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Report on Design and Construction of Fiber- Reinforced Precast Concrete Tunnel Segments

Reported by ACI Committee 544

Emerging Technology Series



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Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments

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Fiber reinforcement has emerged as an alternative to traditional reinforcing bars and welded wire mesh reinforcement for precast concrete tunnel segments. Due to significantly improved post-cracking behavior and crack control characteristics, fiber-reinforced concrete (FRC) segments offer advantages over tradition-

ally reinforced concrete segments such as saving cost and reducing production time while developing a more robust product with improved handling and long-term durability. Specific guidance on the design of fiber-reinforced precast concrete tunnel segments is needed for this emerging technology. This document offers general information on the history of FRC precast segments from tunneling projects throughout the world; a procedure for structural analysis and design based on governing load cases; and a description of the material parameters, tests, and analyses required to complete the design. The proposed guidelines are based on the knowledge gained from experimental research, analytical work, and the experience gained on numerous FRC precast tunnel projects.

Keywords: crack widths; earth pressure; fibers; fiber-reinforced concrete; grout pressure; hydrostatic pressure; lining; precast segment; stripping; surcharge load; thrust jack forces; tunnel.

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APPENDIX A—CALCULATION OF AXIAL FORCE-BENDING MOMENT INTERACTION DIAGRAM, p. 33**CHAPTER 1—INTRODUCTION AND SCOPE****1.1—Introduction**

Precast concrete segments are installed to support the tunnel bore behind the tunnel-boring machine (TBM) in soft ground and weak rock applications. The TBM advances by reacting against the completed rings of precast concrete segments that typically provide both the initial and final ground support as part of a one-pass liner system. These segments are typically designed to resist the permanent loads from the ground and groundwater, as well as the temporary loads from production, transportation, and construction. Tunnel segments are generally reinforced to resist the tensile stresses at both the serviceability limit state (SLS) and the ultimate limit states (ULS). With traditional reinforcing bar, a significant amount of labor is needed to assemble the cages and place the reinforcing bar.

Fiber-reinforced concrete (FRC) can be used to enhance handling and placement of precast concrete segments with the added benefit of reducing job-site labor requirements. FRC considerably improves the post-cracking behavior, defined as toughness (di Prisco et al. 2009), and it has better crack control characteristics than conventional steel-bar-reinforced concrete (Minelli et al. 2011; Tiberti et al. 2014). The use of FRC generally results in smaller crack widths and improved durability over the life of the structure. Because of the uniform dispersion of fibers throughout the segment, including the area around the segment face, fiber reinforcement effectively resists the bursting and spalling stresses that develop during the TBM jacking process. de Waal (1999) and Schnütgen (2003) highlight the beneficial effect of FRC in the presence of concentrated loads and bursting. Furthermore, the presence of fiber in the concrete matrix increases the fatigue and impact resistance of the segments that help mitigate against unintentional impact loads during segment handling and tunnel construction operations (di Prisco and Felicetti 2004).

Reinforcing bar is efficient for resisting localized stresses in the concrete segment such as stresses due to concentrated loads during production. The distributed stresses such as stresses due to earth pressure and groundwater loads at final service stage, however, are better dealt with by fiber reinforcement. Because both localized and distributed stresses are generally present in tunnel linings, segments can be manufactured using a combination of conventional reinforcing bar and fiber reinforcement—that is, a hybrid system. For larger-diameter tunnels with high internal forces, a combined solution of fibers and reinforcing bar may present an ideal solution (Plizzari and Tiberti 2006, 2007; de la Fuente et al. 2012). Using current technology with high-strength concrete segments, tunnel rings of more than 23 ft (7 m) in diameter have been used successfully (Abbas et al. 2014). Examples include Grosvenor Coal Mine, Channel Tunnel Rail Link Tunnel, and Blue Plains Tunnel with internal diameters of 23, 23.5, and 23 ft (7, 7.15, and 7 m), respectively.

The slenderness of the tunnel segment (λ), defined as the ratio between the breadth or curved length of segment along

its centroid (developed segment lengths) and its thickness, is a key parameter to determine when fibers can be used as the only source of reinforcement in the concrete tunnel segments. When the slenderness of a segment is higher than 10, it is generally necessary to adopt a hybrid reinforcement of fibers and conventional bars; however, **Beño and Hilar (2013)** have proposed to increase the slenderness limit up to 12 to 13 using the pilot test tunnel segments used in Prague Metro Line A Extension in Czech Republic as a model. Full-scale tests are needed to validate the usage of fibers with such slenderness conditions.

