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Report on Thin Reinforced Cementitious Products

Reported by ACI Committee 549

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Secretary

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Nandakumar Natarajan[‡]
P. Paramasivam

D. V. Reddy
Surendra P. Shah[‡]
Yixin Shao[‡]
Anil K. Sharma
Parviz Soroushian[‡]
Narayan Swamy
George J. Venta[‡]
Robert C. Zellers
Ronald F. Zollo

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[*] Chair of the subcommittee responsible for preparing this report.
[†] Co-chair of the subcommittee responsible for preparing this report.
[‡] Members of the subcommittee responsible for preparing this report.

Thin reinforced cementitious products offer a useful balance of properties such as strength, toughness, environmental durability, moisture resistance, dimensional stability, fire resistance, esthetics, and ease of handling and installation. The growing emphasis on environmental durability and fire resistance of cementitious products has led to their increased use worldwide. This report summarizes the current knowledge of reinforcements, manufacturing methods, engineering properties, and applications of thin reinforced cementitious products.

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Keywords: cement-based composites; cement boards; cement panels; composite materials; concrete panels; ductility; durability; engineering properties; ferrocement; fiber-reinforced cement-based materials; fibers; flexural strength; manufacturing methods; mesh reinforcement; reinforcing materials; toughness.

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CHAPTER 1—INTRODUCTION

Thin reinforced cementitious products are used widely today in a variety of applications worldwide. Thin reinforced cementitious products are strong, possess superior deformability characteristics and enhanced impact and fatigue resistance—properties that are of great value in many practical applications. The aforementioned performance characteristics result primarily due to the inclusion of reinforcement in the cementitious matrixes of these products. In the past, asbestos fibers were the popular form of reinforcement in manufacturing thin cementitious products because asbestos fibers were widely available, inexpensive, possessed favorable processing characteristics, and provided significant improvements in strength and toughness characteristics of cements and mortars (Table 1.1). The use of asbestos fibers, however, continues to decline rapidly due to the serious health hazard risk to people involved in handling asbestos fibers and products. Consequently, other reinforcement materials have been developed to replace asbestos fibers in thin cementitious composites. These reinforcements are available in different geometric configurations such as discrete fibers, continuous fibers, and meshes. The former can be classified as a discontinuous reinforcement and the latter two as continuous reinforcement. The choice of reinforcement in terms of material type and geometric configuration has a significant influence on the engineering properties of the resulting thin cementitious products. Thin cementitious products that incorporate metal meshes as reinforcement are commonly referred to as ferrocement. A detailed description of metal mats and meshes and products made thereof is covered in ACI 549R and not covered in this report. Readers are referred to that document for further information. Thin cementitious products may contain both discontinuous and continuous reinforcements to produce products possessing tailored performance characteristics.

Table 1.1—Mechanical properties of cement paste, cement mortar, and asbestos cement (Studinka 1989; Hannant 1978)

	Property				
Material type	Flexural strength, MPa	Tensile strength, MPa	Elastic modulus, GPa	Tensile strain at failure, %
Cement paste	7 to 8	3 to 6	15	0.01 to 0.05
Cement mortar	—	2 to 4	25 to 35	0.005 to 0.015
Asbestos cement	30 to 40	17 to 20	28 to 35	0.40 to 0.50

Typical applications of thin reinforced cementitious products include exterior façade claddings, architectural elements, roofing panels and tiles, substrate panels for installation of tiles and other finishes, tunnel and sewer linings, cable ducts, permanent formwork, and pipes. Thin reinforced cementitious products have the ability to satisfy diverse requirements in these applications, such as strength, deformability, environmental durability, moisture resistance, dimensional stability, fire resistance, and rapid and economic construction.

As diverse are the reinforcement and the applications of thin reinforced cementitious products, so are the manufacturing methods to produce these products. A variety of cost-effective and rapid manufacturing methods have been developed to produce thin reinforced cementitious products having diverse performance characteristics and a range of geometric and aesthetic features. Popular manufacturing methods of thin reinforced cementitious products are described in this report.

Chapter 2 describes different types of reinforcements used to produce thin reinforced cementitious products. Known and popular manufacturing methods of thin reinforced cementitious products are described in Chapter 3. Chapter 4 describes the engineering properties of thin reinforced cementitious products. Finally, different applications of thin reinforced cementitious products are highlighted in Chapter 5.

CHAPTER 2—REINFORCEMENT TYPES AND REINFORCING MECHANISMS

A variety of reinforcement types are used to manufacture thin reinforced cementitious products today. These reinforcements can be broadly classified into three categories:

- Discontinuous or discrete reinforcing fibers;
- Continuous reinforcing fibers; and
- Reinforcing meshes.

Discrete (discontinuous) fibers are the most popular form of reinforcement used in thin cementitious products. Discrete fibers are made from a variety of materials and are available in different lengths and diameters. Examples of discrete fiber reinforcements include natural/cellulose fibers, glass fibers, polymer (polyvinyl alcohol and polypropylene) fibers, and carbon fibers. Continuous reinforcing fibers made from materials such as glass and polymers have also been used to manufacture thin cementitious products.

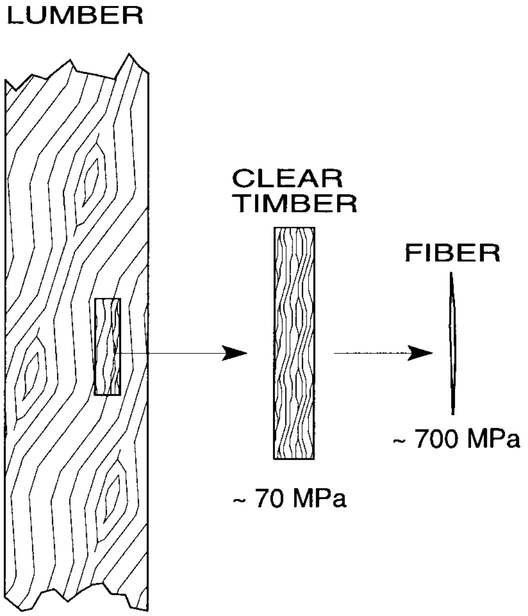


Fig. 2.1—Schematic presentation of the substructure of wood (Coutts 1983).

Meshes are yet another form of reinforcement that are becoming increasingly popular in thin cementitious products. The performance characteristics of thin reinforced cementitious products depend significantly on the type of reinforcement used.

2.1—Discontinuous or discrete reinforcing fibers

2.1.1 *Natural/cellulose fibers*—Figure 2.1 illustrates the structure of wood. A piece of lumber may have defects, such as knots or cracks, that adversely affect its strength. A piece of clear wood (nearly defect-free at a macroscopic level) would have a tensile strength of approximately 70 MPa. A single wood fiber (natural/cellulose fiber), which constitutes the reinforcing unit of bulk wood, however, can have tensile strength greater than 700 MPa (Coutts 1983).

The major chemical components of wood are cellulose, hemicellulose, lignin, and a small fraction of extractives. Natural/cellulose fibers, in their natural arrangement in softwoods and in hardwoods, are bonded together by a layer of amorphous cementing material. In the cellulose fiber production (pulping) process, this cementing material is broken by either chemical or mechanical means to obtain the individual cellulose fibers.

Pulping processes are classified as chemical, semichemical, or mechanical, based on how the original fibrous structure is broken down. This classification refers to the nature of the process used to separate the fibers. In the mechanical pulping process, frictional forces, often aided by steam pressure, separate the fibers. In the chemical process, the fibers are separated from one another primarily by dissolving and removing the natural bonding agent. Semichemical processes use a combination of chemical reactions and mechanical power to achieve the same objective (Kocurek and Stevens 1983; Suchsland and Woodson 1986). Chemical pulp, also called kraft pulp, is commonly used in the production of book paper and writing paper, whereas mechanical pulp is used regularly for the manufacture of newsprint.

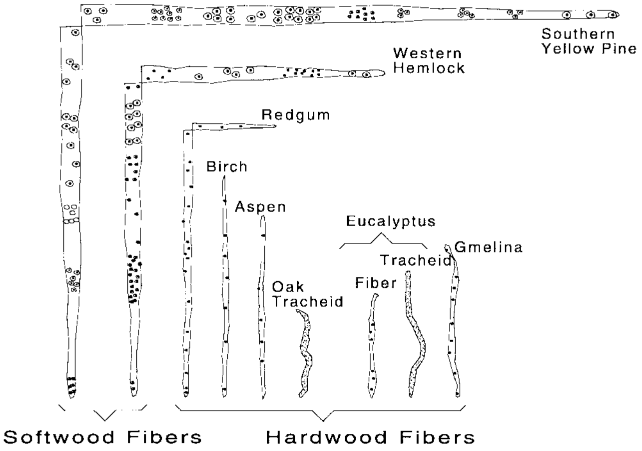


Fig. 2.2—Major fiber types in softwoods and hardwoods (Kocurek and Stevens 1983).

Table 2.1—Important properties of cellulose fibers (kraft fibers from softwood species *Pinus Radiata*) (Soroushian and Marikunte 1992)

Fiber	Specific gravity	Diameter, microns	Elastic modulus, GPa	Tensile strength, MPa
Cellulose (kraft pulp)	1.5	15 to 80	10 to 30	500

Among commercial trees, softwoods are the source of so-called long fibers. The length of unbroken cellulose fibers in important softwoods ranges between 2.5 to 7 mm, but the vast majority of fibers are between 3 to 5 mm in length. Even within the same tree species, fiber lengths can vary considerably. The diameter of softwood cellulose fibers ranges between 15 and 80 microns, but the majority of fibers are between 30 and 45 microns in diameter.

Figure 2.2 provides information on the shape and appearance of the major fiber types in softwoods and hardwoods. All diagrams in this figure are at the same magnification to show the relative sizes of these elements.

Table 2.1 shows important properties of cellulose fibers represented by kraft fibers from the softwood species *Pinus radiata*. Processed cellulose fibers also possess a relatively high elastic modulus that is about twice that of the ordinary cementitious materials.

Among processed cellulose fibers, kraft fibers are most commonly used in modern thin-sheet production. These fibers are highly alkali-resistant and produce cementitious composites with desirable durability characteristics. Cellulose fibers are also available in a form that is readily dispersible in conventional cementitious mixtures using normal mixing procedures in mortar or concrete mixers (Soroushian 1996).

2.1.2 *Glass fibers*—The most common form of glass fibers used as reinforcement in composites is generally referred to as E-glass fibers. E-glass fibers have traditionally been used in conjunction with polymeric resin systems. When E-glass fibers are exposed to portland-cement-based mixtures such as mortars or regular concrete, however, the alkaline nature

Table 2.2—Chemical compositions of E-glass and AR-glass fibers, percent by weight (PCI MNL-128-01)

Component	E-glass, %	AR-glass, %
SiO_2	54.0	61.0 to 62.0
Na_2O	—	14.8 to 15.0
CaO	22.0	—
MgO	0.5	—
K_2O	0.8	0.0 to 2.0
Al_2O_3	15.0	0.0 to 0.8
Fe_2O_3	0.3	—
B_2O_3	7.0	—
ZrO_2	—	16.7 to 20.0
TiO_2	—	0.0 to 0.1
Li_2O	—	0.0 to 1.0

Table 2.3—Properties of E-glass and AR-glass fibers (PCI MNL-128-01)

Property	E-glass	AR-glass
Specific gravity	2.54	2.70 to 2.74
Tensile strength	2000 MPa	1700 MPa
Modulus of elasticity	75.5 GPa	72.0 GPa
Strain at break	2.0%	2.0%

of the cementitious mixtures rapidly deteriorates the glass fibers. Two approaches are commonly adopted to overcome the problem of glass fiber durability. The first approach involves coating the E-glass fibers with special polymeric coatings that prevent the glass fibers from directly coming in contact with the cementitious matrix. The second approach involves modifying the chemical composition of glass fibers so that they are inherently more chemically resistant to the alkaline nature of cementitious matrixes. This is achieved by adding zirconium in the mixture composition before melting the raw materials for producing glass fibers. The added zirconium becomes part of the glass fiber molecular structure in the manufacturing process. Extensive research has shown that the minimum zirconium content required to achieve good long-term durability is approximately 16% by weight of the overall glass fiber composition (Majumdar 1985; Fyles, Litherland, and Proctor 1986; PCI MNL-128-01). The glass fibers with such zirconium modification are usually referred to as alkali-resistant glass fibers or AR-glass fibers. AR-glass fibers are chemically stable, resisting both alkali and acid conditions. The chemical compositions of the E-glass and AR-glass fibers are shown in Table 2.2. The physical and mechanical properties of these two types of glass fibers are shown in Table 2.3.

Glass fibers for use in concrete are available in three basic forms—discrete chopped strands, continuous rovings, and meshes. Continuous glass fiber rovings and meshes are discussed in Sections 2.2.1 and 2.3.1. AR-glass fiber discrete chopped strands are used primarily in premix glass fiber-reinforced concrete (Section 3.3) and in crack control of concrete. Glass fiber strands are made up of bundles of individual filaments. The typical diameter of these individual filaments ranges between 12 and 20 microns.

Typically, AR-glass fiber chopped strands are available in two types: integral and water dispersible. Integral strands are designed to stay as bundles of filaments through mixing and placing, with as little breakdown of the bundle as possible. Integral strand bundles can contain as many as 400 and as few as 50 filaments. The number of filaments per bundle is usually referred to as strand geometry. The diameter of the individual filaments, the number of filaments that are bundled together, and the integrity of the bundle are the key factors that determine performance characteristics of the strand. The typical length of discrete AR-glass fiber strands used in thin reinforced products ranges between 5 and 40 mm. The strand geometry, strand length, and glass fiber content all contribute to the composite processing characteristics and final composite mechanical performance.

Water dispersible AR-glass fiber strands are designed to disperse quickly into individual strands on contact with water or aqueous cementitious mixtures. These fibers are used in composites where a fine dispersion of monofilaments is desired rather than intact fiber bundles. In particular, water-dispersible AR-glass fibers are commonly used in manufacturing processes that involve cementitious slurries with initial high water content such as the Hatschek process or the filter-press process. In these processes, slurries with excess water are dewatered by vacuum or pressure to provide the desired final low water-cementitious material ratio (*w/cm*). Typical length of water-dispersible AR-glass fiber strands used in thin reinforced cementitious products ranges between 5 and 25 mm.

2.1.3 *Carbon fibers*—Carbon fibers used in thin cementitious-based composites are available in a variety of forms.

- Polyacrylonitrile-based carbon fibers (PAN): Polyacrylonitrile-based carbon fibers are produced by carbonization of polyacrylonitrile textile yarns;
- Isotropic pitch-based carbon fibers: Isotropic pitch-based carbon fibers are produced by spinning and carbonizing an isotropic petroleum, coal tar, or synthetic pitch. These raw materials are typically glassy and amorphous in nature; and
- Mesophase (high-modulus) pitch-based carbon fibers: Mesophase pitch-based carbon fibers are produced by spinning and carbonizing a mesophase (liquid crystal, oriented) petroleum, coal tar, or synthetic pitch.

