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Precast tunnel segments reinforced by macro-synthetic fibers

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ABSTRACT

The use of fiber reinforced concrete in tunnel linings, with or without conventional rebars, has increased in the two last decades, especially with regard to precast tunnel segmental linings. In addition, there is a general growing interest in the scientific community on macro-synthetic fibers for use in underground structures.

Within this framework, the present study investigates the possibility of using polypropylene (PP) fiber reinforcement in hydraulic precast tunnel segments by means of an experimental program on six full-scale segments of Monte Lirio hydraulic tunnel (Panama). Three different reinforcement solutions were studied both under flexure and point load test: typical conventional reinforcement generally adopted in practice (reference samples, RC); PP fibers only (PFRC specimens); combination of PP fibers and conventional reinforcement (hybrid solution, RC + PFRC segments). Based on the loading configurations considered, experimental results showed that PP fibers (with or without reinforcing bars, depending on loading conditions) represent an efficient reinforcement for hydraulic precast tunnel segments. PP fibers can be used as flexural, splitting and minimum shear reinforcement, while concerning the spalling reinforcement, only PP fiber reinforcement could be used even if the combination with conventional reinforcement (hybrid solution) guarantees a better control of spalling cracks for high load levels.

1. Introduction

In the modern society, due to the traffic increase in bigger cities welcoming people from the country sides as well as the need of preserving ground surface, there is an increasing interest in tunnel linings. As consequence, the main issue is the reduction of the construction time and the enhancement in safety of workers in underground conditions. Full face mechanized excavation methods are consequently under improvement all over the world with the adoption of bigger and more powerful tunnel boring machines (TBMs) with linings made of precast segments.

In addition to the progress in mechanized excavation methods, it is evident the need of improving the structural behavior of segmental linings in terms of bearing capacity, crack control and water-tightness. To this aim, in the last two decades, Fiber Reinforced Concrete (FRC), with or without conventional rebars, was progressively adopted in several tunnel projects (Hansel and Guirguis, 2011; Hilar and Beno, 2012; Liao et al., 2015). The benefits related to the inclusion of fiber reinforcement in the cementitious composites are several but, the most important, is the noticeable increase of the post-cracking tensile properties. Fiber reinforcement also enables a considerable boost of the tunnel elements production process, since fibers, which spread uniformly in segments (Kooiman, 2000; Carmona et al., 2016), can be easily added during concrete mixing. The enhancement of the general structural behavior together with the improvement of the industrialization process of tunnel segments are probably the two main key-factors of the continuously growing use of FRC in precast tunnel linings (De la Fuente et al., 2017).

Recently, guidelines on structural design of FRC elements have been developed in some countries (e.g.: ACI report 544.1R-96, 1996; CNR DT 204, 2006; DAfStb, 2012); more importantly, FRC was recently included in the fib Model Code 2010 (2012) and is going to be included in the new Eurocode 2 (CEN TC 250, 2016). At the same time, the International Tunnelling Association (ITA) as well as the American Concrete Institute (ACI) recently published guidelines for FRC segmental linings (ITA report n.16, 2016; ACI 544.7R-16, 2016) and fib WP 1.4.1 (2016) is preparing design guidelines for the same structural elements.

Steel Fiber Reinforced Concrete (SFRC) has been generally used in precast tunnel elements (ITA report n.16, 2016; ACI 544.7R-16,

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Nomenclature

CMOD	crack mouth opening displacement
f_{cm}	mean value of the cylindrical compressive concrete strength
f_{ck}	characteristic value of the cylindrical compressive concrete strength
$f_{cm,cube}$	mean value of the cubic compressive concrete strength
f_{Lm}	mean value of the limit of proportionality
f_{Lk}	characteristic value of the limit of proportionality
$f_{R,jm}$	mean value of the residual flexural tensile strength corresponding to CMOD = CMODj
$f_{R,jk}$	characteristic value of the residual flexural tensile strength corresponding to CMOD = CMODj
$P_{cracking}$	flexural cracking load
P_{max}	flexural maximum load
$M_{cracking}$	bending moment at $P_{cracking}$
M_{max}	bending moment at P_{max}
V_f	fiber volume fraction
$\delta_{cracking}$	mid-span deflection at $P_{cracking}$
δ_{max}	mid-span deflection at P_{max}
ρ_s	longitudinal reinforcement ratio

2016) even though, in the last decade, important research efforts have been devoted to the development of some types of structural macro-synthetic fibers, which are now able to impart significant toughness and ductility to concrete, as soon as fiber long-term behavior is guaranteed (Model Code 2010, 2012). Therefore, there is a growing interest in the scientific community on precast tunnel elements reinforced by macro-synthetic fibers (Tiberti et al., 2015a; Di Prisco et al., 2015; Gilbert and Bernard, 2015; Conforti et al., 2016); the latter could be used when a high resistance to the environmental attack (Caratelli et al., 2016) is required together with a long specific lining service life (Kasper et al., 2008) since macro-synthetic fibers do not suffer corrosion problems, e.g. hydraulic tunnels or tunnels in presence of aggressive soil environment.

