

IN-LB

Inch-Pound Units

SI

International System of Units

Glass Fiber-Reinforced Concrete Premix—Report

Reported by ACI Committee 549

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Glass Fiber-Reinforced Concrete Premix—Report

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Glass Fiber-Reinforced Concrete Premix—Report

Reported by ACI Committee 549

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Alkali-resistant (AR) glass fiber-reinforced concrete premix technology has become increasingly popular worldwide for manufacture of precast concrete products used in industrial, architectural, civil engineering, and construction applications. AR glass fiber-reinforced concrete premix products provide a useful balance of properties such as strength, toughness, durability, moisture resistance, dimensional stability, fire resistance, and aesthetics. This report summarizes the current knowledge of materials, manufacturing methods, engineering properties, and applications of AR glass fiber-reinforced concrete premix.

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

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The use of glass fiber-reinforced concrete (GFRC) started in the late 1960s with the development and commercialization of alkali-resistant (AR) glass fiber (GRCA Technical Working Group 2019). The technology spread rapidly throughout the world because of desirable physical properties and durability performance of products reinforced with AR glass fibers. GFRC premix, as known in the industry and presented in this report, is a material that incorporates AR glass fibers into the slurry during mixing and slurry preparation. In AR GFRC premix, fibers of various lengths from 0.25 to 1.5 in. (6 to 38 mm) and in concentrations of 0.25 to 4.0% by weight of the mixture are typically used and mixed with the cementitious mixture while preparing the slurry. This fiber-reinforced slurry is then used to produce GFRC premix products by selecting an appropriate manufacturing process. AR GFRC premix products are now manufactured in more than 100 countries.

Specific property improvements obtained with GFRC premix include superior crack resistance and enhanced mechanical performance that includes improved tensile,

flexural, and impact strength behavior. Note that GFRC premix differs from another class of material, herein called spray-up GFRC, primarily in the method of delivering fibers into the slurry and the amount of fiber reinforcement in the composite. Spray-up GFRC typically incorporates greater than 4% AR glass fibers by weight and, during production, keeps the glass fibers and slurry separate until delivering both simultaneously to the mold surface through a special spraying apparatus (ACI 544.1R; ACI 549.2R).

GFRC premix is a mixture of AR glass fiber, sand, cement, water, chemical and mineral admixtures, and aggregate if required. Mixture proportions are determined by the physical property requirements of the end product. Physical properties of AR GFRC premix, such as tensile and flexural strength, are influenced by the fiber content, geometry, length, orientation, and the water-cementitious materials ratio (w/cm) of the mixture. The maximum amount of fiber successfully incorporated in the mixture is influenced by the fiber length, strand structure and integrity, and the ability of the mixer to efficiently disperse the fibers evenly throughout the matrix. Introducing over 4% of glass fibers by weight of the mixture does not significantly improve the mechanical strength of GFRC premix composites. Spray-up GFRC generally provides higher mechanical strength and ductility from its ability to incorporate higher fiber content, longer fiber lengths, superior two-dimensional (2-D) fiber orientation, and lower water content. Both types of manufacturing methods are widely used commercially, and the choice between the two is primarily dictated by the required performance and aesthetical characteristics of the end product and application. The economics of manufacturing GFRC premix are generally superior to that of spray-up GFRC, mainly due to the lower labor costs per unit area of manufactured premix product.

Several manufacturing processes for producing GFRC premix products have been developed, such as casting, spray premix, press molding, extrusion, calender extrusion, and pultrusion. Many new products have been designed and produced to capitalize on the good performance of GFRC premix. AR GFRC premix material and process technologies are commonly used for manufacturing precast concrete products for industrial, architectural, and ornamental applications. Examples include trench lid covers for underground electrical distribution lines, modular building panels, decorative architectural products, terra cotta replacement products, and many other industrial products.

