Fiber-reinforced concrete in precast concrete applications: Research leads to innovative products

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- This paper summarizes common fiber types and their application in precast concrete.
- The role of fiber reinforcement in improving the mechanical properties and durability of cement-based systems is described.
- Recent findings illustrate the mechanisms that underlie the benefits accruing from fibers.

Fiber-reinforced concrete (FRC) is a composite material made of hydraulic cement or cements; water; fine and coarse aggregate; and short, uniformly dispersed discontinuous fibers. Fibers may be of steel, glass, polymeric materials, carbon, cellulose, and so forth, and their lengths vary from 3 to 64 mm (0.12 to 2.52 in.). The diameters may vary from a few µm to about 1 mm (0.04 in.). The sections may be round, oval, polygonal, triangular, crescent shaped, or even square depending on the manufacturing process and the raw material used. The two broad categories of fibers are micro and macro. Microfibers have diameters or equivalent diameters less than 0.3 mm (0.012 in.), and macrofibers have diameters or equivalent diameters greater than 0.3 mm. The equivalent diameter of a fiber is the diameter of a round fiber having the same cross-sectional area A as the fiber in question, that is, $\sqrt{4A/\pi}$.

Fibers may be used in concrete at volume fractions varying from 0.1% to 5%. The volume fraction is determined by both the ease of mixing and the application. For example, a low fiber dosage in the range of 0.1% to 0.3% is often provided for control of secondary stresses arising from shrinkage and temperature change. At dosage rates above 0.3%, the mechanical response of FRC is substantially

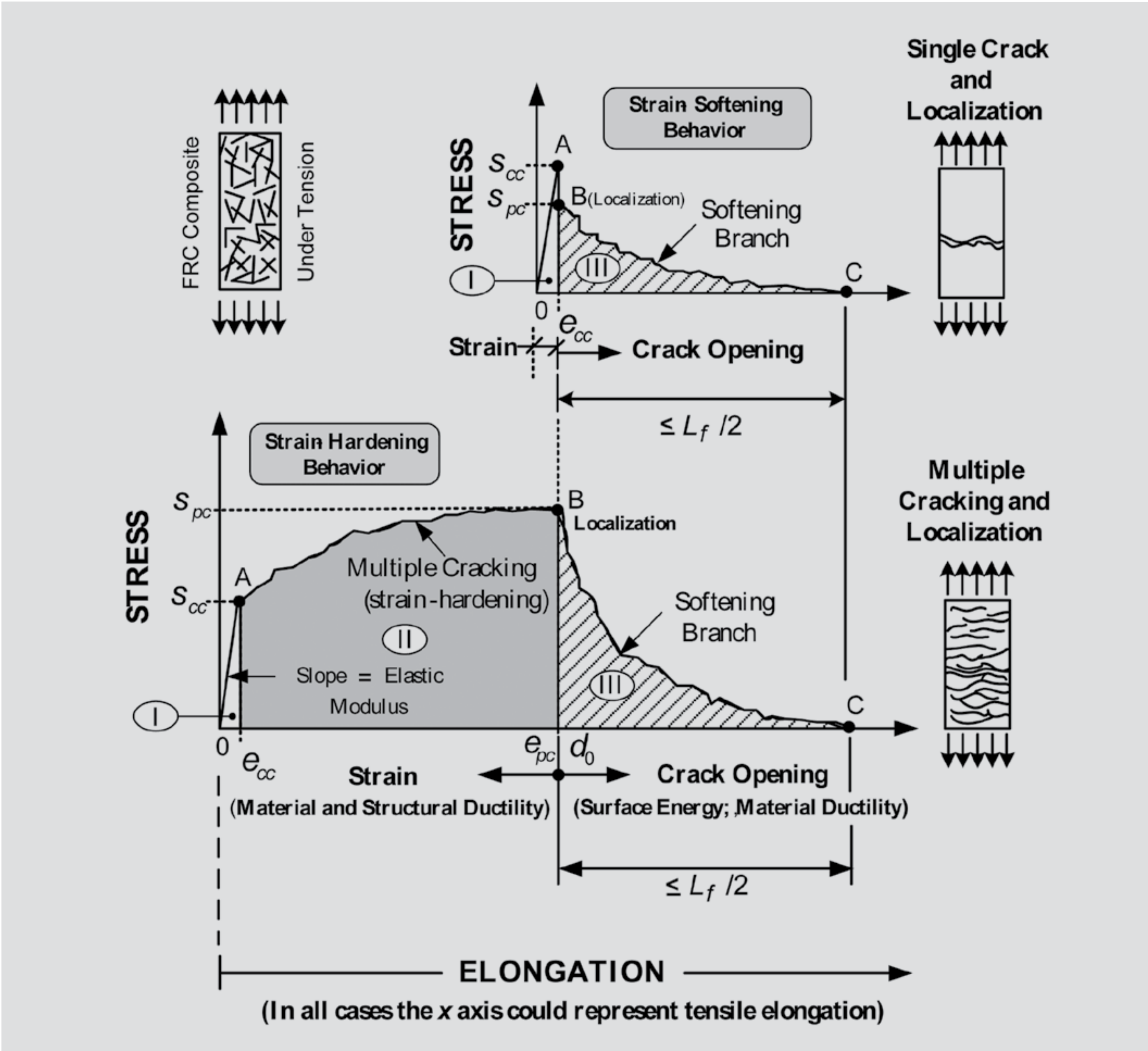


Figure 1. Description of the tensile stress-strain response of fiber-reinforced concrete and its relation to flexural behavior. Source: Naaman (2007).
Note: FRC = fiber-reinforced concrete; L_f = length of fiber; δ_0 = deflection; ε_{cc} = first cracking strain; ε_{pc} = postcracking strain; σ_{ee} = first cracking strength; σ_{pc} = postcracking strength in tension.