The reinforcement adopted in precast tunnel elements is generally designed according to the standard load cases of demoulding, storage, embedded ground condition (final stage) and grouting process (ITA Official report, 2000; DAUB, 2014). Nevertheless, besides these loading conditions, the high concentrated loads exerted by TBM rams, occurring during the construction process, may govern the structural size and may explain the crack patterns that are frequently observed in practice in tunnel segments (DAUB, 2014; ITA report n. 16, 2016).

Regarding the local behavior under TBM thrust shoes, it was proven that fibers enable a stable development of splitting cracks, leading to relatively small cracks and a possible reduction or elimination of stirrups placed in the regions under the thrust jacks (Tiberti et al., 2015a). Moreover, fibers could be used as shear reinforcement (Cuenca et al., 2015; Caratelli et al., 2011) and for withstanding spalling tensile stresses which occur between TBM rams (Conforti et al., 2016). In addition, fibers help to prevent local damage as spalling at edges and chipping of corners (Kasper et al., 2008). Accordingly, tunnel segments reinforced only by steel fibers were successfully used in several tunnel projects (ITA report n. 16, 2016; Kasper et al., 2008; Caratelli et al., 2012). Nevertheless, high localized stresses (e.g. bending stresses) can occur if some irregularities take place during the tunnel construction process (e.g.: eccentricity of jacks, gaps between rings). The probability of occurrence and the extent of these irregularities directly govern the amount of localized stresses in segments and, consequently, the possible complete or partial substitution of rebars by fibers (Tiberti, 2014; ITA report n. 16, 2016).

When the previously mentioned unfavorable conditions cannot be avoided or cannot be limited in terms of frequency of occurrence or because of a high flexural demand in the tunnel lining, a hybrid reinforcement solution can be used, based on a limited amount of conventional rebars in combination with FRC having adequate post-cracking residual strengths in order to cope with splitting and spalling stresses (Plizzari and Tiberti, 2007; Tiberti, 2014; Tiberti et al., 2015a) or for providing a contribution in terms of segment flexural behavior (De la Fuente et al., 2012; Caratelli et al., 2012; Tiberti, 2014).

Within this framework, the research work presented herein investigates the use of polypropylene fiber reinforcement (PP fibers) in precast tunnel elements for underground water conduits. To this aim, the case study of Monte Lirio hydraulic tunnel in Panama was considered and an experimental campaign on full-scale segments was carried out. Three different reinforcement solutions were considered: typical conventional reinforcement generally adopted in practice (reference samples, RC); polypropylene fibers only (PFRC specimens); combination of polypropylene fibers and conventional reinforcement (hybrid solution, RC + PFRC segments). Two different experimental tests were performed:

- flexural tests to evaluate the flexural bearing capacity, which is mainly required during transitional stage (demoulding, storage, transportation and positioning) or in the final stage;
- point load tests to reproduce the TBM action on the segment during the excavation process.

2. Experimental program

2.1. Specimen geometry and reinforcement details

The Monte Lirio hydraulic tunnel (Panama) is an underground water conduit (water without any pressure) characterized by a total length of 7.88 km. The tunnel is excavated with a Tunnel Boring Machine (TBM). The segmental lining presents an internal diameter of 3200 mm, a thickness of 250 mm (external diameter of 3700 mm), leading to a lining aspect ratio (the ratio of internal diameter to ring thickness) equal to 12.8. Each lining ring is composed by five different precast concrete segments (Fig. 1a). The precast tunnel segments hereafter considered are the left (Fig. 1b) and right (Fig. 1c) counter-key segments of the Monte Lirio lining ring (Fig. 1a). These counter-key segments are characterized by an inclined side in order to correspond with the shape of the key segment, as well as by an average length of 1810 mm and a width of 1200 mm. Hence, the segment aspect ratio (ratio of segment length to segment thickness) is about 7.2. Moreover, two bolting openings are included on the internal segment surfaces, as well as sockets are present on segment sides for the connection with the adjacent rings.

Six full-scale counter-key segments of Monte Lirio hydraulic tunnel (Fig. 1a) characterized by three different reinforcement solutions were constructed and tested. In particular for each reinforcement solution both left (Fig. 1b) and right (Fig. 1c) counter-key segments were produced by a singular concrete batch. Then, left counter-key segments were tested under flexure, while the right ones were subjected to a point load test. The three reinforcement solutions studied were: