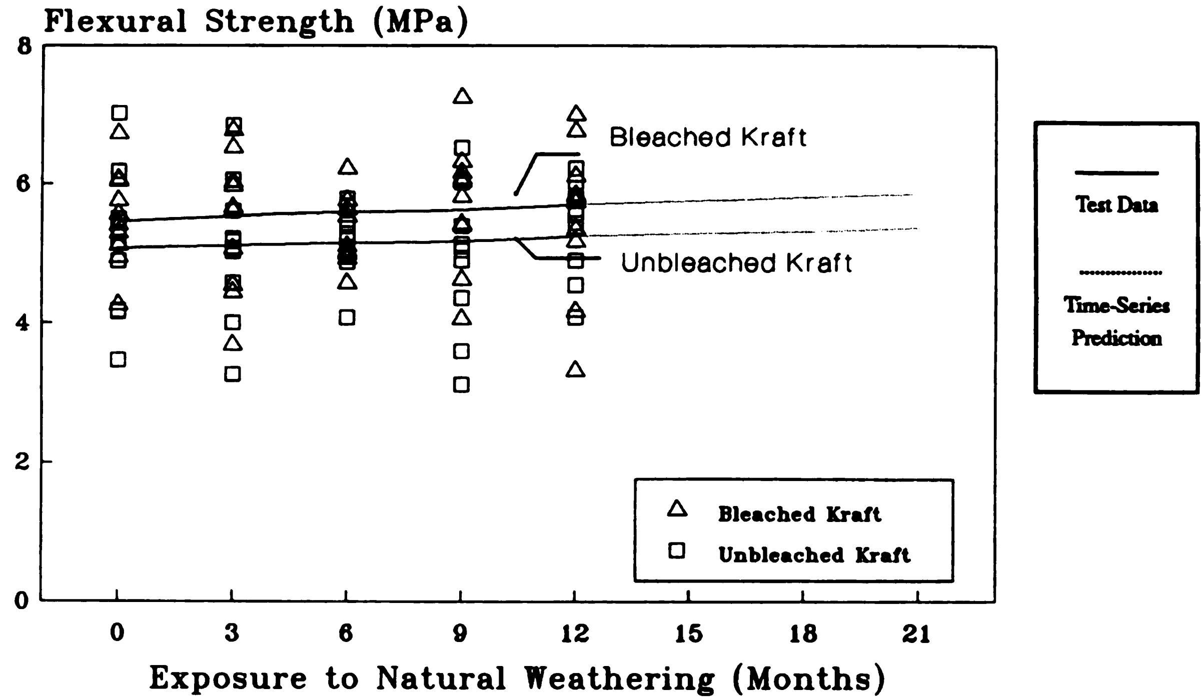
Table 6.13 Effects of Natural Weathering on the Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers (average of 10 tests ± standard deviation).

(a) Flexural Strength (MPa)

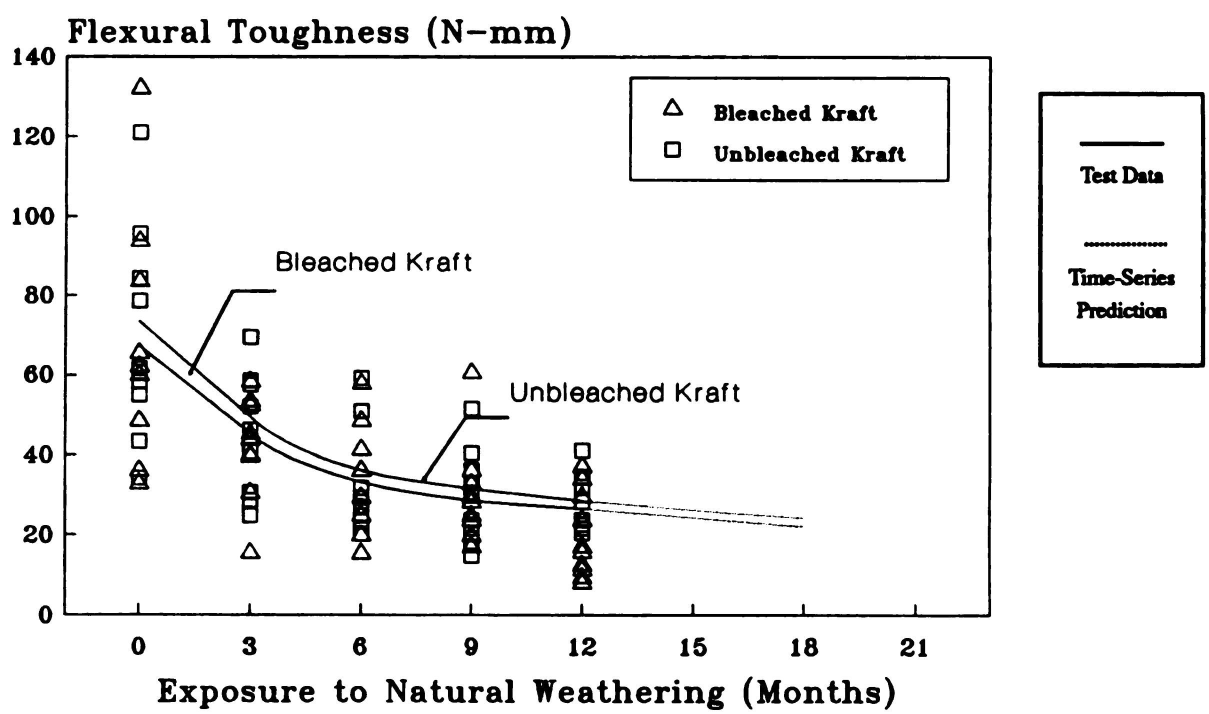
Fiber Type & Content	Outdoor Exposure (Number of Months)				
	0	3	6	9	12
2% Kraft (SSK) Bleached	5.4726 ± 0.609	5.4767 ± 0.790	5.5332 ± 1.071	5.6518 ± 1.4317	5.7189 ± 1.4332
2% Kraft (SSK) Unbleached	5.0135 ± 1.244	5.0185 ± 0.804	5.1031 ± 1.252	5.2319 ± 1.5846	5.2840 ± 1.202

(a) Flexural Toughness (N-mm)

Fiber Type & Content	Outdoor Exposure (Number of Months)				
	0	3	6	9	12
2% Kraft (SSK) Bleached	68.019 ± 29.39	48.104 ± 24.38	40.387 ± 16.44	33.123 ± 17.88	31.886 ± 21.91
2% Kraft (SSK) Unbleached	78.895 ± 29.84	51.230 ± 17.91	42.108 ± 15.05	34.003 ± 12.15	32.572 ± 13.38



(a) Flexural Strength



(b) Flexural Toughness

Figure 6.20 Effects of Natural Weathering on the Flexural Performance of Composites Containing Bleached and Unbleached Wood Fibers.

The flexural strengths of unaged and aged bleached wood fiber reinforced cement composites were on the average, higher (by 9% and 8%, respectively) than those of unbleached wood fiber reinforced cement composites. Exposure to natural weathering tends to increase the flexural strength and stiffness of both bleached and unbleached wood fiber reinforced cement composites. The increases in flexural strength with ageing for composites containing bleached and unbleached wood fibers were comparable (about 3% increase). Analysis of variance and multiple comparison of test results at 95% confidence level did not indicate any statistically significant effect of ageing on flexural strength. It should be noted here that exposure to natural weathering for only one year may not be sufficient to derive reliable conclusions on ageing effects. However, statistical time-series analysis with regression forecasting predicted continued increase in flexural strength for both composites with increased exposure to natural weathering.

The flexural toughness of unaged and aged unbleached wood fiber reinforced cement composites were higher (by 16% and 20%, respectively) than those of bleached wood fiber reinforced cement composites. Accelerated wetting-drying cycles caused a drop in flexural toughness for both bleached and unbleached fibrous composites. The reduction in flexural toughness with ageing for composites containing bleached and unbleached wood fibers were comparable (approximately 55% drop). Analysis of variance of the toughness test data at 95% level of confidence confirmed the statistically significant drop in flexural toughness of both composites. Statistical time-series analysis with regression forecasting predicted continued decrease in flexural toughness with increased exposure to natural weathering.

The trends observed in this study under exposure to natural ageing are in close comparison with the results obtained in accelerated wetting and drying tests.

6.7.3 Comprehensive Statistical Study of Different Parameters and their Effects

This section presents the test results of a comprehensive statistical study of different parameters and their effects on ageing. An experimental program was developed based on the statistical method of fractional factorial design. The composites were manufactured using the slurry-dewatering technique. The variables of the experimental study were: (1)

wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash & 15% silica fume); and (4) silica sand content (silica sand-cement ratio = 0.5 & 1.0). Wood fiber reinforced cement composites were tested for flexural performance before and after ageing.