1.2—Scope

This report considers AR GFRC premix and reviews the state of knowledge regarding selection of materials, mixture proportions, and manufacturing methods for producing premix products. Also highlighted is a diverse range of AR GFRC premix applications from around the world and dry-bagged premix materials that are used in surface bonding, stucco, and certain shotcrete applications. The terms “AR glass fiber-reinforced concrete premix,” “glass fiber-reinforced concrete premix,” and “AR GFRC” are used interchangeably throughout this report.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

V_f = volume fraction of fibers

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

acrylic copolymers—acrylic thermoplastic copolymer is a resinous substance made by reacting acrylic monomers together; the type of copolymer used in concrete and glass fiber-reinforced concrete is either a powder or an emulsion of submicron-size polymer particles dispersed in water.

alkali-resistant glass fiber—glass fiber using at least 16% zirconia by mass to provide alkali resistance.

dry cured—curing of the product without the addition of water.

filament—single glass fiber, sometimes called a monofilament.

filamentizing—dispersion of a multifilament strand into individual filaments.

glass fiber-reinforced concrete—cementitious mixture that usually contains a minimum of 4.5% alkali-resistant glass fiber by total mass of composite, and is usually manufactured by the spray-up process.

glass fiber-reinforced concrete premix—mixture of prechopped alkali-resistant glass fibers; cementitious materials; water; chemical admixtures; fine aggregate; and, if required, coarse aggregate.

glass fiber strand—group of filaments of predetermined quantity (100, 200, or 400 filaments per strand) bundled together to resist splitting (filamentizing).

high integrity—a characteristic of specific glass fiber strands that are difficult to break down into individual filaments during processing or mixing; also classified as nondispersible.

limit of proportionality—stress in a flexural bending test where the stress/strain plot deviates from a straight line (also referred to as elastic limit or yield point).

mesh—structured form of glass reinforcement in which continuous strands (or yarns) are laid down to produce a grid pattern (also referred to as scrim).

roving—numerous parallel, continuous, not twisted, glass fiber strands bundled together and wound to form a cylindrical package.

tex—weight of glass fiber per kilometer in grams (that is, 2500 tex = 2500 g/km).

yarn—bundle of multiple glass fiber strands that are twisted together.

CHAPTER 3—MATERIALS AND MIXTURE PROPORTIONS OF ALAKLI-RESISTANT GLASS FIBER-REINFORCED CONCRETE PREMIX

The materials and mixture proportions of glass fiber-reinforced concrete (GFRC) premix are selected to achieve the desired mixture consistency to suit the production method used and to develop the design mechanical properties in the composite. Mixture ingredients should always comply with

local regulations and state-of-the-art recommendations. When GFRC premix products are produced on an industrial scale, certificates of conformance are normally obtained from the raw material suppliers for review and proper documentation.

3.1—Types of premix

In the past 40 years, a range of production methods have been developed to manufacture products from premix. The most popular are cast-and-spray premix, but products have also been developed using press molding, extrusion, calendar extrusion, and pultrusion. Each use unique processing methods that require variations in the typical mixture proportion. The sand-cementitious materials ratio and w/cm are typically adjusted to suit the production system. Bagged dry mixtures of premix are also commercially available for manufacturing, stucco, surface bonding, and shotcrete applications.

3.2—Typical mixture ingredients

This section describes the basic raw ingredients used for producing premix products. Mixture ingredients reported are used worldwide to manufacture premix products. Note that in some countries, certain chemical and mineral admixtures are unavailable or too expensive. In such cases, the mixture proportions are adjusted to allow product manufacturing using the production process equipment available.