Each type of carbon fiber has a different molecular structure with inherent advantages and limitations, although considerable overlap in measured properties and performance is possible. As a class, carbon fibers exhibit excellent resistance to chemical attack and possess adequate temperature resistance to allow autoclaving of cementitious products.

Based on cost economics, isotropic pitch-based carbon fibers have been the most popular form used in applications involving thin cementitious products. Even for this fiber form of carbon fiber, however, its relatively high cost has been a major drawback. With worldwide production of carbon fibers increasing and significant improvements being made in the carbon fiber production technology, the cost of carbon fibers, particularly for the pitch-based products, is expected to decline significantly in the future.

General property ranges for the three types of carbon fibers discussed above are shown in Table 2.4. Carbon fibers with tensile modulus values above 520 GPa are available, but their usefulness in cementitious-based products is limited. Most commercially available PAN- and pitch-based carbon fibers have a smooth surface with a round or oval cross section. Surface treatments such as air or ozone oxidation or plasma etching are used to improve adhesion to the matrix. Mechanical bond of the fiber to the matrix may also be enhanced by intentionally including deformations on the fiber surface during the fiber manufacturing process. Such surface deformations, however, normally have a negative influence on the fiber mechanical strength.

2.1.4 *Polymer fibers*—Several types of discrete polymer reinforcing fibers have been used to produce thin reinforced cementitious composites. These include acrylic fibers, polyvinyl alcohol (PVA) fibers, polyester fibers, nylon fibers, polypropylene fibers, polyethylene fibers, and aramid fibers. In the manufacturing processes of thin cementitious products such as Hatschek, the use of polymer fibers as a part or full substitution for natural/cellulose fibers continues to grow. Today, acrylic, polyvinyl alcohol, and polyethylene pulp (Gale, Guckert, and Shelbume 1990) fibers are used in the Hatschek process to produce thin cementitious composites.

Table 2.4—Properties of carbon fibers

Fiber precursor	Fiber diameter, μm	Specific gravity	Tensile strength, MPa	Tensile modulus, GPa
Polyacrylonitrile	7 to 8	1.6 to 1.8	2800 to 4800	210 to 290
Isotropic pitch	7 to 18	1.6 to 1.8	590 to 840	28 to 35
Mesophase pitch	9 to 18	1.8 to 2.1	1700 to 3200	170 to 520

Table 2.5 shows properties of various polymer and other varieties of synthetic fibers as reported by several investigators. Polymer fibers are available in a wide range of properties. The primary differences between the various polymer fibers exist in their elastic modulus, strength, adhesion characteristics, chemical stability, and geometric configuration. Elastic modulus, strength, adhesion characteristics, and geometrical characteristics of fiber are some critical properties that play a significant role in influencing the strength and toughness of thin cementitious composites.

The geometrical characteristics of different polymer fibers, such as length, diameter, cross section, and shape, vary significantly. These geometrical characteristics influence fiber performance. For example, straight polyethylene staple fibers, typically with a round cross section, generally have poor adhesion to cementitious matrixes, whereas pulp forms of polyethylene have good bond owing to their irregular shape that promotes mechanical adhesion.

2.2—Continuous reinforcing fibers

Reinforcing elements available in continuous form are also commonly used in thin reinforced cementitious products. AR-glass fibers and polymer fibers are available in continuous form and serve as two examples that fall in this category of reinforcing fibers. A description of these two continuous fiber types is given below.

2.2.1 *Continuous alkali-resistant glass fibers*—Continuous AR-glass fibers are available in the form of roving. Figure 2.3 shows an AR-glass fiber roving used in thin reinforced cementitious products. The basic building blocks of a roving are AR-glass fiber monofilaments. A roving is an assemblage

Table 2.5—Properties of different varieties of polymer and other synthetic fibers used as reinforcement in thin cementitious products (Banthia and Dubeau 1993; Gale 1990; Hannant 1978; Naaman 2000)

Fiber type	Tensile strength, MPa	Tensile modulus, GPa	Tensile strain, % (maximum to minimum)	Fiber diameter, μm	Adhesion to matrix (relative)	Alkali stability (relative)
Asbestos	600 to 3600	69 to 150	0.3 to 0.1	0.02 to 30	Excellent	Excellent
Carbon	590 to 4800	28 to 520	2 to 1	7 to 18	Poor to good	Excellent
Aramid	2700	62 to 130	4 to 3	11 to 12	Fair	Good
Polypropylene	200 to 700	0.5 to 9.8	15 to 10	10 to 150	Poor	Excellent
Polyamide	700 to 1000	3.9 to 6.0	15 to 10	10 to 50	Good	NC*
Polyester	800 to 1300	Up to 15	20 to 8	10 to 50	Fair	NC*
Rayon	450 to 1100	Up to 11	15 to 7	10 to 50	Good	Fair
Polyvinyl alcohol	800 to 1500	29 to 40	10 to 6	14 to 600	Excellent	Good
Polyacrylonitrile	850 to 1000	17 to 18	9	19	Good	Good
Polyethylene	400	2 to 4	400 to 100	40	Good	Excellent
Polyethylene pulp (oriented)	—	—	—	1 to 20	Good	Excellent
Highly oriented polyethylene (high molecular weight)	2585	117	2.2	38	Good	Excellent
Carbon steel	3000	200	2 to 1	50 to 85	Excellent	Excellent
Stainless steel	3000	200	2 to 1	50 to 85	Excellent	Excellent
Alkali-resistant glass	1700	72	2	12 to 20	Excellent	Good

*NC = no consensus.

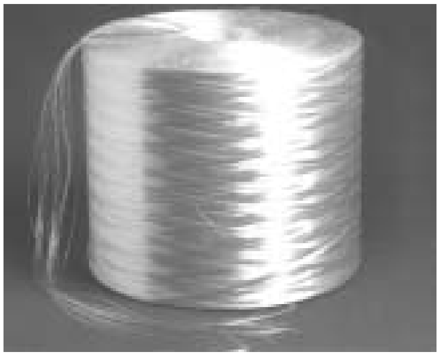


Fig. 2.3—Alkali-resistant glass fiber roving.

Table 2.6—Typical properties of fibrillated polypropylene networks (Xu and Hannant 1991)

Property	Value
Thickness	60 to 80 μm
Specific gravity	0.93
Elastic modulus	4 to 12 GPa
Tensile strength	400 MPa
Poisson's ratio	0.46
Tensile elongation at break	8.0%

of several continuous AR-glass fiber monofilaments. The manner in which the monofilaments are assembled varies and differentiates one roving type from another. Fundamentally, the construction of an AR-glass fiber roving is as follows:

- Several continuous AR-glass fiber monofilaments are gathered together to form a continuous strand. The typical diameter of the individual AR-glass fiber monofilaments ranges between 10 to 20 microns. Typically, the number of monofilaments that are gathered together to form a continuous strand ranges between 50 to 400.
- Several continuous strands as discussed previously are assembled together to form a continuous roving. Typically, the number of continuous strands that are assembled to form a continuous roving ranges between 20 to 100.

2.2.2 *Continuous polymer fibers*—Continuous fibrillated polypropylene networks have been used to reinforce thin cementitious products. These networks are made from a highly stretched (15:1 draw ratio) polymer before being partially split parallel to the molecular chains in a pin-roller (Hannant and Zonsveld 1980; Ohno and Hannant 1994; Xu and Hannant 1991). This process results in a filament of approximately rectangular cross section that is strong and stiff in the direction of the aligned polymer chains but weak and easily split or sheared between the chains. The polypropylene fiber network consists of layers of opened nets oriented longitudinally and transversely. Table 2.6 shows some typical properties of continuous fibrillated polypropylene networks.

2.3—Reinforcing meshes and mats

Meshes are also commonly used to reinforce thin cementitious products. Meshes are two-dimensional reinforcing structures in which the individual reinforcing strands are interwoven and run in different directions. An interstrand opening may exist, depending on the extent of spacing between the individual reinforcing strands. Reinforcing meshes are made from a variety of materials such as glass fibers, polymer fibers, carbon fibers, and metal wires/fibers. Meshes are also commonly known as scrims or fabrics. A description of different types of reinforcing meshes is presented as follows.

2.3.1 *Glass fiber meshes*—Glass fiber meshes for reinforcing thin cementitious products have traditionally been woven products of E-glass fiber yarn (Venta, Cornelius, and Hemmings 1995; Venta et al. 1997; Venta, Ling, and Porter 1998). To prevent alkali attack of glass in high-pH environments of the cementitious matrixes, the individual glass fiber yarns are first coated using specially formulated polyvinyl chloride (PVC) based compounds known as plastisols during the manufacturing of mesh products. These individual PVC-coated yarns are then woven and fused to form of a mesh of desired configuration. The amount of plastisol used to protect the glass fiber fabric is substantial with weight ratios of plastisol to glass typically ranging from 60:40 to 70:30. As an alternative, an AR-glass fiber mesh can be used to reduce the need for the plastisol coating.

An alternative to the aforementioned woven mesh is nonwoven glass fiber mesh. Nonwoven glass fiber mesh is produced by first assembling the uncoated glass fiber yarns to form a mesh followed by dipping the assembled mesh in a coating material bath of plastisol. The plastisol coating serves as both the glue to bind the glass fiber yarns together and as a protective coating against alkali attack. The current generation nonwoven glass fiber mesh reinforcement products appear to answer some earlier durability problems by improving and providing sufficient coating material to ensure long-term protection of glass fibers against alkali attack (Venta, Cornelius, and Hemmings 1995; Venta et al. 1997; Venta, Ling, and Porter 1998). Such nonwoven meshes are functionally equivalent to older woven reinforcement, and in some aspects, specifically in the deflection at break, they are perhaps superior to their woven counterparts (Venta, Porter, and Pierson 1999).

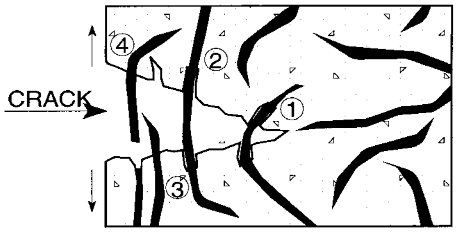
2.3.2 *Polymer and carbon fiber meshes*—Woven polypropylene mesh fabrics have been used to produce thin-sheet cementitious products (Swamy 1992). Co-extended webs or weaves made from flat strips of fibrillated film, although relatively expensive, have the potential to find use in specialized applications such as sheathing panels for buildings (Hannant and Zonsveld 1980). Meshes made from high-performance reinforcing materials such as highly oriented high-strength polyethylene, carbon, and oriented aramid have also been investigated (Naaman 2000; Naaman and Chandrangsu 2000) for producing high-performance thin cementitious composites.

2.3.3 *Metal wire meshes and mats*—Many thin cementitious products that typically incorporate metal wire mats and meshes as reinforcement are commonly referred to as ferrocement. ACI 549R provides the following definition: "Ferrocement is a type of thin wall reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh. The mesh may be made of metallic or other suitable materials." Specific mesh types that have been widely used include woven or interlocking meshes such as chicken wire cloth; woven cloth meshes in which filaments are interwoven with their intersections not rigidly connected; welded wire meshes in which a rectangular pattern is formed by perpendicular intersecting wires welded together at their intersections; and specially woven mesh patterns that may include diagonal filament woven through the rectangular mesh pattern. Two other forms of metal reinforcing mats that have been widely used include expanded metal lath formed by slitting thin-gage sheets and expanding them in a direction perpendicular to the slits, and punched, or otherwise perforated, sheet products. Another form of reinforcement consists of continuous filaments that are randomly, or at least irregularly, assembled into a two-dimensional mat form. A detailed description of the metallic mats and meshes is covered in ACI 549R.

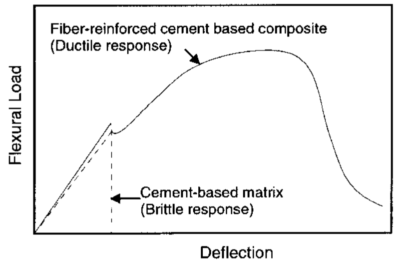
Carbon steel and stainless steel fibers are available in nonwoven mat forms. The fibers used in making such mats are typically produced by shaving (as in traditional steel wool manufacture), drawing (generally used for diameters below 50 μm), or direct casting (generally suitable for stainless steel but not carbon steel). Commercial stainless steel nonwoven mats have been commercially introduced in thicknesses ranging between 3 to 50 mm. In these mat systems, the fiber volume fractions range from 1.0 to 6.0%, and the individual fiber lengths range from 50 mm to 5.5 m with a typical range of 75 to 250 mm.

2.4—Reinforcing mechanisms

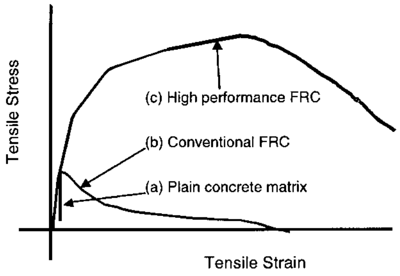
Failure in a cementitious composite emanates from defects such as flaws in the matrix and debonding at interfaces. Fibers in brittle cementitious materials help to enhance the composite toughness and tensile strength by interacting with the microcracks that develop when the composite is loaded. Fibers restrain crack opening and crack growth by effectively bridging across the microcracks. Figure 2.4(a) shows a schematic of a cross section through a matrix reinforced with fibers with several possible local failure events occurring before complete composite fracture. This figure illustrates how the fiber-matrix interaction takes place at the cracked front. In the highly stressed region near the crack tip, fibers may debond from the matrix, as indicated by Fiber 1 in Fig. 2.4(a). The rupture of bonds at the interface consumes energy from the stressed system during the fracture process. If bond failure does not occur, then sufficient stress may be transferred to a fiber, as in the case of Fiber 2, to cause the fiber to fracture, as does Fiber 4. When debonding occurs, the strain energy in the debonded length of the fiber is dissipated as heat. A completely debonded fiber can be pulled out from the matrix, and this process dissipates more energy in the form of frictional energy, as in the case of Fiber 3. It is also possible for fibers to store elastic energy while they bridge the crack during crack propagation. The net effect of interaction between the fibers and the cementitious matrix during crack growth in cementitious composites is improved ductility, energy absorption, and flexural strength, as demonstrated by the flexural load-deflection behavior shown in Fig. 2.4(b). With an increase in the volume fraction of fibers, the distribution of fibers in the matrix becomes more uniform and fibers become more effective in hindering the growth of microcracks, distributing microcracks, and increasing the strength and toughness of the composite.



(a) Schematic representation of a crack traversing through a composite



(b) Improvement in composite ductility in flexure with fibers



(c) Improvement in composite ductility in tension with fibers

Fig. 2.4—Interaction of fibers with cracks and its influence on flexural load-deflection behavior and tensile stress-strain behavior of fiber-reinforced cementitious composites (FRC).

