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Report on Thin Reinforced Cementitious Products

Reported by ACI Committee 549



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Report on Thin Reinforced Cementitious Products

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Report on Thin Reinforced Cementitious Products

Reported by ACI Committee 549

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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.

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

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

Material type	Property			
	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

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.

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.

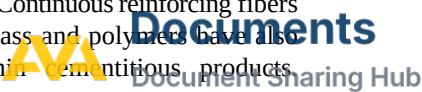
Chapter 2 describes different types of reinforcements used to produce thin reinforced cementitious products. Known and popular manufacturing methods of thin reinforced cementitious products are described in Chapter 3. Chapter 4 describes the engineering properties of thin reinforced cementitious products.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



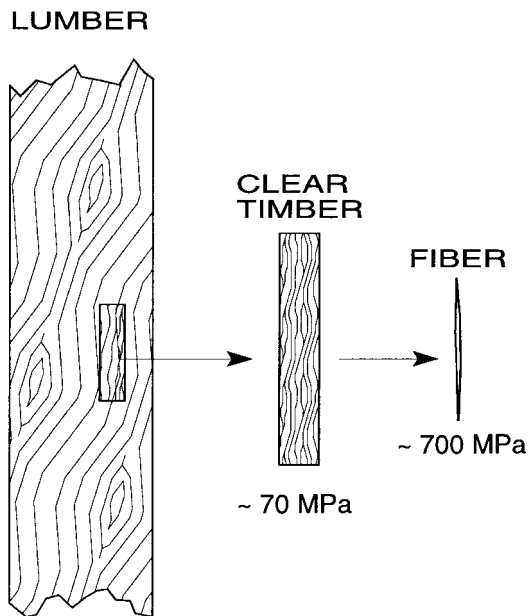


Fig. 2.1—Schematic presentation of the substructure of wood (Coutts 1983).

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 (pulp) 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

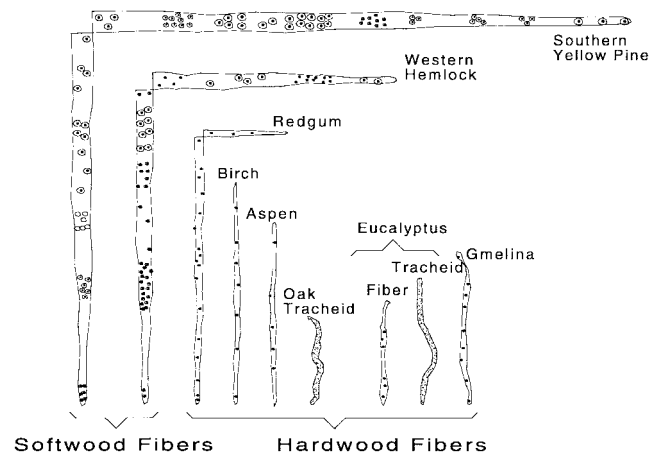


Fig. 2.2—Major fiber types in softwoods and hardwoods (Kocurek and Stevens 1983).

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

of book paper and writing paper, whereas mechanical pulp is used regularly for the manufacture of newsprint.

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 ₂ O	—	14.8 to 15.0
CaO	22.0	—
MgO	0.5	—
K ₂ O	0.8	0.0 to 2.0
Al ₂ O ₃	15.0	0.0 to 0.8
Fe ₂ O ₃	0.3	—
B ₂ O ₃	7.0	—
ZrO ₂	—	16.7 to 20.0
TiO ₂	—	0.0 to 0.1
Li ₂ O	—	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 2.5 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 2.4—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—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	Excellent

*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 Chandrangu 2000) for producing high-performance thin cementitious composites.

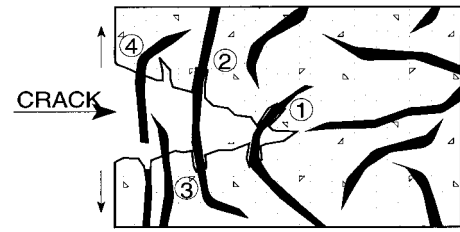
2.3.3 Metal wire meshes and mats—Many thin cementitious products that typically incorporate metal wire mats and meshes as reinforcement are commonly referred to as ferrocement. ACI 549R provides the following definition: "Ferrocement is a type of thin wall reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small size wire mesh. The mesh may be made of metallic or nonmetallic 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.

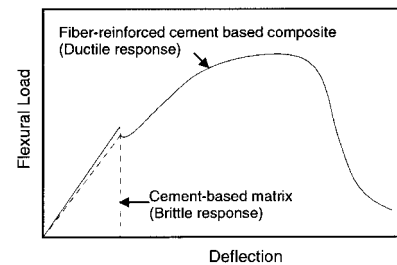
Carbon steel and stainless steel fibers are available in nonwoven mat forms. The fibers used in making such mats are typically produced by shaving (as in traditional steel wool manufacture), drawing (generally used for diameters below 50 μm), or direct casting (generally suitable for stainless steel 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

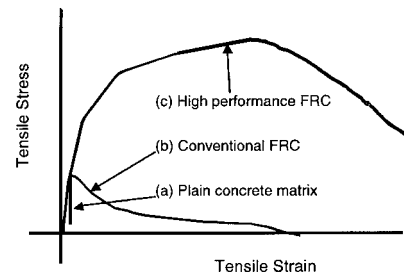
Failure in a cementitious composite emanates from defects such as flaws in the matrix and debonding at interfaces. Fibers in brittle cementitious materials help to enhance the composite toughness and tensile strength by interacting with the microcracks that develop when the composite is loaded. Fibers 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



(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).

hindering the growth of microcracks, distributing microcracks, and increasing the strength and toughness of the composite.

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 the matrix 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

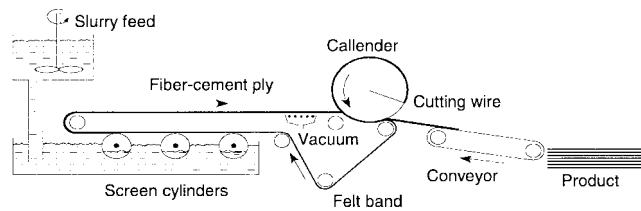


Fig. 3.1—The Hatschek process for manufacturing fiber-cement sheets.

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 Shelburne 1990) has been reported as having both reinforcement and filter fiber characteristics.

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,