3.2.1 Cement—The most widely used cements in premix production are ordinary portland cement (OPC), rapid-hardening portland cement (RHPC), and white portland cement. The cements should conform to the relevant local standards and specifications, such as **ASTM C150/C150M** or **ASTM C595/C595M** in the United States or **BS EN 197-1** and **BS EN 197-2** in Europe. Fast-setting hydraulic cements are more finely ground and develop strength more rapidly. They are used to reduce set times and increase production rates of AR GFRC composites (**Freiderich 2001**; **Gartshore et al. 1991**; **Harmon et al. 1994**). White cement is normally used to produce decorative and architectural products. Other types of cements, such as high-alumina, sulfate-resistant, and rapid-setting cements, are used in certain applications (**Molloy and Jones 1993**; **Molloy and Peter 1998**; **ASTM C1157/C1157M**; **ASTM C1600/C1600M**). Premix producers ensure that the choice of cement is appropriate for the application and production process involved.

3.2.2 Sand—The choice of sand is an important aspect for preparing GFRC premix and should conform to the relevant local standards and specifications, such as **ASTM C144**. Silica sands with nonangular grains are recommended and should be used where available, as their particle shape and grain size are ideal for premix production. The sand should be clean and graded. A typical grading is shown in Table 3.2.2a. Sands with well-graded, rounded grains are easier to pump, less abrasive on equipment, and less apt to cause blockage than crushed sand. Table 3.2.2b shows a typical specification of silica sand used for producing premix. Generally, sands with maximum grain sizes of 0.075 mm (No. 200) are common but sands up to 0.09 mm (No. 200) are also often used.

Silica sands can be susceptible to alkali-silica reactivity but most GFRP is not subjected to prolonged moist conditions and there has been little historical evidence of alkali-silica reaction in GFRP products. If the use of sands with a high susceptibility for alkali-silica reactivity, determined using **ASTM C295/C295M**, is unavoidable, then they should be further evaluated using **ASTM C1260**, **ASTM C1293**, or **BS EN 812-123** before use.

When sands other than silica are used, the producer should have evidence of their suitability in the form of composite test results for mechanical performance and durability. There are other high-quality sands with lower silica content available that are suitable for premix manufacture. The silica content of these sands need not be as high as 96%. Loss on ignition for these sands is acceptable up to 3%, provided that the material is hard, noncrushable, nonreactive, and similar in shape and grading to the silica sand described in Table 3.2.2a.

3.2.3 Alkali-resistant glass fiber—The AR glass fibers used to reinforce the premix should have a zirconia content of at least 16% by weight (Majumdar 1970, 1985; Fyles et al. 1986; PCI MNL-128; GRCA Technical Working Group 2019). Table 3.2.3 provides the specification for AR glass fibers used in the premix. The cement solution and concrete mortar are highly alkaline (typical pH > 12) and chemically aggressive. E-glass fibers, which are typically

used as reinforcement in plastic products, if used in the highly alkaline environment of cementitious materials, rapidly deteriorate and lose strength due to the alkaline chemical attack (Majumdar 1970).

The AR glass fibers for use in premix production are typically available in the form of short, chopped strands supplied directly by a glass fiber manufacturer. The fibers may also be chopped directly from a continuous roving by the premix manufacturer. AR glass fibers, specifically produced for use in premix, come in the form of a high-integrity, nondispersible strand. The strand, composed of 50 or more filaments, resists filamentizing (that is, splitting of individual filaments) during the mixing process. A loss of integrity of the strand bundle results in a loss of processability and workability of the mixture. The fiber amount and fiber geometry (fiber length and number of filaments per strand) used in the mixture significantly influence the mechanical strength of the premix product. Physical properties of the premix may be tailored by testing the finished product and optimizing the addition of AR glass fibers in an iterative process.

3.2.4 Water—Clean water should conform to the relevant local standards and specifications, such as **ASTM C1602/C1602M** in the United States or **BS EN 1008** in Europe, and should be used to prepare the cementitious mixture for producing premix products. The water should be of consistent temperature, if possible, to control or predict the setting behavior of the cementitious mixture.