6.7.3.1 Accelerated Wetting-Drying

Accelerated wetting-drying tests were performed to study the ageing behavior of thin-sheet wood fiber reinforced cement composites. Flexural tests were performed on unaged (0 cycles) and aged composites subjected to 25 cycles of accelerated wetting and drying. The effects of fiber type, fiber mass fraction, binder type, and ageing on the flexural strength and toughness of wood fiber reinforced composites are presented in Table 6.14. Statistical fractional factorial analysis was performed on the generated test data in order to distinguish the effects of different factors involved.

Table 6.14 Effects of Accelerated Weathering on the Flexural Performance of Wood Fiber Reinforced Cement Composites - Comprehensive Statistical Study (average ± half the range of two replications)*

Mix	1	2	3	4	5	6	7	8
Fiber Type	SSK	NHK	NHK	NHK	NHK	NHK	NHK	SSK
Fiber Content (%)	8	8	8	4	8	4	8	4
Binder	SF	FA	SF	FA	SF	FA	FA	FA
Wet-Dry Cycles	0	25	0	0	25	25	0	25
Sand Content (S/B)	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0
Flexural Strength (MPa)	10.61 ±0.54	8.738 ±0.65	9.654 ±0.65	7.765 ±0.53	9.422 ±0.72	8.224 ±0.82	8.970 ±0.62	6.322 ±0.49
Flexural Toughness (N-mm)	417.3 ±50.3	259.2 ±42.7	444.9 ±58.9	261.8 ±30.5	259.1 ±38.3	161.4 ±49.5	417.3 ±59.1	182.2 ±45.7

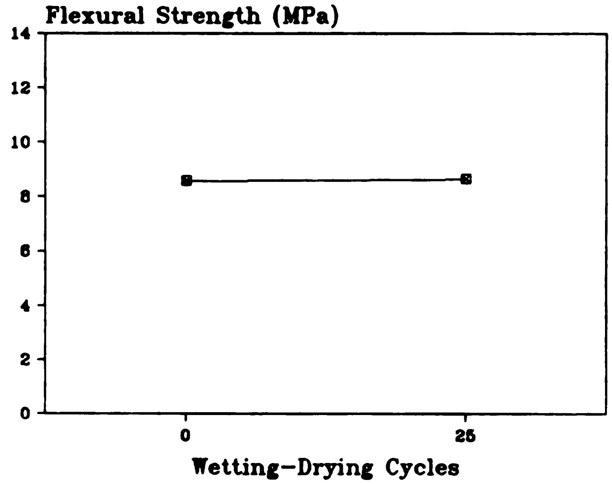
Mix	9	10	11	12	13	14	15	16
Fiber Type	SSK	SSK	NHK	NHK	SSK	SSK	SSK	SSK
Fiber Content (%)	8	4	4	4	8	8	4	4
Binder	FA	SF	SF	SF	FA	SF	SF	FA
Wet-Dry Cycles	0	0	0	25	25	25	25	0
Sand Content (S/B)	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5
Flexural Strength (MPa)	8.970 ±0.72	6.956 ±0.57	8.541 ±0.46	7.597 ±0.57	10.40 ±0.61	1.087 ±0.35	6.985 ±0.62	7.570 ±0.52
Flexural Toughness (N-mm)	437.5 ±72.2	255.4 ±47.9	241.9 ±49.5	167.8 ±45.9	248.3 ±50.3	265.4 ±48.5	165.5 ±51.0	274.8 ±48.2

* see Appendix B for notation

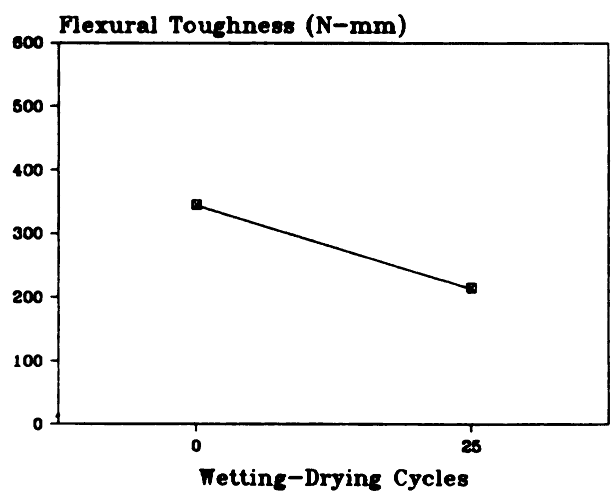
The following conclusions could be derived from the test data regarding the effects of accelerated weathering on flexural performance.

Composites containing softwood kraft pulp (SSK) and hardwood kraft pulp (NHK) produced comparable flexural strength and toughness. Fiber content, changing from 4% to 8%, increased both flexural strength and toughness significantly. Partial substitution of cement with silica fume when compared to fly ash produced higher flexural strengths; toughness values, however, were comparable. Reduced sand content significantly increased the flexural strength, whereas toughness was reduced at lower sand contents.

Accelerated wetting-drying slightly improves the flexural strength of wood fiber reinforced cement composites at all fiber contents (Figure 6.21 a). However, the increase was not statistically significant at 95% level of confidence. There were significant effects of ageing on flexural toughness (Figure 6.21 b), where toughness reduced considerably with ageing (25 cycles of wetting and drying). It should be noted that ageing leads to petrification (filling) of fibers with cement hydration/carbonation.



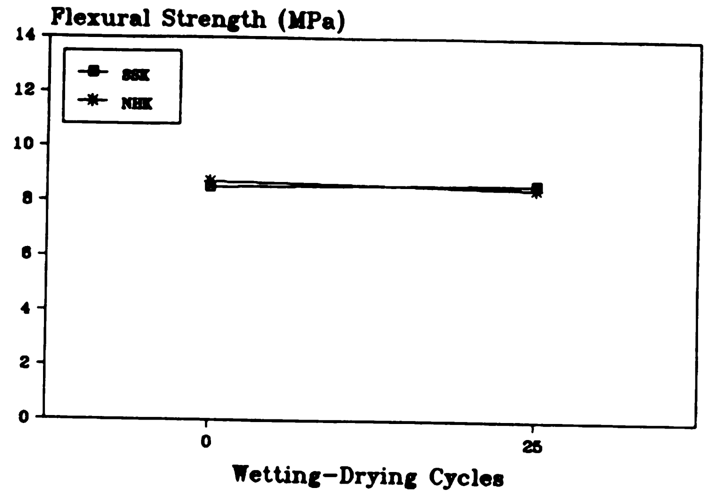
(a) Flexural Strength



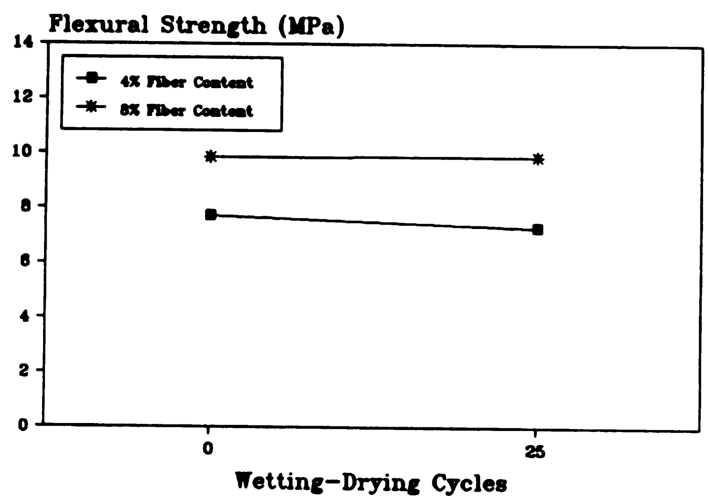
(b) Flexural Toughness

Figure 6.21 Effects of Accelerated Weathering on the Flexural Performance of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

The interaction curves obtained through fractional factorial analysis of variance of the results are presented in Figure 6.22 for flexural strength and Figure 6.23 for flexural toughness. Each curve represents the trend in ageing effects at two different levels of a specific variable. Similar slopes of the trends would indicate weak interaction between ageing and the variable while different slopes are indicative of different ageing performances at different levels of the variable.