Broadly, fiber-reinforced cementitious composites can be classified into two categories: conventional fiber-reinforced cementitious composites and high-performance fiber-reinforced cementitious composites (Fig. 2.4(c)). The relatively small volume fraction of short, discontinuous fibers used in conventional fiber-reinforced cementitious composites generally leads to the strain-softening response (Fig. 2.4(c), curve (b)) (Shah et al. 1988). The composites that exhibit a strain-hardening response in their stress-strain curves are commonly referred to as high-performance fiber-reinforced cementitious composites (Fig. 2.4(c), curve (c)). This type of response has been observed in the case of composites containing a large volume fraction of discrete/discontinuous fibers or in composites reinforced with continuous aligned fibers (Mobasher, Stang, and Shah 1990). The strain-hardening type of response has also been achieved through an extrusion processing using discontinuous reinforcing fibers (Shao, Marikunte, and Shah 1995). For conventional fiber-reinforced cementitious composites (Fig. 2.4(c), curve (b)), the strain softening is associated with widening of a single localized crack. On the other hand, the strain-hardening response

(Fig. 2.4(c), curve (c)) seen in the case of high-performance fiber-reinforced cementitious composites is usually associated with multiple bands of distributed matrix cracking. In addition to the strain-hardening response, high-performance fiber-reinforced cementitious composites also exhibit higher strength and greater deformation in comparison to conventional fiber-reinforced cementitious composites.

The preferential alignment of fibers in one dimension or in two dimensions also helps to increase the reinforcing efficiency of fibers. Consequently, for a given volume fraction of fibers in the composite, improvements in composite strength and toughness are greater when fibers are preferentially aligned.

CHAPTER 3—MANUFACTURING METHODS OF THIN REINFORCED CEMENTITIOUS PRODUCTS

3.1—Hatschek process

Thin cementitious building products reinforced with asbestos fibers have been known since the turn of the 20th century when, in Austria, Ludwig Hatschek formed cement sheets on a modified cardboard paper-making machine (Studinka 1989). Figure 3.1 shows a schematic of the Hatschek process for manufacturing thin cement sheets. The slurry used in the Hatschek process is diluted to a solid content of approximately 20% in large slurry vats. The solids in the dilute slurry are comprised of cements, sand, and fibers. This slurry is picked up on rotating drums located in vats, transferred to a continuous, perforated belt, and dewatered. The removal of excess slurry water through dewatering operation is achieved through the application of suction and possible external pressure. Thin layers are then collected over each other on an accumulator roll and processed further into a wide variety of product shapes such as flat sheets, corrugated sheets, and pipes. The freshly cast products are cured at ambient conditions or in a steam autoclave.

In the Hatschek process, the retention of fine cement particles is critical to the success of the dewatering operation. Asbestos fibers, due to their fine size, display excellent characteristics in transferring the cement slurry to the forming belt from the rotating wire drums located in the vats. In addition, asbestos fibers are also very helpful in retaining cement particles during the dewatering operation of the manufacturing process. Thus, by not allowing the cement fines to filter through during the dewatering operation, the asbestos fibers serve well in the role of filter fiber. Concerns over health and environmental issues, however, have forced the industry to find substitutes for asbestos fibers.

During the 1970s, several asbestos-cement manufacturers began research efforts to replace asbestos fibers with polymer fibers, natural fibers, glass fibers, and other varieties of synthetic fibers. Ultimately, collaboration with fiber producers led to the development of products that contain polymer fibers, natural fibers (particularly highly refined wood cellulose), glass fibers, or carbon fibers. When other fiber varieties replace asbestos fibers, it becomes necessary to include in the composition the fiber varieties that perform the functions of reinforcing fiber and filter fiber. While the reinforcing fiber is primarily responsible for providing strength to the composite, the filter fiber retains cement fines during the dewatering operation in the manufacturing process. Other examples of filter fibers include refined wood cellulose, polyethylene pulp, acrylic pulp, and carbon. Natural/cellulose fibers such as softwood kraft fibers satisfactorily work to prevent removal of cement particles in the dewatering operation. Defibrillation (exposure of microfibrils on fiber surfaces) through beating or chemical treatment can be used to improve the ability of fibers to retain cement particles. Fibers possessing high strength and high modulus are preferred as reinforcing fibers. Most commercial systems where discrete polymer fibers replace asbestos fibers contain a reinforcing fiber—usually polyvinyl alcohol or acrylic (polyacrylonitrile [PAN]) and, to a lesser extent, polypropylene (PP), and one or more filter fibers—usually a combination of refined wood cellulose and a polyethylene pulp (PE pulp). While the exact percentages of these ingredients tend to be held secret by the manufacturers, a typical formulation might contain a combination of 2% by weight of reinforcing fibers and 4% by weight of filter fibers. Molecularly oriented PE pulp (Gale, Guckert, and Shelbume 1990) has been reported as having both reinforcement and filter fiber characteristics.

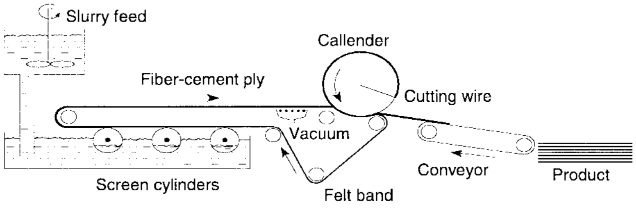


Fig. 3.1—The Hatschek process for manufacturing fiber-cement sheets.

A typical solids composition used in the Hatschek process contains approximately 40 to 90% portland cement, 0 to 50% silica sand, and 7 to 15% fibers. Sometimes, for less-critical applications, inexpensive additives such as fly ash, calcium carbonate, limestone, and gypsum are included in the composition. Silica fume is sometimes added to improve fiber-matrix adhesion. The addition of small dosages of flocculants, such as anionic polyacrylamide, to the mixture also helps to reduce the amount of cement fines passing through the screens during dewatering operation. Flocculating agents help to achieve agglomeration of cement fines in the slurry. The replacement of asbestos with other types of fibers generally reduces the productivity of the manufacturing process. Also, when fiber types other than asbestos are used, it is usually necessary to use a dispersant to help open the fibers in a mixing tank, and a flocculent to coagulate the fibers and cement fines before slurry is picked up on the rotating drum.

When products are prepared by curing in a steam autoclave at 170 to 190 °C, silica from different sources (sand, silica fume) combines chemically with cement to form a stable calcium-silicate phase that is different from the hydrated cement product obtained when portland cement is cured at ambient temperatures. When silica is present, the cure can be achieved overnight at elevated autoclave temperatures. Without silica, a normal long-term (28 day) cure at ambient temperatures is required. When polymeric fibers are used, the curing should be done under ambient conditions because polymer fibers generally cannot withstand the temperatures in the range of 170 to190 °C of autoclave curing. On the other hand, when fiber types such as glass, carbon, and other mineral fiber varieties are used, autoclave curing can be conducted in the aforementioned temperature range without damaging the reinforcing fibers.

Typical applications of asbestos cement products manufactured using the Hatschek process include flat and corrugated roofing sheets, exterior sidings and fascia, backerboards, high-pressure water pipes, and drain and sewer pipes. Thin reinforced cementitious products based on fibers other than asbestos have been successful in replacing most asbestos-cement products, including roofing sheets, exterior sidings and fascia, backerboards, and low-pressure pipes such as drain and sewer pipes. High-pressure pipes, such as water pipes, are not currently found in nonasbestos compositions.

3.2—Simultaneous spray process

In the simultaneous spray process, continuous fibers such as AR-glass fibers are chopped continuously using a chopper gun and air-sprayed simultaneously with the cementitious slurry onto a mold surface (Fig. 3.2). Both the fibers and the cementitious slurry are sprayed either using separate spray guns or using a single concentric spray gun. To spray the entire mold area, both the fiber and cementitious slurry spray guns are moved with respect to the mold. Sprayed thin reinforced cementitious products are manufactured in layers. The typical thickness of each layer deposited on the mold ranges between 4 to 6 mm. Thus, a typical 12.5 mm-thick panel requires two to three layers to achieve full thickness. After each layer is sprayed, the wet composite is roller compacted to help remove entrapped air, aid the coating of glass fibers by cementitious paste, and ensure that the panel surface will conform to the mold face. Early composite manufacturers used a dewatering process to remove the excess mixing water that was necessary to achieve a sprayable mixture. Dewatering helps to lower the *w*/*cm* and increase the extent of compaction. Dewatering involves suction applied to either side of a permeable mold to remove excess water immediately after spraying. The spray-dewatering process is most suited for automation where the composite is transported over a vacuum system using conveyors.

The simultaneous spray process can be manual or automated. The spray process allows tremendous flexibility in manufacturing complex architectural shapes and producing a high-strength product. Consequently, architects around the globe commonly design and specify architectural shapes manufactured using the spray process. For example, glass fiber-reinforced concrete (GFRC) products available in complex shapes are commonly produced using the spray process.

3.3—Premix process

The premix process consists of first mixing the discrete reinforcing fibers together with other ingredients (cement, sand, admixtures, and water) in a standard or specialized mixer to prepare a slurry and then using this slurry to cast a thin product of desired shape in a mold. The casting process may or may not involve the spraying of fiber-cement slurry as a method to fill the mold and vibration to achieve satisfactory slurry compaction in the mold. In the premix process, the maximum amount of fibers that can be incorporated in the mixture is dependent on the length and diameter of the fibers used. Additives such as polymers and pozzolans (for example, metakaolin, pulverized fly ash, and silica fume), and flow aids such as water-reducing agents are generally used to facilitate the mixing operation. The premix process typically yields a three-dimensional, random orientation of fibers in the mixture and in the final cast product. Consequently, premix products are not as strong as simultaneous sprayed ones, but the process has a lower skill level requirement to produce the finished product.

Fig. 3.2—Spray process for manufacturing thin reinforced cementitious products.

3.4—Extrusion process

The extrusion process, originally a method used to produce plastic products, has also been employed to manufacture thin reinforced cementitious products. Two different types of extruder can be potentially used to manufacture thin reinforced cementitious products. The first is an auger-type extruder in which a highly viscous, dough-like plasticized mixture is forced through a shaped die by the application of pressure derived from the rotation of an auger. An auger extruder is capable of providing a continuous production process. The second is a piston extruder in which the reciprocating action of a piston applies the pressure to move the plasticized mixture. The piston extruder generally results in less wear of machine surfaces in contact with the cementitious mixture. Also, the piston extruder does not lend itself to a continuous production process.

The typical material compositions used in the production of extruded fiber-reinforced cementitious composites generally contain the following ingredients: portland cement, silica fume, slag, discontinuous fibers, a small amount of water-soluble polymer, water, high-range water-reducer, and fine

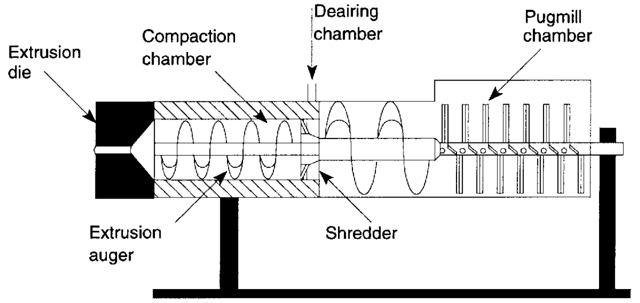


Fig. 3.3—An auger extruder for manufacturing thin reinforced cementitious products (Shao, Marikunte, and Shah 1995).

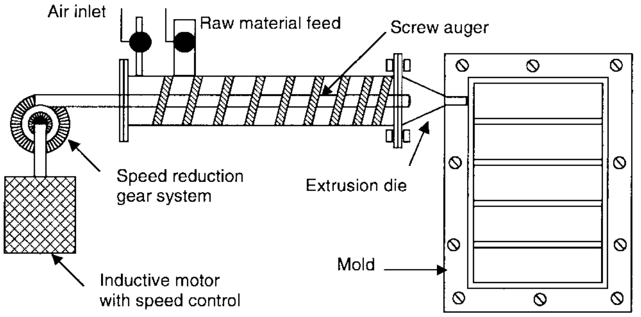


Fig. 3.4—Schematic of an extrusion process (Mobasher and Li 1996a).

silica sand. In contrast to the Hatschek process, which uses very dilute slurry of fiber and cementitious materials, the extrusion process uses much less water. The mixing action results in a dough-like material that is plastic enough to flow under pressure through the shaped die, yet stiff enough to resist deformation after exiting the die. The advantage of extrusion manufacturing is that the products are formed under high shear and high compression, which lead to improved material and product performance characteristics (Zollo 1975). With the proper combination of material composition, viscosity control, and die design, the fibers tend to orient preferentially to improve product strength and toughness. Oriented short fibers bridge multiple matrix cracks and provide maximum reinforcing efficiency. The flow-induced mechanical shear force during extrusion also helps to improve the interfacial bond between the fibers and the matrix.

Figure 3.3 shows an example of an auger extruder (Shao, Marikunte, and Shah 1995). An auger extruder consists of several sections and is capable of continuous operation. The first section of the shown auger extruder is a pug mill. The pug mill contains several blades mounted on the auger shaft. The shaft rotates, providing a high-shear mixing action. A dough-like mixture is fed into the pug mill. The pug mill kneads the mixture to provide homogeneity to maximize plasticity and to squeeze out the entrapped air. The mixture then enters a deairing chamber that uses auger motion plus an applied vacuum to remove as much air as possible. The mixture finally moves to the compaction chamber where the auger motion precompacts the mixture and removes the remaining air voids before extruding the material through a shaped die. The plasticized mixture is then forced under pressure through the shaped die to form the product. The formed product having the desired shape is then cut to length, cured, and stored. The auger extruder shown in Fig. 3.3 has been used to produce thin reinforced cementitious composites reinforced with synthetic fibers (Shao, Marikunte, and Shah 1995).

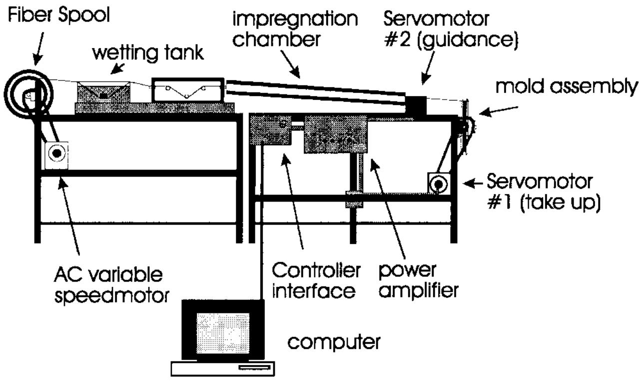


Fig. 3.5—Schematic side view of a filament winding process (Mobasher and Pivacek 1998).

Figure 3.4 shows another auger-type extrusion apparatus that has been developed to manufacture thin reinforced cementitious composites (Mobasher and Li 1996a; Mobasher, Pivacek, and Haupt 1997; Pivacek and Mobasher 1997). The system configuration for this extrusion apparatus is based on a single screw auger that is operated by an inductive motor (one-horsepower capacity operating at 1750 rpm). The auger is connected to the motor through a speed-reducing gear drive. A combination of air pressure at the inlet and vacuum at the vent holes in the mold is used to control the hydrostatic back pressure that is developed due to compaction of material in the die. The system has been used to manufacture thin reinforced cementitious products with relatively high volume fractions of hybrid polypropylene, ceramic, and carbon fibers (Mobasher and Li 1996b).