3.2.5 Additives and admixtures—Standard additives and admixtures, such as high-range water-reducing admixtures, water-reducing admixtures, accelerators, acrylic copolymers, pozzolans, and pigments, are used in premix to achieve specific end results. Benefits provided by additives and admixtures include increased workability without an increase in the w/cm , improved cohesion, reduced segregation, reduced bleeding, and retarded or accelerated setting times.

Additives are added in small, measured amounts and correct dosage rates to achieve optimal results. Calcium-chloride-based accelerators are not recommended if the premix end product contains steel reinforcement or inserts. When copolymer dispersions or other liquid additives are used, the water content of the additive should be accounted for in the calculation of w/cm .

Table 3.2.2a—Typical silica sand gradation

Mesh size	Percentage passing, %
No. 30 (600 μ m)	All
No. 40 (425 μ m)	30
No. 50 (300 μ m)	52
No. 70 (212 μ m)	13
No. 100 (150 μ m)	4
No. 140 (106 μ m)	1
No. 200 (75 μ m)	Trace

Table 3.2.2b—Typical silica sand specification

Silica content	>96%
Moisture content	<2%
Soluble salts	<1%
Loss on ignition	<0.5%
Sulfate ions (maximum)	4000 ppm
Chloride ions (maximum)	600 ppm

Table 3.2.3—Alkali-resistant glass fiber specification (ASTM C1666/C1666M)

Property	Specification value	Test method
Zirconia content	Minimum 16% by weight	X-ray fluorescence analysis*
Density	167.0 $\pm$ 19 lb/ft ³ (2.68 $\pm$ 0.3 g/cm ³)	ASTM D3800
Tensile strength	145 $\times$ 10 ³ to 246 $\times$ 10 ³ psi (1.0 to 1.7 GPa)	ASTM D2256/D2256M, ISO 3341, JIS R 3420
Filament diameter	31 $\times$ 10 ⁻⁵ to 118 $\times$ 10 ⁻⁵ in. (8 to 30 μ m)	ASTM D578/D578M, ISO 1888, JIS R 3420
Roving tex	$\pm$ 10% of manufacturer's nominal	ASTM D1577, ISO 1889, JIS R 3420
Strand length	$\pm$ 0.118 in. ($\pm$ 3 mm) of manufacturer's nominal	Caliper—average of 20 measurements
End count	$\pm$ 20% of manufacturer's nominal	Physical count
Loss on ignition	<3%	ASTM D4963/D4963M, ISO 1887, JIS R 3420
Strength retention	Minimum value after 96 $\pm$ 1 hour in water at 176 $\pm$ 2°F (80 $\pm$ 1°C) *36,250 psi (250 MPa) for water-dispersible strands *50,750 psi (350 MPa) for integral strands	CEN EN 14649

*Any party interested in performing this test should contact an AR glass fiber manufacturer before running it to avoid possible erroneous results.

3.2.6 Acrylic copolymers—Acrylic copolymer powders and dispersions (also referred to as copolymers in the report) may be added to the premix to eliminate the requirement for wet curing (Daniel and Pecoraro 1982; Ball 2005). Cementitious products are normally moist cured to ensure proper hydration of the cement. Proper curing is especially essential for thin-section concrete products. When acrylic copolymers are added to the mixture at recommended dosage rates, the hardened product forms a film within the matrix during the early stages of curing. The formation of this film significantly reduces the surface permeability of the product and reduces loss of water by evaporation. This ensures that sufficient water is retained and available in the product to achieve proper cement hydration. An additional benefit of adding acrylic copolymers in the premix is the improvement in pumpability and workability obtained, even at low w/cm . Table 3.2.6 shows an example specification of copolymer dispersion for use in premix.

3.2.7 Additional reinforcement and cast-in items—If the use of reinforcing bar is required for additional reinforcement, nonferrous fiber-reinforced polymer (FRP) should be used (ACI 440R; ACI 440.6). Also, all cast-in items, including inserts and attachments, should be nonferrous, cadmium-coated galvanized steel, or stainless steel.