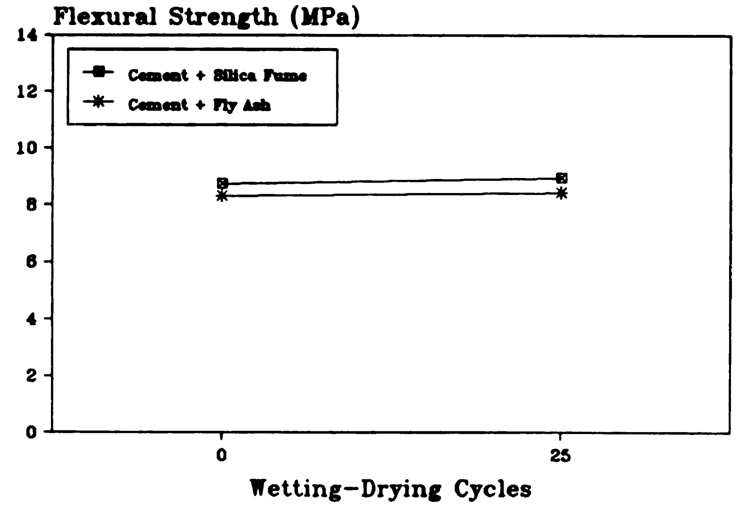


(a) Fiber Type

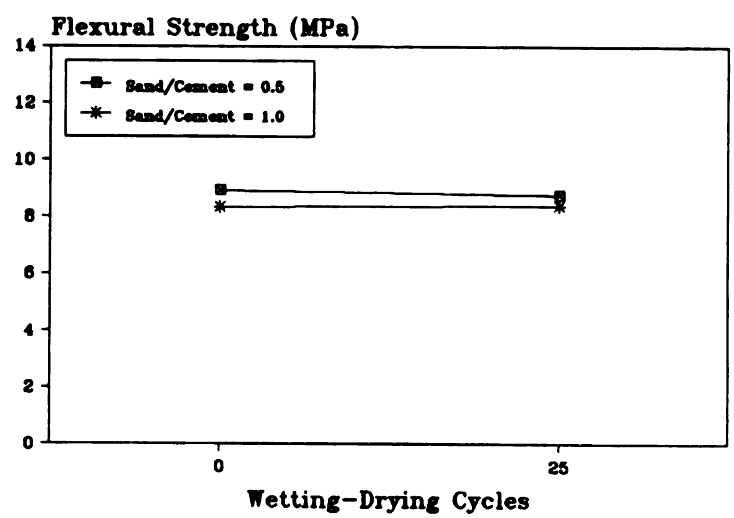


(b) Fiber Content

Figure 6.22 Interaction of Different Parameters and Accelerated Weathering on the Flexural Strength of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

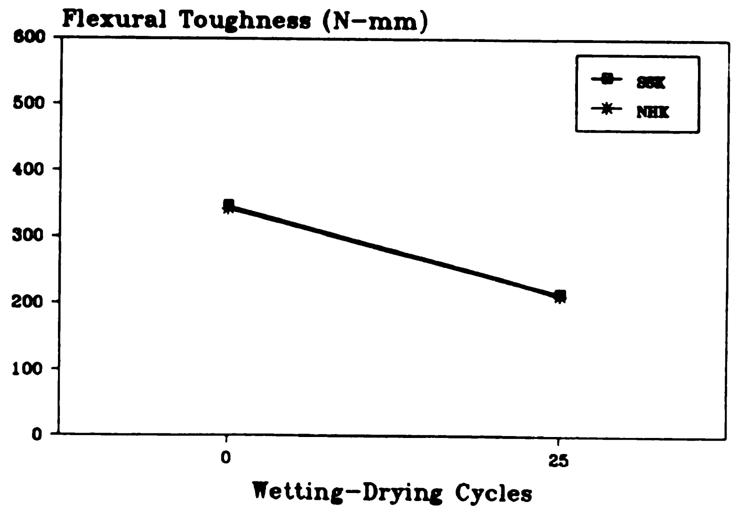


(c) Binder

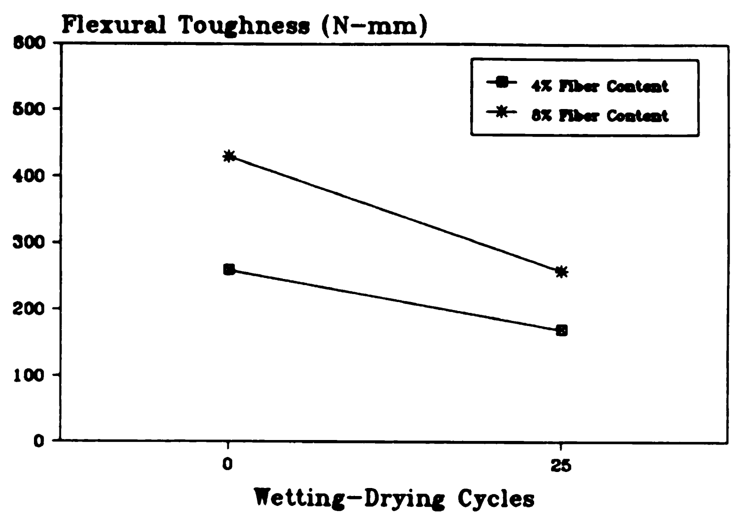


(d) Sand Content

Figure 6.22 (cont'd) Interaction of Different Parameters and Accelerated Weathering on the Flexural Strength of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

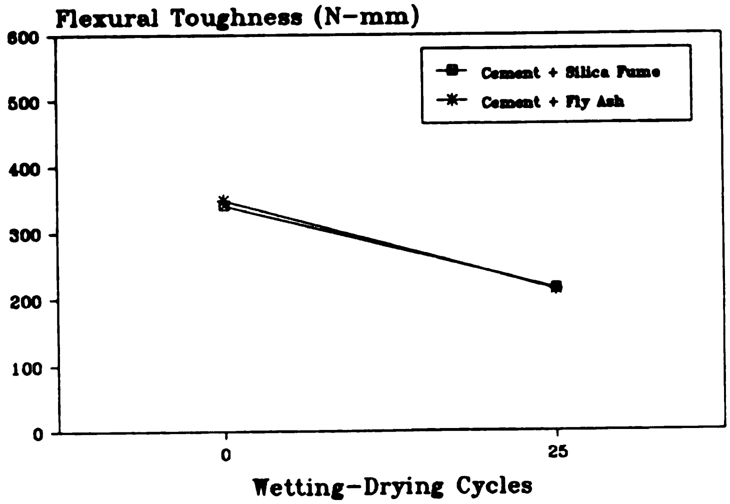


(a) Fiber Type

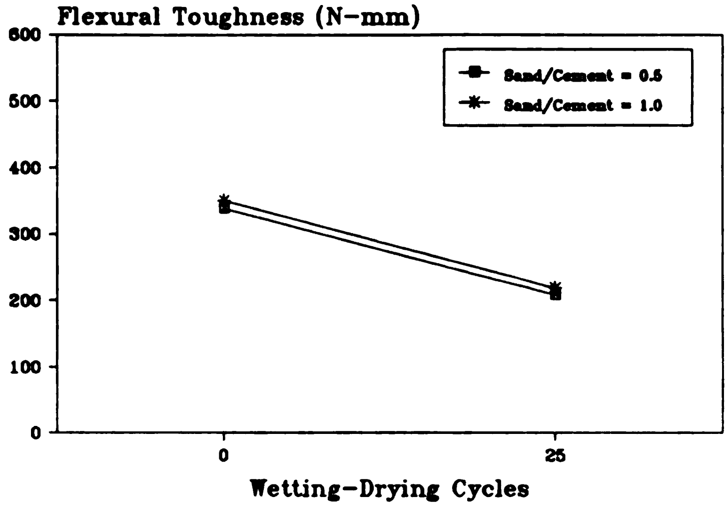


(b) Fiber Content

Figure 6.23 Interaction of Different Parameters and Accelerated Weathering on the Flexural Toughness of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.



(c) Binder



(d) Sand Content

Figure 6.23 (cont'd) Interaction of Different Parameters and Accelerated Weathering on the Flexural Toughness of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

Statistical analyses indicated that only fiber content (Figure 6.33 b) influenced the aging effect on flexural toughness at 95% level of confidence. The adverse effects of ageing on flexural toughness were reduced at lower fiber contents.

6.7.3.1 Hot Water Soak

Thin-sheet wood fiber reinforced cement composites were subjected to hot water soak for 55 days in order to study their ageing behavior. Flexural tests were then performed on saturated unaged and aged composites. The effects of fiber type, fiber mass fraction, binder type, and ageing on the saturated flexural strength and toughness of wood fiber reinforced cement composites are presented in Table 6.15. Statistical fractional factorial analysis was performed on the generated test data in order to evaluate the effects of different factors involved.

Table 6.15 Effects of Hot Water Soaking on the Flexural Performance of Wood Fiber Reinforced Cement Composites - Comprehensive Statistical Study (average ± half the range of two replications)*

Mix	1	2	3	4	5	6	7	8
Fiber Type	SSK	NHK	NHK	NHK	NHK	NHK	NHK	SSK
Fiber Content (%)	8	8	8	4	8	4	8	4
Binder	SF	FA	SF	FA	SF	FA	FA	FA
Hot Water (days)	55	0	55	55	0	0	55	0
Sand Content (S/B)	0.5	1.0	1.0	1.0	0.5	0.5	0.5	1.0
Flexural Strength (MPa)	8.102 ±0.53	5.201 ±0.47	7.417 ±0.69	5.992 ±0.63	8.554 ±0.48	6.794 ±0.51	6.856 ±0.51	6.018 ±0.38
Flexural Toughness (N-mm)	330.6 ±61.2	561.2 ±63.1	346.3 ±49.9	205.7 ±43.4	547.8 ±72.3	325.8 ±58.4	307.9 ±47.2	369.0 ±49.2