3.5—Filament winding process

The filament winding process is another manufacturing method that can be used to produce thin reinforced cementitious products. Figure 3.5 shows an example of a filament winding process that has been used to produce high-fiber-content cementitious products (Mobasher, Pivacek, and Haupt 1997; Pivacek and Mobasher 1997; Mobasher and Pivacek 1998). The mechanical components used in this process consist of a feed section, guide, and take-up (mold) section. The electrical and electronic components consist of servomotors, encoders, limit switches, and a portable computer used to monitor a closed-loop controller. The configuration of the servomotors determines the winding, pulling, and guidance of the composite, while the take-up section controls the orientation of fibers in the lamina. The feed section consists of a single spool of fiber, a wetting tank, and an impregnation chamber. The fiber spool is mounted on the setup table, and the power to rotate it is supplied by an AC motor. As shown in Fig. 3.5, the fiber roving passes over several round steel bars placed below the water level. Wetting separates the fibers and allows access for the paste. The roving is partially drained off by passing over several bars before entering a long tube that acts as the impregnation chamber. The tube is filled with cement paste that impregnates the fiber along its travel path. The exit end of the tube rests on a platform on a sliding table that moves transverse to the fiber direction. Various continuous fiber cementitious composites consisting of unidirectional fiber-reinforced lamina and angle-ply laminates can be manufactured by stacking several layers of lamina to achieve the desired composite thickness. Composites have been manufactured with up to 15% continuous alkali-resistant glass and fibrillated polypropylene fibers using the filament winding process. By controlling the orientation of the lamina during the stacking of layers, various cross-ply and angle-ply composites are manufactured. For example, a 0/90/0 lamina has three unidirectional layers stacked such that the middle layer is at a 90-degree orientation to the outer layers. Similarly, a $[0,\pm 45,\pm 90]_S$ represents a symmetric lamina with layers configured as 0, +45, –45, +90, –90, –90, +90, –45, +45, and 0-degree orientation. In addition, composite lamina, laminates, pipes, sandwich composites, and pultruded sections can be manufactured using the filament winding process. The tested composites have been found to possess tensile strengths as high as 50 MPa and flexural strengths as high as 35 MPa (Mobasher and Pivacek 1998; Pivacek et al. 2000). Due to the presence of various failure mechanisms, such as delamination and crack deflection, the strain capacity of composites is approximately 2%, and the fracture toughness of composites is as high as two orders of magnitude that of the conventional fiber-reinforced concrete materials.

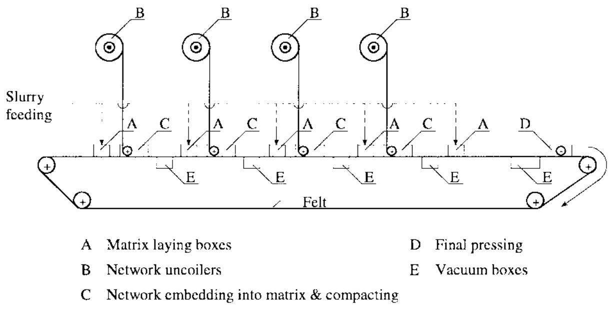
The filament winding process has been refined commercially in the U.S. for the production of a range of cement-based poles and inductively transparent, high-temperature ladles. In these applications, AR-glass fibers have been used as reinforcement with fiber volume fraction ranging from 10 to 25%. This process and the resulting products are described in the U.S. Patents 5,039,345 (Mott 1991) and 5,880,404 (Stanley and Mott 1999).

3.6—Filter-press process

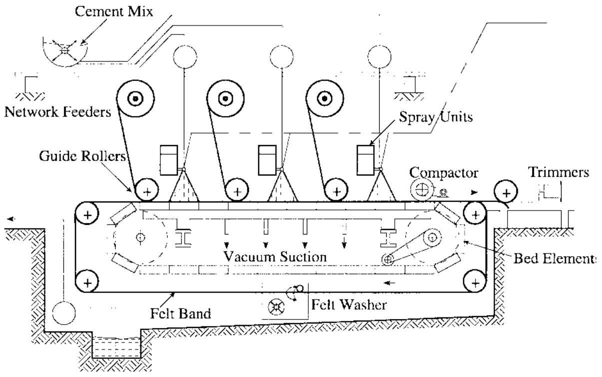
In the filter-press process, a cementitious mixture containing discrete fibers is first produced with an excess amount of water. This mixture is then charged into a mold having a perforated plate at the base. A filter material is laid on top of the mold base. The mixture is then pressed by a top plate, which squeezes out the excess water through the base of the mold and through a small gap between the top plate and the sides of the mold. The compressed board or tile is then removed from the mold and stacked for curing. Depending on the shape, the product can be demolded immediately while in the unhardened state. It is also possible to use rapid-setting cements to accomplish instant demolding. The filter-press process is well suited for mass production of products having simple or complex shapes.

3.7—Compression molding process

In the compression molding process, a viscous cementitious slurry containing discrete reinforcing fibers is first confined in a closed mold of the desired end product. The mold design is such that it has at least one movable surface that helps to compress and compact the slurry contained in the mold. This movable surface is normally hydraulically driven. After compaction of the cementitious mixture, the cast product is demolded and allowed to cure. The compression molding process is particularly useful for manufacturing thin reinforced cementitious products having complex shapes.



(a) Continuous polypropylene networks laid onto matrix



(b) Matrix sprayed onto continuous polypropylene networks

Fig. 3.6—Examples of the production processes of thin cement sheet products with continuous reinforcement (Keer 1990).

3.8—Processes with continuous reinforcement

Thin cementitious sheet products with continuous reinforcement are normally produced by depositing thin layers of the cementitious matrix on a moving belt followed by laying the continuous reinforcement onto the slurry layers. Special compaction and dewatering devices may be used to fully impregnate the fibers and consolidate the composite system. The sheets are then pressed and finished. Figure 3.6(a) shows a schematic view of such a process. When discrete fibers are combined with continuous fibers, the discrete fibers may be distributed on and pushed into the surface layers of the matrix before the continuous fibers are laid. Figure 3.6(b) shows another process in which the matrix is sprayed onto the continuous reinforcement to form a panel product.

CHAPTER 4—ENGINEERING PROPERTIES OF THIN REINFORCED CEMENTITIOUS PRODUCTS

From engineering behavior consideration, thin reinforced cementitious composites are distinct, owing to their exceptional

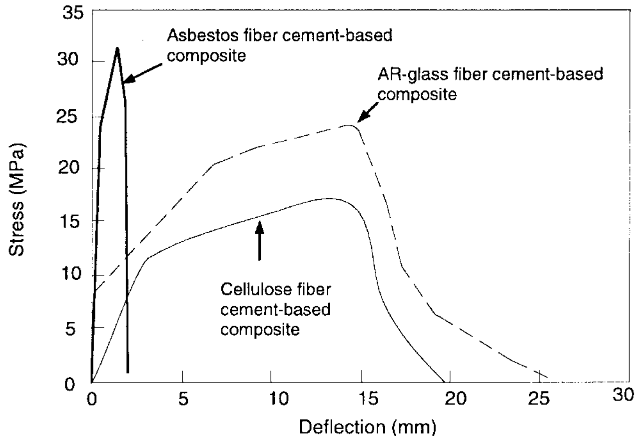


Fig. 4.1—Flexural performance of thin cementitious products reinforced with asbestos, alkali-resistant glass (AR-glass) and cellulose fibers (Vinson and Daniel 1990).

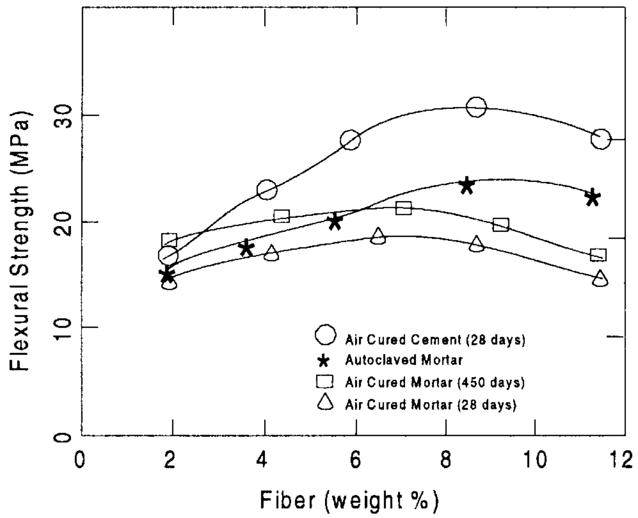


Fig. 4.2—Flexural strength as a function of fiber weight fraction for cements and mortars reinforced with unbeaten Pinus radiata *kraft pulp (Coutts 1987a).*

toughness and ductility. Unlike their plain concrete counterparts that tend to be extremely brittle, thin reinforced cementitious composites continue to deform and dissipate a significant amount of energy beyond the formation of the first crack. Consequently, thin reinforced cementitious composites display very ductile tensile and flexural behavior. The presence of reinforcement in the cementitious matrix also helps to enhance the ultimate tensile strength of the composite. These engineering features make thin reinforced cementitious composites very useful in practical applications subjected to impact loads and other abusive conditions. This chapter describes the important engineering properties and attributes of thin cementitious products strengthened and toughened by different reinforcement types.

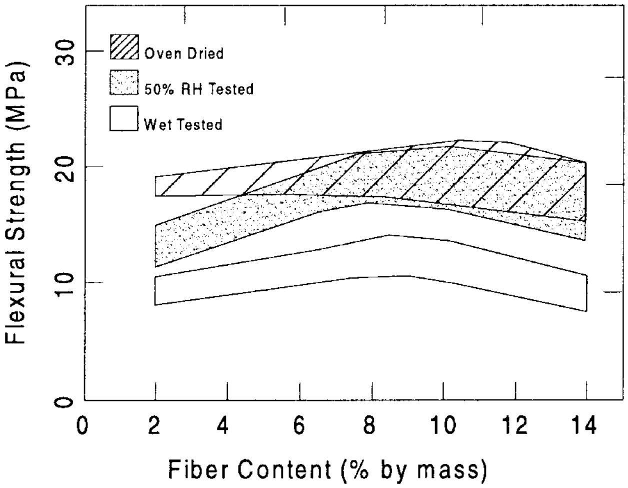


Fig. 4.3—Effects of moisture content on flexural strength of cellulose fiber-cement composites (Coutts 1983).

4.1—Natural/cellulose fiber-reinforced products

A comparison of the flexural performance of thin cementitious composites reinforced with natural/cellulose fibers, asbestos fibers, and AR-glass fibers is shown in Fig. 4.1 (Vinson and Daniel 1990). As depicted in this figure, the products reinforced with natural/cellulose fibers display superior toughness characteristics in comparison to their asbestos fiber-reinforced counterparts. In terms of composite's ultimate flexural strength, however, the cellulose fiber-reinforced composites are not capable of matching the performance levels attained by the asbestos fiber and AR-glass fiber-reinforced composites (Fig. 4.1).

Figure 4.2 shows the influence of fiber content, matrix type, and curing condition on the flexural strength of thin cementitious products reinforced with natural/cellulose fibers of *Pinus radiata* kraft pulp (Coutts 1987). An increase in flexural strength results with an increase in fiber content up to a certain limit. Whereas the air-cured and autoclaved mortars give comparable flexural strengths, the air-cured cementitious products have higher flexural strengths. The maximum flexural strength in any case seems to have been achieved at a fiber weight fraction of 8%. Some cellulose fiber-cement formulations are observed to reach flexural strengths exceeding 30 MPa. Studies also indicate that a significant increase in fracture toughness results with an increase in cellulose fiber content. There seems to be little difference in fracture toughness of air-cured cements and autoclaved mortars reinforced with comparable fiber fractions. The tests presented in Fig. 4.2 were conducted at 50% relative humidity.

Natural/cellulose fiber-cement composites are highly sensitive to moisture variations. Differences in flexural strength and toughness values occur when specimens are tested at different moisture contents (Coutts 1983; Soroushian 1996). Figure 4.3 shows the variations in flexural strength of a cellulose fiber-cement composite as a function of moisture conditioning for different fiber contents. The test results presented in this figure depict a general tendency of cellulose fiber-cement composites to lose strength with an increase in moisture content. Studies also indicate that the toughness of composites increases with an increase in moisture content, particularly at higher fiber contents.

Microstructural studies conducted on cellulose fiber-cement products (Soroushian and Marikunte 1992) indicate that an increase in moisture content reduces fiber-matrix interfacial bond strength, which in turn reduces the composite flexural strength. In addition, the decrease in modulus of elasticity of cellulose fibers on wetting further reduces the composite flexural strength. A reduction in fiber-matrix interfacial bond, however, encourages fiber pullout (rather than fiber fracture) at cracked sections. Fiber pullout dissipates frictional energy and leads to improved composite toughness. This energy dissipation mechanism is further enhanced by the fact that wet fibers tend to swell and produce a higher frictional resistance against pullout.

Pedersen (1980) reported that treated cellulose fiber-reinforced cement composites have withstood outdoor exposure in fairly harsh climatic conditions over periods of 30 to 40 years. Soroushian and Marikunte (1992) investigated the effects of accelerated and natural weathering on cellulose fiber (kraft pulp) reinforced-cement composites. These composites were fairly resistant to the effect of repeated freezing-and-thawing cycles and immersion in hot water. Repeated wet-dry cycles, particularly under accelerated carbonation condition, caused an increase in strength and stiffness but encouraged brittle modes of failure. Microstructural investigations by Soroushian, Shah, and Won (1995) suggested that the aging of cellulose fiber-cement composites involves dissolution of calcium hydroxide from the matrix followed by its precipitation and deposition in fiber cores and porous interfaces. The precipitation of calcium compounds within the fiber cores and at the interfaces makes fibers stronger, stiffer, and more brittle, and leads to increased interfacial bond with the matrix. These conditions lead to an increase in composite strength and stiffness and a decrease in composite toughness. Reduction in composite toughness has been attributed to the suppression of fiber pullout. Carbonation of calcium hydroxide has been found to further accelerate this aging process. Consumption of the calcium hydroxide through the use of pozzolanic admixtures, such as silica fume, or the use of special cements may inhibit the aforementioned aging effect (Soroushian, Shah, and Won 1995).

Shao and Moras (2002) evaluated the use of extrusion technology for the production of cement boards with unbleached kraft pulps. Cement boards reinforced with both hardwood and softwood pulp at weight fractions of 2, 4, and 8% were fabricated using an auger-type laboratory extruder. Higher pulp content increased the toughness of the composite but did not enhance the flexural strength appreciably due to a higher water content required for workability. In addition, extruded composites possessed anisotropic mechanical behavior. The extruded products exhibited good resistance to natural weathering and rapid freezing-and-thawing cycling. Hardwood pulps, cheaper and more available than the softwood ones, were more suitable for extrusion production in terms of extrudability, finished surface appearance, and long-term mechanical properties.