3.2.8 Pozzolanic materials and hydraulic cement—Metakaolin, microsilica, and fly ash (all pozzolanic materials), and slag cement (hydraulic cement) are all materials that are commonly used to enhance the properties of GFRP-based materials. Pozzolanic materials work by reacting with the free lime produced during the cement hydration process. This reaction produces additional cementitious hydration products that help further enhance strength and durability of the premix. (Molloy et al. 1993).

3.2.9 Pigments and coloring systems—Powder pigments or dispersions are commonly used in the industry to produce

colored premix products. Pigments are normally iron oxide-based, and typically conform to ASTM C979/C979M. Post-demolding coloring systems that use stains to color or enhance color consistency and provide a protective surface seal are also commonly used.

3.3—Typical mixture proportions

Mixture proportions presented in this report are for informational purposes only. Producers typically develop their own mixture proportions to accommodate their manufacturing process and raw material availability. Table 3.3 shows typical mixture proportions used for producing cast premix and spray premix products. Variations in mixture proportions from manufacturer to manufacturer are possible due to local conditions and materials, type of manufacturing equipment used, type of product produced, quality-control procedures implemented, and other conditions. The selection of production method, mixture proportion, and fiber content are generally decided after considering the engineering design of the product. It is possible to fix these first and then develop the product design.

An increase in flexural and tensile strengths generally results with an increase in fiber content. However, beyond a certain fiber content, termed herein as “optimal fiber content”, any further increase in the fiber content makes little improvement in mechanical performance (Peter 2004). The optimal fiber content varies depending on the mixture proportion and fiber type. The workability and compactability of the mixture diminish with the increase in number of strands per unit weight of composite. It is observed that a larger strand—that is, a strand with a greater number of filaments—provides a lower number of strands in the composite for a given fiber content. Accordingly, the optimal fiber content in the premix, to achieve satisfactory workability and compactability, increases with an increase in the strand size. For example, the optimal fiber content for a 45 tex strand is approximately 2 to 3% by weight of composite, while the same for an 82 tex strand ranges between 3 and 4% by weight of composite. Workability and compactability of the material may also influence the mechanical properties of premix composite as described in Section 4.4.

3.3.1 Water-cementitious materials ratio—The w/cm is ideally kept as low as possible, consistent with obtaining the required workability for the production process involved. The total amount of water in the mixture (and the resulting w/cm) is also controlled by the use of high-range water-

Table 3.2.6—Typical copolymer dispersion specification

Compound type	Aqueous thermoplastic copolymer dispersion
Polymer type	Acrylic copolymer
Percent solids	44 to 55%
Appearance	Milky white, creamy, free of lumps
Minimum film formation temperature	45 to 54°F (7 to 12°C)
Ultraviolet resistance	Good
Alkali resistance	Good

Table 3.3—Typical GFRP premix mixture proportions

Ingredients	Cast premix*	Spray premix*
Cement	50 lb (22.7 kg)	50 lb (22.7 kg)
Sand	37 to 50 lb (16.8 to 22.8 kg)	37 to 50 lb (16.8 to 22.8 kg)
Water	15 lb (6.8 kg)	15 lb (6.8 kg)
High-range water-reducing admixture†	8 oz (227 g)	3 to 5 oz (85 to 142 g)
Chopped AR glass fibers	3 to 4 lb (1.4 to 1.8 kg)	3.5 to 4.5 lb (1.6 to 2.0 kg)
Copolymer†	5 lb (2.3 kg)	5 lb (2.3 kg)

*The batch yield of a premix made with the above mixture proportions varies between 0.82 and 0.92 ft³ (0.023 and 0.026 m³).

†Not an essential ingredient but added to improve workability and mechanical properties.

reducing admixtures. When chemical admixtures are used, the water content of the admixture is typically added to the mixture water content to obtain the total water content for the batch. The w/cm in the premix typically ranges from 0.30 to 0.50.

