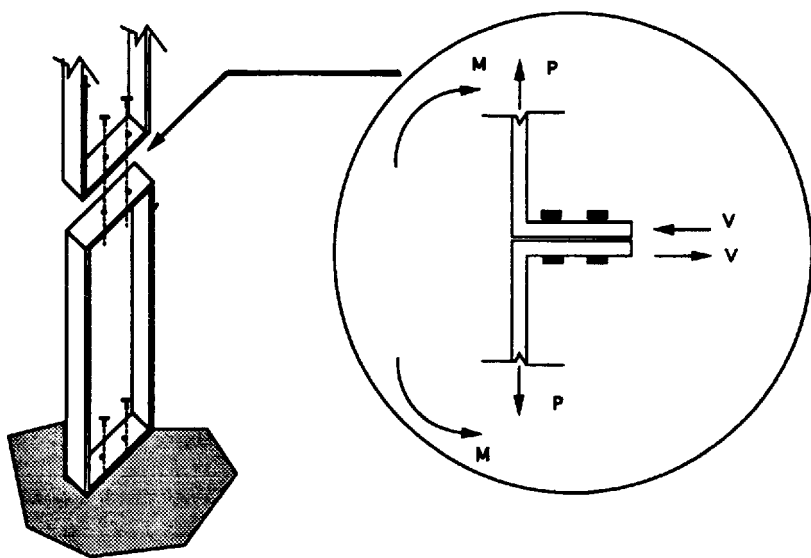


Thin Reinforced Concrete Products and Systems



P. Balaguru,
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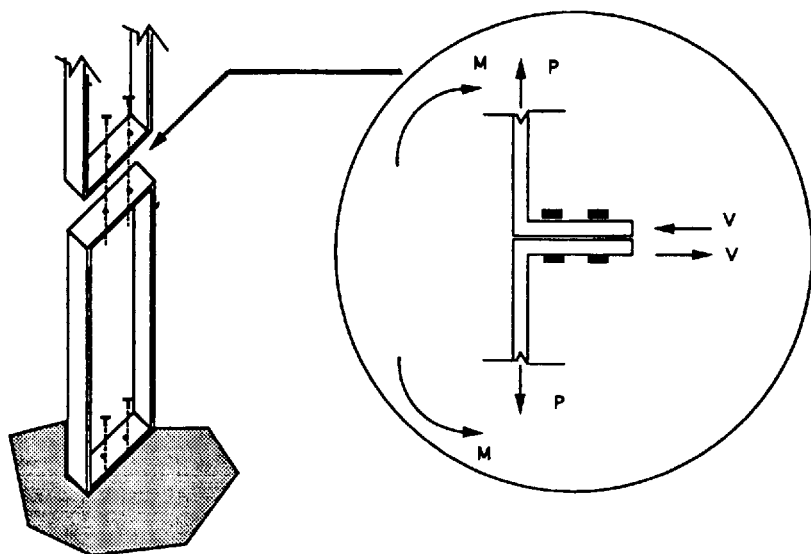
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Thin Reinforced Concrete Products and Systems



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PREFACE

Since the use of asbestos fibers is totally banned in the industrialized countries and discouraged in almost all countries, a large number of researchers around the world are working to obtain a replacement. Various forms of fabrics, meshes, and discrete fibers made of metal, mineral, polymeric, and naturally occurring materials have been investigated. ACI Committee 549 on Ferrocement and Other Thin Reinforced Products sponsored an international symposium to address the various aspects of thin sheet products. The original papers for this symposium were presented at the ACI Fall Convention of 1992 in San Juan, Puerto Rico. Subsequently, the full length papers that were submitted were reviewed by the committee members, as well as the experts in the field. This volume contains these original, reviewed and revised papers.

The subject areas covered in this volume include: tensile and bending behavior of micro-fiber reinforced composites, a state-of-the-art review of the synthetic fiber used in thin sheet products, statistical evaluation of physical properties, mathematical models for members subjected to bending and axial forces, pavement overlay application, and ferrocement moment-resisting joints. The reinforcement consisted of steel wire meshes, glass fibers, naturally occurring fibers, or micro-fibers made of steel, carbon, cellulose, or polymeric material.

The editor gratefully acknowledges members of the ACI Committee 549, the reviewers, the authors, Professor Parvis Soroushian (symposium co-chairman and Secretary of ACI Committee 549), and the staff of ACI who have made this volume a timely contribution to the state-of-the-art of thin-section fiber reinforced composite and ferrocement.

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Chairman, ACI Committee 549

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Synthetic Fibers in Thin-Section Cement Products: A Review of the State of the Art

by D.M. Gale

Synopsis:

Since the turn of the century, thin-section asbestos-cement sheet and pipe products have been manufactured by the Hatschek Process. Health and environmental concerns with the use of asbestos has led to a worldwide search for alternative fibers. This paper reviews the state-of-the-art in using synthetic fibers to replace asbestos in fiber-cement products.

Keywords: Aramids; asbestos; carbon; cellulose fibers; durability; esters; fiber reinforced concretes; nylon fibers; pipes (tubes); polyethylene; polypropylene fibers; polyvinyl alcohol; pulp; reinforcing materials; sheets; synthetic fibers

Dr. David M. Gale is a Senior Research Associate for the DuPont Co. in Wilmington, Delaware, specializing in fiber reinforcement. He is currently active in ACI Committees 440, 544 (Executive Sub-Committee) and 549. In addition, he is Chairman of ASTM Committee C-17, Fiber-Cement Products, and active in ASTM Sub-Committee C09.42, Fiber Reinforced Concrete.

INTRODUCTION

A process for making sheet and pipe asbestos-reinforced cement products was invented in Austria at the turn of the century. The so-called Hatschek Process is similar to paper-making, wherein a slurry of asbestos and cement is picked up on a drum, transferred to a belt and dewatered. Thin layers are collected on an accumulator roll and further processed into a wide variety of sheet and pipe product shapes. The "green" products are cured at ambient conditions or in a steam autoclave. Typical applications are roofing, siding, high pressure water, drain and sewer pipes.

Recent concern with health and environmental issues has led the industry to seek substitutes for the asbestos in these products. During the 1970's, several asbestos-cement manufacturers, for example, the Swiss and Belgium Eternit groups, Dansk Eternit in Denmark, and James Hardie in Australia, led extensive efforts to replace asbestos with synthetic and natural fibers. Ultimately, collaborative efforts with fiber producers such as Kuraray in Japan, Hoechst in Germany and Du Pont in the U.S., led to products which contain synthetic fibers, whereas other developments produced products with natural fibers, particularly highly refined wood cellulose. This paper will focus on the state of the published art with respect to synthetic fiber developments.

In order to replace asbestos with synthetic fibers (which act as reinforcing agents), it is necessary to include other fibers that retain cement fines and hence act as "filter" fibers. Many synthetic reinforcing fibers have been studied, e.g., acrylic, polyvinyl alcohol (PVA), rayon, polyester, nylon, polypropylene, aramid, and carbon. Because of a combination of cost and other properties, acrylic, PVA and polypropylene are most popular today. Popular filter fibers consist of refined wood cellulose, polyethylene pulp, and acrylic pulp. One brand of polyethylene pulp, which is molecularly oriented, has both reinforcing and filter characteristics.

When asbestos is replaced with synthetic fiber systems, the ambient cure version of the Hatschek Process must be employed; synthetic fibers generally cannot withstand the 170-190°C temperatures of the autoclave cure. In general, for systems that replace asbestos, synthetic fibers impart highest ultimate flexural strengths (modulus of rupture) to the cement products. With both synthetic and cellulose fibers, first crack and ultimate strengths as well as rigidity tend to be lower than for asbestos systems.

Today, asbestos replacement is limited to sheet and low pressure pipe products, regardless of whether synthetic or natural fibers are employed.

Replacement fibers in the pressure pipe application have not yet been found because these products require high hoop strengths at low cost.

DISCUSSION

Asbestos-Cement Technology

Thin-section asbestos-cement building products have been known since the turn of the century, when, in Austria, Ludwig Hatschek formed sheets on a modified cardboard paper-making machine. By the beginning of the last decade this industry had grown to consume 1.5 million metric tons of asbestos fibers annually (Vinson and Daniel, 1990). The asbestos-cement products, although they use Portland cement, are quite different from typical aggregate-filled concrete products. A typical asbestos-cement product contains 40-90% Portland cement, 0-50% fine silica and the rest asbestos fibers, typically 7-15% by weight. Sometimes, for less critical applications, cheap diluents (fillers), such as fly-ash and calcium carbonate, are used. High silica content is usually reserved for products prepared by curing in a steam autoclave at 170-190°C. The silica is needed to combine chemically with the cement to form a stable silica-cement phase that is different from the hydrated cement product obtained when Portland cement is cured at ambient temperatures. When the silica is present, the cure can be achieved over night at the elevated autoclave temperatures. Otherwise, without silica, a normal 28-day ambient temperature cure is typical.

In the Hatschek process, a dilute aqueous slurry of cement and asbestos fibers, usually 5-10% solids, are mixed in a tank and transferred to vats containing one or more rotating sieved drums (Hannant, 1978), (Figure 1, after Coutts and Mitchell, 1983). A broad distribution of asbestos fiber lengths is used, the shorter to form an elementary web layer on the drum which will trap cement fines and the longer for reinforcement in the final cured product. As the elementary layer forms, hydrostatic pressure causes the slurry to be filtered through the sieves into center of the drum as solids are removed. The filtered fluid is returned to the mixing tank for recycle, while the asbestos-cement layer is held by the rotating drum until it is transferred to a moving fabric belt. If more than one vat is employed, layers are plied on one another as the belt passes. Suction is applied to the reverse side of the belt to dewater the cement layers, which then are transferred to a large accumulator roll; the roll builds up layers until a desired thickness is achieved. At this point, a knife is used to cut the roll into sheets. (If pipe is desired, the roll of product can be removed and a new mandrel inserted in an automated process.)

"Green" asbestos-cement sheets can be further shaped, cut or otherwise processed. For example, a sheet may be individually pressed (to achieve better properties such as higher flexural strength), stack pressed between steel divider sheets, corrugated, embossed, or even hand molded into accessories such as the peak of a roof or a downspout pipe. Once the final shape is obtained, the green product is cured before shipping and ultimate use. Final product properties depend on whether the high cement content/ambient cure or silica-cement/autoclave cure has been employed. In general, the higher cement/ambient cured products have higher flexural strengths, whereas the silica-cement/autoclave cured products have better dimensional stability.

Health Concerns with Asbestos-Cement Products

Although enormously successful throughout the 20th Century, the validity of asbestos-cement products began to be seriously doubted because of health concerns (Gilson, 1972). These problems are well known because of the anti-asbestos legislation that ensued. In the U.S.A., for example, asbestos will be phased out completely by 1997. Also, more recently, health concerns have been extended to the fine silica used in autoclaving (Westerholm, et al, 1986). In any case, the asbestos health concerns of the 1970's caused major asbestos-cement producers worldwide, e.g., the Swiss and Belgium Eternit groups, Dansk Eternit in Denmark, James Hardie in Australia, and others to earnestly seek alternative fibers. Collaborations with fiber producers, such as Kuraray in Japan, Hoechst in Germany and Du Pont in the U.S.A., followed initial scouting studies. Much of the details of this work is still considered proprietary and has not been published or discussed openly. Fortunately, however, a sufficient amount has been published to provide a useful overview of the state of the art.