different from that of the plain matrix in that it has post-cracking load-carrying ability. The ability of FRC to absorb energy beyond matrix cracking is often termed *toughness*. At significantly higher dosages, in addition to postcrack toughening, FRCs can also exhibit strain hardening; that is, the composite can support stresses beyond the strength of the matrix. Multiple cracking is often noted in these pseudo-ductile composites, and significant energy absorption is achieved. **Figure 1** is a schematic description of the possible tensile response for a fiber-reinforced cement-based composite.[1]

Fibers used in precast concrete

ASTM C1116/C1116M[2] describes four types of FRC. Type I is steel-fiber-reinforced concrete (SFRC) containing stainless steel, alloy steel, or carbon steel fibers. Type II is glass-fiber-reinforced concrete (GFRC) containing alkali-resistant glass fibers. Type III is synthetic-fiber-reinforced concrete (SynFRC). Type IV is natural-fiber-reinforced concrete (NFRC).

Table 1 gives typical properties of fibers used for reinforcing cementitious materials. Representative fibers and their use in FRC are described in the following paragraphs.

Table 1. Properties of fibers used in concrete

Fiber type	Tensile strength, MPa	Tensile modulus, GPa	Tensile strain, % max to min	Fiber diameter, µm	Relative adhesion to matrix	Relative alkali stability
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	n.c.
Polyester	800 to 1300	up to 15	20 to 8	10 to 50	Fair	n.c.
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)	n/a	n/a	n/a	1 to 20	Good	Excellent
Highly oriented polyethylene (high molecular weight)	2585	117	2.2	38	Good	Excellent
Carbon steel	1000	200	2 to 1	50 to 85	Excellent	Excellent
Stainless steel	1000	200	2 to 1	50 to 85	Excellent	Excellent
Alkali-resistant glass	1700	72	2	12 to 20	Excellent	Good

Note: n/a = not applicable; n.c. = no consensus. 1 MPa = 145 psi, 1 GPa = 145 ksi.

Steel fiber

Steel fibers have relatively high strength and modulus of elasticity and are protected from corrosion by the highly alkaline matrix. The fiber-matrix bond can be enhanced by mechanical anchorage through surface roughness or deformation. ASTM A820[3] establishes the minimum tensile strength, bending requirements, and tolerances for steel fibers for reinforcing concrete.

Synthetic fibers

Developed primarily by the petrochemical and textile industries, synthetic fibers are nonmetallic fibers including polymers that are available in a variety of formulations. Following is an account of some of the commonly used synthetic fibers in precast concrete products.

Carbon The advantages of carbon-fiber reinforcement over steel, polypropylene, or glass fibers are in its inert nature, high modulus, thermal resistance, and long-term chemical stability in alkaline and other chemically aggressive environments. In addition, carbon-fiber reinforcement improves the mechanical properties.

Historically, the first uses of carbon fibers in cement-based matrices were in the form of high-modulus polyacrylonitrile fibers,[4] whereby significant improvements in the mechanical properties were noted. These carbon fibers are manufactured by carbonizing polyacrylonitrile yarn at high temperatures and then aligning the resultant graphite crystallites by a process called hot stretching. However, polyacrylonitrile-based fibers were not commonly used in FRC because of their high cost. In the early 1980s, interest in the use of carbon fibers in cementitious matrices was revived with the development of relatively inexpensive pitch-based carbon fibers.[5,6] Banthia[7] compares the properties of polyacrylonitrile and pitch-based carbon fibers.

Nylon Characterized by the presence of the amide functional group,[8] nylon represents a family of polymers. These fibers exhibit good tensile strength, high toughness, excellent elastic recovery, a hydrophilic character, and relative stability in cementitious matrices.[9] Their performance under accelerated aging conditions has been encouraging.[10]

Polypropylene Produced from the homopolymer polypropylene resin, this fiber has a low modulus of elasticity and also a low melting point, which may hinder its use in autoclaved precast concrete products.[11] However, the low melting point may be beneficial in producing refractory products or products with a high fire resistance because the fiber is expected to melt and provide a system of relief channels to dissipate internal pressure.

