ACI 544.7R-16

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

Reported by ACI Committee 544

Emerging Technology Series

American Concrete Institute
Always advancing

First Printing
January 2016
ISBN: 978-0-87031-948-8

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

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at http://concrete.org/Publications/DocumentErrata.aspx. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised ACI Manual of Concrete Practice (MCP).

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

544.7R-16

Emerging Technology Series

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

Reported by ACI Committee 544

Barzin Mobasher, Chair
Neven Krstulovic-Opara, Secretary

Clifford N. MacDonald, Membership Secretary

Corina-Maria Aldea
Emmanuel K. Attiogbe
Mehdi Bakhshi*
Nemkumar Banthia
Joaquim Oliveira Barros
Amir Bonakdar
Amanda C. Bordelon
Jean-Philippe Charron
Xavier Destree
Ashish Dubey
Mahmut Ekenel
Liberato Ferrara
Gregor D. Fischer
Dean P. Forgeron
Emilio Garcia Taengua

Rishi Gupta
Heidi Helmink
George C. Hoff
Marco Invernizzi
John Jones
David A. Lange
Maria Lopez de Murphy
Michael Mahoney
Bruno Massicotte
James Milligan
Nicholas C. Mitchell Jr.
Verya Nasri†
Jeffrey L. Novak
Giovanni A. Plizzari†
Klaus Alexander Rieder

Pierre Rossi
Steve Schaef
Surendra P. Shah
Flavio de Andrade Silva
Giuseppe Tiberti†
Thomas E. West
Kay Wille
Robert C. Zellers

Consulting Members
P.N. Balaguru
Hiram Price Ball Jr.
Gordon B. Batson
Arnon Bentur
Andrzej M. Brandt

James I. Daniel
Sidney Freedman
Christian Meyer
Henry J. Molloy‡
Antoine E. Naaman
Venkataswamy Ramakrishnan

*Chair of the task group that prepared this report.
†Individuals who prepared this report.
‡Deceased.

V. Nasri is acknowledged as a significant contributor to this report. Special acknowledgements to M. Invernizzi, W. Bergeson, and S. Giuliani-Leonardi for their contributions to this report.

ACI encourages the development and appropriate use of new and emerging technologies through the publication of the Emerging Technology Series. This series presents information and recommendations based on available test data, technical reports, limited experience with field applications, and the opinions of committee members. The presented information and recommendations, and their basis, may be less fully developed and tested than those for more mature technologies. This report identifies areas in which information is believed to be less fully developed, and describes research needs. The professional using this document should understand the limitations of this document and exercise judgment as to the appropriate application of this emerging technology.

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 traditionally 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.

CONTENTS

ACI 544.7R-16 was adopted and published January 2016.

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