Problems with Replacing Asbestos

In order to understand the difficulties encountered with trying to replace asbestos, it is important to understand the properties of asbestos and its function in the cement matrix. Asbestos fibers are very strong and stiff (Table 1) whereas cement paste is relatively weak, especially in tension or flexure. The abundant tensile strength of asbestos is put to good use in the cement composite and makes up for an inherent defect in cement. Another important property of asbestos is to act as a filter fiber in the Hatschek process. The smallest of cement fines must be trapped on the sieve for transfer to the belt in the Hatschek process. Otherwise, they will accumulate in the water that is returned for recycle. The trade uses the term "dead" to describe cement that has lost its ability to hydrate because it has been recycled too many times through the process before getting incorporated into the product. Fine asbestos fibers are included in the recipe to trap cement fines before they die. Compare, for example, the retention of solids for asbestos fiber vs. other filter fibers (Figure 2, after K. Saimen, Kuraray, quoted with permission in Gale, 1990-Milan). Note that asbestos is particularly effective at trapping solids at low flocculent concentrations; this is because asbestos usually carries both positive and negative charges as measured by zeta-potentials, and so is self-flocculating.

In addition to imparting strength and retaining cement fines, asbestos is chemically inert and a close relative of calcium silicate, the major chemical species in Type I Portland cement. Most asbestos fibers are largely magnesium and aluminum silicates. Because of its inertness and natural compatibility, asbestos-cement products have served in weathering environments for decades without being replaced. Indeed the only drawback to the product prior to discovery of the health issue, is that asbestos-cement products have lower than desired toughness. Also, embrittlement increases with age and sometimes weakens structures with fatal results.

In summary, although asbestos-cement products would be more desirable if they were tougher, the major needs of a replacement product are strength, cement retention and durability. In order to meet these major needs, most

formulations use more than one fibrous ingredient to replace asbestos. This paper will focus on formulations that employ synthetic fibers and are used for ambient cure products. Since most synthetic fibers can not survive at full strength in the highly alkali environment of cement during an autoclave cure, commercial systems using synthetics tend to be limited to ambient cure products. Where installed autoclaves are available as part of an existing asbestos plant, the usual course of action in converting away from asbestos is to install a cellulose-cement process. These products do not contain synthetic fibers.

Typical Formulations Using Synthetics

Today, most commercial systems that use synthetic fibers to replace asbestos use a reinforcing fiber, most usually polyvinyl alcohol (PVA) or acrylic (polyacrylonitrile, PAN) and to a lesser extent polypropylene (PP), and one or more filter fibers, most usually a combination of refined wood cellulose and a polyethylene pulp (PE pulp). For the reinforcing fibers, a special high strength, high modulus grade is preferred. The exact percentages of these ingredients tend to be held in secret by the manufactures, but a typical formulation might contain 2% of reinforcing fiber and 4% of the filter fiber combination. The rest of the formulation can be Portland cement or a mixture of mostly Portland cement and locally available fillers, e.g., fly-ash, mineral wools, sand, limestone, gypsum, etc. Fumed (microscopic) silica is sometime used to control the moisture content of the green cement product and/or to improve fiber-matrix adhesion. In most cases, only modest modifications of commercial Hatschek asbestos-cement equipment is required, however, asbestos-free systems tend to run slower. Also, it is usually necessary to use a dispersant to help open the fibers in the mixing tank and then a flocculent to coagulate the fibers and cement fines in the vat prior to being filtered by the sieve roll. One filter fiber, a molecularly oriented polyethylene pulp, has been reported as having both reinforcement and filter fiber characteristics (Gale, et al, 1990-ACI, 1990-Milan, 1990-Lyon).

In addition to the commercial formulations discussed above, many synthetic fibers have been studied in connection with asbestos replacement (Studinka, 1986 and 1989; Zhou, 1986; Okuda, 1986; Miko, et al, 1986; Hikasa, et al, 1986; Haehne, 1986; Gale, et al, 1986; Koenig, 1987). In addition to those already discussed, synthetic reinforcing fibers studied are carbon, aramid, nylon-66, polyethylene (PE), polyester and rayon. Additional filter fibers include polypropylene and acrylic pulps. In discussing the advantages and disadvantages of various synthetic reinforcing fiber ingredients, the authors cited do not always agree. For example, concerning the alkali stability of polyester fibers, Studinka (1989), Hikasa (1986) and Gale (1986) consider it poor, whereas Zhou (1986) considers it good. But for the most part, the authors do tend to agree. A consensus listing is offered (Table 2). Significant differences in opinion are indicated by the code "NC" for "no consensus." The table format is taken from Studinka (1989). Note that fiber form can effect fiber properties and hence its function in cement. For example, polyethylene staple fiber (generally has a round cross-section) has generally poor adhesion, where as pulp forms of polyethylene have good adhesion owing to the irregular shapes in pulps that promote mechanical adhesion.

Cement Product Properties

Asbestos-free cement product properties can be varied considerably by controlling the amount of Portland cement vs. inert fillers, the amount of fibers, their type, the treatment of the green cement product prior to cure, for example, whether or not it is pressed. And, if it is pressed in the green state, the conditions of pressing can markedly control properties. For this reason, generalizations stated herein should not be relied on without experimental verification.

In comparing ambient-cured asbestos-free cement products to those containing asbestos, the asbestos-free products will tend to have lower tensile or flexural strength and higher elongation-at-break or toughness. Pressed products will tend to have higher properties vs. unpressed, the better properties associated with higher densities. Thinner products will tend to have higher strengths than the identical product in thicker form. The range of properties expected in synthetic fiber reinforced cement products tends to be in the higher grade range as defined by ASTM Standards. Typical properties for synthetic systems are given in Table 3 (after Gale et al, 1990-ACI).

ASTM Standards and Test Methods

ASTM Committee C-17 has recently set detailed specifications for flat asbestos-free sheets (C 1186), along with test methods for strength and durability (C 1185). Four different grades of product, with flexural strength that varies from Grade I at 580 psi (4 MPa) to Grade IV at 2610 psi (18 MPa) wet strength, or 580 to 3190 psi (22 MPa) equilibrium strength, respectively. The flexural strength referred to is not an average strength, but a more statistically significant 4% acceptable quality level (AQL) at 90% confidence; in other words, no more than 4% of specimens in a specified number tested can have strengths lower than the minimum strengths indicated to make the specified grade. Flexural strength of asbestos-free thin section products are measured by 3-point bending and not the normal third (or 4-point) bending used in most concrete standards. The main reason for this is that industry has used this method for many years and all previous asbestos-cement standards use 3-point bending.

Supplementary requirements on moisture movement, water absorption, moisture content, water tightness, frost resistance, warm water resistance and heat/rain resistance are included for sheets intended for exterior applications. These supplementary requirements are intended to provide a measure of long term durability.

Durability

While some asbestos-cement products have been in service since the turn of the century, synthetic fiber reinforced products are relatively new so that anecdotal information concerning long term durability in the field is not readily available. In addition to tests provided in the new ASTM standards, and the expert opinions found in brief tables or in general discussions referenced above,

a few fuller reports have appeared outside commercial trade bulletins. Akers et al (1989) discuss the long term durability of PVA reinforcing fibers in cement, and relate accelerated tests to fibers extracted after up to 7 years in the cement composite. While loss in tensile strength is noted, the authors conclude that it appears that the PVA fibers are adequately durable. Hachne (1986) studied the alkali resistance of PAN fibers in pH 12 alkali media. He found a 10% decrease in tensile strength, and 15% loss in elastic modulus in the first few months of a 12 month test under ambient conditions. However, the loss in properties leveled off, so it was concluded that the fiber has adequate durability. Gale et al (1990-ACI) studied the durability of cement products reinforced with an oriented PE pulp using accelerated tests. Retention of composite properties was reported as excellent, consistent with the known alkali stability of PE. Keer (1990) studied the property retention of PP (network) reinforced cement and predicted at least a 30 year lifetime. Ando et al (1990) reports excellent retention of properties for carbon fiber reinforced cement composites based on freeze-thaw and hot water accelerated tests.

Applications

Typical applications for fiber-cement products are roofing (slates and corrugated), siding, clapboards, fascia, backer-board, high pressure water pipes, drain pipes, and sewer pipes.

Asbestos-cement products are useful in both sheet and pipes. In substituting asbestos, synthetic fiber reinforced systems have been generally successful (Studinka, 1986 and 1989). High pressure pipes, where the combined requirements of high hoop strengths and low cost are not easily met, have no asbestos-free equivalents. Also, for pressure pipes, crack-free performance is required to prevent leaks. For this reason, first crack stress must be high. With asbestos cement, first crack and ultimate stresses are almost indistinguishable (Hannant, 1976), whereas for synthetic reinforced systems, first crack stresses are generally less than ultimate. In practical terms, high fiber loadings are required to raise first crack stresses, and this becomes too costly.

In summary, to date, synthetic systems have been successful in replacing most asbestos-cement systems, sheets, such as roofing, siding, fascia, clapboards, backer-boards, and low pressure pipes, such as drain and sewer pipes. High pressure pipes, such as water pipes, however, are not currently found in non-asbestos compositions.

References

Akers, S. A. S., Studinka, J. B., Meier, P., Dobbt, M. G., Johnson, D. J., and J. Hikasa, "Long Term Durability of PVA Reinforcing Fibers in a Cement Matrix," *The International Journal of Cement Composites and Lightweight Concrete*, Vol. 11, No. 2, pp 79-91 (1989).

Coutts, R. S. P., Michell, A. J., "Wood Pulp Fiber-Cement Composites, J. Applied Polymer Science: Applied Polymer Symp. 37, pp 829-844 (1983).



Gale, D. M., "Oriented Polyethylene Pulp for Asbestos Replacement in Asbestos-Cement Building Products," Progetto Finalizzato Edilizia, Composite Material in Building, State of the Art, Research and Prospects, Consiglio Nazionale Delle Ricerche, Milan, Italy, pp 115-119 (1990).

Gale, D. M., Guckert, J. R., and Shelburne, S. S., "Oriented Polyethylene Pulp For Asbestos Replacement in Cement Building Products," Textile Composites in Building Construction, Part 1, pp 47-56 Pluralis, Lyon, France (1990).

Gale, D. M., Shah, A. H., and Balaguru, P., "Oriented Polyethylene Fibrous Pulp Reinforced Cement Composites," pp 61-77, ACI Publication SP-124-4 (1990).

Gilson, J. C., "Health Hazards of Asbestos," Composites, Vol 3. No. 2, pp 57-59 (1972).

Haehne, H., "High Tenacity Acrylic Fibres for Composites," 25th International Man-Made Fibres Congress, Dornbirn, Austria September 24-26, (1986).

Hannant, D. J., "Fibre Cements and Fiber Concretes," Chap. 2-4, John Wiley & Sons, Ltd., (1978).

Hikasa, J., Genba, T., Mizobe, A., Okazaki, M., "Replacement for Asbestos in Reinforced Cement Products - Kuralon' PVA Fibres, Properties, Structure," 25th International Man-Made Fibres Congress, Dornbirn, Austria, September 24-26 (1986).

Keer, J. G., "Performance of Non-Asbestos Fiber Cement Sheeting," ACI Publication SP-124-2, pp 19-38 (1990).

Koenig, G., Haehne, H. and Woerner, J. D., "Behaviour and Applications of Polyacrylonitrile Fibre-Concrete," International Rilem Congress, Versailles and Paris, France, September 9 (1978).

Miko, H. J. and Kirchmayr, K., "Effects of Various Fibre Types in Cement-Bonded Composite Materials," 25th International Man-Made Fibres Congress, Dornbirn, Austria, September 24-26, (1986).

Okuda, K., "Production, Property and Application of Carbon Fibres From Pitch," 25th International Man-Made Fibres Congress, Dornbirn, Austria, September 24-26 (1986).

Studinka, J. B., "Replacement of Asbestos in the Fiber Cement Industry - State of Substitution, Experience Up to Now," 25th International Man-Made Fibres Congress, Dornbirn, Austria September 24-26, (1986).

Studinka, J. B., "Asbestos Substitution in the Fibre Cement Industry," The International Journal of Cement Composites and Lightweight Concrete, Vol. 11, No. 2, pp 73-78 (1989).

Vinson, K. D., and Daniel, J. I., Specialty Cellulose Fibers for Cement Reinforcement, pp 1-18 ACI Publication SP-124-1 (1990).

Westerholm, P., et al., "Silicosis and the Risk of Lung Cancer or Lung Tuberculosis: A Cohort Study," Environmental Research, Vol. 41, No. 1, pp 339-350 (1986).