3.3.2 Acrylic copolymer content—The acrylic polymer content is normally expressed as a ratio of the weight of copolymer solids to the weight of cementitious materials. To achieve a satisfactory air cure, the acrylic copolymer content is typically in the range of 3 to 7%. Acrylic polymers also have a plasticizing effect on the mixture. For certain mixture proportions and manufacturing processes, the addition of extra water-reducing admixture may not necessarily be required when acrylic copolymers are used in the mixture.

CHAPTER 4—PROPERTIES OF ALKALI-RESISTANT GLASS FIBER-REINFORCED CONCRETE PREMIX

Typical properties of GFRG premix are shown in Table 4. For GFRG premix, properties such as modulus of rupture, tensile strength, impact strength, compressive strength, shear strength, and surface and acoustic properties are influenced by the properties of the fibers and the matrix used to produce the composite. Chapter 4 discusses the influence of fiber content; fiber length; fiber orientation; fiber geometry; use of alternate reinforcements such as scrims, meshes, nets, and textiles; and mixture ingredients on the resulting properties of premix.

4.1—Influence of fiber content

The maximum number of fibers that may successfully be incorporated in the mixture is influenced by the fiber length, the strand structure and integrity, and the ability of the mixer to efficiently disperse the fibers evenly throughout the matrix. The mechanical properties of the composite increase with an increase in the fiber content in the matrix. It was found through testing, however, that introducing over 4% of glass fibers by weight of the mixture does not significantly

improve the mechanical strength of the premix composites (Peter 2004). At higher fiber contents, in the same base matrix, the fiber-to-fiber interaction increases significantly, making it more difficult to mix and place the premix material. Moreover, at higher fiber content, the compaction and finishing of the cast mixture becomes difficult, resulting in lower product density and inferior mechanical properties. The fibers to produce these data were composed of 200 monofilament strands, with each monofilament having a diameter of 13 microns. The curves in Fig. 4.1a demonstrate that, for different manufacturing methods, the flexural strength of the glass fiber-reinforced concrete composites increases with both the use of longer fibers, and an increase in fiber content up to approximately 4% fibers by weight.

Figure 4.1b shows a typical load-versus-deflection curve for flexural testing of premix. Point B on the curve is the yield point, also referred to as limit of proportionality (LOP), and Point C on the curve is the ultimate strength of the premix composite, also referred to as modulus of rupture

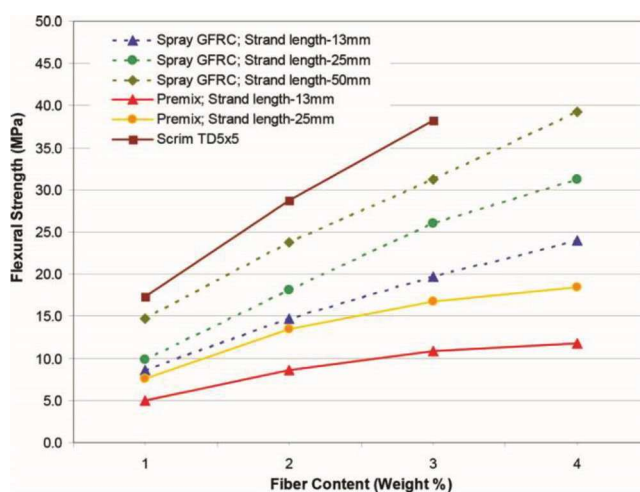


Fig. 4.1a—Influence of fiber length and content on flexural strength (MOR) (NEG Report 1985). (Note: 1 in. = 25.4 mm; 1 psi = 0.007 MPa.)