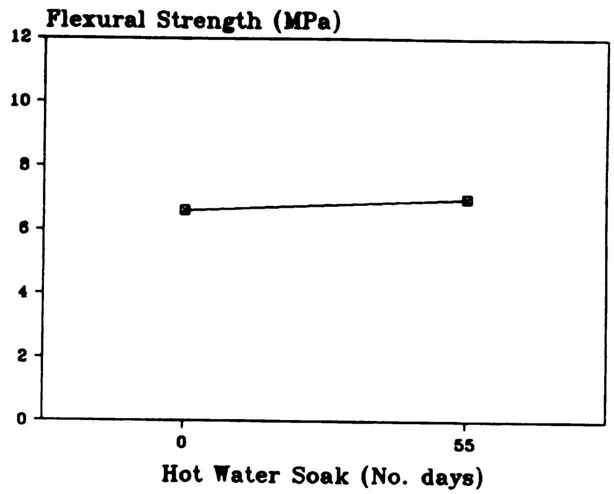
Mix	9	10	11	12	13	14	15	16
Fiber Type	SSK	SSK	NHK	NHK	SSK	SSK	SSK	SSK
Fiber Content (%)	8	4	4	4	8	8	4	4
Binder	FA	SF	SF	SF	FA	SF	SF	FA
Hot Water (days)	55	55	55	0	0	0	0	55
Sand Content (S/B)	1.0	1.0	0.5	1.0	0.5	1.0	0.5	0.5
Flexural Strength (MPa)	7.992 ±0.62	6.475 ±0.60	6.574 ±0.56	6.212 ±0.47	6.844 ±0.51	5.475 ±0.35	7.571 ±0.59	6.380 ±0.62
Flexural Toughness (N-mm)	326.6 ±62.6	203.4 ±49.5	194.4 ±45.5	324.9 ±50.3	538.4 ±60.1	567.9 ±80.5	320.4 ±53.1	207.3 ±42.6

* see Appendix B for notation

The following conclusions could be derived from the test data regarding the effects of hot water soak on flexural performance in saturated condition.

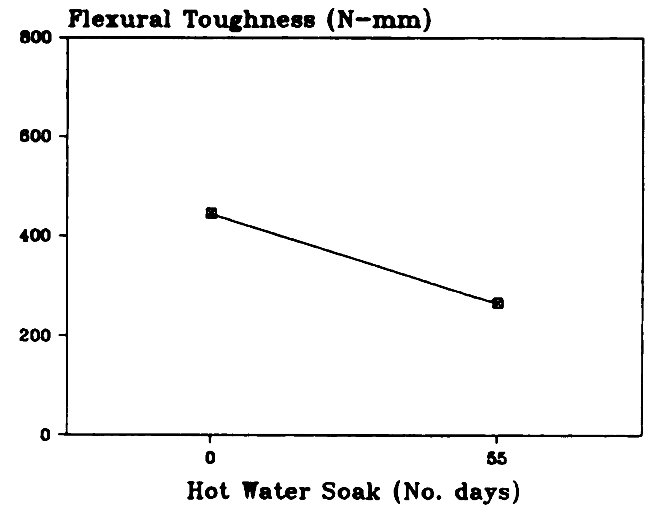
Composites containing softwood kraft pulp (SSK) and hardwood kraft pulp (NHK) produced comparable flexural strength and toughness (at 95% level of confidence). Fiber content, changing from 4% to 8% increased both flexural strength and toughness significantly. Partial substitution of cement with silica fume when compared to fly ash produced higher flexural strengths; toughness values were, however, comparable. Reduced sand content significantly increased flexural strength, whereas toughness was reduced.

Hot water soaking of wood fiber reinforced cement composites slightly improved flexural strength at all fiber contents (Figure 6.24 a). However, the increase was not statistically significant at 95% level of confidence. There were significant effects of ageing on flexural toughness (Figure 6.24 b), where toughness was considerably reduced with ageing (hot water soaking for 55 days). The trends observed here are in comparison with those obtained in accelerated (wetting-drying) weathering. It should be noted that ageing causes densification of the interfaces and petrification of wood fibers, thus improving the flexural strength and reducing the toughness of composites.



(a) Flexural Strength

Figure 6.24 Effects of Hot Water Soaking on the Flexural Performance of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.



(b) Flexural Toughness

Figure 6.24 (cont'd) Effects of Hot Water Soaking on the Flexural Performance of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

The interaction curves obtained through fractional factorial analysis of variance of the results are presented in Figure 6.25 for flexural strength and Figure 6.26 for flexural toughness. Each curve represents the trend in ageing effects at two different levels of a specific variable. Similar slopes of the trends would indicate weak interaction between ageing and the variable while different slopes are indicative of different ageing performances at different levels of the variable.

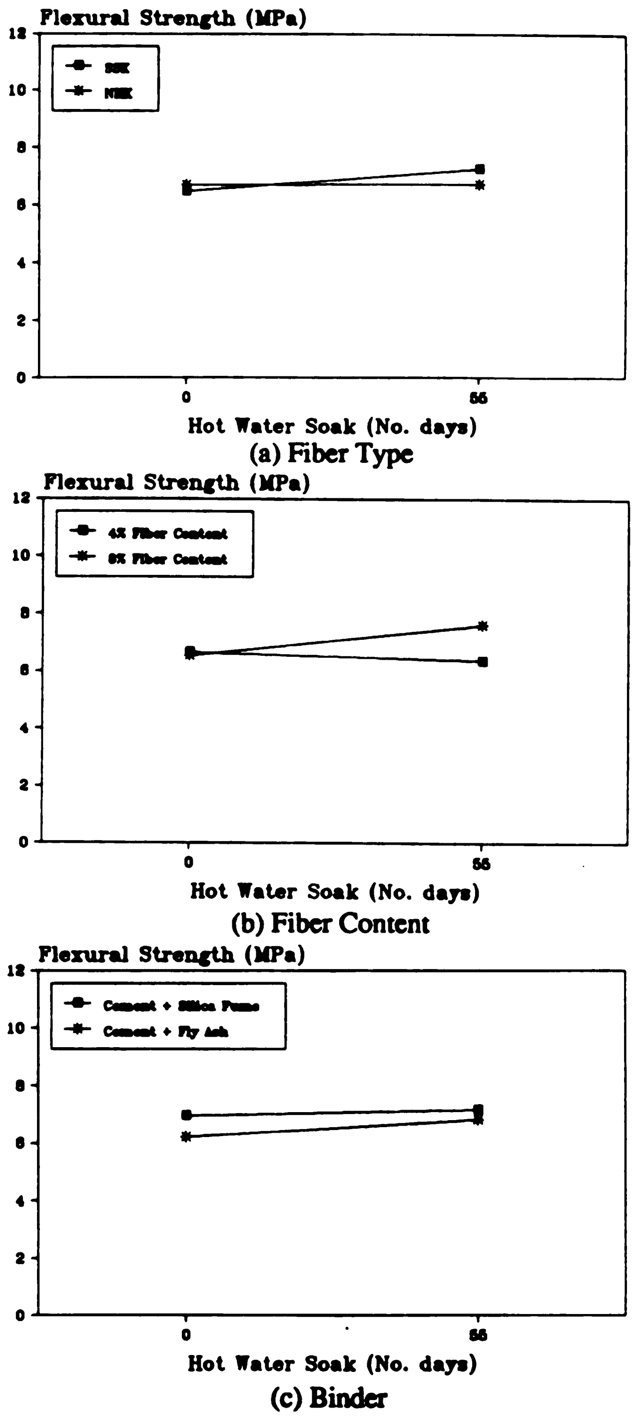
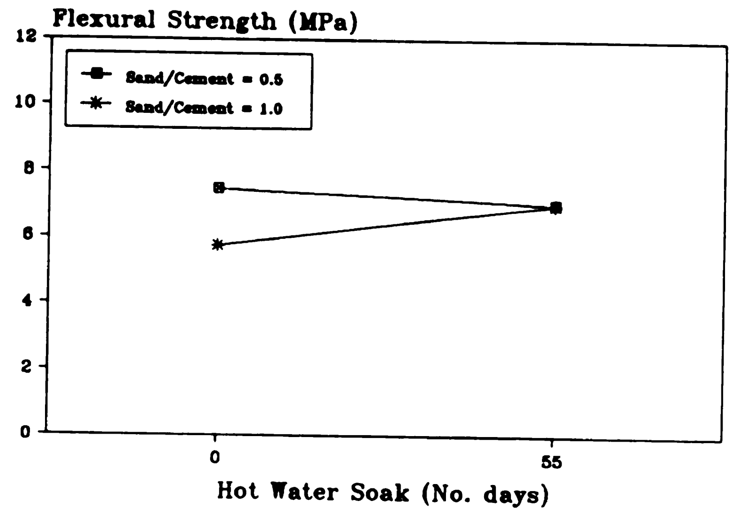
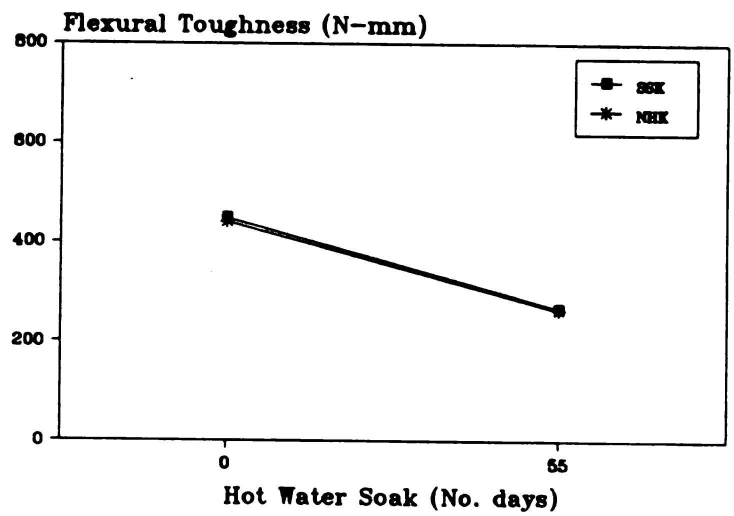


Figure 6.25 Interaction of Different Parameters and Hot Water Soaking on the Flexural Strength of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.