There are two types of polypropylene fibers available for concrete reinforcement, monofilament and fibrillated. These fibers are hydrophobic and exhibit a high contact angle with water. Hence they develop a poor bond with the matrix relative to hydrophilic fibers. In addition, there is no evidence of a chemical bond with the matrix. However, geometrical deformations obtained during the process of fibrillation can provide a mechanical bond with the matrix.[12]

Polyvinyl alcohol Polyvinyl alcohol (PVA) fiber is manufactured from PVA resin where a multistep high-stretch production process provides a high stiffness and water insolubility. A special surface treatment allows for improved fiber dispersion in cementitious systems.[13] Unfortunately, PVA fiber has a negative coefficient of thermal expansion, shrinking 4% in length at 200°C (392°F). PVA is generally resistant to alkaline and organic solvents but demonstrates a minor strength loss after long-term exposure to ultraviolet radiation.

Glass fibers

Glass fibers that are used in concrete must contain a minimum of 16% of zirconia for alkali resistance. Other glass fibers, such as E-glass fibers, are not recommended for use as concrete reinforcement. Glass fibers have a high modulus and high strength and develop a strong bond with concrete.

Glass-fiber-reinforced concrete (GFRC) is different from other fiber-reinforced concretes that typically use steel or polypropylene fibers. The primary difference is fiber content, in that GFRC typically has a fiber content of 4% to 6% by volume, whereas in other types of FRC the fiber content is usually 0.1% to 1% by volume. To achieve the high glass fiber content the concrete mixture has to have a high cement content and no large aggregate; typically the matrix of GFRC is a mixture of 50:50 cementitious material, such as cement or cement/pozzolan, to sand (typically 30/40 mesh). A full list of GFRC properties is given in PCI's *Recommended Practice for Glass Fiber Reinforced Concrete Panels*.[14]

Properties of fiber-reinforced concrete

Quasi-static and impact response

The role of fibers in improving the mechanical properties of concrete is well known. Experiments using the drop weight method that evaluates resistance to blows have shown that concrete specimens with polypropylene fibers at 0.1% to 0.2% by volume have higher impact strength for both first crack and final fracture compared with plain concrete.[15] Similar results were obtained for concrete of normal strength having deformed steel fibers.[16,17] There is no standard test method to evaluate the dynamic compressive response for fiber-reinforced concrete. Bischoff and Perry[18] found that the axial compressive strength of plain concrete increased 85% to 100%, but further research has shown that there is no postpeak ductility in the compressive response under impact loading largely because the concrete fragments do not bond to the fibers.[19] Also, whereas deformed steel fibers were seen to result in a dynamic impact factor of 3 at a strain rate of 50 s^{-1}, polymeric fibers did not perform any differently from plain concrete and had a dynamic impact factor of 1.5.[20]

Also, their study showed steel fibers with three-dimensional deformation to impart considerably higher dynamic impact factor in compression over those with two-dimensional deformation. However, there is a significant improvement to the tensile strength and postcrack residual flexural strength in cementitious systems under dynamic loading.[21,22] Fiber reinforcement improves the energy absorption capacity of concrete by enhancing its postpeak stress-transfer capability and, hence, is an effective way of improving concrete's resistance to impact. However, the choice of fiber type, its length, and its shape greatly influence these properties. As stated, there are various types of fibers, such as steel, synthetic, glass, and natural fibers. Short, discrete polymeric fibers increase the energy dissipated by concrete under impact loading,[23] sometimes even exceeding the dynamic impact factor of steel fibers.[24] A case may be made for hybrid fiber-reinforced systems that have both steel and a low-modulus fiber. The existing reports show synergy under impact for concrete with steel and cellulose fibers[25] and similarly for steel and polypropylene fibers.[26,27] The failure performance of polypropylene fibers is said to change from fracture to pullout in the presence of the steel fibers.

The performance of fibers in concrete under impact loading depends largely on how the fiber-matrix bond behaves at high rates of crack opening displacement. Bindiganavile and Banthia[28] used contoured double cantilevered beam specimens to find that at increasing loading rates, the steel-fiber-reinforced concrete shows greater crack growth resistance than a companion set of concrete specimens reinforced with polypropylene fibers. However, the latter appeared to catch up with the steel-fiber-reinforced specimens, presumably because polypropylene itself is more strain-rate sensitive than steel. This stiffening in the response of a low-modulus fiber under higher stress rates was manifest in the progressive drop of the crack opening displacement associated with peak bond stress in a fiber subjected to impact loading.[29] For instance, glass fibers were seen to pull out from an MgO-based ceramic matrix under quasi-static loading but without exception fractured under impact loading, leading to poor postcrack dynamic toughness.[30] However, at significantly higher dosage (about 2% by volume) these fibers imparted a substantial increase in the flexural strength under impact loading, which indicates fiber bridging and crack arrest during subcritical crack growth.