Zhou, Z., "High-Tenacity PVA Fibres, A Suitable Alternative for Asbestos," 25th International Man-Made Fibres Congress, Dornbirn, Austria, September 24-26, (1986).

TABLE 1 — MECHANICAL PROPERTIES OF ORDINARY PORTLAND CEMENT PASTE, MORTAR, ASBESTOS CEMENT AND CHRYSOTILE ASBESTOS (STUDINKA, 1989; HANNANT, 1978)

	Flexural Strength, MPa	Tensile Strength, MPa	Elastic Modulus, GPa	Tensile Strain to Failure, %
Cement Paste	7-8	3-6	15	0.01-0.05
Cement Mortar	---	2-4	25-35	-----
Asbestos Cement	30-40	17-20	28-35	0.4-0.5
Chrysotile Asbestos	---	200-3600	150-164	0.1-3.0

TABLE 2 — SYNTHETIC FIBERS FOR ASBESTOS REPLACEMENT: PROPERTIES OF VARIOUS REINFORCING FIBERS USED FOR CEMENT REINFORCEMENT (CONSENSUS OF MANY AUTHORS)

	Tensile Strength, MPa	Tensile Modulus, GPa	Tensile Strain, %	Fiber Diameter, micron	Adhesion to Matrix, relative	Alkali Stability, relative
Asbestos	600-3600	69-150	0.1-0.3	0.02-30	excellent	excellent
Carbon	590-3000	30-500	<1-2	8-18	poor	excellent
Aramid	2700	62-130	3-4	11-12	fair	good
PP	200-700	0.5-9.8	10-15	10-150	poor	excellent
Polyamide	700-1000	3.9-~6	~15	10-50	good	NC
Polyester	800-1300	up to 15	8-20	10-50	fair	NC
Rayon	450-1100	up to 11	7-15	10-50	good	fair
PVA	1150-1470	21-36	15	4-14	good	good
PAN	850-1000	17-18	9	19	good	good
PE	400	2-4	100-400	40	poor	excellent
PE pulp (oriented)	---	---	---	1-20	good	excellent

TABLE 3 — TYPICAL PROPERTIES OF SYNTHETIC FIBER REINFORCED CEMENT VERSUS OTHER REINFORCED CEMENT PRODUCTS

Cement Product	Flexural Strength, MPa (1)	Flexural Toughness, KJ/sq m (2)
2.0 wt % PAN and 2.5 wt % Oriented PE Pulp	28.0	0.92
2.0 wt % PVA and 2.5 wt % Oriented PE Pulp	23.7	2.44
Commercial Asbestos (Ambient Cure)	30.2	0.19
Commercial Asbestos (Autoclaved)	14.1	0.06
Commercial Cellulose (Autoclaved)	13.5	0.78

- (1) Ultimate flexural strength (modulus of rupture) in 3-point bending.
- (2) Area under load-deflection curve to point of maximum stress, divided by the cross-sectional area of the specimen.

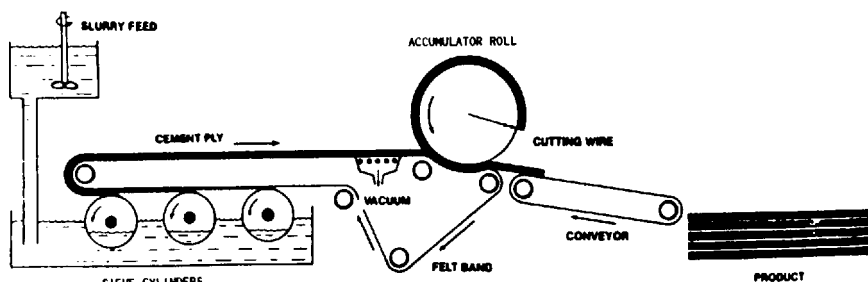


Fig. 1—The Hatschek Process for the manufacture of fiber-cement sheets

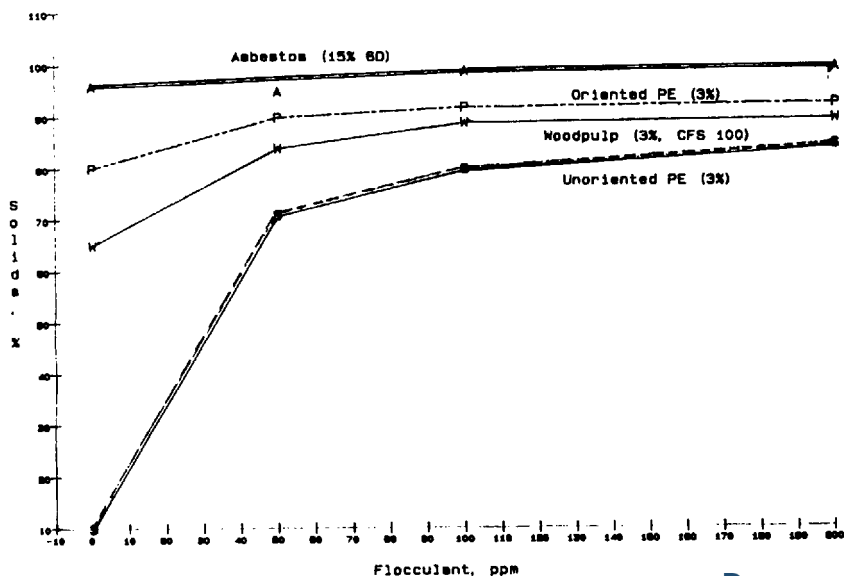


Fig. 2—Retention of cement fines

SP 146-2

Flexural Behavior of Micro Fiber Reinforced Cement Composites

by P. Balaguru

Synopsis: Results of an experimental investigation on the behavior of a cement composite reinforced with short (micro) fibers are presented. The primary response variable was flexural behavior measured in terms of modulus of rupture and toughness index. The independent variables were: fiber content, addition of silica fume, cement: sand ratio, specimen size and casting procedure. Most of the specimens were cast using spray up (shotcreting) process. The results indicate the following trends. The micro fibers can be used to increase flexural strength in rich cement mortars. The fibers do not provide significant increase in strength but provide improved ductility. The addition of silica fume improves the fiber performance. Fibers are more effective on thinner sections. The author believes that the properties of the composite can be considerably improved by removing the excess water and entrapped air by applying external pressure during the manufacturing process.

Keywords: Cements; composite materials; ductility; fiber reinforced concretes; fibers; flexural strength; micro-fibers; placing; sands; shotcrete; silica fume; strength

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INTRODUCTION

When the use of asbestos fibers were restricted for health reasons, researchers around the world started investigating the various types of fibers for asbestos replacement. In the case of thin sheet products, polymeric fibers were preferred because of their low unit weight and non-rusting characteristics. Extensive discussion of the usefulness of the various types of fibers can be found in Ref 1. The following are the basic variables that were evaluated.

Matrix composition: cement, cement and sand, cement and silica fume, cement and fly ash, cement mortar with fly ash or silica fume.

Fiber Material: aramid, nylon, polyethylene, polypropylene, polyvinyl alcohol, polyester, glass, cellulose, and other naturally occurring fibers.

Fiber Type: meshes, fabrics, films, and discrete fibers

Fiber volume fraction: 3 to 18 percent

Casting Process: normal casting using a mold, filtration of preplaced fibers, spray-up process, and casting under pressure (Hatchek process)

The results indicate that the aforementioned fibers can be utilized to improve the strength and ductility of cement composites. However, the industrial use is not highly successful. The primary concerns seem to be fire resistance which also interferes with manufacturing using autoclaving methods, durability of certain fibers, and economy. The search for the replacement of asbestos fibers is still continuing.

This paper presents the results of an experimental investigation on the use of micro (length varies from a fraction of a mm to a few mm and diameters in microns) fibers in cement composites. Since flexure is the primary mode of loading in actual applications most of the tests were conducted using beam specimens. Only the flexural test results are presented in this paper.

EXPERIMENTAL PROGRAM

The experimental program was designed to study the effect of the following basic parameters: (i) matrix composition, (ii) fiber content, (iii) specimen thickness, and (iv) manufacturing technique. The various mix proportions are presented in Tables 1 to 3. Mixes A to D were cast using spray up process. Mixes CA were cast using a mold. A few specimens were also cast using external pressure. Series A and B, designed to study the influence of fiber content, had a cement: sand ratio of 1:3.5 with fiber contents varying from 0.5 to 4 percent. Series C and D were designed to study the influence of cement: sand ratio. Sprayed-up specimens were either 1.5 in. (38 mm) or 3 in. (76 mm) thick. The cast-in mold specimens were 0.5 in (13 mm) thick.

MATERIALS, MIX PROPORTIONS, AND SPECIMEN PREPARATION

The materials consisted of ASTM Type I portland cement, concrete sand, silica fume in powder form, tap water and micro fibers. The mix proportions are presented in Tables 1 to 3. The batching was on the weight basis. The ratio of fiber: silica fume was 1:3 for all the mixes containing silica fume.

Silica fume was blended with fibers before adding them to cement-sand mixture. The sprayed-up specimens were cast using dry shotcrete method. Two sets of slabs that were 1.5 and 3 in. thick (38 and 76 mm) were shotcreted. Since water was added at the nozzle, exact water/cement ratio could not be determined. All the specimens were moist cured for 28 days. Bending specimens with cross-sections of 3 x 3 in. (76 x 76 mm) and 3 x 1.5 in. (76 x 38 mm) were cut from the 3 and 1.5 in. (76 and 38 mm) thick slabs. All the specimens were 14 in. (354 mm) long.

TEST METHODS

Samples were tested for load-deflection behavior in flexure. Densities of hardened composites were also measured.

The flexure test was conducted by loading the prisms at third points over a simply supported span of 12 in. (300 mm), using MTS testing machine with servo control. The load-deflection curves were recorded using a x-y recorder. These curves were used to compute the modulus of rupture and toughness indices. Three specimens were tested for each test variable.

TEST RESULTS AND DISCUSSION

Density

Variation of densities measured in saturated surface dry condition, is shown in Fig. 1 for series A and B specimens.

- ° In general, density decreases with increase in fiber content.
- ° The density of about 2.1 at 0.5% fiber content is a little lower than the normal weight concrete density of about 2.2. The density decreases to as low as 1.6 at 4% fiber content.
- ° Samples with silica fume had a lower density than the samples without silica fume except at 4% fiber content.

Modulus of Rupture and Toughness

Modulus of rupture results are presented in Fig. 2 to 7. Fig. 2, 3, and 4 present the results for specimens cast using a mold. Fig. 2 shows the variation of modulus of rupture with respect to fiber content for specimens that contained no sand. Fig. 3 and 4 show the influence of sand content for fiber contents of 1 and 2%. Fig. 5, 6, and 7 representing specimens cast using spray-up process show the influence of fiber content, silica fume, and sand content. In addition, these figures also show the influence of specimen size.

The toughness indices were computed using the ASTM C-1018 procedure [2]. The toughness index I_5 was computed using the equation:

$$I_5 = \frac{\text{Area under the load-deflection curve up to a deflection of 3}}{\text{Area under the load-deflection curve up to the first crack deflection,}} \quad (1)$$

The toughness results for the sprayed-up specimens are shown in Fig. 8, 9, and 10. Fig. 8 shows the influence of fiber content where as Fig. 9 and 10 show the influence of silica fume and sand content. The corresponding modulus variations are shown in Fig. 5, 6 and 7 respectively. The specimens that were cast using mod and plain cement did not show improvement in toughness up to a fiber content of 1.5%. The values were less than 1.5. At a fiber content of 2%, I_5 was 4.9. There seems to be a critical minimum fiber content below which, the beams fail in a brittle mode. When sand was added, the ductility improved. For a fiber content of 1%, the I_5 values were 1.3, 4.1, and 4.2 for cement: Sand ratios of 1:0, 1:0.5, and 1:1 respectively. The corresponding strength variations are shown in Fig. 3.