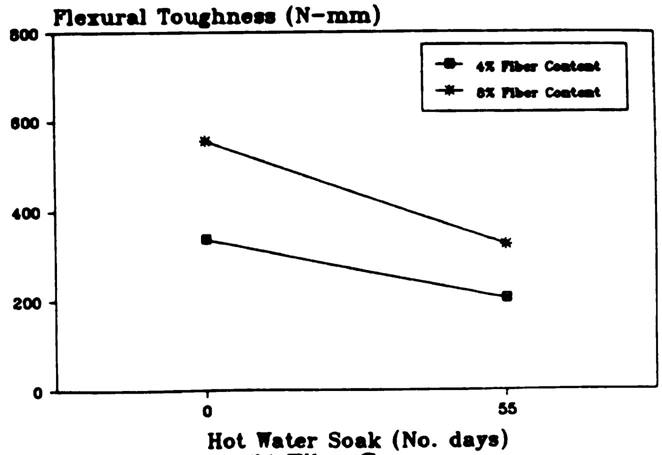
(d) Sand Content

Figure 6.25 (cont'd) Interaction of Different Parameters and Hot Water Soaking on the Flexural Strength of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

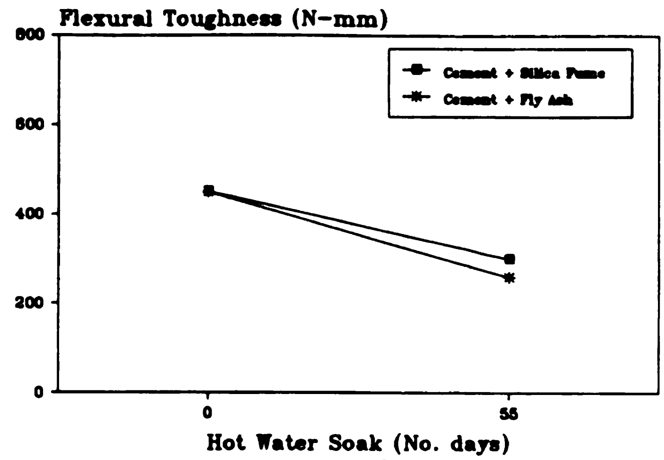


(a) Fiber Type

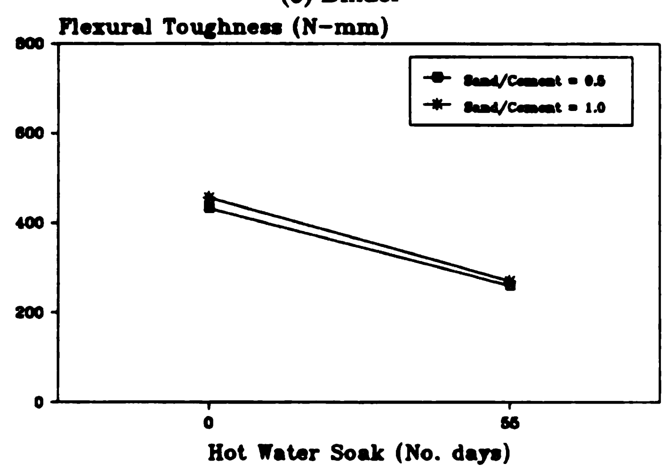
Figure 6.26 Interaction of Different Parameters and Hot Water Soaking on the Flexural Toughness of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.



(b) Fiber Content



(c) Binder



(d) Sand Content

Figure 6.26 (cont'd) Interaction of Different Parameters and Hot Water Soaking on the Flexural Toughness of Wood Fiber Reinforced Cement Composites Based on Fractional Factorial Analysis of Variance.

Statistical analyses indicated that only fiber content (Figure 6.25 b) and sand content (Figure 6.25 d) influenced the aging effect on flexural strength at 95% level of confidence. Composites with higher fiber content and higher sand content produced a more positive effect of ageing in hot water on flexural strength.

As far as flexural toughness was concerned, ageing effects in hot water showed statistically significant interactions (at 95% level of confidence) with fiber content and binder type. The adverse effects of ageing on flexural toughness were reduced at lower fiber contents and in the presence of silica fume.

CHAPTER 7

SUMMARY AND CONCLUSIONS

An experimental study was conducted to assess the mechanical and physical properties, moisture-sensitivity, and long-term durability of wood fiber reinforced cement composites.

The research was conducted in three phases concerned with: (1) fiber characterization and mechanical/physical properties of wood fiber reinforced cement composites; (2) moisture-sensitivity of wood fiber reinforced cement composites; and (3) long-term durability characteristics of wood fiber reinforced cement composites.

Comprehensive sets of replicated experimental data were generated in this study and were analyzed statistically using the analysis of variance and multiple comparison techniques in order to derive statistically reliable conclusions. Statistical time-series analysis was also used in durability studies to predict the long-term behavior of composites beyond the testing period.

A summary of the activities related to these phases together with the corresponding conclusions are given below. In these discussions, a significant effect represents a confidence level between 95 to 99%, and a highly significant effect represents confidence levels higher than 99%.

7.1 FIBER CHARACTERIZATION AND MECHANICAL/PHYSICAL PROPERTIES OF WOOD FIBER REINFORCED CEMENT COMPOSITES

The main emphasis in this phase of the research was to establish the reinforcing action of wood fibers in cement matrix. In order to achieve this objective, the following steps were taken: (a) selection and characterization of different wood fiber types; (b) assessment of the mechanical and physical properties of wood fiber-cement composites; (c) optimization of the fiber mass fraction in different manufacturing conditions; (d) modification of the matrix with pozzolanic admixtures and latex; (e) Investigation of the bleaching effects; (f) modification of the processing (manufacturing) parameters; (g) combination of wood fibers with synthetic fibers; and (h) comprehensive statistical investigation of the effects of different parameters relevant to wood fiber reinforced composites.

7.1.1 Characterization of Different Wood Fiber Types

A variety of commercially available wood fiber types were selected and characterized for cement applications. The wood fibers selected for this investigation were: Southern Softwood Kraft (SSK), Northern Hardwood Kraft (NHK), and Mechanical Pulp (1000L). The findings of this phase of research are summarized below:

- Relatively large variations in fiber lengths were observed for all fiber types. This variation is a particularity of wood fibers.

- High moisture content and regain values (of the order of 8%) were observed for all the fiber types.

- High water solubility of mechanical pulp (1000L) observed is a concern during the hydration process of cementitious matrix.

- Kraft fibers were observed to be resistant to alkali attack under extended exposure to the alkaline pore water of cement and some comparable solutions.

7.1.2 Mechanical and Physical Properties of Molded Wood Fiber-Cement Composites

The effects of wood fiber reinforcement on the fresh mix and hardened material properties of the composite were assessed in this investigation. The wood fibers used were Southern Softwood Kraft (SSK), Northern Hardwood Kraft (NHK), and Mechanical Pulp (1000L). The matrix used in this study was neat cement paste, and the composites were manufactured by the molding method. The fiber mass fractions were 0%, 1% and 2%. The test results indicated that:

- Wood fiber reinforcement leads to increased water requirement, setting time and air content of cementitious materials.

- Highly significant improvements (up to 500% at a fiber mass fraction of 2%) in the flexural strength of cement can be reached by the use of kraft pulps. The increase in fracture toughness is even more significant. Mechanical pulps are less effective than kraft pulps in increasing flexural strength and fracture toughness.

- There is a gradual tendency for the compressive strength and toughness of cementitious composites to drop with increasing wood fiber content.

- Highly significant improvements in the impact resistance of cementitious materials can be reached through reinforcement of the material with kraft pulp. Some improvements in impact resistance can also be achieved by mechanical pulps.

- Wood fiber reinforcement results in a decrease in specific gravity and increase in water absorption of cementitious materials.