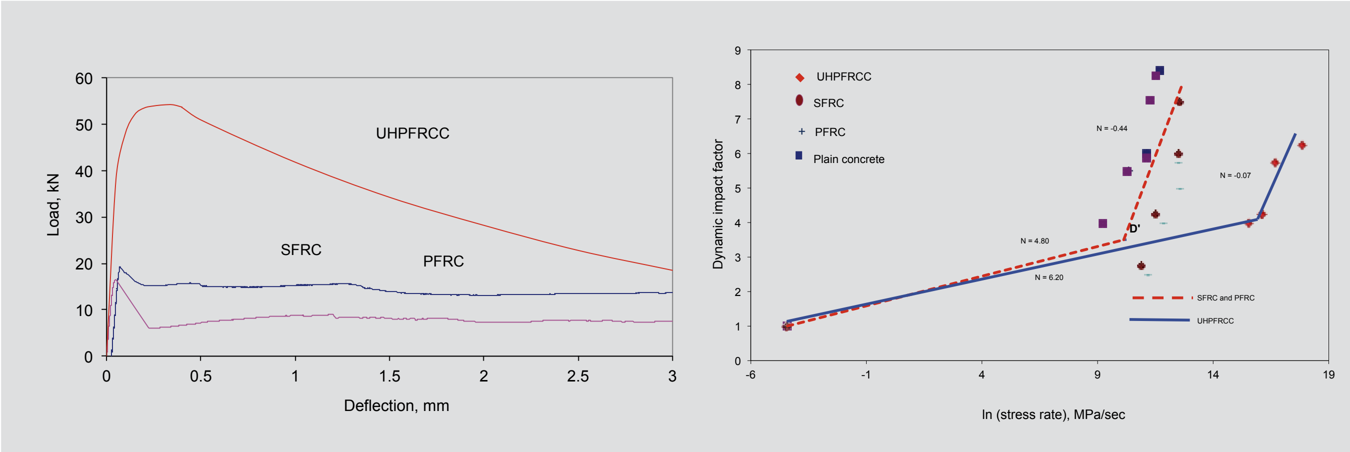


Figure 2. Quasi-static response of an ultra-high-strength fiber-reinforced cementitious composite (UHPFRCC) showing strain-hardening response and conventional fiber-reinforced concrete (FRC) with either steel (SFRC) or polypropylene (PFRC) that display a deflection hardening response (left). Stress rate sensitivity plot for the three types of fiber-reinforced concrete (right). Source: Bindiganavile, Banthia, and Arup (2002). Note: sensitivity is inversely proportional to 1 + N. HPFRCC = high performance fiber-reinforced cementitious composites; N = fracture mechanics constant. 1 mm = 0.0394 in; 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

The nature of the cementitious system also plays a significant role in how the system will respond to higher rates of loading when reinforced with fibers. A stronger matrix will be stiffer but less resilient. Bischoff and Perry[18] reported a higher dynamic impact factor for high-strength fiber-reinforced concrete in compression compared with normalstrength FRC. However, Bentur et al.[31] reported a lower dynamic impact factor for high-strength FRC, which was further verified for an ultra-high-strength cement-based composite by Bindiganavile et al.[32] (**Fig. 2**). According to Ross,[33] lower-strength materials have smaller fracture process zones and it manifests as higher strength under impact loading. Bindiganavile and Banthia[34] found that if fiber pullout can be ensured as the dominant mode of failure, then a high-strength matrix favors their impact response (**Fig. 3**).

Shrinkage crack control

Fibers are known to significantly affect the free shrinkage and other early-age properties of cement-based composites. A study by Kronlof et al.[35] found that the use of polypropylene fibers (1% by volume) reduced free plastic shrinkage by about 30%. Qi et. al.[36] found that a mere 0.2% by volume of polypropylene fibers resulted in both a lower and a more uniform settlement in concrete. Wang et al.[37] reported that fiber addition increased the number of large pores in cement paste, thereby changing the bleeding behavior and reducing the free shrinkage.

In addition to free shrinkage, the effect of fibers on restrained shrinkage has also been studied using various techniques. The presence of fiber is expected to influence both the lengths and the widths of shrinkage-induced cracks under restrained conditions.[11,38-41] A major study by Gupta[42] provided insight into the effectiveness of various fibers in controlling shrinkage cracking (**Fig. 4**). Other conclusions from the study were the following:

- Fiber material and type have a pronounced effect on

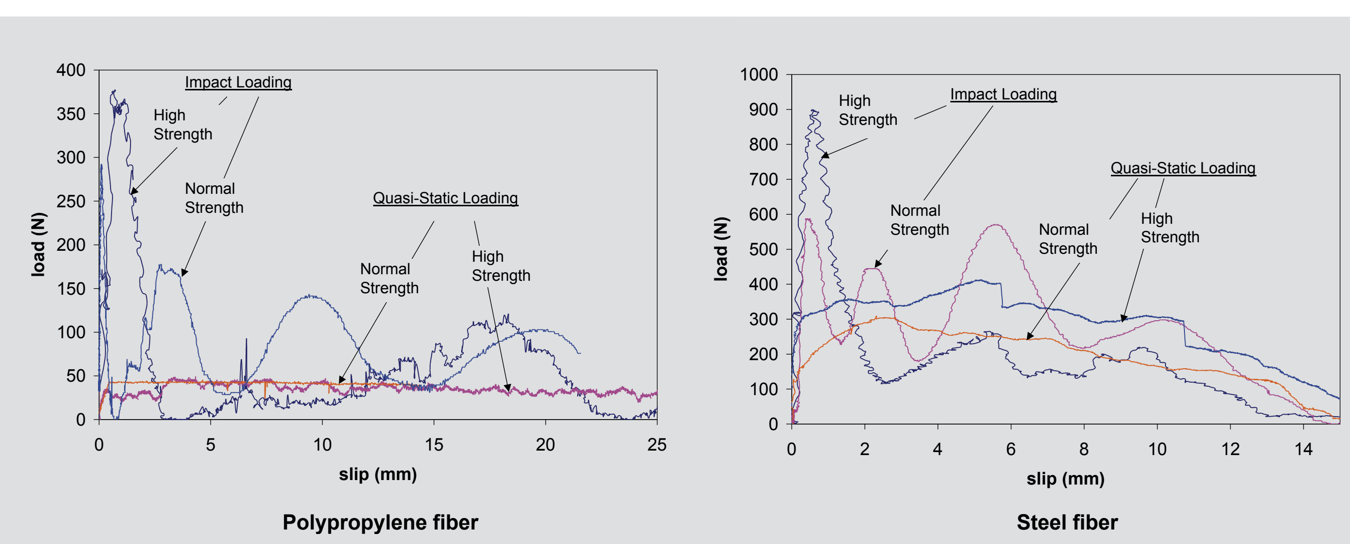
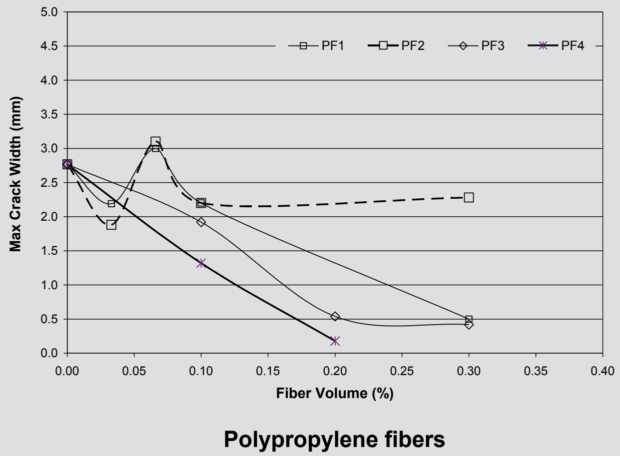


Figure 3. Effect of matrix strength on the static and impact response of fibers. Source: Bindiganavile and Banthia (2005). Note: 1 mm = 0.0394 in.; 1 N = 0.225 lb.



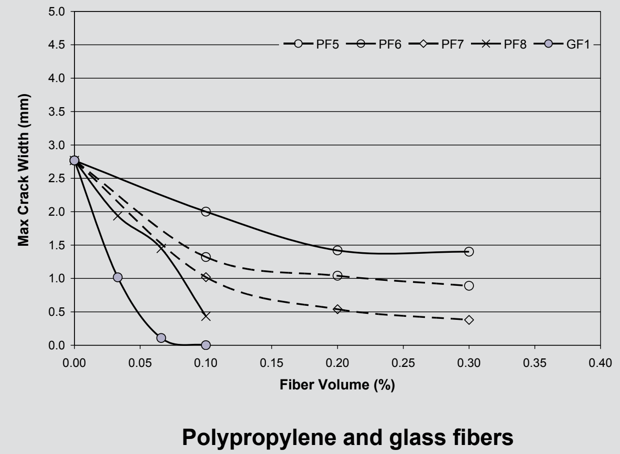


Figure 4. Shrinkage control of various fibers. Source: Gupta (2008). Note: PF1 through PF8 are various polypropylene fibers, and GF1 is a glass fiber. 1 mm = 0.0394 in.

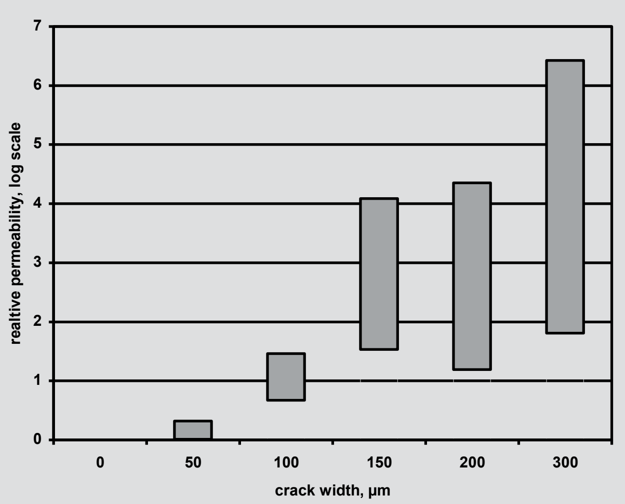


Figure 5. Effect of crack width on permeability. Source: Bentur et al. (2005).