Based on the results presented in Fig. 2 to 10, observations during the casting and testing of specimens, the following observations can be made. The discussion is divided into three parts dealing with: cast-specimens, sprayed-up specimens, and their comparative behavior.

Cast Specimens

- For specimens containing no sand, the modulus of rupture is higher for a fiber content of 1.0% as compared to specimens with 0.5% fiber content, Fig. 2. Further increase in fiber content results in decrease in modulus. The author believes that this reduction is due to difficulties in consolidation rather than the increase of fiber content. The mixes containing higher fiber contents typically had more entrapped air and were difficult to consolidate. This was confirmed by the reduction in density with increase in fiber content. Fiber dispersion was also a problem at higher fiber contents.

- Addition of sand resulted in a consistent decrease in flexural strength for the fiber content of 1%, Fig. 3. However for a fiber content of 2%, the strength was the highest for Cement:Sand ratio of 1.0:0.5, Fig. 4. The strength for Cement: Sand ratio of 1.0:1.0 was lower than for 1.0:0.5 ratio, but higher than the mix with no sand. The mixes containing sand were easier to mix and consolidate during the casting process. This might have influenced the strength increase for the mixes with sand.

- For mixes with sand, the modulus was higher for 2% fiber content as compared to 1% fiber for both the Cement:Sand ratios whereas the modulus decreased for the mix with no sand.

- Based on the results obtained in this investigation it can be said that a mortar mix will provide better strength results than cement paste mix, if the consolidation is done by just vibration. If the consolidation is done under pressure, thus removing entrapped air and the excess water, the cement paste provide better strengths [1,3].

- As mentioned earlier, a minimum fiber content of 2% is needed to obtain significant improvement in ductility for mixes with no sand. Mortar mixes provided better ductility at fiber contents of 1 and 2%. Difficulties in obtaining good consolidation and the brittle nature of the cement paste could have contributed to the better performance of mortar mixes.

Sprayed-Up Specimens

- Addition of silica fume typically increased the modulus of rupture, Figs. 5 and 6. Increase in fiber content lead to a general reduction in strength for both mixes (with and without silica fume). Here again, it is suspected that mixes with more fibers have more entrapped air and lower consolidation. The reduction in density shown in Fig. 1 support this observation.

- For mixes with no silica fume, modulus consistently decreased with increase in sand content. For a fiber content of 2%, the modulus decreases from about 1000 psi (6.9MPa) for the paste to about 700 psi (4.8 MPa) for the mortar with Cement:Sand ratio of 1:3.5, Fig. 6 and 7. The decrease is not significant between the paste and the mortar for Cement:Sand ratio of 1:1. The mortar mix could have better shrinkage characteristics because of the presence of sand. Hence, this mix is more preferable for field use than the cement paste.

- For mixes that had silica fume, the decrease in modulus was not significant up to a Cement:Sand ratio of 1:2, Fig. 7.

- In general 1.5 in. (38 mm) specimens had a higher modulus of rupture than 3.0 in. (76 mm) specimens. The magnitude of difference did not show any consistent pattern.

- Toughness values increased consistently with increase in fiber content in all cases, Fig. 8 and 9. Mixes with silica fume had higher toughness than mixes without silica fume. The magnitude of difference increased with increase in fiber content. This was evident for all mixes with and without sand, Fig. 8, 9 and 10.

- For the fabrication technique used, a minimum of 2% fiber content is needed to produce considerable toughness. This could be changed by pressing the specimens to remove excess water.

- There was considerable difference in toughness between 1.5 in. (38 mm) and 3.0 in. (76 mm) specimens. Thinner specimens recorded higher toughness values in all cases. The magnitude of difference was more for mixes with silica fume. Thinner specimens can undergo larger deflections for the same maximum strain (strain at the extreme tension face). Since the micro fibers used in this investigation can sustain only limited amount strain at the crack before failure, the above phenomena should be expected. Better bond (in the case of silica fume mix) between matrix and fiber magnifies the difference because most fibers fracture rather than pull-out, thus further reducing the strain capacity at the extreme tension face.

Comparison of Cast and Sprayed-Up Specimens

Specimens made using spray-up process resulted in better modulus and toughness characteristics as compared specimens cast using a mold. The author believes that the sprayed-up process resulted in a better compaction. It is also possible that the longer fibers align themselves along the length. It was difficult to consolidate the specimens using the vibration. The cement paste specimens were the toughest to consolidate. It may not be possible to use plain cement paste for industrial production without some mechanism for good consolidation and possibly removal of excess air.

CONCLUSIONS

Micro fibers can be used to improve the toughness characteristics of cement paste and mortar. The method of production plays an important role in the behavior of the composite. Spray-up process provided better results than standard casting using molds. The author believes the properties of the composite can be further improved by removing the excess water and entrapped air.

For processing techniques used in this investigation, increase in fiber content lead to decrease in density, decrease in modulus of rupture and increase in toughness. A minimum of 2% fiber content is needed to obtain significant toughness.

Thinner specimens (1.5 in., 38 mm thick) exhibited higher toughness than the thicker (3 in., 76 mm thick) specimens. The magnitude of difference was more for mixes with silica fume. In most cases, modulus of rupture was also higher for thinner specimens. The magnitude of difference was more significant in the case of toughness than the strength.

Mortar mixes with Cement:Sand ratios up to 1:2, behaved very much similar to cement paste specimens. Cement:Sand ratio of 1:3.5 resulted in about 30% strength reduction. Addition of sand did not affect the toughness values.

REFERENCES

1. Balaguru, P., and Shah, S. P., Fiber Reinforced Cement Composites, McGraw-Hill, 1992, 530 pp.
2. ASTM, Annual Book of ASTM Standards, Vol. 04.02, Concrete and Mineral Aggregates, 1992.
3. Gale, D. M., Shah, A. H., and Balaguru, P., "Pulplus (TM) Oriented Polyethylene Pulp as Reinforcing Agent in Thin Section Fiber Cement Products", American Concrete Institute Special Publication, SP-124, 1990, pp. 61-77.

TABLE 1 — MIX PROPORTIONS: GROUPS A AND B

Mix Designation	Fiber Content ¹	Silica fume Content ²	Cement: Sand Ratio
A1	4	12	1:3.5
A2	3	9	1:3.5
A3	2	6	1:3.5
A4	1	3	1:3.5
A5	0.5	1.5	1:3.5
B1	4		1:3.5
B2	3		1:3.5
B3	2		1:3.5
B4	1		1:3.5
B5	0.5		1:3.5

¹Percentage by weight of total solids²Percentage by weight of total solids

TABLE 2 — MIX PROPORTIONS: GROUPS C AND D

Mix Designation	Fiber Content ¹	Silica fume Content ²	Cement: Sand Ratio
C1	2	6	1:2
C2	2	6	1:1
C3	2	6	1:0
D1	2	0	1:2
D2	2	0	1:1
D3	2	0	1:0

¹Percentage by weight of total solids²Percentage by weight of total solids

TABLE 3 — MIX PROPORTIONS FOR CAST SPECIMENS

Mix Design- Dosage	Fiber Content %	Silica Fume %	Cement:Sand Ratio	Water C+SF Ratio	Super Plasticizer Dosage %	Air Entraining Agent nation %
CA1	0.5	1.5	---	0.28	3.0	0.15
CA2	1.0	3.0	---	0.28	3.0	0.15
CA3	1.5	4.5	---	0.28	3.0	0.15
CA4	2.0	6.0	---	0.28	3.0	0.15
CA5	1.0	3.0	1:0.5	0.33	3.0	0.10
CA6	2.0	6.0	1:0.5	0.36	3.0	0.10
CA7	1.0	3.0	1:1	0.38	3.0	0.10
CA8	2.0	6.0	1:1	0.44	3.0	0.10

1. Silica Fume = 3.0 x Fiber Content

2. Fiber Content % is with respect to combined total wt. of cement, sand and silica.

3. Admixture content % is with respect to cement weight.

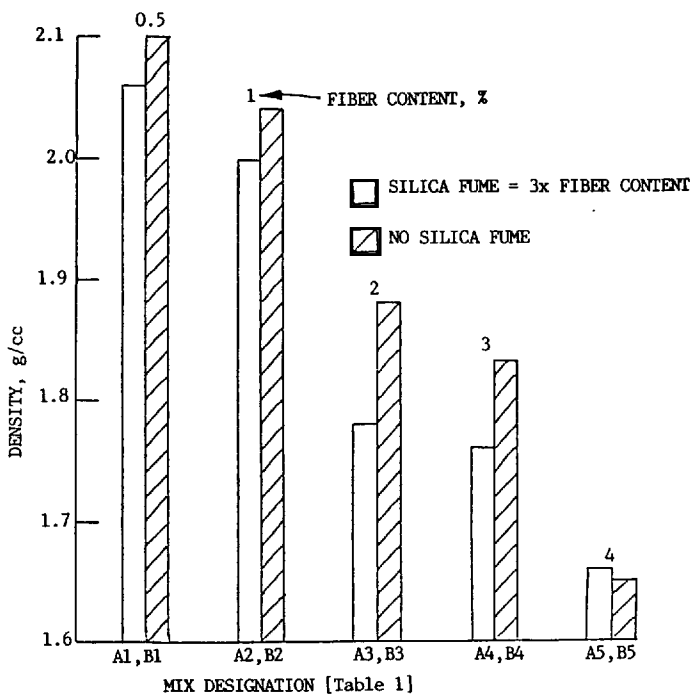


Fig. 1—Variation of density versus fiber content

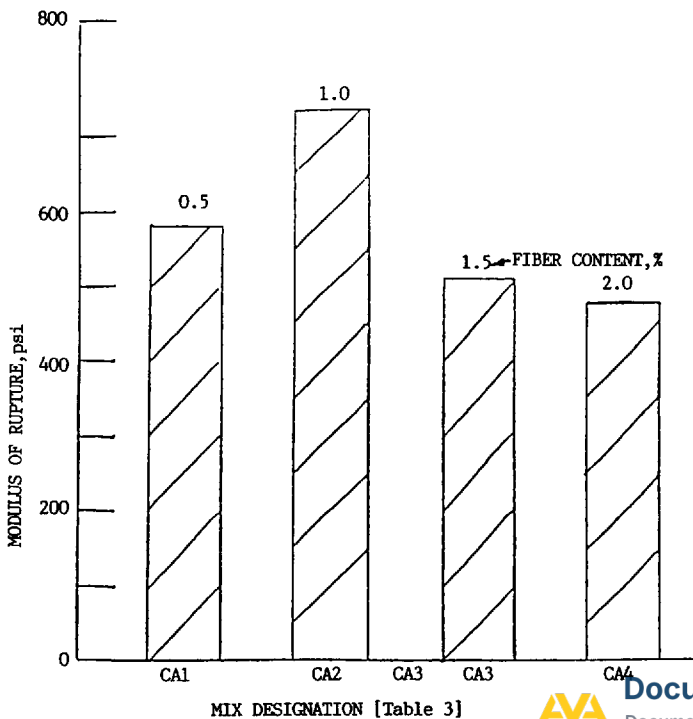


Fig. 2—Modulus of rupture versus fiber content, cast specimens

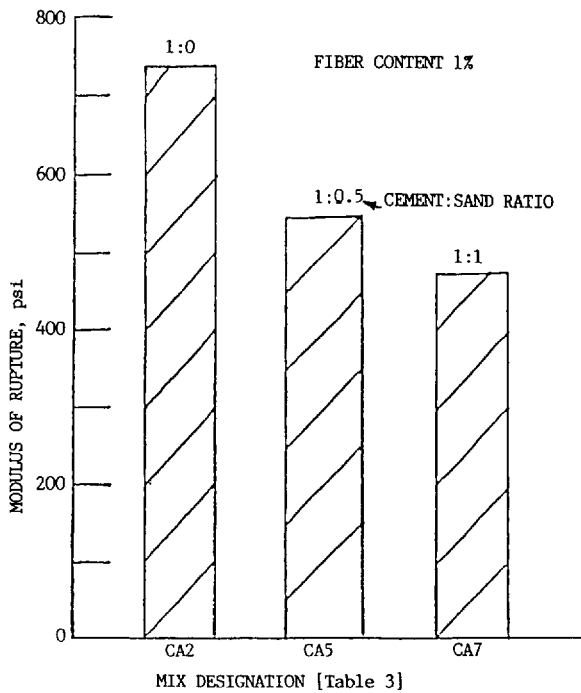


Fig. 3—Modulus of rupture versus cement: sand ratio, cast specimens, fiber content 1 percent