Table 4.1—Typical range of traditional GFRC properties[*]

Property		28-day	Aged[†‡]
Density (dry)		1900 to 2000 kg/m^3	1900 to 2000 kg/m^3
Compressive strength		50 to 80 MPa	70 to 80 MPa
Flexural	Yield (FY)	6 to 10 MPa	7 to 10 MPa
	Ultimate strength (FU)	14 to 24 MPa	9 to 17 MPa
	Modulus of elasticity	10 to 20 GPa	10 to 20 GPa
Direct tension	Yield (TY)	5 to 7 MPa	5 to 8 MPa
	Ultimate strength (TU)	7 to 11 MPa	5 to 8 MPa
	Strain to failure	0.6 to 1.2%	0.03 to 0.08%
Shear	Interlaminar	3 to 5.5 MPa	3 to 5.5 MPa
	In-plane	7 to 11 MPa	5 to 8 MPa
Coefficient of thermal expansion		Approximately 20 × 10^{-6}, mm/mm/°C	Approximately 20 × 10^{-6}, mm/mm/°C
Termal conductivity		0.5 to 0.6, W/m °C	0.5 to 0.6, W/m °C

[*] These are typical values and are not to be used for design or control purposes. Each manufacturer must test production composites to establish properties for design. The values achieved in practice will be dependent on mixture proportion, quality control of materials, fabrication process, and curing. Cement/sand ratio in the above composites ranges between 1:1 and 3:1.

[†] Developed from accelerated testing programs on GFRC specimens immersed in 50 to 80 °C water. On the basis of comparisons between behavior in real weather and accelerated tests, predictions can be made of properties for 50+ years in different climates.

[‡] Commercially available modified cementitious matrixes specially developed for GFRC yield substantial improvements in long-term properties, particularly the tensile strain capacity.

4.2—Glass fiber-reinforced products

Glass fiber-reinforced concrete (GFRC) is a composite material consisting of a mortar of cement and fine aggregate reinforced with AR-glass fibers. The GFRC industry has been in existence since the early 1970s when the AR-glass fibers were launched in the UK. GFRC materials have been widely used and their properties and characteristics studied extensively worldwide. GFRC may be thought of as a thin-section concrete, with a typical thickness of 10 to 15 mm. GFRC lends itself to use in a wide variety of applications, such as cladding panels, small enclosures, noise barriers, drain channels, formwork, and many architectural details. Generally for these products, GFRC is a factory-produced material where the composite performance is obtained with a fiber content of 2 to 5% by weight, depending on product application and production method used.

The physical and mechanical properties of GFRC are discussed more fully in ACI 544.1R. The mechanical properties of GFRC composites depend on the fiber content, *w/cm*, density, sand content, fiber orientation, fiber length, and polymer content, if used. Typical properties for traditional spray-up GFRC containing 5% by weight of glass fibers are shown in Table 4.1 (PCI MNL-128-01). As shown in this table, GFRC composites have significant load and strain capacity at early ages. These mechanical performance characteristics, however, tend to diminish with time in traditional GFRC that has no modification in the chemistry of the cementitious matrix. This reduction in mechanical performance is well documented, and all accepted design procedures allow for it in establishing design values. PCI publication

Table 4.2—Typical range of premix GFRC properties* (PCI MNL-128-01)

Property		28-day
Density (dry)		1800 to 2000 kg/m^3
Compressive strength		40 to 60 MPa
Flexural	Yield (FY)	5 to 8 MPa
	Ultimate strength (FU)	10 to 14 MPa
	Modulus of elasticity	10 to 20 GPa
Direct tension	Yield (TY)	4 to 6 MPa
	Ultimate strength (TU)	4 to 7 MPa
	Strain to failure	0.1 to 0.2%
	Shear: In-plane	4 to 7 MPa
Coefficient of thermal expansion		Approximately 20 × 10^{-6}, mm/mm/°C
Thermal conductivity		0.5 to 0.6, W/m °C

*These are typical values and are not to be used for design or control purposes. Each manufacturer should test production composites to establish properties for design. The values achieved in practice will be dependent on mixture proportion, quality control of materials, fabrication process, and curing.

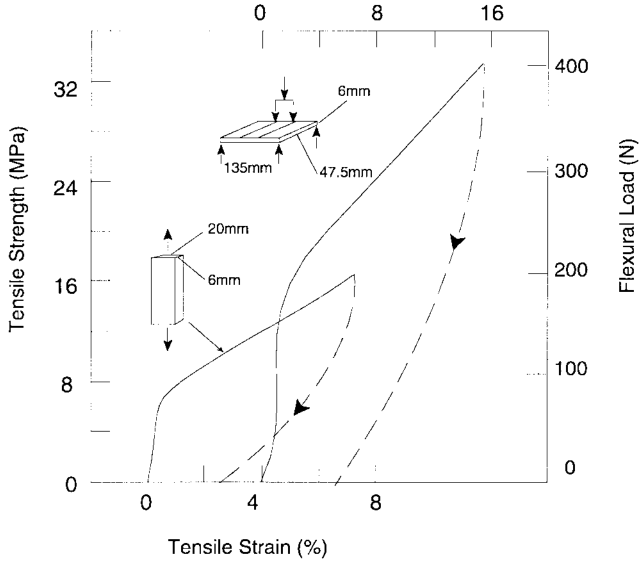


Fig. 4.4—Tensile stress-strain and flexural load-deflection curves for thin cement products reinforced with fibrillated polypropylene film network (volume fraction—5.7%) in the direction of stress (Hannant and Zonsvled 1980).

MNL-128-01 details the most widely accepted design procedure in the industry.

If a reduction in mechanical performance of composites is a concern, GFRC composition can be modified in several ways to prevent this from occurring. The formation of calcium hydroxide within the fiber strands has been held to be largely responsible for the change in properties with time (Bentur 1985). The measures that are used to arrest the change in properties generally attempt to prevent the formation of calcium hydroxide. The glass fiber manufacturers have made available AR-glass fibers with special coatings that reduce the affinity of the fibers for calcium hydroxide (Hayashi, Sato, and Fuji 1985). Most other methods to improve GFRC durability rely on either the use of pozzolanic admixtures, such as silica fume, metakaolin or fly ash (Marikunte, Aldea, and Shah 1997; Soukatchoff 1999; Soukatchoff and Ridd 1991; Purnell and Short 1998), or use special cements such as calcium sulphoaluminate cements that do not produce calcium hydroxide as a hydration product (Molloy, Jones, and Harmon 1993; Molloy and Jones 1993). Acrylic thermoplastic copolymers can also reduce the extent of reduction in mechanical performance with time (Ball and Wackers 2001). Acrylic thermoplastic copolymers are usually used in GFRC products because they provide an equivalent cure to 7-day wet cure, without the need to provide space for fog rooms.

In addition to the traditional spray-up GFRC, the use of premix GFRC is growing for the production of certain thin cementitious products. Typical properties for premix GFRC are shown in Table 4.2 (PCI MNL-128-01). Generally, premix GFRC has a lower fiber content, uses shorter fibers, and has significantly greater three-dimensional fiber orientation than the largely two-dimensional orientation obtained with spray-up GFRC, which all contribute to it having lower mechanical performance than the spray-up GFRC.

4.3—Polymer fiber-reinforced products

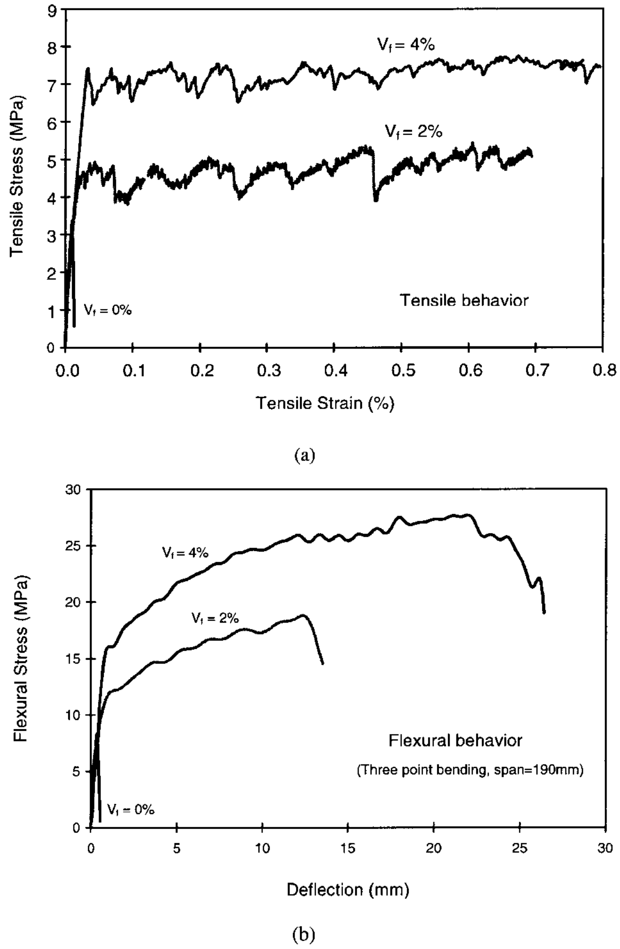
The use of different types of polymer fibers as a reinforcement of thin cementitious products has been an extensive subject of investigation. The different types of polymer fibers that have been studied include polypropylene fibers, nylon fibers, polyacrylonitrile fibers, polyethylene fibers, and polyvinyl alcohol fibers. Typical tensile stress-strain and flexural load-deflection curves for thin cementitious sheets reinforced with fibrillated polypropylene film at a volume fraction of 5.7% are presented in Fig. 4.4. The direct tensile stress-strain response is basically bilinear. The initial linear part of the tensile curve represents the uncracked state of the composite, while the second linear part represents the state after initial matrix cracking has occurred in the composite. A maximum tensile strain of 7% can be observed in the tensile stress-strain response. Provided that the ultimate load has not been achieved, significant strain recovery occurs upon unloading, even at large strains, as shown in Fig. 4.4. For complete composite failure to occur, all fibers should fracture, as pullout mode is not possible for the fibrillated polypropylene fibers. The flexural load-deflection curve is also bilinear and similar to the tensile stress-strain curve. The large area under the tensile stress-strain and flexural load-deflection curves imply high composite toughness and relatively high composite impact resistance.

The tensile stress-strain response of extruded polyvinyl alcohol fiber composites exhibits bilinear behavior with a tensile strain up to 0.8%, as shown in Fig. 4.5(a). Such response has been obtained for composites with fiber volume fractions of 2.2 to 4.2%. Extruded cement-based composites possess high early strength and toughness. Typical bending stress-deflection curves for extruded composites demonstrate a significantly large deflection at the peak load, as shown in Fig. 4.5(b). Figure 4.5(b) also shows that the composite's flexural strength obtained from the three-point bending test was about three times greater than the composite's tensile strength (Shao, Marikunte, and Shah 1995; Shao and Shah 1997).

Thin cementitious products reinforced with asbestos fibers have been in service since the turn of the century, and much information is available with regard to their long-term durability. On the other hand, thin products reinforced with polymer fibers are relatively new, and comprehensive information concerning their long-term durability is not readily available. Akers et al. (1989) discussed the long-term durability of polyvinyl alcohol reinforcing fibers in cements by conducting tensile tests on fibers extracted from cementitious composites that had been subjected to accelerated aging. In their studies, although some loss in fiber tensile strength was observed, the authors concluded that the polyvinyl alcohol fibers were adequately durable for use as a reinforcement for cementitious composites. Haehne (1986) studied the alkali resistance of polyacrylonitrile fibers in an alkaline medium of pH 12. He found a 10% decrease in composite tensile strength and 15% loss in composite elastic modulus in the first few months of a 12-month test under ambient conditions. The loss in properties leveled off and it was concluded that the polyacrylonitrile fibers had adequate durability. Gale, Guckert, and Shelbume (1990) studied the durability of cementitious products reinforced with oriented polyethylene pulp using accelerated tests. They reported excellent retention of composite properties in these tests, which was consistent with the known alkali stability of polyethylene. Keer (1990) studied the strength retention of cementitious composites reinforced with polypropylene network and predicted a lifetime durability of at least 30 years.

4.4—Carbon fiber-reinforced products

Engineering properties of thin cementitious products reinforced with carbon fibers have been the subject of extensive laboratory studies. The experimental results presented as follows have mostly been obtained using isotropic pitch-based carbon fibers. Figure 4.6 shows load versus load-point displacement plots obtained in center-point flexure tests conducted on carbon fiber-reinforced cementitious composites (Ohama, Amano, and Endo 1985). The two parts of the figure correspond to 3 and 10 mm-long fibers, and the numbers represent the volume percentage of fibers. There is a major increase in the strength at the end of the linear portion of the curve with increasing fiber content. More importantly, there are almost one to two orders of magnitude increase in toughness brought about by the carbon fibers. The flexural behavior of cementitious composites reinforced with carbon fibers is influenced not only by the fiber length but also by other factors such as cement matrix strength, elastic modulus of fibers, fiber-matrix interfacial bond, aggregate size, and extent of fiber dispersion. The use of a finer aggregate size has been reported to improve both the flexural strength and the toughness (Ohama, Demura, and Sato 1987; Soroushian, Aouadi, and Nagi 1991).



(a)

(b)

Fig. 4.5—Mechanical properties of extruded thin cementitious composites reinforced with polyvinyl alcohol fibers: (a) tensile behavior; and (b) flexural behavior (Shao, Marikunte, and Shah 1995).

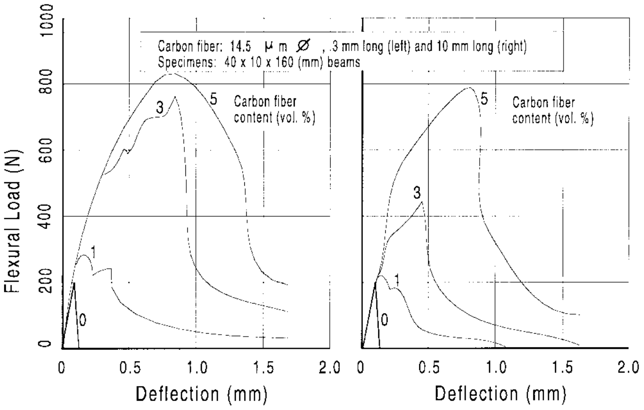


Fig. 4.6—Flexural behavior of carbon fiber-reinforced cement composites (Ohama, Amano, and Endo 1985).

Ohama, Amano, and Endo (1985) performed an impact test on 100 x 100 x 10 mm carbon fiber-reinforced plate specimen supported on a sand bed by consecutively dropping an 80 g steel ball from a height of 200 mm. A large increase in the number of blows required to cause cracking was observed with addition of fibers. Using the same test procedure but specimens of larger size (152 mm-diameter x 64 mm-thick circular specimens), Soroushian, Aouadi, and Nagi (1991) also reported an increase in the number of blows required to cause cracking in carbon fiber-reinforced composites. Instrumented impact tests in uniaxial tension were performed by Banthia and Ohama (1989) using a modified Charpy impact test machine, and the results confirmed the improvement in impact resistance with the inclusion of carbon fibers.