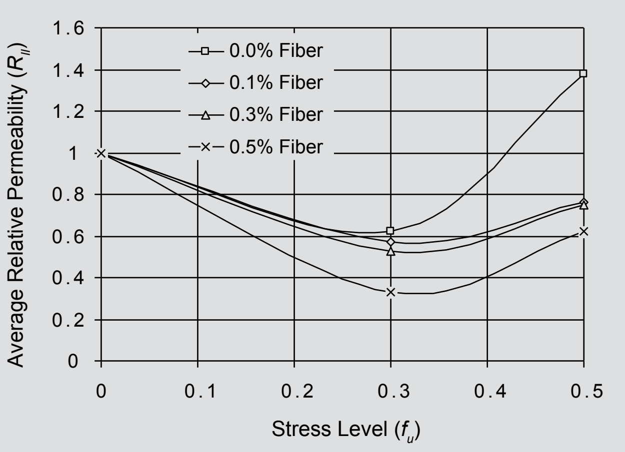


Figure 6. Normalized permeability coefficients for plain and cellulose-fiber-reinforced concrete. Source: Banthia and Bhargava (2007).

shrinkage cracking. At the same fiber volume, glass fibers are the most effective in inhibiting crack growth, followed by synthetic fibers.

- For a given fiber volume fraction and type, longer fibers and fibers of smaller diameter are much more effective than shorter fibers and coarser fibers. Fibers with extensive geometric deformations—such as fibrillations—impart greater efficiency than their undeformed counterparts.

- In the case of cellulose fibers, both coated and uncoated fibers are effective only at dosages above 0.3% by volume.

Watertightness and durability

Precast concrete products are susceptible to degradation as a result of sulfate attack, freeze-thaw cycling, alkali-silica reaction, and corrosion of embedded reinforcing bars, if present. In all of these cases, permeability to water plays an important part. Durability of precast concrete products is therefore influenced by the rate at which water may enter. Results have indicated that permeability, in turn, depends largely on cracking in concrete, and an increase in the crack width will produce a highly permeable concrete (**Fig. 5**).[43] Fiber reinforcement improves crack resistance, increases the surface roughness of cracks, and promotes multiple-crack development, thereby significantly reducing the permeability of concrete in service. In case of stresses and stress-induced cracks, results have shown that cracks dramatically increase the permeability of plain concrete, while the permeability of fiber-reinforced concrete remains far below that of plain concrete under service conditions (**Fig. 6**).[44] Other research[45,46] has shown a similar trend, but the effectiveness of a fiber in controlling permeability is a function of the crack opening. A detailed review of the effectiveness of fibers in controlling water permeability under stress is given by Hoseini et al.[47] Fiber reinforcement has also been shown to reduce gas permeability under stress.[48]

In a study of how fibers improve watertightness, thermoporometry coupled with mercury intrusion porosimetry on cellulose-fiber-reinforced concrete revealed pore size refinement.[49] Results are given in **Fig. 7**, where it is clear that microporosity in plain concrete was transformed into nanoporosity when fiber reinforcement is used.

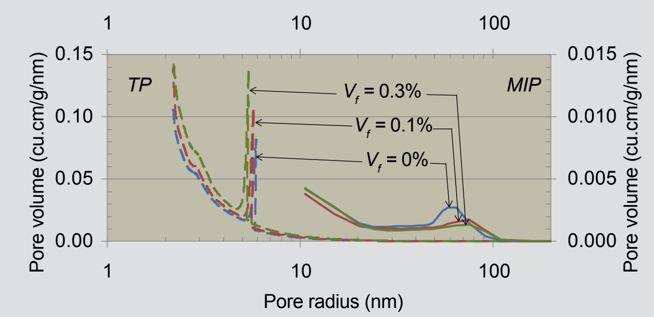


Figure 7. The pore size distributions in plain and fiber-reinforced cement pastes based on cryoporometry and mercury intrusion porosimetry. Source: Sappakittipakorn, Banthia, and Jiang (2010). Note: MIP = mercury intrusion porosimetry; TP = cryoporometry; V_f = fiber volume fraction. 1 nm = 0.0394 × 10^{-6} in.; 1 cu. cm = 1 cm^3 = 0.0610 $in.^3$; 1 g = 0.0353 oz.

Corrosion of steel reinforcing bars in precast concrete remains a major concern. Chloride contamination of concrete is usually to blame, and the mechanisms by which chloride ions promote reinforcing bar corrosion in concrete are well understood.[50] Unfortunately, cracks in concrete permit ready ingress of chlorides and other deleterious chemicals and further promote corrosion.[51] Because chloride ions diffuse only through water in the capillaries, chloride diffusion depends principally on water permeability. As indicated before, fibers decrease water permeability in both stressed and unstressed concrete and, hence, slow the rate of chloride diffusion. The inclusion of fiber in concrete could be a feasible solution for prolonging the life of concrete structures. A recent study[52] has indicated that both cellulose and polypropylene fibers might increase the coefficient of apparent (total) chloride diffusion but decrease the coefficient of effective (free) chloride diffusion. In other words, while greater amounts of chlorides diffuse through fiber-reinforced concrete, fibers chemically combine with the passing chlorides such that only limited amounts of free chlorides are available for steel corrosion. This ability of fibers to bind chlorides was further verified in loaded reinforced concrete beams where corrosion was delayed significantly as a result of fiber reinforcement (**Fig. 8**).[53]

Applications

PCI was involved in the early introduction of FRC in precast concrete through its efforts to develop design procedures. For example, PCI's GFRC committee developed a design procedure that is still used today.[14] These design practices have been validated with time, and some products have now been in service for more than 40 years.