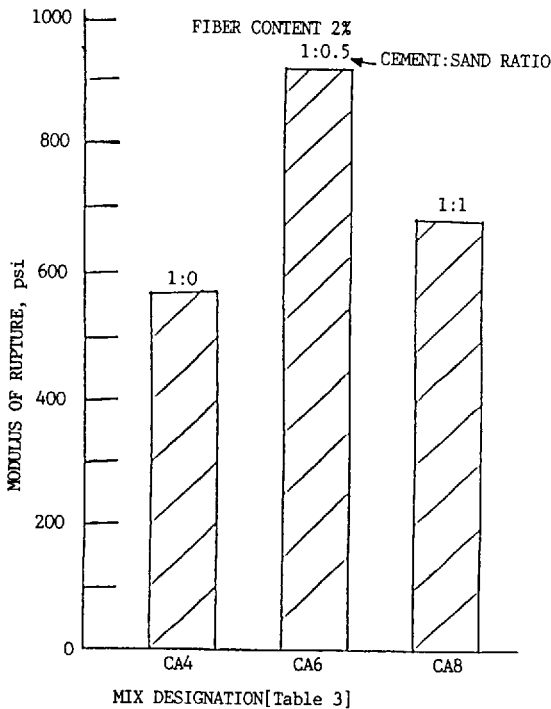


Fig. 4—Modulus of rupture versus cement: sand ratio, cast specimens, fiber content 2 percent

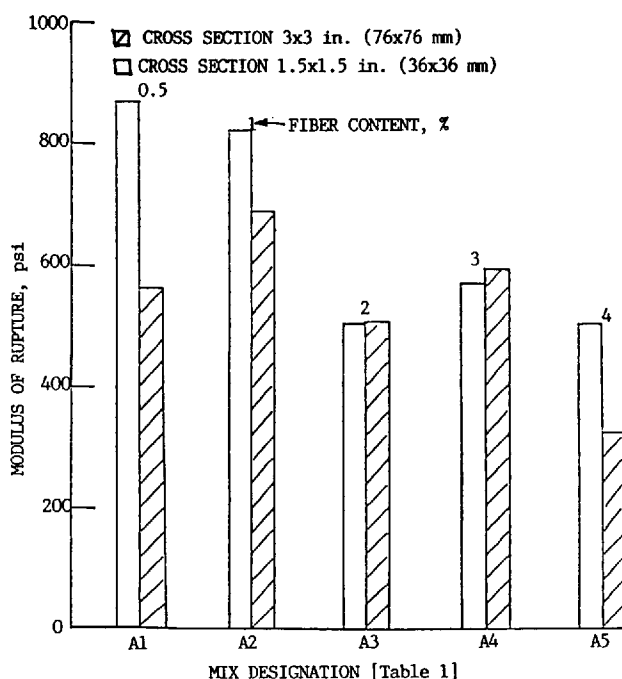


Fig. 5—Modulus of rupture versus fiber content, sprayed-up specimens, with silica fume

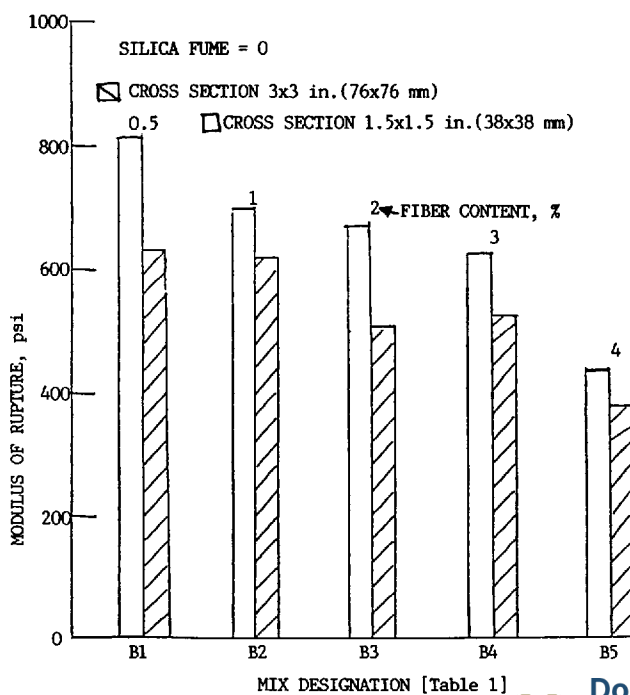


Fig. 6—Modulus of rupture versus fiber content, sprayed-up specimens, no silica fume

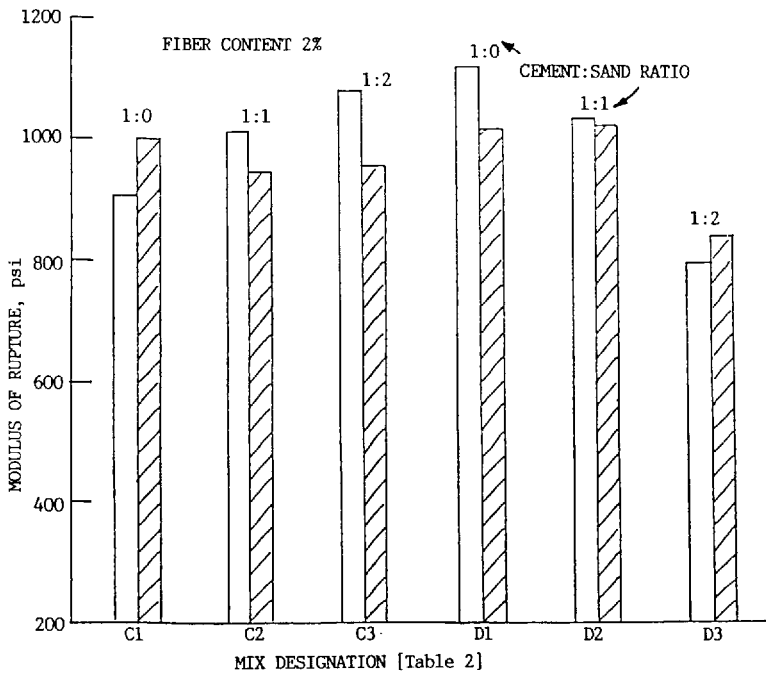


Fig. 7—Modulus of rupture versus cement: sand ratio, sprayed-up specimen, with and without silica fume

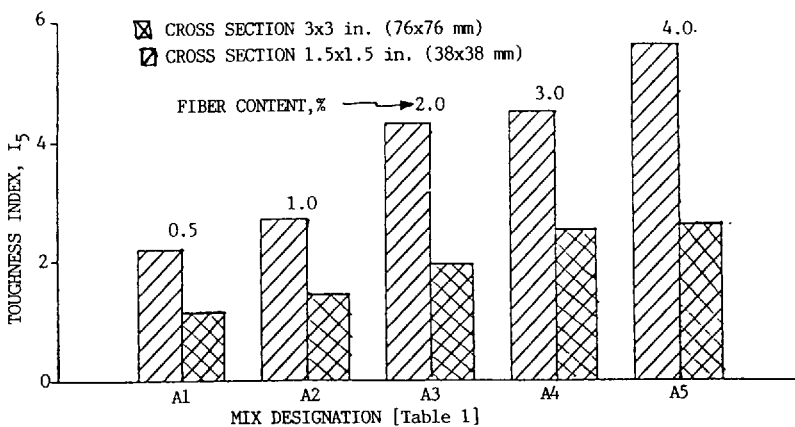
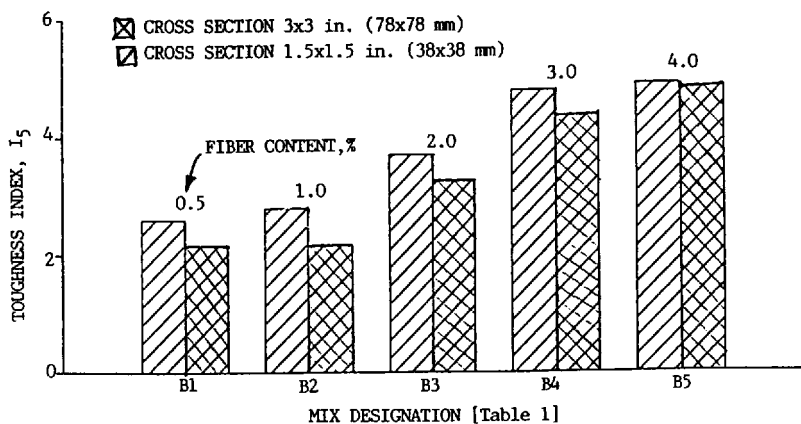
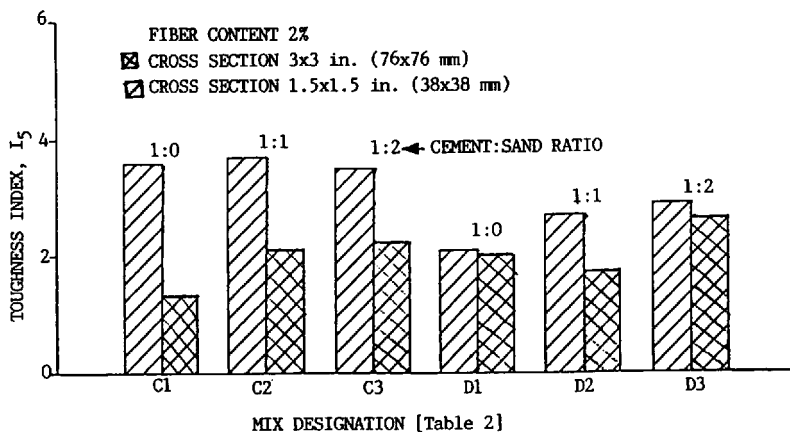


Fig. 8—Toughness index, I_5 versus fiber content, sprayed-up specimens with silica fume

Fig. 9—Toughness index, I_5 versus fiber content, sprayed-up specimens no silica fumeFig. 10—Toughness index, I_5 versus cement: sand ratio, sprayed-up specimens, with and without silica fume

Reinforcement of Thin Cement Products with Wastepaper Fibers

by P. Soroushian, Z. Shah, and S. Marikunte

Synopsis: Potentials of wastepaper fibers for the reinforcement of thin-sheet cement products were investigated. The slurry-dewatering method followed by pressing was used to manufacture the products. The fiber reinforcement conditions, matrix mix composition, and processing variable are being optimized through experimental studies and statistical analyses based on fractional factorial design of experiments and analyses of variance of results. The results are indicative of strong potentials for the recycling of wastepaper for the reinforcement of thin cement products.

Keywords: Absorption; cellulose fibers; composite materials; density (mass/volume); fibers; flexural strength; fracture properties; reinforcing materials; wastepaper; water

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INTRODUCTION

Unreinforced cement-bases materials suffer from one common shortcoming - they fail in a brittle manner under tensile stresses or impact loads. An effective approach to resolve this problem involves the use of cellulose fibers in cement-based materials. The reason why brittle materials like cement are made stronger and tougher by relatively small addition of cellulose fibers is that cracks are stopped or deflected by the presence of fibers and, as a result, the toughness and tensile strength are dramatically increased. Cellulose fiber reinforced cementitious materials, with their desirable toughness characteristics and cracking resistance, have found broad applications in the construction of various thin-sheet products ranging from major components in industrial manufacturing to uses in commercial, residential and agricultural construction (Figure 1). These include siding, soffits and roofing tiles, construction uses as equipment screens, substrate for tiles, utility building cladding, duct lining and air shafts, stair treads and sub-flooring, substrate for laminated panels, window sills, fire resistant paneling, partition components, fencing and sunscreens, poultry houses, farm building siding, and green house panels. Some industrial components made with cellulose fiber reinforced cement include cooling tower elements, heat shields, sound barriers, storage for combustible materials, fire walls, and equipment gaskets.

