Guide to Design with Fiber-Reinforced Concrete

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New developments in materials technology and the addition of field experience to the engineering knowledge base have expanded the applications of fiber-reinforced concrete (FRC). Fibers are made with different materials and can provide different levels of tensile/flexural capacity for a concrete section, depending on the type, dosage, and geometry. This guide provides practicing engineers with simple, yet appropriate, design guidelines for FRC in structural and nonstructural applications. Standard tests are used for characterizing the performance of FRC and the results are used for design purposes, including flexure, shear, and crack-width control. Specific applications of fiber reinforcement have been discussed in this document, including slabs-on-ground, composite slabs-on-metal decks, pile-supported ground slabs, precast units, shotcrete, and hybrid reinforcement (reinforcing bar plus fibers).

Keywords: crack control; fiber-reinforced concrete; flexural toughness; macrofiber; moment capacity; precast; residual strength; shear capacity; shotcrete; slabs-on-ground; steel fibers; synthetic fibers; tensile strength; toughness.

CONTENTS

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The aim of this guide is to provide practicing engineers with design guidelines and recommendations for fiber reinforcement. Several approaches for designing fiber-reinforced concrete (FRC) have been developed over the years that are based on conventional design methods modified by special procedures to account for contributions of the fibers. These methods generally modify the internal forces in the member to account for the additional tensile capacity provided by the fibers. When compared with full-scale test data, these methods have provided satisfactory designs for FRC members (Parra-Montesinos 2006; Moccichino et al. 2006; Altoubat et al. 2009).

Concrete is a brittle material that is strong in compression but weak in tension. Steel bars are traditionally used to carry the tensile forces after concrete has cracked in structural applications. In reinforced concrete, the tensile strain of the concrete at cracking is much lower than the yield strain of the steel bars, which results in cracking of concrete before any significant load is transferred to the steel. Steel reinforcement is also used to limit the crack widths under specified levels for serviceability requirements. Unlike reinforcing bars, fibers are uniformly distributed in the volume of concrete; hence, the distance between fibers is much smaller than the spacing between bars. Fibers can provide post-crack tensile and flexural capacity and crack-width control in concrete elements.

Natural sources of reinforcement were used for brittle construction materials more than 3000 years ago, such as straw reinforcement in mud bricks. The first scientific studies on the use of steel fibers in concrete date back to the 1960s (Romualdi and Batson 1963; Naaman and Shah 1976). Since then, thousands of projects have been successfully completed using fiber reinforcement, including slabs-on-ground, composite steel decks, slabs-on-pile, precast, and shotcrete.

The major differences in the proposed methods are in the determination of the increase in tensile capacity of concrete provided by the fibers and the manner in which the total force is calculated. A conservative but justifiable approach in structural members such as beams, columns, walls, or elevated suspended slabs is that reinforcing bars should be used to support the total tensile loads. ACI 544.6R, however, describes the design for elevated suspended slabs where steel fibers are used as the primary reinforcement along with a minimum of continuous bars from columns to columns. Fibers can be used, in general, to supplement and reduce the reinforcing bars in various structural members. In applications where the presence of continuous reinforcement is not essential to the safety and integrity of the structure such as slabs-on-ground, pavements, overlays, shotcrete linings, slabs-on-piles (ACI 544.6R), and some precast units, fibers may be used as the sole means of reinforcement.

Fibers reliably control cracking and improve material resistance to deterioration as a result of fatigue, impact, and shrinkage, or thermal stresses. Fibers can contribute to the improved performance of concrete members in two ways: 1) by resisting the tensile stresses and, therefore, playing a structural role; or 2) by controlling crack development and, therefore, improving the durability of concrete. When fibers are intended to contribute to the structural performance of an element or structure, the FRC should be designed accordingly and the fiber contribution to the load-bearing capacity should be properly assessed and justified.

The commercial momentum for using steel fibers occurred during the 1970s for industrial floors as a major application. Other applications for steel fibers include composite metal deck, pile-supported slabs, precast units, and shotcrete. Synthetic macrofibers became available in the 1990s with applications such as slabs-on-ground, composite decks, pavements, shotcrete, and some precast units. Steel fibers and synthetic macrofibers can be viable alternatives for full replacement of steel bars in concrete elements with continuous support such as slabs-on-ground or shotcrete. For free-standing elements such as suspended slabs and tunnel lining segments, steel fibers at medium to high dosages have been shown to successfully replace a large portion of steel bars in the section (ACI 544.6R; ACI 544.7R).