An important feature of the use of FRC in precast concrete products is that one needs a systems approach involving not only the choice of fiber but also the appropriate mixture formulations, curing details, transportation, methods of handling, and design tools. This allows FRC to be designed and formulated specifically for end-use application requirements and conditions of use. **Figures 9** to **16** give some typical applications.

- Figure 9 shows a project that comprises 2275 panels covering 243,100 ft^2 (22,600 m^2). The types of panels were window box units, which had the windows installed in the factory before they were delivered to the field; spandrel panels; solid wall panels; and column covers. The panels have custom-colored aggregate and sand. The panels received a medium sandblast. The GFRC panel was manufactured by first spraying into the mold a face coat (about $^3/_{16}$ in. [4.8 mm] thick), which would provide the ultimate decorative finish.

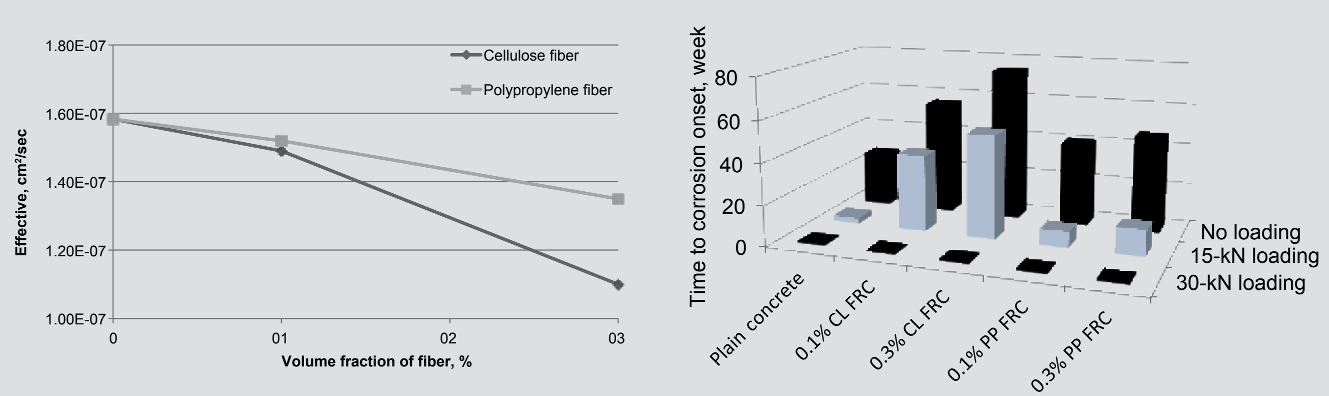


Figure 8. Effective coefficients of chloride diffusion for various volume fractions of fibers (left) and time to onset of corrosion in reinforcing steel for various mixtures (right). Note: CL = cellulose fiber; FRC = fiber-reinforced concrete; PP = polypropylene fiber. 1 cm^2 = 0.155 $in.^2$; 1 kN = 0.225 kip.

Figure 9. Glass-fiber-reinforced concrete in Stanford Graduate School of Business. Courtesy of Nippon Electric Glass America Inc.

Figure 10. Glass-fiber-reinforced concrete pipeline trench application. Courtesy of Nippon Electric Glass America Inc.

Figure 11. Glass-fiber-reinforced concrete sewer lining. Courtesy of Nippon Electric Glass America Inc.

This was followed by the GFRC backup with 6% by volume of alkali-resistant glass fibers. The overall thickness of the GFRC panel, face coat, and GFRC backup was approximately $^3/_4$ in. (19 mm). The complete panel was made with the GFRC attached via flex anchors to a steel frame. The flex anchors allow for differential movement between the GFRC and the steel frame to avoid any possible problems with shrinkage or temperature movements that could cause cracking of the GFRC.

- Figure 10 shows a GFRC pipeline trench application. Box pads support electrical cabinets. These hollow pads are 4 × 4 × 4 ft (1.2 × 1.2 × 1.2 m) in dimension with 0.5 in. thick (13 mm) sheets. The pads were designed to support a load of 1.5 tonnes (1.7 tons). The vertical sides of the larger pads were stiffened with ribs made by overspraying polystyrene strips with GFRC. GFRC was used because its strength and slenderness made the pads easy to handle. The high impact strength of GFRC was also a benefit in that if the pads were dropped they were not damaged or cracked.

- Figure 11 shows a GRFC sewer lining application. Lightweight GFRC panels were used to reline old brick sewers in London, UK. The sewer lining comprises two pieces, an upper segment mated with a lower segment via overlapping flanges. The mixture contained 6% by volume of alkali-resistant glass fiber and was sprayed with a high water-cement ratio (*w/c*). The sheet was then dewatered to a *w/c* of about 0.3. Such a system has a proven durability record against sewer fluids and gases such as hydrogen sulfide and sulfur dioxide.

- Figure 12 shows GFRC permanent formwork for beams constructed in Puerto Rico. The hotel structure was to be poured using permanent GFRC forms for the beams and columns. The U-shaped beam forms were manufactured using folding steel molds. More than 11,100 m^2 (120,000 ft^2) of GFRC was used. The manufacturer used the spray-up process in which the open steel molds were first sprayed with a mist coat followed by the GFRC. After the GFRC had reached

Figure 12. GFRC permanent formwork for beams in Puerto Rico. Courtesy of Nippon Electric Glass America Inc.

