Tunnelling and Underground Space Technology 77 (2018) 13–25

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Analytical and experimental evaluation of the use of fibers as partial reinforcement in shotcrete for tunnels in Chile

Leonardo M. Massone*, Francisco Nazar

Department of Civil Engineering, University of Chile, Blanco Encalada 2002, Santiago, Chile

ARTICLE INFO

Keywords:
Tunnel
Shotcrete
Fiber reinforced concrete
Seismic response
Steel fiber
Polypropylene fiber

ABSTRACT

This work evaluates experimentally the use of steel or polypropylene fibers in shotcrete as a partial replacement for the traditional reinforcement of electrowelded mesh used at the tunnel support for the subway in Santiago (Chile). For the experimental part, 8 tests were performed on section-scaled (1:2) slender (half-span to depth ratio a/d ~ 5) specimens under transversal (flexure and shear) and axial loads ($0.02f'_cA_g$ and $0.07f'_cA_g$) and with different reinforcements layout; and another 4 tests of similar specimens, but with low half-span to depth ratio (a/d ~ 1.5). The section includes welded mesh (one face), a central reticulated frame and a plane shotcrete with a welded mesh (opposite face) or reinforced shotcrete (steel or polypropylene). The results showed a very important contribution of the reticulated frame in flexion (main internal reinforcement) and a modest contribution of the welded mesh and fibers. A two-dimensional finite element modeling of the tunnel-ground system using OpenSees is also performed using calibrated models for the tunnel section based on the experimental part. The soil is modeled with 9-node quadrilateral elements, the lining is modeled with beam-column elements with fiber sections, and the interaction between the lining and the soil is modeled by the Winkler approach without tension in the direction normal to the contact surface and with perfect adherence in the tangential direction. The model is subjected to the static loads from the excavation, modeled considering the constructive sequence of the tunnel using the α method, and then to a seismic analysis by means of the shear wave method (distortion). The results show that the safety factors implicit in the traditional design are high, implying that the structure remains elastic.

1. Introduction

A tunnel is an underground passageway dug through the surrounding rock or soil, which is used to enable passage for vehicles, people, or water. The material surrounding the tunnel depends on the terrain conditions. In rock, for example, there may be no need for any support to be sustained, and structural stability is entirely dependent on the rock itself. In materials of lower self-supporting capacity, such as soil, it is necessary to incorporate some additional structure that supports the material, and since tunnels usually require their interior with open access, the use of linings that act as arches (together with the soil's own self-support capacity) is the preferred solution.

The structural design should consider the bending induced on the lining. Estimating the bending stresses induced on the tunnel support is complex, because it is difficult to estimate how the loads are distributed between the lining and the soil, as well as the earthquake-induced loads. The literature recognizes three different systems of commonly used concrete tunnel linings: (i) prefabricated segment linings; (ii) projected (shotcrete) concrete linings; and (iii) in-situ concrete linings. Other support measures are reticulated frames, glass fiber bolts, and longitudinal umbrellas, among others. The first system consists of prefabricating curved segments and joining them together by being seated in the ground. The second consists of shotcreting against the ground and other supporting elements, such as meshes, reticulated frames, bolts, etc. The last system consists of concreting in a traditional way, with moldings, and could be combined with the second method. Nowadays, thanks to the proliferation of the New Austrian Tunneling Method (NATM), the use of shotcrete for the lining has become more widespread (Kolymbas, 2005). The shotcrete is typically reinforced with electrowelded meshes, and in recent times discrete fibers have been used as replacement of steel mesh, using what is traditionally known as fiber reinforced concrete (FRC). FRC is a material made with hydraulic cement, aggregates of various sizes, incorporating discrete, discontinuous fibers (Bentur and Mindess, 2006). FRC is attributed great benefits, both structural and non-structural. Examples of the first are: (i) greater ductility; (ii) better cracking control; (iii) better flexural behavior; and (iv) residual tensile strength, among others. Examples of the second ones are: (i) a better performance in the case of freeze-thaw

* Corresponding author.
E-mail addresses: lmassone@ing.uchile.cl (L.M. Massone), francisco.nazar@ing.uchile.cl (F. Nazar).

https://doi.org/10.1016/j.tust.2018.03.027
Received 4 September 2017; Received in revised form 20 March 2018; Accepted 24 March 2018
0886-7798/