7.1.3 Optimization of Fiber Content in Molding and Slurry-Dewatering Processes

An experimental study was conducted to optimize the fiber mass fraction in different manufacturing precesses. Composites containing lower fiber contents (< 2%) were manufactured through the molding method; composites containing higher fiber contents (> 4%) were manufactured by slurry-dewatering. The wood fibers used in the molding method were Southern Softwood Kraft (SSK) and Mechanical Pulp (1000L), and only Southern Softwood Kraft (SSK) was used in slurry-dewatering. The matrix contained equal amounts of cement and silica sand. The composites were tested for their flexural performance. The test results indicated that:

- In the molding method, addition of 1% mass fraction of fibers to plain cement matrix has a highly significant effect on flexural strength. However, fiber content, changing from 1% to 2% mass fraction does not show any significant effect on flexural strength. The effect of fiber content on flexural toughness is highly significant.

- In the slurry-dewatering method, fiber mass content has highly significant effects on flexural strength and toughness. Maximum flexural strength was obtained at 8% fiber mass fraction. Flexural toughness continues to increase with increasing fiber mass fraction; maximum toughness values were obtained at the maximum fiber mass fraction considered (14%).

- Fiber type (kraft vs. mechanical pulp), in molding method, had a highly significant effect on flexural strength at 1% fiber content (with kraft fibers giving higher strength), while at 2% fiber content the effect of fiber type on flexural strength was not significant. Effect of fiber type on flexural toughness was highly significant at all fiber contents (with kraft fibers producing higher toughness values).

- Increasing wood fiber content results in reductions in specific gravity and increase in water absorption of cementitious materials.

7.1.4 Matrix Modification

An experimental study was conducted to assess the effects of modification of matrix mix constituents through pozzolanic admixtures (15% silica fume or 30% fly ash) and latex (10%) on the flexural performance of wood fiber reinforced cement composites. The fiber used in this study was Southern Softwood Kraft (SSK). The samples contained an optimum fiber content of 2% in the molding method and 8% in slurry-dewatering. The test results indicated that:

- Addition of pozzolans (silica fume and fly ash) led to increased flexural strength of composites while slightly reducing flexural toughness. These effects were more pronounced with silica fume.

- Modification of the matrix with latex polymer (10% Styrene Butadiene by weight of cement) in the molded wood fiber reinforced cement composites showed highly significant improvement in flexural performance.

7.1.5 Effect of Bleaching

An experimental study was conducted to assess the flexural performance of molded cement composites reinforced with bleached and unbleached wood fibers. The fiber used in this study was bleached and unbleached Southern Softwood Kraft (SSK) and the composites contained an optimum fiber content of 2%. The test results indicated that:

- Cement composites containing bleached wood fiber show higher flexural strength and lower toughness than unbleached wood fiber reinforced cement composites. However, the effects were not statistically significant at 95% confidence level.

7.1.6 Modification of Processing Parameters in the Slurry-Dewatering Technique

An experimental study was conducted to assess the effects of the slurry-dewatering processing parameters on the flexural performance of composites containing 8% and 16% fiber contents. The fiber used in this study was Southern Softwood Kraft (SSK). The processing parameters studied were casting pressure and pressing time. The test results indicated that:

- Flexural strength of composites drops and flexural toughness increases significantly (at 95% confidence level) when fiber mass fraction is increased from 8% to 16%.

- Flexural strength of composites increases with increased casting pressure and pressing time. These effects are more pronounced at higher fiber contents. However, statistical analysis of the test data showed only significant effect of pressing time on flexural strength of composites with 16% fiber content, at 95% level of confidence.

- Flexural toughness of composites at all fiber contents remains virtually constant with increased casting pressure and pressing time. These results were confirmed statistically at 95% confidence level.

- Higher fiber contents (16% when compared to 8%) significantly increase water absorption and reduce specific gravity of the composite. There is a clear reduction in water absorption and increase in specific gravity of the composite with the increase in casting pressure and pressing time at all fiber contents.

7.1.7 Combination with Synthetic Fibers

An experimental study was conducted to assess the flexural performance of composites containing combinations of synthetic and wood fibers. The wood fiber used was Southern Softwood Kraft (SSK), which was combined with Polyethylene Pulp (PulPlus). The combined fiber content was kept constant at 8%. The test results indicated that:

- Cement composites containing synthetic vs. wood fibers show comparable flexural strength. Composites containing synthetic fibers have slightly better flexural toughness. Statistical analysis of the test results at 95% level of confidence, however, indicated that, considering random experimental variations, the flexural strength and toughness of composites with different combinations of wood and synthetic fibers were comparable.

7.1.8 Comprehensive Statistical Study of Different Parameters and their Effects

An experimental study based on the statistical method of fractional factorial design was conducted to determine the effects of different variables on specific gravity, water absorption, and moisture movement. The composites were manufactured using the slurry-dewatering technique. The variables of the experimental study were: (1) wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash or 15% silica fume); and (4) silica sand content (silica sand-cement ratio = 0.5 & 1.0). Test results indicated that:

- Fiber content has significant effect (at 95% confidence level) on specific gravity, water absorption, and moisture movement. Fiber content, when increased from 4% to 8% reduces specific gravity, and increases water absorption and moisture movement.

- Partial substitution of cement with silica fume when compared with fly ash significantly increases specific gravity and reduces water absorption.

- Fiber type and sand content do not have significant effect on specific gravity, water absorption and moisture movement.

- A very strong negative correlation between specific gravity and water absorption was observed, which indicates that composites with a higher specific gravity tend to have a lower water absorption capacity.

Similar results were produced for the effects of different parameters on flexural performance at different moisture conditions, to be discussed next.

7.2 MOISTURE-SENSITIVITY OF WOOD FIBER REINFORCED CEMENT COMPOSITES

In this phase of research, the moisture-sensitivity of wood fiber reinforced cement composites was assessed. For this purpose, the following tasks were performed regarding moisture effects on the flexural performance of wood fiber-cement composites: (a) assess the effect of fiber type and content on moisture-sensitivity; (b) modify the matrix with pozzolanic admixtures and latex to enhance stability under moisture effects; (c) study the effects of bleaching on moisture-sensitivity; (d) modify the processing variables in manufacturing to induce stability under moisture effects; (e) combine wood fibers with synthetic fibers to reduce moisture-sensitivity; and (h) comprehensive statistical study of the effects of different parameters relevant to wood fiber reinforced cement composites with emphasis on moisture resistance.

7.2.1 Effects of Fiber Type and Content

An experimental study was conducted to assess the moisture-sensitivity of wood fiber reinforced cement composites through the assessment of moisture effects on flexural performance. Composites containing lower fiber contents (< 2%) were manufactured through the molding method; composites containing higher fiber contents (> 4%) were manufactured through slurry-dewatering. The wood fibers used in the molding method were Southern Softwood Kraft (SSK) and Mechanical Pulp (1000L), and only Southern Softwood Kraft (SSK) was used in slurry-dewatering. The matrix contained equal amounts (by weight) of cement and silica sand. The test results indicated that:

- In the molding method, fiber content, changing from 1% to 2% mass fraction, has a highly significant effect on the flexural strength of wet specimens where strength is reduced with increasing fiber content. Fiber content (1% vs. 2%) does not have any significant effect on the flexural strength of air or oven dried specimens. The effect of fiber content on flexural toughness is highly significant for both the kraft and mechanical pulps at all moisture contents.

- In the slurry-dewatering method, fiber mass content has highly significant effects on flexural strength and toughness at all moisture conditions. Maximum flexural strengths for different moisture conditions was obtained at 8% fiber mass fraction. Flexural toughness at all moisture conditions continues to increase with increasing fiber mass fraction; maximum toughness values are obtained at the maximum fiber mass fraction considered (14%).

- Fiber type (kraft vs. mechanical pulp), in molding method, has a highly significant effect on flexural strength at 1% fiber content for all moisture conditions (with kraft fibers giving higher strength), while at 2% fiber content the effect of fiber type on flexural strength is not significant. Effect of fiber type on flexural toughness is highly significant at all fiber contents and for all moisture conditions.

- Oven-drying of the composites, when compared with air-drying, has no statistically significant effect on flexural strength, but has significant (adverse) effects on flexural toughness. Wetting of the composites, when compared to air-drying, has highly significant effects on flexural strength and toughness (where strength is reduced and toughness is increased). There are also strong interactions between fiber content and moisture condition as far as the flexural strength and toughness are concerned. In other words, the effects of moisture on composites are dependent on their fiber content.

- Microstructural studies indicated that wetting leads to increased tendency towards fiber pullout rather than rupture of fibers at failure surfaces, while oven drying promotes fiber rupture. This may illustrate why increased moisture condition tends to produce higher flexural toughness and lower flexural strength in wood fiber reinforced cement composites.

7.2.2 Matrix Modification

An experimental study was conducted to assess the effect of modification of matrix mix constituents through pozzolanic admixtures (15% silica fume or 30% fly ash) and latex (10%) on moisture-sensitivity of wood fiber reinforced cement composites. The fiber used in this study was Southern Softwood Kraft (SSK). The samples contained optimum fiber contents of 2% in the molding method and 8% in slurry-dewatering. The composites were tested for flexural performance in different moisture conditions. The test results indicated that:

- Addition of pozzolans (silica fume and fly ash) leads to increased flexural strength of composites while slightly reducing flexural toughness at all moisture conditions. These effects were confirmed statistically at 95% level of confidence; they were more pronounced with silica fume and at the saturated condition.