Table 4—Typical premix properties (PCI MNL-128)*

Properties		Measured values at 28 days
Dry density		110 to 130 lb/ft ³ (1750 to 2100 kg/m ³)
Compressive strength		6000 to 9000 psi (41.4 to 62.0 MPa)
Flexural	Yield†	700 to 1200 psi (4.8 to 8.3 MPa)
	Ultimate strength	1450 to 2000 psi (10.0 to 13.8 MPa)
	Modulus of elasticity	1.45 to 2.9 × 10 ⁹ ksi (10.0 to 20.0 GPa)
Direct tension	Yield‡	600 to 900 psi (4.1 to 6.2 MPa)
	Ultimate strength	600 to 1000 psi (4.1 to 6.9 MPa)
	Strain to failure	0.1 to 0.2%
Shear	In-plane	600 to 1000 psi (4.1 to 6.9 MPa)
Coefficient of thermal expansion at 77 to 115°F (25 to 46°C) (at 50 to 80% relative humidity)		12 × 10 ⁻⁶ in./in./°F (20 × 10 ⁻⁶ mm/mm/°C)
Thermal conductivity		3.5 to 7 BTU/in./h/°F (0.5 to 0.6 W/m/°C)

*These are typical values and are not to be used for design purposes. Each manufacturer tests its own composites and uses testing results for design purposes. Composite properties are influenced by raw materials used, mixture proportions, and production method involved.

†The term “flexural yield (point)” is sometimes referred to as limit of proportionality (LOP) and is defined as the elastic limit of the composite. The portion of the curve after LOP is not a true plasticization as in the case of steel.

‡The term “tensile yield (point)” is sometimes referred to as bend over point (BOP) and is defined as the elastic limit of the composite. The portion of the curve after BOP is not a true plasticization as in the case of steel.

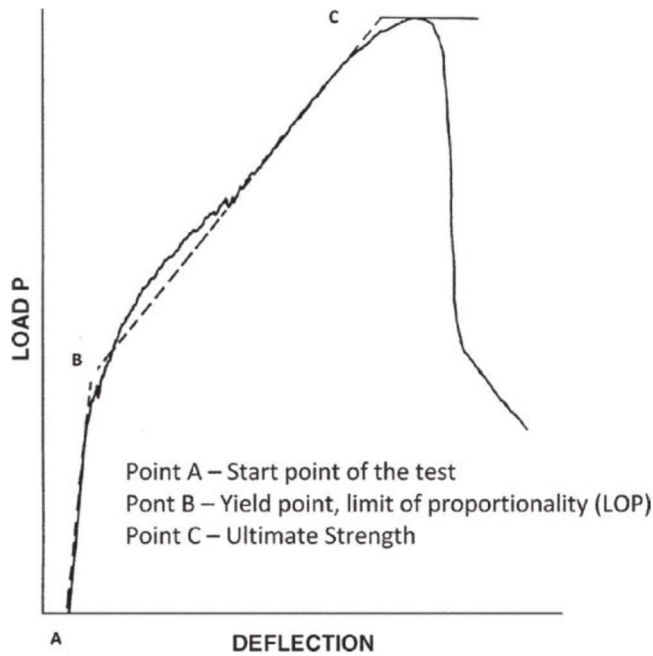


Fig. 4.1b—Typical flexural load-versus-deflection curve for glass fiber-reinforced concrete premix.

(MOR). Testing of the composite shown in Fig. 4.1b was performed according to [ASTM C947](#).

4.2—Influence of fiber length

The length of chopped strands in commonly used commercial premix ranges from 0.25 to 1.5 in. (6 to 38 mm). The fiber length influences the tensile and flexural strengths of the GFRC premix. Flexural strength increases with fiber length. Figure 4.1a illustrates the increase in flexural strength obtained with an increase in fiber length at different fiber contents. The test method used third-point bending with a 8.86 in. (225 mm) span and test coupons 10.8 in. (275 mm) long, 2 in. (50 mm) wide, and 0.6 in. (15 mm) thick ([NEG Report 1985](#)).