The global use of thin-sheet fibrous cement products is estimated at 2.5 million tons each year, consuming close to 0.3 million tons of reinforcing fibers annually. The market for fibers in thin cement products was dominated by asbestos

through 1970's and in early 80's. Annual consumption of asbestos for cement reinforcement reached 1.5 million tons of fiber in early 1980's.¹ Usage was principally for factory-made cement cladding panels and pipes produced in some 800-900 manufacturing units operating virtually in every country of the world. Due to the health risk associated with the use of asbestos, virgin cellulose has recently been substituted asbestos in cement products.²

The use of recycled paper as a source of reinforcing fibers for thin-sheet cement products presents an attractive market for wastepaper. Relatively large volumes of different wastepaper grades can potentially replace virgin cellulose fibers currently used by the thin-sheet cement products industry.

VIRGIN CELLULOSE FIBER REINFORCED CEMENT COMPOSITES

Cellulose fibers have been used for many years as an additive in the conventional asbestos cement industry; some of the asbestos cement replacement products also utilize cellulose fibers. In these cases, cellulose fibers contribute mainly processing benefits rather than reinforcement. Recent studies have shown that the reinforcement action of cellulose fibers in cementitious matrices is quite good relative to other fibers such as glass (Figure 2).³

Cellulose fibers derived from softwood and hardwood, being fairly strong and stiff as well as cheap and plentiful with relatively low energy demand, are particularly suited for reinforcement of thin-sheet cement products.^{4,5} They offer the highest performance-to-cost ratio among fibers considered for thin-sheet cement products (Table 1). Cellulose fibers are effective in increasing the fracture energy of cementitious matrices, and also in enhancing the tensile and flexural strength, toughness, and impact resistance of these composites.^{2,3,6} These improvements are achieved mainly through the stopping and deflection of micro-cracks by fibers, and also through the pull-out action of fibers at cracks.⁷ There are, however, concerns regarding the moisture resistance and long-term durability of cellulose fiber-cement composites. Considerable differences in flexural strength and toughness values are observed when the specimens are tested at different moisture contents. High moisture contents tend to damage the fiber-to-matrix bond strength, leading to changes in failure mechanism which seem to cause the trends observed in moisture effects on flexural performance of cellulose cement composites. Recent studies on the aging behavior of cellulose fiber-cement composites in natural and accelerated weathering tests have indicated a small increase in flexural strength and stiffness with aging; however, the aged composites were more brittle than the original cellulose fiber-cement composites. Microstructural studies have shown that petrification of fibers (i.e. filling of the fiber cores with hydration and carbonation products) and densification of interface zone with aging are responsible for the increased

strength and stiffness, and reduced flexural toughness.

RECYCLED CELLULOSE FIBER REINFORCED CEMENT COMPOSITES

The use of recycled magazine and newsprint as source of cellulose fiber for the reinforcement of cement products has been reported by Coutts (1989)⁸ and Hirajima et al (1982)⁹. The main fiber constituents of the wastepaper fiber used by Coutts (1989)⁸ were Kraft pulped *P. radiata* and mixed eucalypts, thermomechanical pulped *P. radiata*, neutral sulphite semichemical pulped mixed eucalypts, and other fiber types present in small amounts in waste products. The distribution of fiber lengths in the wastepaper sample is shown in Table 2 along with data for Kraft *P. radiata* and Kraft *E. regnans* virgin fibers. At least 10,000 fibers were analyzed for the wastepaper and *E. regnans* pulps, and in excess of 5,000 fibers for the *P. radiata* pulp. The wastepaper fiber was treated in the laboratory in a Valley beater. The matrix was prepared from ordinary Portland cement.

Composites were prepared from the wastepaper fibers using different fiber fractions (2 - 16% fiber by mass). In earlier studies of cellulose fiber reinforced cement composites, flexural strength was at a maximum value at about 8 - 10% fiber mass fraction.^{6,10,11} The wastepaper fiber reinforced cement (WPFRC) developed maximum flexural strength of 2,600 psi (18 MPa) at about 12% fiber content by mass, when tested in a controlled atmosphere (Figure 3). The effect of moisture on the samples is to reduce the flexural strength to approximately 47 - 75% of the dry strength (Figure 3). This is in general agreement with the reduction in strength observed with other air-cured wood-fiber reinforced cement composites when tested both wet and dry.^{6,10}

The wastepaper considered by Coutts (1989)⁸ contains softwoods and hardwoods, but these fibers had experienced considerable damage due to processing and recycling as shown by high fines content (Table 2). Much of the damaged material will act more as a filler-diluent than as a reinforcing fiber. The flexural strength increased up to higher than usual fiber loadings before the maximum value was reached at 12% fiber content by mass. This could be due to the fact that much of the short material (say < 0.6 mm) offers little reinforcement to the composite and so a greater mass of fiber must be added to achieve sufficient numbers of the longer reinforcing fibers. The flexural strength values were lower than those of cement composites reinforced with the short *E. regnans* fibers (Figure 3). This might be attributed to the fact that although the numbers of long fibers are sufficient to provide high strength, inefficient fiber packing had already taken place due to the total volume of fibrous material.

A similar shift of the maximum flexural strength value, with respect to fiber content, was noted for *P. radiata* thermomechanical pulp reinforced air-cured cement,¹² the maximum being around 10% by mass. In that instance, the higher fiber content required and the lower flexural strength achieved were related to the lower number of fibers for a given mass (due to the extra mass of extractives not removed during the pulping process).

In addition to reduced fiber length, the altered surface properties of physically and chemically recycled fibers may also influence both the flexural strength and fracture toughness properties of fiber-cement composites.

The mechanisms that take place during the fracture of a composite include fiber breakage and fiber pullout. The latter can have a considerable influence on the value of fracture toughness. If the fiber is short, then the energy used up in pulling the fiber through the matrix after the fiber to matrix bond is broken can contribute little to the dissipation of energy contained in the advancing crack. Therefore, the crack continues to propagate through the sample and the material appears brittle. In Figure 4 a comparison is made between the fracture toughness versus fiber content of wastepaper and *E. regnans* fiber reinforced cements. The *E. regnans* fiber provides fracture toughness values almost twice those of wastepaper fiber at comparable fiber mass fractions. This would confirm the presence of shortened fibers derived from wastepaper. Of course, other factors, such as refining which takes place during paper manufacture, would have an effect on fiber performance; this has been reported elsewhere.¹⁰ Kraft *E. regnans* fiber reinforced cement composites⁶ produce fracture toughness, noting that the average fiber lengths of *E. regnans* and *P. radiata* are approximately 0.04 and 0.1 in (1.0 and 3.2 mm), respectively (Table 2). Although the average fiber length in the wastepaper pulp is 0.07 in (1.9 mm), the amount of fine material 0.02 in (0.6 mm) constitutes almost 28% of the mass of the fiber whereas *P. radiata* and *E. regnans* have values of only 6.6% and 14.8%, respectively (Table 2).

When the wastepaper samples are tested wet, there is the expected increase in fracture toughness value.^{6,11} The increase is, however, very small, never exceeding 40% of the dry value. With *P. radiata* reinforced samples, increase of up to 150% of dry values have been recorded at certain fiber loadings (6-8% by mass).

The physical properties of air-cured cellulose-fiber reinforced cements containing *E. regnans* fibers are compared with those of wastepaper fiber reinforced cement composites in Figure 5. Density, water absorption and porosity are all inter-related in so far as their magnitude depends upon the free space or void volume present in the material. The higher density of wastepaper fiber reinforced cement could be attributed to the ability of the fine fiber fragments to pack more efficiently with the matrix and so to produce fewer voids. This in turn would

account for the lower water absorption of wastepaper fiber reinforced cement compared to the E. regnans reinforced material at any given fiber content.

Hirajima et al. (1982)⁹ have also used refined pulps recovered from municipal solid waste for the production of thin-sheet cement boards. The results showed that there was no need to modify or change the production process adopted for virgin cellulose fibers in the case of newsprint waste utilization as reinforcing fibers. Thin-sheet cement boards produced with wastepaper fibers fulfilled the Japanese specifications. Refined wastepaper pulp proved to be a suitable reinforcing fiber for thin-sheet cement boards.

EXPERIMENTAL DESIGN

This section reviews the experimental program currently in progress on recycling of wastepaper fibers for the reinforcement of thin-sheet cement products.

Variables

Recycled fiber-cement composites are manufactured by: (1) refinement (beating) of recycled wastepaper fibers; (2) proportioning the fibers (recycled & virgin), sand, flocculating agent and cement; (3) mixing the ingredients in water; (4) vacuum dewatering of the slurry; (5) compaction under pressure; and (6) curing of the composite.

Total of 11 variables (factors) are being investigated in this experimental program. These variables are: (1) recycled magazine fiber source; (2) fiber mass fraction; (3) fiber beating level; (4) substitution level of virgin fibers with recycled ones; (5) sand/binder ratio; (6) maximum particle size of sand; (7) silica fume/binder ratio; (8) flocculating agent/binder ratio; (9) vacuum level; (10) compaction pressure; and (11) curing condition. Each factor is considered at two levels in a (1/64) fractional factorial design of experiments. The results will reveal the significance of different variables in deciding the composite material properties. Once the significant variables have been identified. Their optimum levels will be decided in a follow-up experimental study based on the statistical methods of response surface analysis. Recycled magazine paper from two sources were used in the experimental program; both sources produce the recycled fibers through dry processing of magazine papers. Fiber beating level is another key variable. It is measured in Canadian Standard Freeness (CSF) units. The other variable in the experimental program is fiber substitution level, which has two levels of 50% and 100%; at the 50% level, 50% of fibers (by weight) were virgin cellulose fibers and the remaining 50% were recycled fibers. At 100% substitution level, the whole fiber content was recycled magazine fibers.

Silica Sand was used in this study at sand/binder ratios (by weight) of 0.25 and 0.75. Maximum particle sizes of the two silica sands were 50 μm and 600 μm . Cement substitution with silica fume at 0 and 10% was also considered. Flocculating agent was used to improve the binding of cement particles to cellulose fibers and to control escape of cement particles during the vacuum dewatering process. The dosage rates of the flocculent used were 0.2% and 0.6% of binder (by weight).

The vacuum level was also studied as a variable; vacuum was applied at 5 in and 10 in (127 mm and 254 mm) of mercury to the composite to extract the excess water from the slurry. The compaction pressure was another variable considered; the thin cement sheets were pressed (after applying vacuum) at 100 psi and 200 psi (0.7 Mpa and 1.4 Mpa) pressure levels.

Two curing conditions were considered: moist curing and high pressure steam curing. In moist curing, the composites were stored in a moist room for 7 days followed by 21 days of dry curing in the laboratory. In high-pressure curing, an autoclave was used to cure the specimens at a pressure of 125 psi for 8 hours, with specimens subsequently stored in the laboratory environment up to the test age 28 days.

The cement used in this investigation was Portland cement Type I, and the flocculating agent used was an acrylamide acrylate polymer.

Fiber Characteristics

Recycled magazine paper from two sources were used in this investigation together with virgin cellulose fiber (Southern Softwood Kraft - SSK). The recycled fibers showed a larger scatter in fiber length (see Fig. 6), and that had about 20% impurities (e.g., clay). These recycled fibers were produced by dry mechanical processing of magazine wastepaper. The morphology of the unbeaten (unrefined) virgin and recycled fibers was studied under SEM (Scanning Electron Microscope). The unbeaten virgin cellulose fibers have cylindrical shapes while the recycled fibers are flat and twisted. The surface of the virgin cellulose fibers appears to be smooth while the recycled cellulose fibers seem to have microfibrils on their surfaces (see Fig. 7).