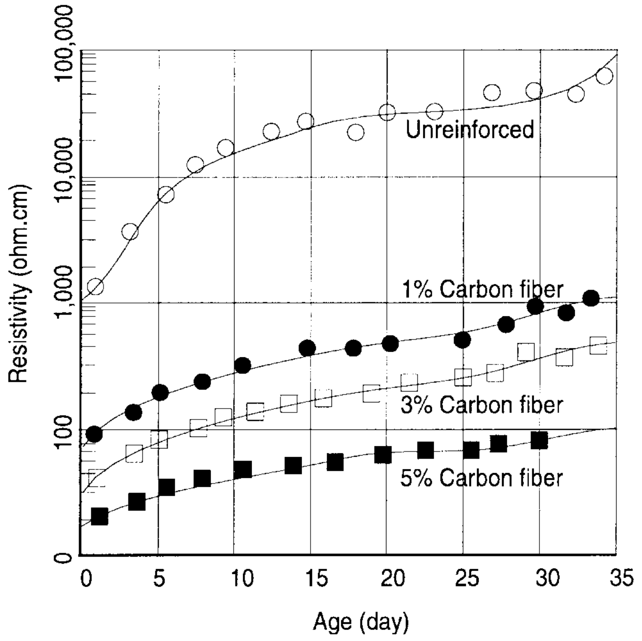


Fig. 4.7—Reduction of electrical resistivity of thin cementitious composites by carbon fibers (Banthia, Djeridane, and Pigeon 1992).

Carbon fibers in cementitious matrixes also help to reduce movements due to drying shrinkage and crack widths due to restrained shrinkage (Akihama, Suenaga, and Nakagawa 1988; Ohama, Demura, and Sato 1987; Soroushian, Aouadi, and Nagi 1991). The resistance to freezing and thawing of carbon fiber-reinforced cements was studied in tests performed in accordance with ASTM C 666. After 300 cycles, the decrease in dynamic modulus of elasticity was insignificant (Akihama, Suenaga, and Banno 1986). Soroushian, Nagi, and Austin (1992) have also reached a similar conclusion in their investigation.

Carbon fibers are basically chemically inert. Pitch-based fibers are more than 90% elemental carbon and are not corroded in the alkaline cementitious environment. Although carbon fibers are attacked by strong oxidizing agents such as nitric and sulfuric acids (Ohama, Demura, and Sato 1987), their composites can maintain strength and toughness when subjected to cyclic exposures of weak acids (pH = 4.0) for up to 90 days (Banthia et al. 1991). Compressive strength of carbon fiber-reinforced composites may decrease under the action of a 5% hydrochloric acid solution, but additives such as latex are helpful in reducing such effects (Soroushian, Aouadi, and Nagi 1991).

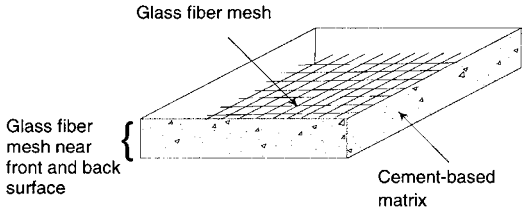
Deterioration in material durability and mechanical performance has been reported in cases where high-modulus carbon fibers are used in combination with a very dense silica fume matrix (Bentur 1994; Katz and Bentur 1995, 1996). This drop in mechanical performance results is most likely due to the densification of the fiber-matrix interfacial transition zone in the presence of silica fume. Densification of the fiber-matrix interfacial transition zone leads to a reduction in the ability of fibers to slip with respect to the surrounding matrix, thereby causing a more brittle composite response. This mechanism is similar to that observed in composites reinforced with AR-glass fibers (Bentur 1994). Theoretical analysis and experimental investigations suggest that such effects are more likely to occur with high-modulus, brittle fibers (such as PAN carbon fibers) than with the low-modulus, pitch carbon fibers (Katz and Bentur 1995).

Cementitious materials are ordinarily poor conductors of electricity, but there are instances when a high electrical conductivity may be desirable, such as in the case of conductive floor panel systems. Because carbon fibers are good conductors of electricity, the electrical conductivity of carbon fiber composites has been studied. Figure 4.7 shows a plot of the electrical resistivity of carbon fiber-reinforced cement as a function of age for various fiber volume fractions (Banthia, Djeridane, and Pigeon 1992). A reduction in the electrical resistivity by two to three orders of magnitude may be noticed. This reduction is proportional to the fiber volume fraction of carbon fibers in the composite.

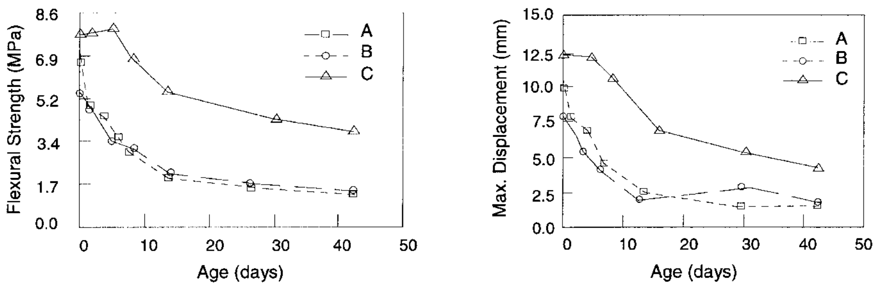
Uniform dispersion of carbon fibers at large volume fractions and processing of resulting cementitious matrixes has been a challenge. The amount of cementing material and its fineness can have a significant influence on the maximum amount of carbon fibers that can be incorporated in cementitious matrixes. With conventional mortar mixing and using cements with normal fineness (for example, ASTM Type I portland cement), approximately 1% volume fraction of carbon fibers can be uniformly incorporated. Using finer cement and substantial quantities of high-range water-reducing admixture, the fiber volume fractions can be increased to approximately 3% (Sheng 1996). Beyond this fiber volume fraction, the use of a suitable dispersing agent becomes necessary. The most commonly used dispersing agents are carboxyl methyl cellulose (Ando et al. 1990), silica fume (Banthia 1992; Ohama, Amano, and Endo 1985), and slag (Furukawa, Tsuji, and Miyamoto 1987). For carbon fiber-reinforced cement, a silica fume/cement ratio of 0.20 or more and a minimum high-range water-reducing admixture of 2% by weight of cement have been suggested (Ohama and Amano 1984). The availability of specialized mixers has also facilitated uniform mixing and dispersion of carbon fibers at high fiber volume fractions (Ando et al. 1990; Soroushian, Aouadi, and Nagi 1991).

4.5—Hybrid fiber-reinforced products

Hybrid fiber-reinforced cementitious products contain two or more types of fibers as the form of composite reinforcement. The use of hybrid fibers as reinforcement in thin cementitious products has also been an important subject of investigation. Table 4.3 depicts properties of thin cementitious products reinforced with hybrid polymeric fiber systems comprising of polyvinyl alcohol (PVA) fibers, polyethylene (PE) pulp, and polyacrylonitrile (PAN) fibers (Gale, Guckert, and Shelbume 1990). The results are compared with the performance of thin cementitious products reinforced with asbestos and cellulose fibers. In the results reported in Table 4.3, the flexural toughness of composite was calculated by integrating the area under the flexural stress-strain curve until the peak stress was attained. The cementitious products reinforced with hybrid polymeric fiber systems are significantly



(a) Schematic of a mesh reinforced cement board



(b) Composite flexural strength

(c) Composite maximum flexural displacement at failure

Fig. 4.8—Effects of extended hot-water immersion on flexural performance of cement boards reinforced with three different types of glass fiber meshes: Mesh A, B, and C are composed of similar fiber glass yarn but with different types of chemical coating (Venta, Cornelius, and Hemmings 1995).

tougher than their counterparts reinforced with asbestos fibers. Carbon fibers have also been studied in cement composites in conjunction with other microfibers such as steel (Banthia, Sheng, and Ohama 1990; Banthia, Djeridane, and Pigeon 1992) and polypropylene (Banthia and Ohama 1989). The various fibers maintain their individual reinforcing capabilities in these hybrid composites. This may lead to tailor-made cementitious composites with a desired combination of mechanical and physical properties. Effects of carbon, polypropylene, and ceramic fibers on mechanical performance of thin cementitious composites have also been studied (Mobasher and Li 1996b). Both the strength and crack-resistant properties of composites significantly improve with the use of a hybrid combination of brittle and ductile fibers.

4.6—Mesh/mat-reinforced products

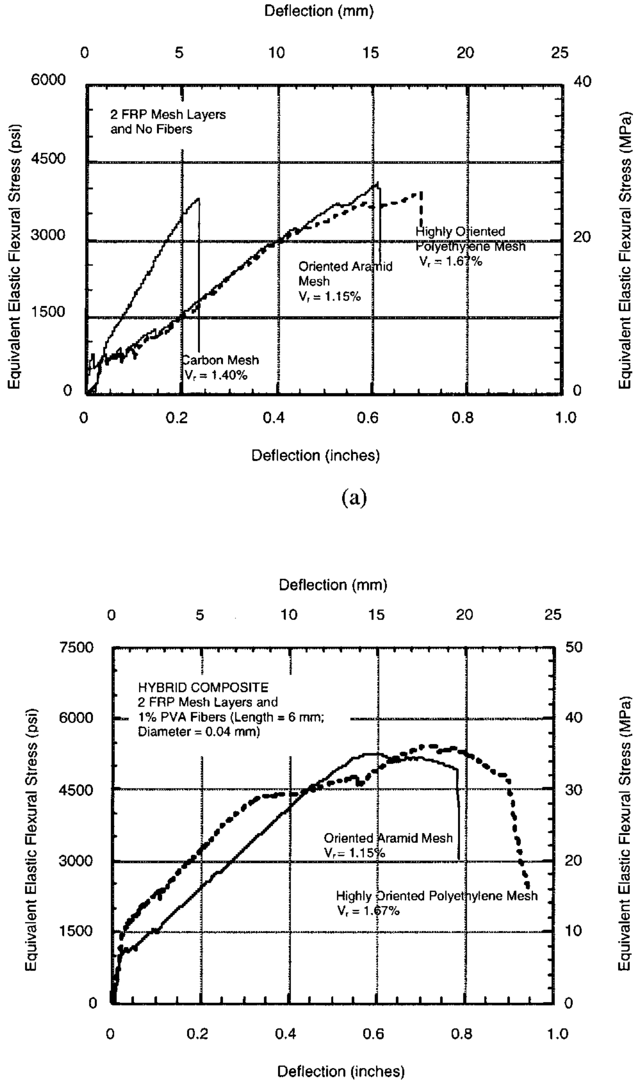
Thin reinforced cementitious products reinforced with meshes and mats are commercially produced worldwide. Many thin cementitious products that typically incorporate wire mats and meshes as reinforcement are commonly referred to as ferrocement. Readers are referred to ACI 549R for further information on mechanical properties and applications of ferrocement, and to Naaman (2000), where an extended definition is used to accommodate both compatibility of the matrix and the addition of discontinuous fibers.

Thin cementitious flat panels reinforced with meshes are used in a variety of applications in building construction, both residential and commercial. The most common application of mesh-reinforced cementitious panels is using them as substrate walls or floor panels for installation of finish materials such as ceramic tiles, marble, granite, and cementitious plaster finishes. The majority of thin cementitious panels that are commercially available in North America today are reinforced on surfaces with glass fiber mesh (Fig. 4.8(a)). These glass fiber meshes typically tend to be bidirectional and possess equal strength in both directions. Also, these

Table 4.3—Typical properties of cement products reinforced with polymer fibers, cellulose fibers, and asbestos fibers (Gale, Guckert, and Shelbume 1990)

	Properties	
Product type[*][†][‡]	Flexural strength, MPa	Flexural toughness,[§] N/m^2
Product reinforced with 2.0% PAN by weight and 2.5% PE pulp by weight	28.0	0.10
Product reinforced with 2.0% PVA by weight and 2.5% PE pulp by weight	23.7	0.25
Commercial asbestos (ambient curing)	30.2	0.02
Commercial asbestos (autoclaved)	14.1	0.005
Commercial cellulose (autoclaved)	13.5	0.10

[*] PAN = polyacrylonitrile.
[†] PVA = polyvinyl alcohol.
[‡] PE = polyethylene.
[§] Composite flexural toughness calculated by integrating the area under the flexural stress-strain curve until the peak stress is reached.

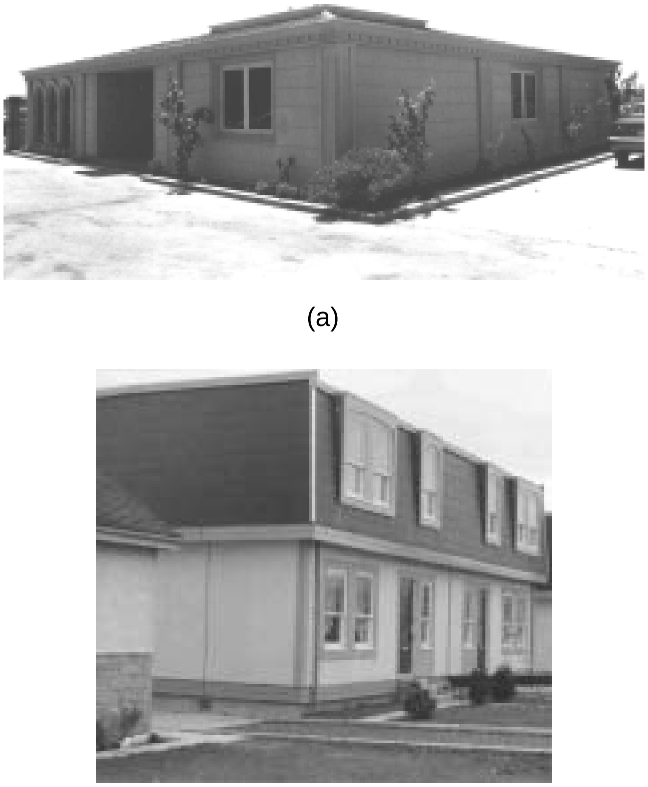


(a)

(b)

Fig. 4.9—Influence of meshes made from high-performance materials on the flexural behavior of thin cementitious composites: (a) flexural behavior of composites reinforced with meshes only; and (b) flexural behavior of composites reinforced with meshes and discrete polyvinyl alcohol fibers (Naaman 2000; Naaman and Chandrangsu 2000).

meshes are coated with specialized polymer coatings that improve their long-term durability performance. Figure 4.8 shows the long-term durability performance of thin cementitious panels reinforced with glass fiber mesh evaluated using the extended hot water exposure test (ASTM C 1325). Figure 4.8(b) and (c) show the effects of long-term exposure in hot water (at 80 °C) on flexural strength and maximum deflection at failure. The three curves in Fig. 4.8(b) and (c) correspond to different glass meshes with similar fiber glass yarn but with different types of chemical coating. The relatively superior performance of the glass fiber mesh "C" in comparison to mesh "A" and mesh "B" is attributed to the effectiveness of the coating used to inhibit alkali attack of cementitious matrix on glass fibers.



(a)

(b)

Fig. 5.1—(a) A modular building constructed using thin reinforced cementitious sandwich panels; and (b) a timber frame house involving thin reinforced cementitious panel for exterior wall construction.