1.2—Scope and limitations

The fiber-reinforced concrete (FRC) segment designers should be provided with a clear and simple approach using specified post-crack residual tensile strength σ_p (ACI 544.8R) and specified compressive strength f'_c . This report proposes a procedure for designing FRC tunnel segments to withstand all the appropriate temporary and permanent load cases occurring during the construction and design life of tunnels. This procedure is based on the available design codes, standards, and guidelines. Application of this approach is summarized in this document. Full-scale bending tests are also discussed to evaluate the segment performance during each stage of its design life to include stripping, storage handling, transportation, and the in-service load condition due to earth pressure, groundwater, and surcharge loads. Other full-scale tests performed on the precast segments include thrust tests to reproduce the tunnel boring machine (TBM) action on the segment during the jacking process.

This report is focused on the analysis, design, and manufacturing of FRC segments of one-pass precast segmental lining used with TBM-bored tunnels. The design methods presented can be applied to tunnels of different types such as road, railway, and subway tunnels; headrace, water supply, and wastewater tunnels; and service, gas pipeline, and power cable tunnels. Two-pass lining systems, however, can also benefit from the proposed design procedure.

This document does not address the actions of TBM gantries, thermal variations, fire loads, or internal loads such as train loads within tunnels. Also, further research is needed to establish design checks for concrete breakout strength around bolts and dowels, and resistance against punching shear force in the proximity of stack support at storage phase.

The design procedures presented herein have been developed for steel fibers, and any extrapolation to synthetic or other types of fibers reported in **ASTM C1116/C1116** should be confirmed by repeating small-scale (**ASTM C1609/C1609M**; **BS EN 14651**) and full-scale bending, point load, and cantilever tests explained in **Chapter 8** to show that static and long-term properties are adequately characterized.

Typical volume fraction of steel fibers used in FRC tunnel segments does not exceed 0.5 percent, which typically results in a tensile strain-softening response (ACI 544.8R) of the material. Therefore, this report only covers properties, analysis, and design methodologies of tensile strain-softening FRCs, and not tensile strain-hardening materials (ACI 544.8R). Note that a deflection-hardening response

under flexural tests can be achieved using conventional fiber dosage rates, which is desired due to improved crack control characteristics of concrete materials (ACI 544.8R).

1.3—Applications and uses in existing tunnels

Since 1982, fiber-reinforced concrete (FRC) has been used in numerous projects around the world and is the preferred material for the construction of tunnel precast segmental lining (**de la Fuente et al. 2012, 2013**; **Hilar and Beño 2012**; **Hansel and Guirguis 2011**). FRC technology has developed in recent years with the introduction of high-strength concrete, allowing the use of fibers as the sole reinforcement system for more challenging conditions on larger-diameter tunnel projects (**Barwart et al. 2013**). In other cases, fiber and reinforcing bars have been used in conjunction to reinforce the tunnel segments (de la Fuente et al. 2012). Tunnels with different sizes with internal diameters ranging between 7.2 and 37.4 ft (2.2 and 11.4 m) have been built using fiber reinforcement (Hilar and Beño 2012). Minimum and maximum thickness of the FRC precast segments in existing tunnels are 6 and 16 in. (0.15 and 0.40 m), respectively (de la Fuente et al. 2012).

A number of these projects are shown in Table 1.3 and include water supply, waste water, gas pipeline, power cable, subway, railway, and road tunnels. FRC segments shown in Table 1.3 are reinforced primarily with steel fibers as the main source of reinforcement. In many of the smaller-diameter tunnel projects, the precast concrete segmental liners were reinforced only with steel fibers using dosage rates between 40 and 100 lb/yd³ (25 and 60 kg/m³).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_d	= load distribution area inside segment under thrust jack forces, in. ² (mm ²)
A_g	= gross area of concrete section, in. ² (mm ²)
A_j	= area of contact zone between jack shoes and the segment face, in. ² (mm ²)
A_s	= required area of reinforcing bars, in. ² (mm ²)
a	= distance from edge of vacuum lift pad to edge of segment in the load case of stripping, or dimension of final spreading surface under thrust jack forces, in. (mm)
a_l	= transverse length of contact zone between jack shoes and the segment face, in. (mm)
a_t	= transverse length of stress distribution zone at the centerline of segment under thrust jack forces, in. (mm)
b	= width of tunnel segment, or width of tested specimen, ft (m)
C_c	= compression force in the concrete section, lbf (N)
C_t	= tensile force in the section due to fiber reinforcement, lbf (N)
D_e	= external diameters of the tunnel segmental lining, ft (m)
D_i	= internal diameter of the tunnel segmental lining, ft (m)