Figure 13. Segmental tunnel lining using steel-fiber-reinforced concrete. Courtesy of Bekaert Corp. USA.

a degree of firmness, the two wings of the steel mold were folded up and locked in position, which formed the U-shape for the GFRC beam forms. After the GFRC had set, the wings were folded back down, which made stripping the GFRC piece easy.

- Figure 13 shows a segmental tunnel lining using steel-fiber-reinforced concrete. Segmental tunnel linings are unique structures to design because of the many different loads they must resist. The segments are exposed to bending within a few hours of casting when they are removed from the production molds and stacked in curing chambers. Within 24 hours after curing, the segments are stacked in matched rings on top of each other for storage. Double ring stacks can include as many as 14 individual segments weighing more than 50,000 lb (23 tonnes). The segments are then transported to the jobsite, lowered into the tunnel, and placed into position with the tunnel-boring machine. Once the segments are in place, the tunnel-boring machine pushes off the segments to advance the tunnel boring, creating high localized bearing and splitting forces. The final step is to inject grout into the annular space around the segments to ensure full contact with the surrounding earth. The segments are then left to hold open the hole that was bored into the ground, which imposes high compressive stresses and moderate bending stresses in the lining. Many segments are reinforced with only steel fibers, but reinforcing bar can be used in addition if required to carry large moments, and monofilament polypropylene fibers can be added for fire resistance. It is estimated that there are more than 60 completed projects constructed with steel-fiber-reinforced segmental linings around the world, comprising some 280 to 300 mi (450 to 480 km) of tunnels, with more than 37 mi (60 km) in the United States.[54]

Figure 14. Precast concrete railroad track slabs for high-speed trains. Source: Brite-Euram (2002). Courtesy of Bekaert Corp. USA.

- Figure 14 shows railroad track slabs for high-speed trains. The term *track slab* is used to describe nonballasted track structures that may have combinations of concrete slab and ties used where strength and durability are required. Precast concrete track slabs for high-speed passenger trains in Europe have used steel-fiber-reinforced concrete in combination with traditional reinforcement to significantly reduce crack width and/or the required amount of reinforcement leading to durability improvement. A reduction of reinforcing bar up to 50% is possible while keeping crack width constant. The quality of the structure is increased due to better material properties and workability.[55] Significant time savings can be achieved in addition.

- Figure 15 shows precast concrete sewer pipes. Reinforcing precast concrete pipes using only steel fiber

Figure 15. Precast concrete sewer pipes. Courtesy of Bekaert Corp. USA.

Figure 16. Precast concrete fence panels. Courtesy of Bekaert Corp. USA.

is economically advantageous for pipe diameters up to 36 in. (900 mm). Small pipes are almost impossible to reinforce properly with mesh. More efficient crack control is achieved using steel-fiber-reinforced concrete than with mesh because the first crack load is increased with fibers and at maximum load the crack width is typically smaller than it is for traditional reinforcement at similar loads. Pipes have been reinforced with steel fibers in Europe for more than 15 years and are now being tested in the United States and Canada.

- Figure 16 shows precast concrete fence panels. They are cast and installed vertically to form a continuous wall. Fence panels have been constructed using only zinc-coated steel fibers to reinforce the concrete.

These examples show that FRC is used in a broad range of applications. Care must be taken to suitably match the fiber with the intended purpose. In all cases, the chosen fiber provides select benefits that were not possible either with conventional reinforcement or with an alternate fiber system.

Acknowledgments

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Notation

f_u = stress level

L_f = length of fiber

R_{Π} = average relative permeability

V_f = fiber volume fraction

δ_0 = deflection

ε_{cc} = first cracking strain

ε_{pc} = postcracking strain

σ_{cc} = first cracking strength

σ_{pc} = postcracking strength in tension.

About the authors

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John Jones has a BEng from Liverpool University, UK, and an MSc from the London Business School. He was a member of the original market development group in Pilkington Brothers Ltd. in the United Kingdom that developed alkali-resistant glass fibers and the related glass-fiber-reinforced concrete (GFRC) technology in the early 1970s. Since then he has been involved in developing and manufacturing a wide variety of GFRC products throughout the world. He was the manager for the AR Glass Fiber Division in Nippon Electric Glass America Inc., and is now semiretired but works as a consultant for Nippon.

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Abstract

Although fiber reinforcement in construction is as old as recorded history, its scientific characterization spans only the past few decades. Most significantly, this has led to the development of fiber-reinforced concrete, an industry supported by the emergence of a variety of fiber materials, geometries, and production techniques. This paper provides a summary of common fiber types and their use in precast concrete. It describes the role of fiber reinforcement in imparting superior mechanical performance to cement-based systems and enhancing their durability. In particular, recent findings that illustrate the mechanisms that underlie benefits accruing from fibers are explained. Finally, this report offers a snapshot of some signature fiber-reinforced precast concrete applications.

Keywords

Applications, fiber-reinforced concrete, impact resistance, shrinkage cracking, water-tightness.

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