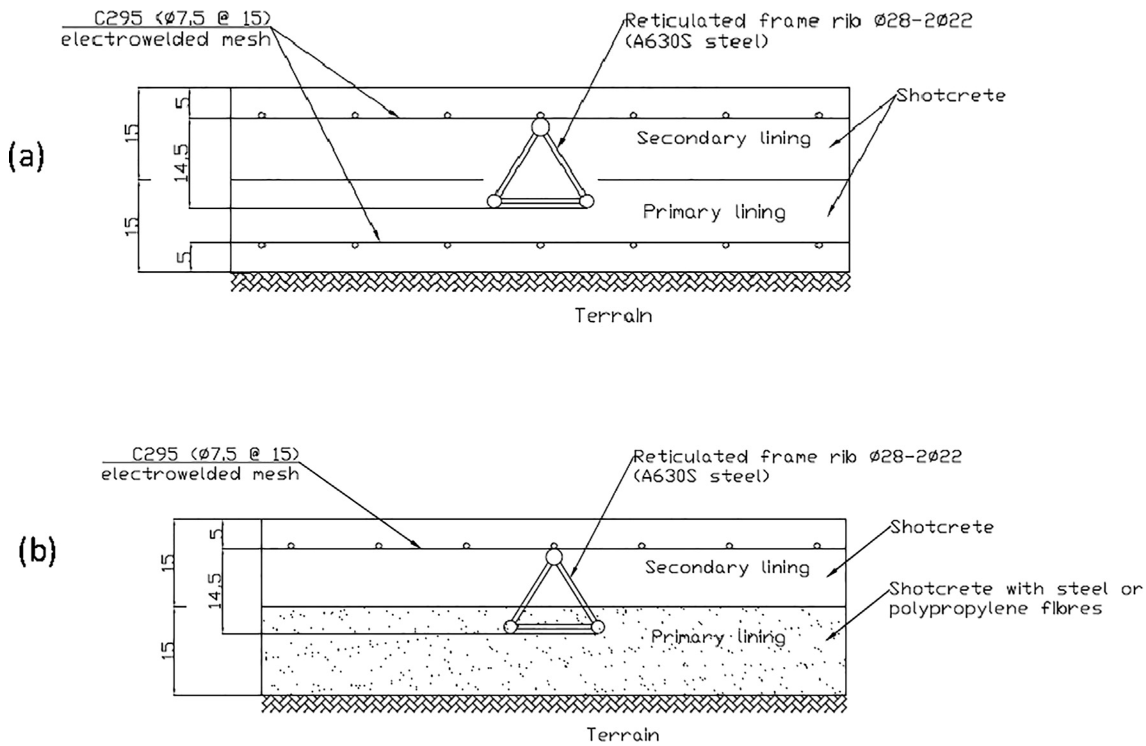

Fig. 1. Sections of the tunnel lining (bottom floor) – (a) Traditional section with double reinforcement of steel welded mesh (primary and secondary lining) and reticulated frame and (b) Proposed section with steel welded mesh in the secondary lining, steel or polypropylene fibers in the primary lining, and reticulated frame.

cycles; (ii) better impact and abrasion behavior; and (iii) increased durability resulting from better cracking control, among others. In addition, in the case of applications where the fibers completely replace the traditional reinforcement, time saving of reinforcement placing can become considerable.

Previous experimental research around FRC (Belletti et al., 2004; Wetzig et al., 2004; Kang et al., 2012) as well as practical usage of FRC in tunnel linings (Chiaia et al., 2009; De la Fuente et al., 2012) can be found mainly in Europe, where the focus has been placed mainly around steel fibers using particular construction methods and technology, as well as shapes and quantity of fibers. On the other hand, polypropylene fibers are currently gaining popularity in the mining industry in Chile and Australia in stiff soil/rock applications, where they are chosen because they are less prone to corrosion and they produce less wear on the machines. Few comparisons can be found in the literature between steel and polypropylene fibers with a particular focus on the structural behavior for shotcrete in tunnels. The motivation of this work is to evaluate the partial replacement of the traditional reinforcement of electrowelded meshes by steel or polypropylene fibers for a subway tunnel in Santiago (Chile), using the fibers and construction technology available and typically used in the Chilean practice. This work carries out an experimental and analytical evaluation of a lining reinforced with electrowelded meshes or with steel or polypropylene fibers. Scaled (1:2) sections under flexo-compression tests are performed on typical sections of shotcrete linings, constructed with concrete with and without fibers, electrowelded meshes, and a reticulated embedded frame. On the other hand, the observed behavior is numerically modeled, and a finite element analysis of the soil-tunnel system is performed to establish the demands to which the tunnel will be subjected, both to static and seismic loads.

2. Design of experiments and construction of specimens

2.1. General description of experiments

The primary objective of the experiments was to evaluate the mechanical behavior of tunnel lining sections structured with reticulated steel frames, shotcrete with fibers (steel or synthetic), and traditional reinforcement meshes subjected to bending, shear and axial loading in the direction perpendicular to the axis of the tunnel. The purpose is to compare the effect of the replacement of the traditional reinforcing mesh with fibers, and to observe the contribution of the reticulated frame.

In order to achieve it, material properties were characterized and also specimens were designed and tested to capture flexural and shear response. With respect to the element tests, 12 bending tests were performed with axial load, with different reinforcement solutions, different half-span to depth ratios (M/Vd, moment-to-shear to reinforcement level arm ratio) and also varying the axial load. The specimens were constructed at 1:2 scale. For the characterization of the material properties, the following additional tests were also performed: (a) bending tests on specimens with indentations and without reinforcement, following the EN 14651 (2007) methodology, (b) compressive tests of cylindrical cores obtained from the test specimens, (c) direct tensile tests on shotcrete cores with and without fibers and (d) uniaxial steel tensile tests of meshes and frames.

According to Nazar (2016), in the actual tunnels under consideration (line 6 of the Santiago Metro), the support (also called the primary lining) is 15 to 25 cm thick, while the lining (also called secondary lining) is of a minimum thickness of 15 cm, being both shotcreted elements. The typical steel meshes used as reinforcement are, depending on the ground type, C295 (295 mm^2/m area) or C338 (338 mm^2/m) grade AT56-50H (f_y = 500 MPa, nominal) electrowelded meshes, with bar diameters of 7.5 mm and 8.5 mm respectively, spaced at 150 mm. In addition, three-bar reticulated frames (one 28 mm diameter bar and two 22 mm diameter bars) of grade A630S steel (f_y = 420 MPa, nominal) or grade A42-27H (f_y = 270 MPa, nominal) with height variable with ground type (145 mm for gravel and 180 mm for soil), and with a variable separation between them, which also depends on the type of ground type (1.0 to 1.5 m for gravel, and 0.5 to 1.0 m for fines or irregular areas) are considered. Fig. 1 shows the sections of the tunnel.

For the purposes of this work, the tunnels found in gravel were