Mechanical behavior of thin reinforced cementitious composites reinforced with meshes made from high-performance reinforcing materials, such as carbon mesh, oriented aramid mesh, and highly oriented, high-strength polyethylene mesh, has also been investigated (Naaman 2000; Naaman and Chandrangsu 2000) as shown in Fig. 4.9(a). The volume fraction of mesh reinforcement in these composites is also shown in the same figure. Cementitious composites with bending strengths in excess of 35 MPa can be obtained with the use of these high-performance reinforcements. Figure 4.9(b) shows the influence of adding discrete polyvinyl alcohol fibers on the mechanical performance of composites reinforced with two layers of oriented aramid mesh and two layers of highly oriented, high-strength polyethylene mesh. Incorporation of discrete fibers in the composite leads to significant improvement in bending strength and toughness. The addition of fibers can be helpful in producing finer crack widths and smaller crack spacing.

CHAPTER 5—APPLICATIONS OF THIN REINFORCED CEMENTITIOUS PRODUCTS

5.1—Claddings

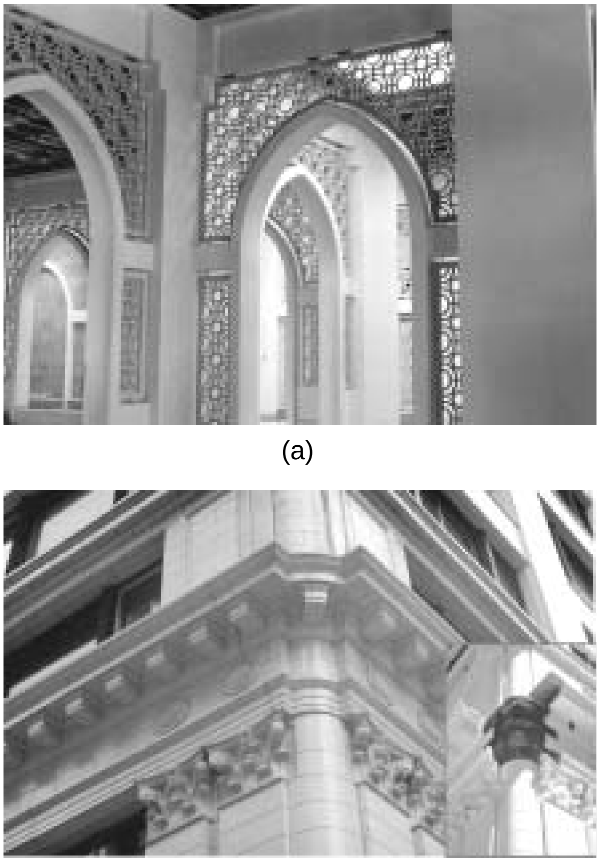
5.1.1 *Modular buildings*—Single- or two-story modular buildings have been constructed with fiber-reinforced cementitious sandwich panels integrated into a steel structural frame during erection. Figure 5.1(a) shows an example of such a system. Sandwich construction of the panel involves two 8 mm-thick fiber-reinforced concrete skins attached onto

Fig. 5.2—Architectural façade panels, Cervantes Convention Center, St. Louis.

both sides of the 155 mm-thick core of lightweight concrete. The thin cementitious panels used in this building are reinforced with AR-glass fibers. This building system has been tested for load capacity, sound insulation, thermal conductivity, and fire resistance.

In the late 1970s, thin reinforced cementitious panels were used on exterior walls of the prefabricated timber frame houses constructed to meet the shortage of dwellings in Scotland. Figure 5.1(b) shows a photograph of such a dwelling. The panels were typically 10 mm thick and had an aggregate finish surface. Simple cast-in washers for face fixing the panels were incorporated at 50 mm on center. Wind pulloff tests conducted on the wall systems yielded results in excess of those needed for the 200 km/h gusts occasionally found in that geographical region. Organic adhesive was used to make connection between the adjacent panels. The panels used were reinforced with AR-glass fibers. The houses inspected 20 years after construction by the Glass Reinforced Cement Association (GRCA), UK, were in good and serviceable condition.

5.1.2 *Architectural façade panels*—Thin reinforced cementitious architectural façade panels can be cast as wall and window wall units, spandrel, soffit and fascia panels, mansard roof elements, mullions, cornices, and column covers. Figure 5.2 shows the Cervantes Convention Center situated in St. Louis in which 1670 m^2 of the building exterior was clad with thin reinforced cementitious architectural façade panels. GFRC was used as the material to manufacture the panels. The size of the panels used in the building varied, but the average size was approximately 2.4 x 6.0 m. The panel skin consisted of 12.5 mm-thick GFRC plus a 6 mm-thick facing mixture. The GFRC skins were attached to a structural steel frame, which in turn was attached to the building. In several panels, two finishes were combined on the same panel. A brick-red finish on the panels was achieved with the use of white cements, sands, and pigments. The intricate architectural details on these panels were created by forming the panels over rubber liner molds. Some panels also had limestone finish, which was achieved with the use of crushed stone, pigment, and sandblasting.



(a)

(b)

Fig. 5.3—Thin reinforced cementitious interior/exterior sunscreen, arches, and panels in Kuwait; and (b) spandrels, columns, capitals, and flat panels match the color and texture of the existing terra cotta in a building located in Chicago.

5.1.3 *Architectural elements*—Thin cementitious architectural elements are commonly used in specialized building construction. These architectural elements fulfill an aesthetic role and have no structural functionality. Thin cementitious architectural elements are capable of closely imitating natural materials, which generally tend to be relatively very expensive and in short supply. Thin, complex shapes with excellent surface finish and surface details can be easily formed using fiber-reinforced cementitious materials. Molds to form these shapes are frequently taken from deteriorated original carvings. Thin cementitious architectural elements tend to be light in weight and require low maintenance. These attributes make thin cementitious architectural elements a sensible choice for both new and refurbished buildings. Figure 5.3 shows two application examples of thin cementitious architectural elements.

5.1.4 *Exterior wall siding panels*—Thin reinforced cementitious siding panels for cladding exterior walls in light-frame construction are used commercially in North America. The primary function of the exterior wall siding panels in buildings is to act as a finishing element of exterior walls. The thickness of the exterior wall siding panels is approximately 6 to 8 mm. The exterior wall siding panels are available in widths up to 300 mm and lengths up to 5 m. The exterior wall siding panels available in North America are reinforced with cellulose fibers and are manufactured using the Hatschek process.

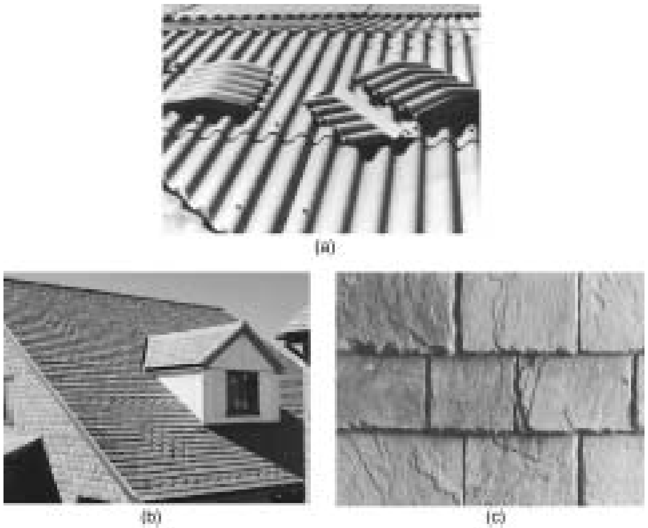


Fig. 5.4—Thin reinforced cementitious roofing panels and tiles: (a) field use of thin reinforced cementitious corrugated roofing panels; (b) use of thin reinforced cementitious roofing tiles in residential construction; and (c) a closeup photograph of simulated stone roofing tiles.

Figure 5.5—Mesh-reinforced cement board substrate for installation of ceramic tiles in wet areas (walls and floors) in buildings.

5.2—Roofing panels and tiles

Thin reinforced cementitious products are commonly used for roofing applications in building construction. Some examples of these products include corrugated roofing panels and roofing tiles. Figure 5.4(a) shows an example of the use of thin reinforced cementitious corrugated roofing panels. Similarly, Fig. 5.4(b) and (c) show examples of thin reinforced cementitious roofing tiles. These roofing tiles are generally designed to possess the aesthetics of natural quarried slates and wood shakes commonly used for roofing applications. The products shown in these photographs contain AR-glass fibers as the primary reinforcement. Thin cementitious roofing products reinforced with other fibers types, such as cellulose fibers, are also commercially available and are popular in building construction. The simulated slate GFRC roofing tiles are manufactured using the cast premix process. ASTM C 1225 and ASTM C 1459 are two standards that cover the use of thin reinforced cementitious products for roofing applications. In addition, the thin reinforced cementitious roofing tiles in North America generally comply with ICC (International Code Council) standards for roofing tiles.

5.3—Substrate panels

5.3.1 *Substrate panels for installation of ceramic tiles and other finishes*—Lightweight cement boards are commonly used as substrates for the installation of ceramic tiles in wet areas in residential and commercial buildings. Typical application areas of lightweight cement boards in buildings include bathroom walls and floors, and kitchen floors and countertops. The following two varieties of lightweight cement boards are very popular for this application:

- Mesh-reinforced cement boards; and
- Fiber-cement boards reinforced with discrete fibers such as cellulose.

The mesh-reinforced cement boards are composed of a lightweight concrete core, sandwiched between two layers of reinforcing mesh (Fig. 5.5). Typically, the reinforcing mesh is bidirectional and is composed of polymer-coated glass fibers for enhanced alkali resistance. The typical density of the mesh-reinforced cement boards ranges between 1100 to 1350 kg/m^3, and the typical weight of a nominal 12.5 mm-thick cement board ranges between 1.3 to 1.6 kg/m^2. These cement boards are moisture resistant, dimensionally stable, mold and mildew resistant, and noncombustible. The typical dimensions of the commercially available mesh-reinforced cement boards are: length: 1.2 to 2.4 m; width: 0.8 to 1.2 m; and thickness: 6 to 16 mm. Other types of finish materials, such as ceramic mosaics, marble tiles, glass tiles, thin stone tiles, thin bricks, cement-based plasters, and gypsum-based plasters, can also be applied over the lightweight cement boards. The use of lightweight cement boards as a substrate panel is covered by ASTM C 1325, ASTM C 1288, ASTM C 1186, and ANSI A118.9.

5.3.2 *Substrates for exterior wall finish systems*—In light-frame wood and steel construction, lightweight cement boards, such as mesh-reinforced cement boards and cellulose fiber-reinforced cement boards, are commonly used in two types of exterior façade systems. These systems are generally termed as “direct-applied exterior finish system (DEFS)” and “exterior insulation and finish system (EIFS).” The primary function of lightweight cement boards in these systems is to act as a suitable substrate for the application of different layers/components of exterior finishes. Typically, the lightweight cement boards used in these applications have a density in the range of 1100 to 1350 kg/m^3, lengths in the range of 1.2 to 2.4 m, widths in the range of 0.8 to 1.2 m, and thicknesses in the range of 6 to 16 mm.

Thin reinforced cementitious products, such as exterior façade cladding, EIFS, or DEFS, differ from portland cement-based plastering. Portland cement-based plastering is not in the scope of this report and readers are referred to ACI 524R, “Guide to Portland Cement Plastering,” for more details on that topic.

A DEFS incorporating lightweight cement boards is popular in both residential and commercial buildings in temperate climates where additional insulation is not an

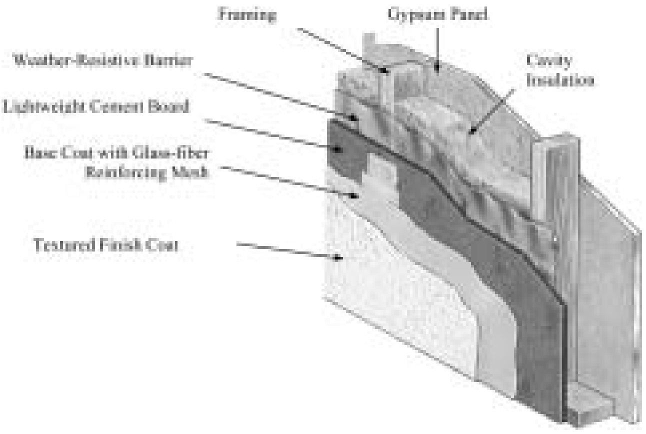


Fig. 5.6—Direct-applied exterior finish system (DEFS) incorporating lightweight cement board and aggregated, acrylic polymer decorative finish coat.

essential requirement to minimize the energy losses occurring from the building. Figure 5.6 illustrates a typical DEFS façade wall design. DEFS exterior walls generally have these components:

- Weather-resistant barrier (applied over the framing);
- Lightweight cement board substrate (applied over the weather-resistant barrier and mechanically fastened to the framing);
- Basecoat (applied over the lightweight cement board);
- Glass fiber mesh (embedded in the base coat); and
- Finish coat (applied over the basecoat). Typically, the finish coat is one of the following:
  - Aggregated, acrylic polymer decorative finish coat; or
  - Ceramic tiles or thin-bricks installed directly over the layer of basecoat using latex-modified portland cement mortar bond coat.

An EIFS is particularly useful in cold climates where additional insulation is sought to minimize the energy losses occurring from the building. Architects and builders can easily use an EIFS to create intricate design detailing such as cornices, quoins, and other decorative accents that are often cost-prohibitive when using traditional stucco construction techniques. Figure 5.7 illustrates a typical EIFS exterior façade wall design incorporating mesh-reinforced cement board as a substrate panel. EIFS exterior walls incorporating mesh-reinforced cement boards generally have these components:

- Weather-resistant barrier applied over the framing for water-managed EIFS;
- Lightweight cement board substrate (applied over the weather-resistant barrier and mechanically fastened to the framing);
- Foam plastic insulation board (adhesively applied or mechanically fastened over the lightweight cement board);
- Basecoat (applied over the foam plastic insulation board);
- Glass fiber mesh (embedded in the base coat); and
- Aggregated, acrylic polymer decorative finish coat (applied over the basecoat).

The use of lightweight cement boards for exterior wall construction and finish systems is covered by ASTM C 1186, ICC-ES Acceptance Criteria AC24, and ICC AC59.

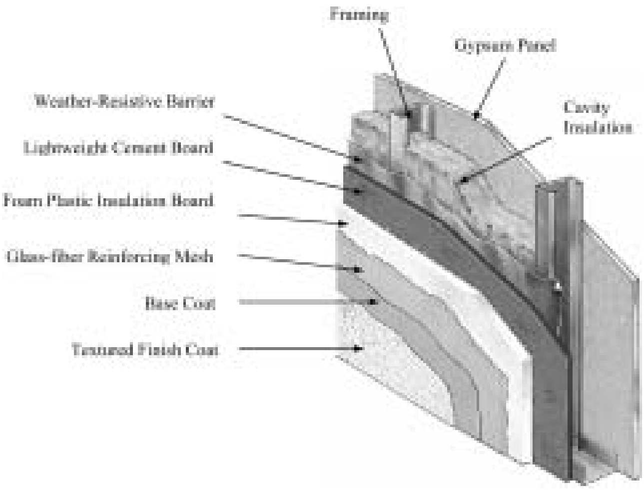


Fig. 5.7—An exterior wall based on exterior insulation and finish system (EIFS) incorporating lightweight cement board as a substrate panel.