Manufacturing Process

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

The mixing procedure for the manufacture of recycled cellulose fiber reinforced cement through slurry dewatering (Fig. 8) was as follow: (1) soak fibers in water for 24 hours and then disperse them using a high-speed mixer for 20 minutes; (2) add other mix constituents and continue mixing for 10 more minutes; (3) add a small quantity of 1% diluted flocculent (flocculent/binder = 0.001) 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 a vacuum box (125 mm x 125 mm, 5 x 5 in) and distribute over the screen (with mild tamping) and apply vacuum of 10 in (254 mm) for 5 minutes; and (5) remove the sheet from the filter screen, store between two plates and apply a constant pressure of 200 psi (1.4 Mpa) for 5 minutes or until all the remaining excess water is removed. The sheets were covered with plastic for 24 hours and then subjected to the curing process.

Test Methods

The flexural test procedures recommended by the Japanese Concrete Institute (JCI-SF) were followed for testing the thin sheet test samples. The flexural test samples had a clear span of 4.5 in (114 mm), width of 1.5 in (38 mm) and thickness of 0.35 in (9 mm). The test set up is shown in Fig. 9. A displacement-controlled flexural test was conducted at a displacement rate of 1/3,000 of span length per minute. A computer-controlled data acquisition was used to get the test data and plot a load-deflection curve. These load-deflection curves can be characterized by flexural strength, flexural toughness (determined by the Japanese Concrete Institute as the area under the load-deflection curve up to a flexural deflection equal to span length divided by 150), and initial stiffness.

EXPERIMENTAL RESULTS

Typical experimental load-deflection curves are shown in Figure 10. Recycled fibers (at 50% and 100% substitution levels) are observed to produce composites with desirable flexural load-deflection characteristics (when compared with composites incorporating 100% virgin fibers). The experimental program based on a frictional factorial design is currently in progress.

One may conclude from the available test data that, through proper proportioning and processing, composites with 50% recycled fibers substituting virgin fibers are capable of producing levels of flexural strength, toughness and stiffness comparable to those obtained with 100% virgin cellulose fibers (control composites). The use of silica fume, finer silica sand and autoclave curing seem to have positive effects on virgin and recycled cellulose fiber-cement composites.

SUMMARY AND CONCLUSIONS

Potentials of recycled fibers derived from wastepaper to substitute virgin cellulose fibers as reinforcement for thin-sheet cement products were investigated through the review of the reported literature and an (on-going) experimental program. The results indicate that satisfactory levels of flexural performance can be reached with cement composites incorporating recycled fibers. Certain proportioning and processing variables may have to be refined in order to achieve the highest level of performance when recycled fibers replace the virgin fibers.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the Michigan Department of Natural Resources (Solid Waste Alternatives Program), the Research Excellence Fund of the State of Michigan, and the U.S. Department of Agriculture (Eastern Hardwood Utilization Program).

REFERENCES

1. Vinson, Kenneth D. and Daniel, James I., "Advances in the Development of Specialty Cellulose Fibers Specifically Designed for the Reinforcement of Cement Matrices, Early Strength of Composites Based upon Ordinary Portland Cement", Paper presented at the 1989 Annual Convention, American Concrete Institute, Atlanta, Georgia, February, 1989, pp. 19-24.
2. Soroushian, P., Suchsland, O. and Marikunte, S., "Cellulose Fiber Reinforced Cement Composites", Proceedings, MSU Concrete Technology Seminar III, Engineering Lifelong Education Program, Michigan State University, February, 1990, pp. 11.1-11.46.
3. Vinson, Kenneth D. and Daniel, James I., "Specialty Cellulose Fibers for Cement Reinforcement", Thin Section Fiber Reinforced Concrete and Ferrocement, American Concrete Institute Publication SP-124, 1990, pp. 99-124.
4. Coutts, R.S.P., "Sticks and Stones", Forest Products Newsletter. CSIRO Division of Chemical and Wood Technology (Australia), Vol. 2, No.1, 1988, pp. 1-4.

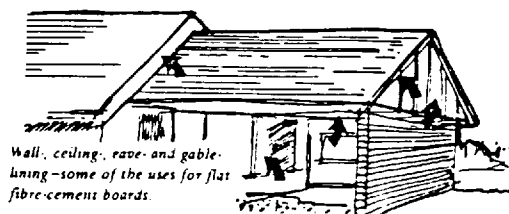
5. CSIRO, "New-A Wood Fiber Cement Building Board", CSIRO Industrial Research News (Australia), 1981, pp. 146.
6. Coutts, R.S.P., "Eucalyptus Wood Fiber Reinforced Cement", Journal of Material Science Letters, Vol. 6, No. 8, August, 1987, pp. 955-957.
7. Coutts, R.S.P., "Wood Fibers in Inorganic Matrices", Chemistry in Australia, Vol. 50, No. 5, May, 1983, pp. 143-148.
8. Coutts, R.S.P., "Wastepaper fibers in cement products", The International Journal of Cement Composites and Lightweight Concrete, Vol. 11, No. 3, August, 1989, pp. 143-147.
9. Hiragima, M., Kago, M., Kobayashi, Y and Matsuo, R., "Research on Manufacture of Pulp Cement Board Using Recovered Pulp From Municipal Solid Waste for Reinforcement (Part II): Batchwise Formation of Pulp Cement Board", Japan Tappi, Vol. 36, No. 5, May, 1982, pp. 557-564.
10. Coutts, R.S.P., "Autoclave beaten wood fiber reinforced cement composites", Composites, Vol. 15, No. 2, April, 1984, pp. 139-143.
11. Coutts, R.S.P and Warden. P.G., "Air Cured Wood pulp, fiber-cement composites", Journal of Materials Letters, Vol. 1, January 1985, pp. 117-119.
12. Coutts, R.S.P., "High Yield Wood Pulps as Reinforcement for Cement Products", Appita, Vol. 39, No. 1, January, 1986, pp. 31-35.

TABLE 1 — RELATIVE COST/STRENGTH AND PRODUCTION ENERGY OF CELLULOSE VERSUS OTHER FIBERS

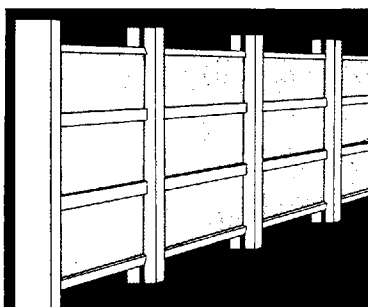
Fiber	Cost/Unit Weight	(Cost/Unit Weight) (Ten. Strength/ Sp. Gr.)	Energy/Unit Weight
Cellulose (Kraft Pulp)	1.0	1.0	1.0
Glass	4.0	2.2	1.4
Kevlar	20.0	3.3	-
Asbestos	1.2	1.3	0.2

TABLE 2 — FIBER LENGTH DATA⁸

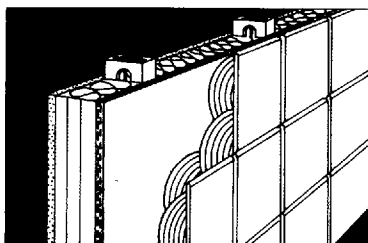
Length (mm)	Weighted Distribution (%)		
	P. radiata	E. regnans	Wastepaper
< 0.2	2.6	2.0	6.6
0.2 - 0.6	4.0	12.8	21.2
0.6 - 1.2	9.1	74.2	40.0
1.2 - 2.0	18.0	9.0	15.3
2.0 - 3.0	28.0	1.5	11.0
3.0 - 4.0	25.0	-	5.2
4.0 - 5.0	11.0	-	1.0
> 5.0	3.0	-	-
Weighted Average (mm)	3.2	1.0	1.9



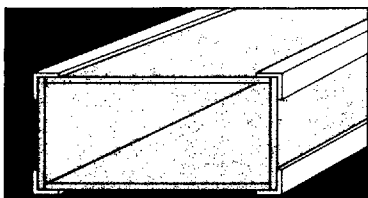
a) Residential and commercial construction



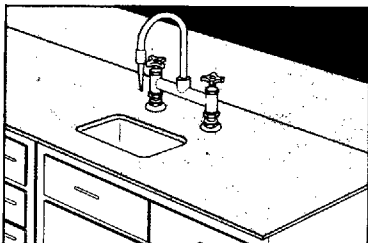
EXTERIOR FENCING



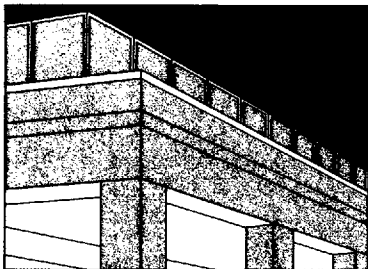
SUBSTRATE FOR TILE



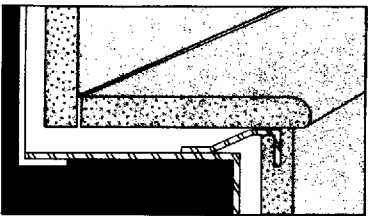
DUCT WORK



LABORATORY TOPS AND SPLASHES



EQUIPMENT SCREENS, FASCIAS & FACADES



STAIR TREADS & RISERS

b) Industrial and commercial components

Fig. 1—Application of cement products reinforced with cellulose fibers

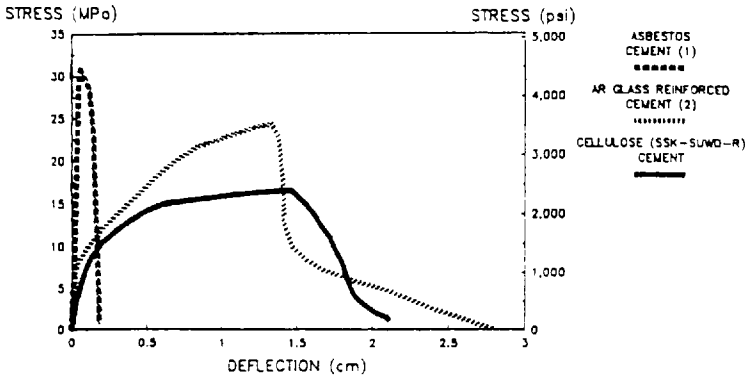


Fig. 2—Flexural performance of asbestos cement compared with cellulose and glass fiber reinforced cement³