The term "fibers" in this document only concerns macrofibers made of steel and polymeric (polyolefin) synthetic materials; hence, the design guides are not applicable to microfibers. Fiber diameter of 0.012 in. (0.3 mm) is the defining limit between microfibers and macrofibers. Synthetic microfibers have been used in concrete since the 1970s and are solely intended to control plastic shrinkage cracks (and sometimes drying shrinkage cracks) without any significant improvement in the mechanical properties of hardened concrete (ACI 360R). They may also affect the bleeding rate of fresh concrete, improving the near-surface properties of the hardened concrete. These fibers have been used to reduce the spalling of concrete exposed to fire and explosion.

When macrofibers are used in concrete to replace steel reinforcement, they can provide enhanced ductility, toughness, and durability. Fiber dosage can be engineered to provide a desired level of crack control, post-crack tensile and flexural capacity, or both. Similar to steel bars for which the size and spacing are calculated to provide the required reinforcement ratio, the dosage of fibers is also calculated to satisfy engineering requirements. Parameters affecting the performance of FRC include fiber type (material, size, and geometry), as well as bond characteristics and concrete mixture design. Fiber dosage may be limited by the practicality of their use in concrete; however, chemical admixtures are widely used for incorporating higher dosages of fibers. In certain applications, especially with congested steel bars, hybrid reinforcement (steel bars plus fibers) can be a viable alternative to conventional reinforcement. Using FRC may allow for applying alternative construction techniques—for example, tailgating concrete instead of pumping it for slabs-on-ground when steel reinforcement is eliminated. This can help in scheduling the project, resulting in a more cost-effective construction. Improved job-site safety is also among the benefits of using fibers from the reduced handling or tripping over the reinforcement at the job site. Using fibers can additionally eliminate the problems caused by misplacing conventional steel at its design position. The durability aspects of FRC and the associated benefits from fibers are extensively presented in ACI 544.5R.

1.2—Scope

Although FRC has been used since the 1960s, there are no agreed design approaches in North America for some of its applications. Unlike reinforced concrete with steel bars or welded wire mesh, the design of fiber reinforcement is not properly covered by national design codes. In Model Code 2010 (*fib* 2013), sections were added for new developments in the design of FRC as a part of the building code. ACI 318 has limited discussion on the use of fibers, such as provisions for using steel fibers as shear reinforcement in flexural members. ACI 360R presents the basics of fiber-reinforced slabs-on-ground, and ACI 506.1R discusses the design and application of fiber-reinforced shotcrete. It is the intent of this document to provide practicing engineers with simple yet appropriate design guidelines and state-of-the-art applications for FRC. This guide is intended for designers who are familiar with structural concrete containing conventional steel reinforcement, but who may need more guidance on the design and specification for FRC. In this document, fibers are treated as reinforcement in concrete and not as an admixture.

This guide discusses the types and typical dosages for fibers, general material properties, and available test methods for characterization of FRC. Explaining the design concepts and existing guidelines for fiber reinforcement is the focus of this document, including constitutive laws, design for flexure, design for shear, and design for crack-width control. This is further extended to specific applications for slabs-on-ground, composite slabs-on-metal decks, pile-supported ground slabs, precast units, shotcrete, and special applications. The final portion of this guide provides brief recommendations for specifying and building with FRC that includes general guidelines for mixing, placing, and finishing.

Although there are several types of fibers commercially available, this document is only applicable to steel fibers and polyolefin synthetic macrofibers that comply with ASTM C1116/C1116M. The formulas and applications discussed in this document should be verified for any other types of fibers. This document provides design guidelines based on the mechanical and structural properties of FRC as a composite material and not individual fiber products. Different fiber products may exhibit different performances in concrete; hence, it is crucial to design and specify FRC properties in addition to fiber types and materials that are suitable to achieve such properties.

1.3—Historical aspects

1.3.1 *Introduction*—Prior to presenting test methods, design philosophies, and applications of FRC, it is beneficial to review some of the historical aspects of this technology. This section summarizes the historical background of FRC since its development, including the mechanical characterization, analytical modeling, and test methods. Some of the earlier design and analysis guides addressing FRC during the 1970s and 1980s are discussed in Hoff (1982), ACI SP-44, SP-81, SP-105, and Shah and Skarendahl (1986). It should be noted that most of the earlier studies and applications of FRC incorporated steel fibers only.

1.3.2 *Mechanical characteristics and modeling*—Understanding the mechanical properties of FRC and their variation with fiber type and dosage is an important aspect of successful design. Fibers influence the mechanical properties of concrete in all failure modes, including compression,