- In the presence of pozzolans no statistically significant difference is observed in the flexural behavior of air dried and oven dried composites; wetting causes adverse effects on flexural strength and positive effects on flexural toughness values, at 95% level of confidence. The presence of pozzolans leads to reduced moisture-sensitivity of wood fiber reinforced cement composites.

- Modification of matrix through latex polymer (10% Styrene Butadiene by weight of cement) in molded wood fiber reinforced cement composites leads to highly significant improvements in flexural performance at all moisture conditions.

- In the presence of latex no statistically significant difference is observed between the flexural behavior of air dried and oven dried composites; wetting still has highly significant effects on flexural performance (adverse effects on flexural strength and positive effects on flexural toughness). Highly improved moisture resistance characteristics of wood fiber reinforced composites are observed in the presence of latex.

7.2.3 Effect of Bleaching

An experimental study was conducted to assess the moisture-sensitivity of molded cement composites reinforced with bleached and unbleached wood fibers. The fiber used in this study was bleached and unbleached Southern Softwood Kraft (SSK) and the composites contained an optimum fiber content of 2%. The composites were tested for flexural performance in different moisture conditions. The test results indicated that:

- Cement composites containing bleached wood fiber show higher flexural strength and lower toughness than unbleached wood fiber reinforced cement composites at all moisture contents. However, these differences are not statistically significant at 95% confidence level.

- Moisture still has highly significant effect on flexural performance (adverse effects on flexural strength and positive effects on flexural toughness). The flexural strength and toughness values of composites containing bleached and unbleached composites in the wet state are comparable.

7.2.4 Modification of Processing Parameters in the Slurry-Dewatering Technique

An experimental study was conducted to assess the effects of the slurry-dewatering processing parameters and moisture condition on the flexural performance of composites containing 8% and 16% fiber content. The fiber used in this study was Southern Softwood Kraft (SSK). The processing parameters studied were casting pressure and pressing time. The test results indicated that:

- Flexural strength of air dried and saturated composites drops significantly (at 95% confidence level) when fiber mass fraction is increased from 8% to 16%. Flexural strength of composites slightly increases with increasing casting pressure and pressing time at all moisture conditions. Statistical analysis of the test data showed only significant effect of pressing time on flexural strength of composites with 16% fiber content, at 95% level of confidence.

- Flexural toughness of air dried and saturated composites increases significantly (at 95% confidence level) when fiber mass fraction is increased from 8% to 16%. Flexural toughness of composites at all fiber contents remains virtually constant with increased casting pressure and pressing time.

- Moisture has significant effects (at 95% confidence level) on the flexural performance (adverse effects on flexural strength and positive effects on flexural toughness) for composites with all combinations of casting pressure and pressing time. There are also strong interactions between pressing time and moisture condition in determining flexural toughness. In other words, the effects of moisture on composites are influenced by pressing time where increased pressing time produced better stable composites under variable moisture conditions.

7.2.5 Combination with Synthetic Fibers

An experimental study was conducted to assess the flexural performance of composites containing combinations of synthetic and wood fibers. The wood fiber used was Southern Softwood Kraft (SSK) and the synthetic fiber was Polyethylene Pulp (PulPlus). The combined fiber content was kept constant at 8%. The test results indicated that:

- Cement composites containing synthetic and wood fibers show comparable flexural strength and toughness in air dried conditions. However, in saturated condition, composites containing synthetic fibers, when compared to wood fibers, show higher flexural strength and toughness. Statistical analysis of the test results at 95% level of confidence, however, indicated that, considering random experimental variations, the flexural strength and toughness of composites with different combinations of wood and synthetic fibers at all moisture conditions are comparable.

- Moisture has highly significant effects (at 95% confidence level) on the flexural performance of composites reinforced with different combinations of wood and synthetic fibers. Wetting of the composites still has adverse effects on flexural strength and positive effects on flexural toughness for both wood fiber and synthetic fiber reinforced cement composites. Composites containing synthetic fibers, when compared with wood fibers, shows slightly improved moisture-sensitivity.

- Synthetic fibers used in this study (specifically made for the slurry-dewatering method of manufacturing cement composites) are also sensitive to moisture effects (although to a slightly smaller extent than wood fibers). Partial or full substitution of wood fibers with synthetic fibers can slightly reduce the sensitivity of the flexural strength and toughness of composites to moisture effects.

7.2.6 Comprehensive Statistical Study of Different Parameters and their Effects

An experimental study based on the statistical method of fractional factorial design was conducted to assess the flexural performance of wood fiber reinforced cement composites under different moisture conditions. The composites were manufactured using the slurry-dewatering technique. The variables of the experimental study were: (1) wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash or 15% silica fume); (4) moisture condition (air dried &

saturated); and (5) silica sand content (silica sand-cement ratio = 0.5 & 1.0). Test results indicated that:

- Composites containing softwood kraft pulp (SSK) and hardwood kraft pulp (NHK) produce comparable flexural strength and toughness. Fiber content, changing from 4% to 8% increases both flexural strength and toughness significantly (at 95% confidence level). Partial substitution of cement with silica fume, when compared to fly ash, produces higher flexural strengths; however, their toughness values are comparable. Reduced sand content significantly increases flexural strength, whereas toughness is reduced.

- Wood fiber reinforced cement composites are sensitive to moisture effects. Wetting of the composite has statistically significant effects, at 95% level of confidence, on flexural strength, which drops sharply upon wetting. On the other hand, there are statistically significant improvements in the flexural toughness of wood fiber reinforced cement composites upon wetting. These effects are more pronounced in composites containing 8% fiber mass fraction.

- The interaction curves obtained through fractional factorial analysis of variance of the results indicated strong interaction between fiber content and moisture condition in deciding flexural strength; composites containing 8% fiber content show higher strength loss due to wetting. The improvements in flexural toughness due to wetting of the composites are comparable. Improved flexural toughness and reduced flexural strength of composites upon wetting can be attributed to the weakening of fiber-to-matrix bond in the presence of moisture, and reduced stiffness and expansion of wet fibers.

7.3 LONG-TERM DURABILITY CHARACTERISTICS OF WOOD FIBER REINFORCED CEMENT COMPOSITES

In this phase of the research, the long-term durability of wood fiber reinforced cement composites was assessed. The specimens were subjected to repeated cycles of freezing and thawing, wetting and drying, hot water immersion, and outdoor exposure. After ageing, the specimens were tested for flexural performance, except for freeze-thaw durability in which case the specimens were subjected to non-destructive testing in order to obtain their relative dynamic modulus of elasticity. The following steps were taken at this stage to study the long-term durability of wood fiber-cement composites: (a) assess the effects of fiber type and content on durability characteristics; (b) study the effect of bleaching on durability; and (c) perform a comprehensive statistical study on the effects of different parameters relevant to wood fiber reinforced cement composites on long-term durability.

7.3.1 Effects of Fiber Type and Content

An experimental study was conducted to assess the long-term durability of wood fiber reinforced cement composites. The wood fibers used in this study were Southern Softwood Kraft (SSK), Northern Hardwood Kraft (NHK), and Mechanical Pulp (1000L). The matrix contained equal amounts (by weight) of cement and silica sand, and the composites were manufactured by the molding method (< 2% fiber content). The test data produced in this investigation indicate that:

7.3.1.1 Accelerated Wetting-Drying

- The flexural strength of unaged and aged molded wood fiber reinforced cement composites (2% fiber mass fraction) are significantly higher than the corresponding strengths of plain mortar. The improvement in strength due to fiber addition is more pronounced in composites containing kraft fibers at all ageing conditions.

- Wetting-drying cycles tend to increase the flexural strength and stiffness of both plain and fiber reinforced cement composites. Statistical analysis of test results at 95% level of confidence, however, indicated that the increase in the flexural strength of plain and fibrous cement composites under repeated wetting-drying cycles is not significant.

- The flexural toughness of unaged and aged fiber reinforced cement composites are significantly higher than those of plain mortar. Accelerated wetting-drying cycles cause a drop in flexural toughness in both plain and fibrous specimens.

- Analysis of variance of the test data at 95% level of confidence confirmed a significant drop in flexural toughness only for composites containing kraft fibers. In this case, it was also noted that, at 95% level of confidence, the initial 12 cycles of wetting-drying cause significant drops in flexural toughness; subsequent cycles cause only gradual drops in toughness. It should be noted that accurate values of toughness for plain matrix and composites containing mechanical pulp could not be obtained due to the very low toughness values of these materials.

- Statistical time-series analysis with regression forecasting predicted continued improvement in flexural strength and drop in flexural toughness with increased number of wetting-drying cycles.

- Microstructural studies indicated that the dominant mode of fracture in aged composite is fiber fracture, while unaged specimens show a combination of fiber pullout and fiber fracture. In the case of aged composites, petrification of fibers and densening of interface zones cause tendencies toward increased strength and embrittlement with ageing. Petrified fibers with excess bonding tend to rupture rather than pullout at fracture surfaces, thus eliminating the desirable toughness characteristics associated with frictional energy dissipation during fiber pullout.