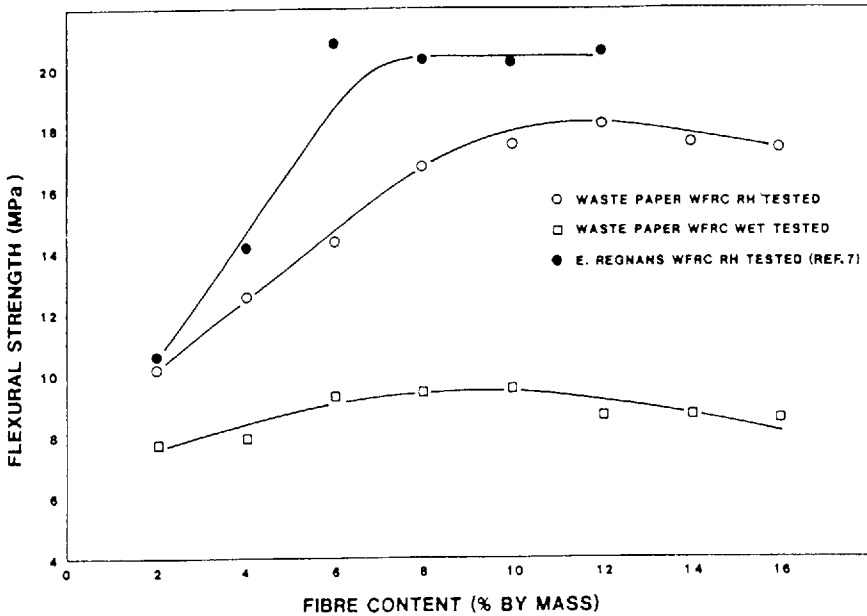


Fig. 3—Flexural strength versus fiber content⁸

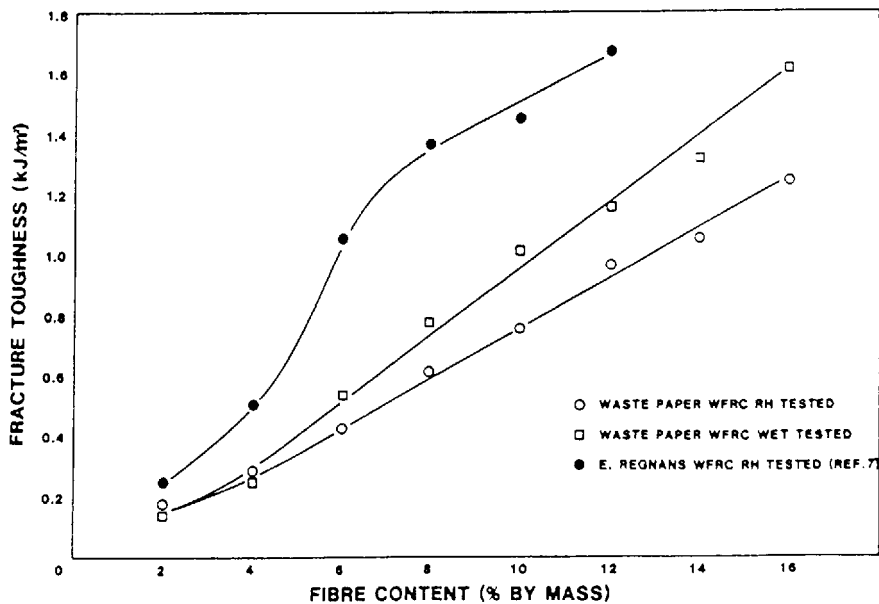


Fig. 4—Fracture toughness versus fiber content⁸

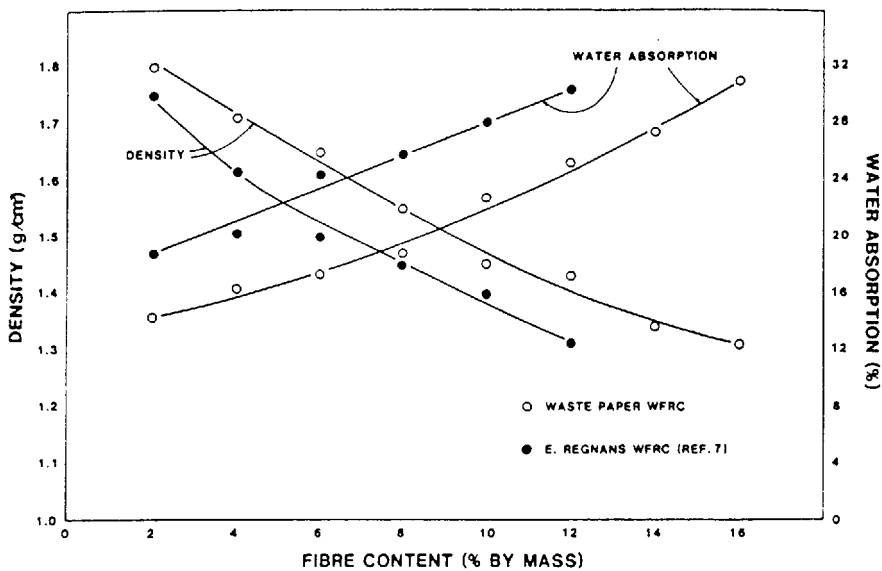


Fig. 5—Density and water absorption versus fiber content⁸

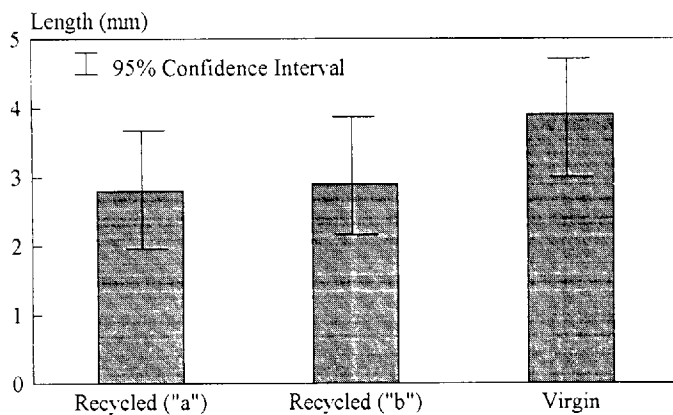
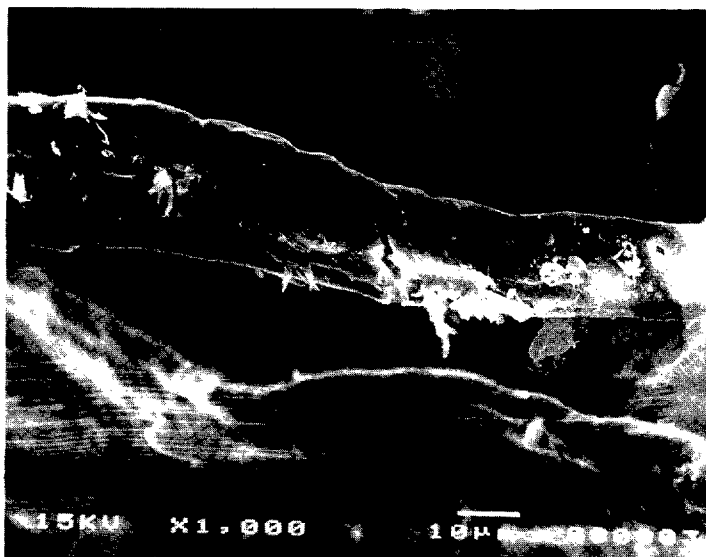
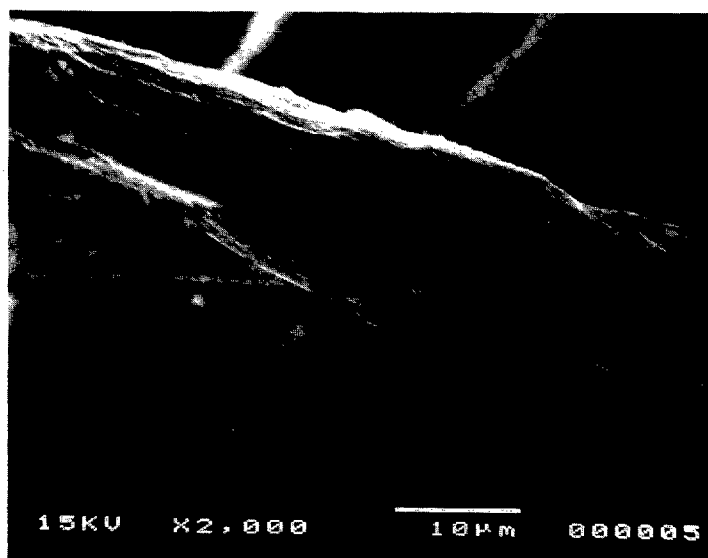


Fig. 6—Length distribution of recycled and virgin cellulose fibers



a) Recycled cellulose fiber



b) Virgin cellulose fiber

Fig. 7—Micrographs of recycled and virgin cellulose fibers

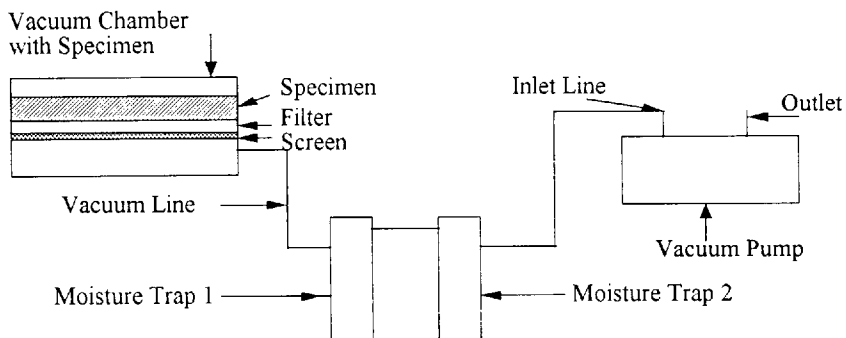


Fig. 8—Slurry dewatering process

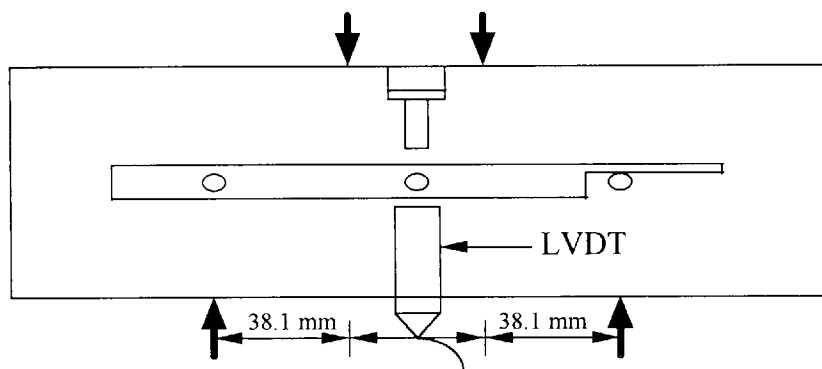


Fig. 9—Flexural test set-up

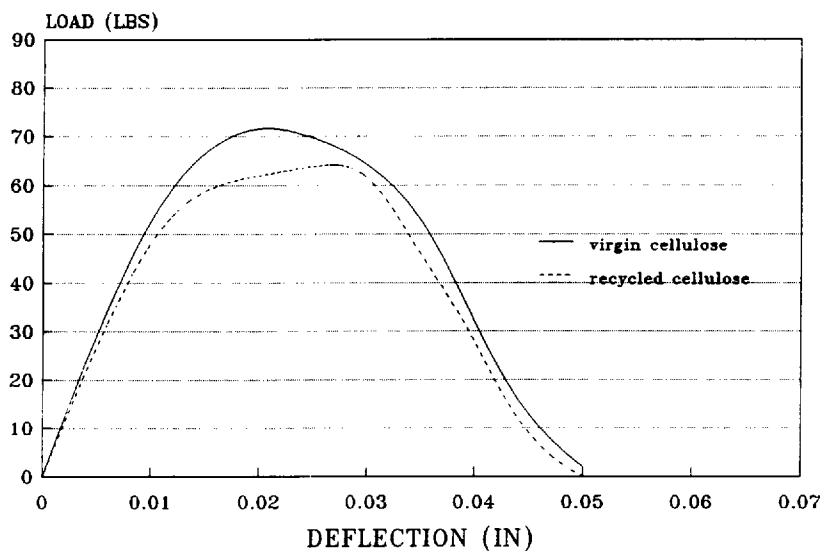


Fig. 10—Typical load-deflection curves

Uniaxial Tensile Response of Cement Composites Reinforced with High Volume Fractions of Carbon, Steel, and Polypropylene Micro-Fibers

by N. Banthia, A. Moncef, and J. Sheng

Synopsis: Stress-strain curves in uni-axial tension are obtained for micro-fiber reinforced cement composites containing high-volume fractions of carbon, steel and polypropylene fibers both in the mono and hybrid (combination) forms. Based on these curves, considerable strengthening, toughening and stiffening of the host matrix due to micro-fiber reinforcement is demonstrated. Fiber characteristics like geometry, tensile strength, elastic modulus and surface texture are shown to be of significance. In hybrid fiber composites, different fibers appear to act as additive phases, i.e., they maintain their individual reinforcing capabilities. The paper recognizes the potential of these composites for use in thin sheet products and other similar applications, and stresses the need for continued research.

Keywords: Compressive strength; fiber reinforced concretes; matrix; micro-fibers; precast concrete; reinforced concrete; stiffness; strengthening; tension