The two curves labeled “Premix” show that the 1 in. (25 mm) long fiber provides higher strength than the 0.5 in. (13 mm) long fiber at any given fiber content. The curves labeled “Spray” refer to the performance of conventional spray-up GFRC composites. Figure 4.1a shows that an increase in fiber length leads to higher flexural strength for the composite. Longer fibers are generally more difficult to mix and place in premix. This characteristic puts a limit on an increase in strength that may realistically be achieved as a result of increase in the fiber length. The curve labeled “Scrim TD 5x5” in the figure relates to a premix composite that uses glass fiber scrim. The performance of this type of composite is discussed in greater detail in Section 4.5.

4.3—Influence of fiber orientation

Fiber orientation in the premix composites is significantly influenced by the type of premix process used to produce the product. The manufacturing processes that lead to a three-dimensional (3-D) fiber orientation yield relatively lower composite mechanical strengths, whereas the processes that

lead to a more two-dimensional (2-D) fiber orientation yield relatively higher composite mechanical strengths.

Premix material is produced by mixing all basic ingredients first and then adding the fibers near the end of the mixing cycle. In cast premix, the material thickness is achieved with one pour, whereas in the sprayed premix, the same result is achieved with multiple spray passes. The cast premix leads to a more 3-D fiber orientation as compared with the sprayed premix, which has a more 3-D orientation of fibers. Other manufacturing processes, such as extrusion, also influence the fiber orientation. In the extrusion process, the fibers tend to orient along the flowing axis of the slurry. In calender extrusion, fibers are aligned along processing direction. This alignment causes an increase in mechanical properties ([Pekmezci 2015](#)).

4.4—Influence of fiber geometry

Fiber geometry involves two features: 1) strand tex; and 2) the filament diameter. The AR glass fiber strand is an assemblage of multiple filaments. Filament diameter is controlled by the glass manufacturer, and may be varied from 13 to 20 μm . During the manufacturing of glass fibers, multiple filaments are bundled together using an organic sizing (a bonding agent) to form a strand. Two strand configurations may be produced: 100 and 200 filaments per strand. It is the fiber strands, and not the individual filaments, that become the primary reinforcing elements in premix. High integrity of strand ensures that the individual filaments in a strand do not separate during mixing. For a given fiber content by weight, the 100-filament strand configuration would provide twice the number of strands (or reinforcing elements) compared to the 200-filament strand configuration.

Figure 4.4 illustrates the effect of one aspect of fiber geometry on composite flexural strengths—namely, number of filaments per strand ([Peter 2004](#)). Two types of strands are compared: 100 and 200 filaments/strand, each containing 13-micron diameter filaments. The figure shows that for the same fiber content by weight, the composite with 100 filaments/strand has higher flexural strength than that with 200 filaments/strand. This behavior is valid only up to approximately 3% fiber content by weight. With

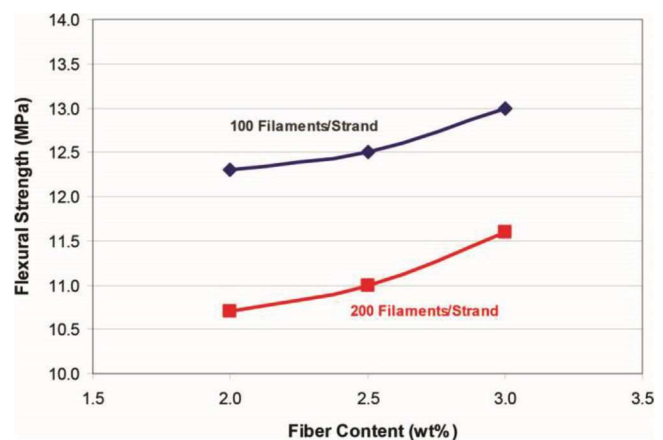


Fig. 4.4—Effect of fiber geometry on flexural strength ([Peter 2004](#)). (Note: 1 psi = 0.007 MPa)