7.3.1.2 Freezing and Thawing

- The relative dynamic modulus of elasticity of plain cementitious matrices decreases under repeated cycles of freezing and thawing; this effect was found to be statistically significant at 95% level of confidence.

- The relative dynamic moduli of composites containing 2% mass fraction of softwood and hardwood kraft fibers show a slight increase with ageing, which is not statistically significant. However, composites containing 2% mass fraction of mechanical pulp show significant increase in relative dynamic modulus of elasticity. Much of the increase was found in earlier cycles of freezing and thawing, while later cycles cause a gradual decrease in relative dynamic modulus of elasticity.

- Statistical time series analysis with regression forecasting predicted an almost constant relative dynamic modulus of elasticity for fibrous composites containing kraft pulp with continued cycles of freezing and thawing. In the case of the plain matrix and fibrous composites containing mechanical pulp, however, the dynamic modulus of elasticity shows a tendency to drop with continued freeze-thaw cycles.

7.3.1.3 Natural Weathering:

- The flexural strengths of unaged and aged fiber reinforced cement composites are significantly higher than those of plain mortar. The improvement in strength due to fiber addition is more pronounced at all ages in composites containing kraft fibers.

- Natural ageing tends to increase the flexural strength and stiffness of both plain and fiber reinforced cement composites. Statistical analysis of test results at 95% confidence level, however, indicated that changes in flexural strength of plain and fibrous cement composites with exposure to natural weathering are not significant.

- The flexural toughness of unaged fiber reinforced cement composites is significantly higher than that of plain mortar. The improvement in flexural toughness due to fiber addition is more pronounced in composites containing kraft fibers.

- Exposure to natural weathering causes a major drop in flexural toughness for both plain and fibrous composites. Statistical analysis of the test data at 95% level of confidence confirmed a significant drop in flexural toughness for plain mortar and fibrous composites. Accurate values of toughness for plain matrix and composites containing mechanical pulp could not be obtained due to the very low toughness values of these materials.

- Statistical time-series analysis with regression forecasting predicted continued improvement in flexural strength and drop in flexural toughness with continued natural weathering.

- It should be noted here that exposure to natural weathering for only one year may not be sufficient to derive reliable conclusions. However, the trends observed in this study under exposure to natural ageing are in close comparison with the results obtained in accelerated weathering (wetting and drying) tests.

7.3.2 Effect of Bleaching

An experimental study was conducted to assess the long-term durability of molded cement composites reinforced with bleached and unbleached wood fibers. The fibers used in this study was bleached and unbleached Southern Softwood Kraft (SSK), and the composites contained an optimum fiber content of 2%. The test results indicated that:

7.3.2.1 Accelerated Wetting-Drying

- Composites reinforced with unbleached wood fibers, which contain small amounts of lignin, produce results comparable to those of composites reinforced with bleached fibers at all ages of wetting and drying.

- Wetting-drying cycles tend to increase the flexural strength and stiffness of both bleached and unbleached fibrous cement composites. Statistical analysis of test results at 95% level of confidence, however, indicated that the increase in flexural strength under repeated wetting-drying cycles was not significant.

- Accelerated wetting-drying cycles caused a severe drop in flexural toughness in both bleached and unbleached fibrous cement composites. Analysis of variance of the test data at 95% level of confidence confirmed the significant drop in flexural toughness.

- Statistical time-series analysis with regression forecasting predicted continued improvement in flexural strength and drop in flexural toughness with increased numbers of wetting-drying cycles for both bleached and unbleached fibers.

7.3.2.2 Freezing and Thawing

- The behavior of composites containing unbleached and bleached fibers under repeated cycles of freezing and thawing are comparable.

- The relative dynamic modulus of composites containing unbleached and bleached fibers shows a slight increase with ageing, which is not statistically significant. Much of the increase take place in earlier cycles of freezing and thawing, while later cycles cause a gradual decrease in relative dynamic modulus of elasticity.

- Statistical time series analysis with regression forecasting predicted a slight drop in relative dynamic modulus of elasticity for both bleached and unbleached fibrous composites with continued cycles of freezing and thawing.

7.3.2.3 Natural Weathering

- Composites reinforced with unbleached wood fibers produce results comparable to those of composites reinforced with bleached fibers when exposed to natural weathering.

- Natural ageing tends to increase the flexural strength and stiffness of both bleached and unbleached fibrous cement composites. Statistical analysis of test results at 95% confidence level, however, indicated that changes in flexural strength are not significant.

- Exposure to natural weathering causes a major drop in flexural toughness for both bleached and unbleached fibrous cement composites. Statistical analysis of test data at 95% level of confidence confirmed the significant drop in flexural toughness for both composites.

- Statistical time-series analysis with regression forecasting predicted continued improvement in flexural strength and drop in flexural toughness with increased numbers of wetting-drying cycles.

- It should be noted here that exposure to natural weathering for only one year may not be sufficient to derive reliable conclusions. However, the trends observed in this study under exposure to natural ageing are in close comparison with the results obtained in accelerated weathering (wetting and drying tests).

7.3.3 Comprehensive Statistical Study of Different Parameters and their Effects

An experimental study based on the statistical method of fractional factorial design was conducted to determine the effects of ageing on flexural performance of wood fiber reinforced cement composites. The composites were manufactured using the slurry-dewatering technique. The variables of the experimental study were: (1) wood fiber type (softwood & hardwood); (2) fiber mass content (4% & 8%); (3) partial substitution of cement with pozzolans (30% fly ash or 15% silica fume); (4) ageing (aged & unaged); and (5) silica sand content (silica sand-cement ratio = 0.5 & 1.0). Test results indicated that:

- Accelerated wetting-drying slightly improves the flexural strength of wood fiber reinforced cement composites at all fiber contents. However, the increase is not statistically significant at 95% level of confidence. There are significant effects of ageing on flexural toughness, where toughness reduces considerably with ageing (25 cycles of wetting and drying).

- Analysis of the interaction of different variables with accelerated weathering effects indicated that only fiber content influences the aging effect on flexural toughness at 95% level of confidence. The adverse effects of ageing on flexural toughness were reduced at lower fiber contents.

- Hot water soaking of wood fiber reinforced cement composites slightly improves flexural strength at all fiber contents. However, the increase is not statistically significant at 95% level of confidence. There are significant effects of ageing on flexural toughness, where toughness is considerably reduced with ageing (hot water soaking for 55 days).

- Interaction of different variables with hot water soaking indicated that only fiber content and sand content influence the aging effect on flexural strength at 95% level of confidence. Composites with higher fiber content and higher sand content produce a more positive effect of ageing in hot water on flexural strength. As far as flexural toughness is concerned, ageing effects in hot water show statistically significant interactions (at 95% level of confidence) with fiber content and binder type. The adverse effects of ageing on flexural toughness are reduced at lower fiber contents and in the presence of silica fume.

APPENDIX A

STANDARD SPECIFICATIONS

The following standard specifications were used in this study:

1.	ASTM C 230	Specification for Flow Table for Use in Tests of Hydraulic Cement (American Society for Testing and Materials)
2.	ASTM C 1185	Standard Test Methods for Sampling and Testing Non-Asbestos Fiber-Cement Flat Sheet, Roofing and Siding Shingles, and Clapboards (American Society for Testing and Materials)
3.	ASTM C 666	Test Method for Resistance of Concrete to Rapid Freezing and Thawing (American Society for Testing and Materials)
4.	ASTM C 403	Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance (American Society for Testing and Materials)
5.	ASTM C 185	Test Method for Air Content of Hydraulic Cement Mortar (American Society for Testing and Materials)
6.	ASTM D 1348	Test Methods for Moisture in Cellulose (American Society for Testing and Materials)
7.	JCI SF 4	Method of Tests for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete (Japan Concrete Institute)
8.	JCI SF 5	Method of Tests for Compressive Strength and Compressive Toughness of Fiber Reinforced Concrete (Japan Concrete Institute)
9.	TAPPI 207	Water Solubility of Pulp (Technical Association of the Pulp and Paper Industry)

APPENDIX B

NOTATION

The following symbols were used in this study:

1000L	1000 Long
AD	Air Dried
ASTM	American Society for Testing and Materials
CD	Cross Direction
CEDED	Chlorine-Extraction-Chlorine-Dioxide-Extraction-Chlorine-Dioxide
CSF	Canadian Standard Freeness
C-S-H	Calcium Silicate Hydrate
E. Grandis	Eucalyptus Grandis
E. Regnans	Eucalyptus Regnans
E. Saligna	Eucalyptus Saligna
FA	Fly Ash
JCI-SF	Japanese Concrete Institute Standards for Test Methods of Fiber Reinforced Concrete
MD	Machine Direction
NHK	Northern Hardwood Kraft
P. Radiata	Pinus Radiata
RH	Relative Humidity
SAT	Saturated
SEM	Scanning Electron Micrographs
SF	Silica Fume
SSK	Southern Softwood Kraft
St. Dev.	Standard Deviation
TAPPI	Technical Association of the Pulp and Paper Industry

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