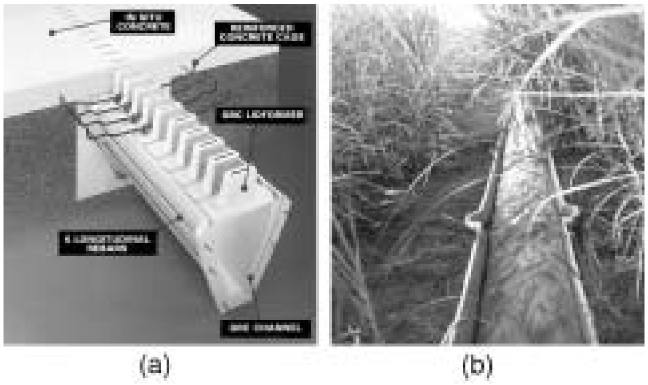


Fig. 5.8—Thin reinforced cementitious drainage ducts and channels: (a) rainwater drainage channel for roads; and (b) irrigation channel for transporting water to irrigate the fields.

5.4—Ducts, channels, and conduits

5.4.1 *Drainage ducts and channels*—Ducts and channels used for drainage and transporting liquids represent another application example of thin reinforced cementitious products. Figure 5.8(a) shows a commercially available rainwater drainage channel used in road and highway applications. Such channels have been widely used in the UK and are available in different cross-sectional sizes and lengths ranging up to 2 m. These channels are lightweight, easy to install in long sections, and require less excavation. The channels are generally produced by vibration casting a cementitious mixture containing discrete reinforcing fibers into a two-part mold. Figure 5.8(b) shows another application of a thin reinforced cementitious drainage channel in which it is used for transporting water for irrigation. Discrete AR-glass fibers, approximately 12.5 mm long added at a weight fraction of approximately 3.0%, have typically been used as reinforcement to commercially produce such channels.

5.4.2 *Cable ducts and conduits*—Cable ducts and conduits represent another application category of thin reinforced cementitious products. Figure 5.9 shows the use of cable ducts under a railway bridge. The cable duct and the

Fig. 5.9—Application of thin reinforced cementitious cable duct under a railway bridge.

Fig. 5.10—Thin reinforced cementitious panels used as tunnel linings, Heathrow Express Railway Station, Heathrow Airport, London.

corresponding lid shown in the figure are manufactured using the premix process and vibration casting. The use of circular conduits for carrying cables and electrical wire is covered by ASTM C 1448.

5.5—Linings

5.5.1 *Tunnel linings*—Thin reinforced cementitious panels have been widely used for tunnel lining applications. Figure 5.10 shows Heathrow Express Railway Station at the Heathrow Airport, London. The panels used in this application are nominally 12 to 18 mm thick and are made from a cementitious mixture reinforced with AR-glass fibers. Lining within the stations consisted of 9000 acid-etched and sandblasted panels 1.8 m long, 0.90 m wide, and 0.70 m deep. A 50 mm-deep recess in each panel allowed enamelled glass advertising panels to be secured within.

5.5.2 *Sewer linings*—Thin sewer linings made of fiber-reinforced cementitious materials have been manufactured and widely used in the UK. An application of fiber-reinforced cementitious sewer lining is shown in Figure 5.11. Thin reinforced cementitious linings bond to the adjacent grout lining and thereby become an essential component of the entire sewer structure. Consequently, thin reinforced cementitious sewer linings have good resistance to the damaging influences of water pressure or ground movement.

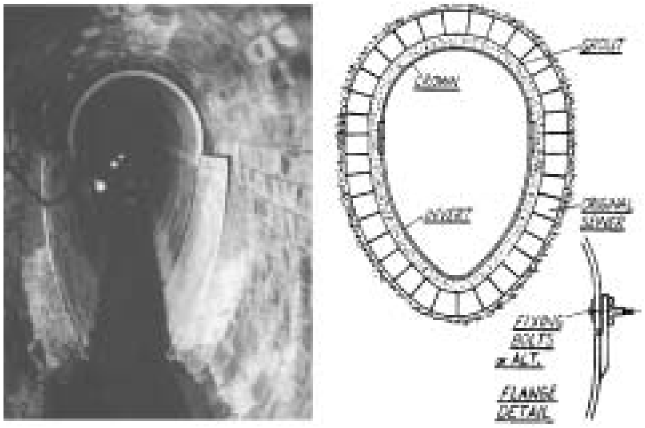
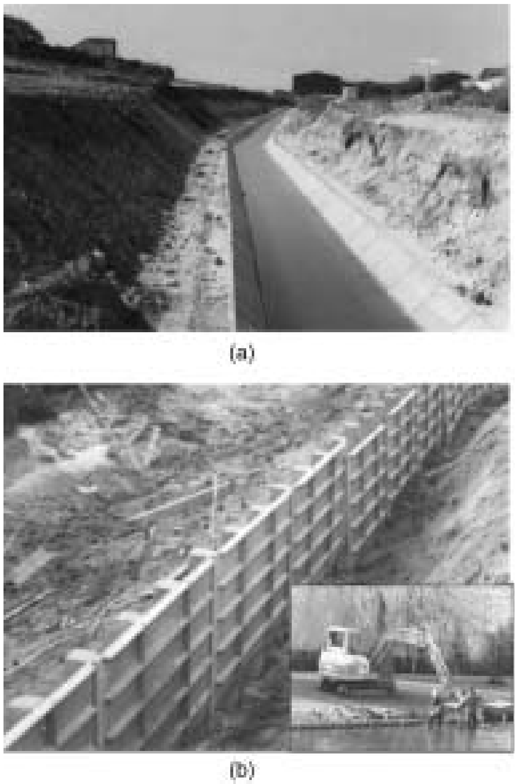


Fig. 5.11—Thin reinforced cementitious curved panels used as sewer linings.


(a)

(b)

Fig. 5.12—Thin reinforced cementitious panels used as canal bank protection linings.

5.5.3 *Canal bank protection linings*—Figure 5.12 demonstrates the use of thin reinforced cementitious products as canal bank protection linings. Such linings are used to prevent erosion of canal banks caused by different sources such as hydraulic discharge and incidental contact with the passing boats. Thin reinforced cementitious canal bank protection lining panels, as shown in the Fig. 5.12, are typically 6 to 9 mm thick, with ribs on rear face for enhanced strength and stiffness. The typical size of the panels shown in the figure is approximately 2 x 1.36 m. The panels shown in Fig. 5.12 are reinforced with AR-glass fibers.

Fig. 5.13—Thin reinforced cementitious pole.

5.6—Pipes and poles

Pipes and poles represent another application category of thin reinforced cementitious products. Most thin reinforced cementitious pipes that are commercially available today are reinforced with cellulose fibers and are generally manufactured using the Hatschek process. These pipe products have a diameter of up to 1.2 m and are typically designed for sewer and storm-water drainage applications. ASTM C 1447, ASTM C 1449, and ASTM C 1450 cover the use of thin reinforced cementitious pipe products.

The filament winding process has also been used to manufacture thin reinforced cementitious pole products. Figure 5.13 shows a pole product manufactured using the filament winding process. In this application example, continuous AR-glass fiber rovings were used to reinforce the product. The fiber volume fraction in such composites can be as high as 25%. The pole products produced using the filament winding process are exceptionally strong in tension (~90 MPa), compression (~175 MPa), and flexure (~150 MPa). Using the filament winding process, the pole products can be easily manufactured in lengths of up to 15 m. Potential applications of the pole products include induction and wireless transmission-invisible poles and permanent formwork for seismic and marine columns.

5.7—Acoustical wall panels and noise barriers

Thin reinforced cementitious panels are commonly used as a component in acoustically rated walls. Figure 5.14(a) shows the use of thin reinforced cementitious acoustical wall panels at the TGV railway station of the Charles de Gaulle International Airport in Paris. The size of an individual panel is 1.6 x 1.4 m. The panels are comprised of two skins that are 22 mm thick and a core of insulation material that is 100 mm thick. The skins of the cementitious panels are perforated and are reinforced with AR-glass fibers. The panels are designed to withstand pressures caused by the passing trains at speeds as high as 160 km/h with a factor of safety of 10.

Where major traffic routes are close to commercial and residential areas, it often becomes necessary to take measures to suppress the noise pollution to the surroundings. As a response to this problem, thin-section cementitious noise barriers are increasingly being used worldwide. This is primarily because they are lightweight and offer simplicity and speed of erection without requiring the use of heavy lifting machinery. This results in minimal disruption to traffic and greatly reduced loads on the elevated structures. Thin cementitious noise barriers with aesthetically pleasing design solutions are easily produced and are attractive and acceptable to both residents and travelers, as well as to highway engineers and architects. Thin cementitious barriers also possess excellent environmental durability characteristics such as resistance to salt attack, freezing and thawing, and rotting. Figure 5.14(b) shows the use of thin reinforced cementitious products as noise barriers.

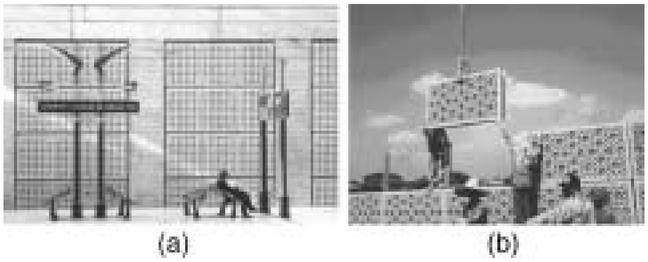


Fig. 5.14—(a) Use of thin reinforced cementitious acoustical wall panels at the TGV railway station, Charles de Gaulle International Airport, Paris; and (b) thin reinforced cementitious noise barriers.

Fig. 5.15—Thin reinforced cementitious permanent formwork panels.

5.8—Permanent formwork

Thin reinforced cementitious products have been used as permanent formwork panels for placement of concrete in applications involving bridge decks, ceilings, and foundations. Figure 5.15 shows an example of thin cementitious formwork panels used in a concrete bridge deck application. In this application, the panels used were 1.0 m long and 12 mm thick. Panels had multiple 50 mm corrugated, trapezoidal sections built in to enhance the panel rigidity. Panels with the aforementioned configuration supporting a 250 mm-thick concrete slab over a span of 0.80 m yield a midspan deflection of approximately 1 mm. Greater spans are possible by altering the panel geometry. Formwork panels are available in a variety of widths, depending on the application and requirement. The weight of the formwork panel is typically about 17 kg/m^2. Thin reinforced cementitious formwork

Fig. 5.16—Thin reinforced cementitious parapets used on the BTS Skytrain in Bangkok, Thailand.

Fig. 5.17—Architectural rocks made using thin glass fiber-reinforced concrete.

panels give additional protection to the concrete deck steel reinforcement because of their exceptionally low permeability to both water and salts and low rate of carbonation.

5.9—Parapets

Figure 5.16 shows thin reinforced cementitious panels used on the BTS Skytrain—Thailand's first mass transit system located in Bangkok. The project extends approximately 23 km through the heart of the Bangkok and is entirely elevated. The parapets shown in this figure are typically 1.1 m high, 2.7 m long, and nominally 15 mm thick, with ribbed top and bottom using expanded polystyrene void-formers. The ribbing provides the panels with additional strength and rigidity to resist the high wind loads caused by the passing trains. The parapet panels shown in this figure are reinforced with discrete, AR-glass fibers.

5.10—Landscaping products

Thin reinforced cementitious products are widely used for manufacturing various types of landscaping products such as artificial rocks, hollow boulders, and planters. GFRC is widely used for simulated rock installations in zoos, hotels, office lobbies, swimming pools, climbing walls, golf courses, and theme parks. Figure 5.17 shows one such example of thin cementitious simulated rock installation. Thin cementitious panels are typically factory prefabricated, using the simultaneous spray process or sprayed premix process. The rubber molds that are used for producing these prefabricated panels are generally castings of actual rock faces. The finished prefabricated panels are transported to the job site and assembled. The panels can be integrally colored during the manufacturing operation or can be colored on the job site using acrylic stains.

CHAPTER 6—SUMMARY

In addition to the use of discrete reinforcing fibers, the use of continuous reinforcements, such as meshes and mats, is becoming increasingly popular in thin cementitious composites. Thin reinforced cementitious products offer a useful balance of properties such as strength, toughness, dimensional stability, environmental durability, moisture resistance, fire resistance, asthetics, and ease of handling and installation. The future of thin reinforced cementitious products will largely depend on their ability to compete cost effectively with similar products made from other materials, such as plastics and metals. For future research and development, this entails understanding and optimizing fiber-reinforced cementitious compositions from a fundamental perspective, developing and implementing the use of cost-effective raw materials—particularly reinforcing fibers and other forms of reinforcement, and developing efficient manufacturing methods to produce thin reinforced cementitious products.

CHAPTER 7—REFERENCES

7.1—Referenced standards and reports

The standards and reports listed as follows were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute (ACI)

524R	Guide to Portland Cement Plastering
544.1R	State-of-the-Art Report on Fiber Reinforced Concrete
549R	State-of-the-Art Report on Ferrocement

ASTM International

C 666	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 1186	Standard Specification for Flat Non-Asbestos Fiber-Cement Sheets
C 1225	Standard Specification for Non-Asbestos Fiber-Cement Roofing Shingles, Shakes and Slates
C 1288	Standard Specification for Discrete Non-Asbestos Fiber-Cement Interior Substrate Sheets
C 1325	Standard Specification for Non-Asbestos Fiber-Mat Reinforced Cement Substrate Sheets
C 1447	Standard Specification for Non-Asbestos Fiber-Cement Underdrain Pipe
C 1448	Standard Specification for Non-Asbestos Fiber-Cement Conduit
C 1449	Standard Specification for Non-Asbestos Fiber-Cement Nonpressure Sewer Pipe
C 1450	Standard Specification for Non-Asbestos Fiber-Cement Storm Drain Pipe

C 1459 Standard Specification for Non-Asbestos Fiber-Reinforced Cement Shake, Shingle, and Slate Roofing Systems

American National Standards Institute (ANSI)

A118.9 American National Standard for Test Methods and Specifications for Cementitious Backer Units

International Code Council—Evaluation Service (ICC-ES)

AC24 Acceptance Criteria for Exterior Insulation and Finish System

AC59 Acceptance Criteria for Direct-Applied Exterior Finish Systems

Precast/Prestressed Concrete Institute (PCI)

MNL-128-01 Recommended Practice for Glass Fiber Reinforced Concrete Panels

These publications may be obtained from these organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

American National Standards Institute
11 West 42nd Street
New York, NY 10036

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428

ICC Evaluation Service, Inc.
5360 Workman Mill Road
Whittier, CA 90601

Precast/Prestressed Concrete Institute (PCI)
209 W. Jackson Blvd.
Chicago, IL 60606

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