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Experimental investigation of the mechanical behavior of the steel fiber reinforced concrete tunnel segment

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HIGHLIGHTS

- A new full-scale test method for SFRC tunnel segments was proposed.
- The composite effects of steel fiber and steel rebar on mechanical behavior of SFRC tunnel segments were investigated.
- SFRC tunnel segments achieved significant reduction in crack width, providing serviceability advantages.
- SFRC improved the cracking load and toughness of tunnel segments.

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ABSTRACT

The main objective of this paper is to investigate the composite effect of steel fiber and steel rebar on the mechanical behavior of full-scale steel fiber reinforced concrete (SFRC) precast tunnel segments fabricated for a subway tunnel in China. A new biaxial loading method was adopted to simulate the loading state of the tunnel segment. The experiment included an initial SFRC tunnel segment proposed for the project, and two other SFRC tunnel segments were employed for comparison. By comparing the test results, the static characteristics of the three segments, including the internal strain, deflection, neutral axis position and crack patterns were determined. The experimental results indicate that the combined used of steel fiber and steel rebar shows an enhanced effect by delaying the initial impact of cracking and increasing the limit of proportionality of the segments. Longitudinal rebar in the tensile region were more helpful in decreasing tension strain and deflection in the mid-span section than the steel fibers. However, steel fibers performed better in improving the cracking load, cracking resistance and toughness. Furthermore, the initial SFRC tunnel segment proposed for the project exhibited a significant reduction in crack width and satisfied the design criteria for load carrying ability and crack width. The combination of steel fiber and steel rebar indicates an optimal choice of reinforcement for a tunnel segment.

1. Introduction

The shield tunnel technology is widely used in tunnel construction under soft soil conditions, and most of the tunnels adopt conventional steel reinforced concrete (RC) tunnel segments. Due to the low tensile strength and brittle characteristics of concrete, traditional RC tunnel segments are prone to crack or become damaged during the fabrication, curing, handling and installation processes. In addition, the safety, permeability, serviceability and durability of the tunnel are greatly influenced by the presence of macro-cracks [1].

In the last two decades, a number of studies have been conducted to investigate the fiber reinforced concrete [2–6]. A common conclusion from these studies is that the use of fiber improves the mechanical behavior of concrete. Fiber reinforced concrete (FRC) is a composite material that has proved to be a competitive material for many types of structures [7]. In particular, there are many advantages when using FRC tunnel segments in the manufacture of segments of the linings of tunnels built by means of a tunnel boring machine (TBM) [8–10]. Conventional tunnel segments reinforced with steel rebar are typically vulnerable to corrosion [11]. This problem can be mitigated using steel fiber reinforced concrete (SFRC) because steel fibers can partially or completely substitute for traditional reinforcing steel cages. SFRC improves the mechanical response of precast segments for tunnels, enhancing their ductility and fire resistance as well as their mechanical performance during transient load stages. In addition,

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SFRC segments typically perform better during the fabrication, curing, handling and installation processes than conventional reinforced segments [12–15]. This performance can be ascribed to the randomly distributed fibers that provide better crack control [12]. Furthermore, due to their ability to hold the concrete matrix together, fibers added to concrete can improve its chipping and spalling behavior under extreme loading, even after the formation of successive cracks [16]. SFRC segments have been used effectively in tunneling projects around the world because the steel fibers lead to an increase in the post-cracking tensile strength and improve the toughness, crack arresting properties and durability properties of the concrete [9,16].

However, due to the lack of special design rules for SFRC tunnel segments, engineers have usually designed SFRC tunnel segments by adopting the same rules that are valid for conventional RC tunnel segments or are based on the national codes concerning the design of an FRC structure [17]. A full-size test is one of the effective ways to study the mechanical behavior of steel fiber reinforced concrete segments [7,18]. At present, the mechanical behavior of segments is usually investigated by testing under three-point bending or four-point bending conditions [16]. Because these tests are generally done under vertical load only, deformation of both ends of the tunnel segments in the horizontal plane is in a free form that is quite different from the actual working conditions of the segments.

The investigation of SFRC tunnel segments lags far behind the construction and structural demands, while the manufacture of the tunnel segments for laboratory investigation is difficult and expensive. A method using a simply supported beam exerting axial force by a jack at each end is usually adopted for laboratory investigation to simulate the stress state of tunnel segments [5]. As segments with different curvature radii and center angles cannot be simulated by a simply supported beam and the axial force exerted by a jack in only one direction cannot reflect the real loading condition of the tunnel segment, there are some unreasonable problems existing in the method mentioned above. Thus, the behavior and the design considerations of the SFRC tunnel linings should be investigated for further applications.

This paper presents the results of a research project in which three full-scale SFRC tunnel segments were tested using a new method of biaxial loading. The tests discussed aim to examine the mechanical behavior of SFRC tunnel segments in terms of the load-strain relationships of the longitudinal rebar and concrete in mid-span, the load-deflection relationship, the neutral axis position and the crack patterns. The SFRC tunnel segments being tested were reinforced with different contents of steel fibers and different amounts of longitudinal rebar.

In the present study, biaxial loading tests were conducted on full-scale SFRC tunnel segments to simulate field loading conditions. The experimental results are discussed and compared to code predictions. The behavior of the SFRC tunnel segments with different contents of steel fibers and different amounts of longitudinal rebar was compared to highlight the potential of SFRC for precast concrete tunnel lining applications.

2. Experimental program

2.1. Materials

Table 1
Composition of concrete.

Material	Dosage (kg/m^3)
Cement type P·O 42.5	400
Fly ash	50
Sand 0–5 mm	800
Coarse aggregate 2.5–10 mm	1100
Water	95
Superplasticizer	7.65
Fibers	25 and 30

The concrete mix was designed for the target of a 28-day compressive strength of 50 MPa. The composition of the concrete used for the fabrication of all of the SFRC tunnel segments is presented in Table 1. The concrete was made with P·O 42.5 Portland cement and first class fly ash. The coarse aggregates were crushed gravel with a maximum size of 10 mm, and the fine aggregates were natural river sand. The amount of superplasticizer added to the concrete was determined by laboratory test to ensure equivalent behavior in terms of fiber distribution inside the segment, which was essential for the comparison of the structural responses. Mixes were produced with different steel fiber contents of 25 and 30 kg/m^3 to assess the mechanical performance of the SFRC tunnel segments with different amounts of fibers.

The experimental program investigated the combined action of steel fiber and steel rebar on the mechanical behavior of SFRC segments. Table 2 shows the properties of the steel fibers used. The nominal diameter of the longitudinal rebar and stirrup for all of the tunnel segments was 12 mm and 6.5 mm, respectively. The longitudinal rebar and stirrups had a yield stress of 450 N/mm^2 and 430 N/mm^2, an ultimate stress of 640 N/mm^2 and 560 N/mm^2, respectively. This information was obtained from uniaxial tension tests.

2.2. Test setup

The design load for the tested segments was calculated by a numerical method according to the specific case of the Metro Ling 7 from Shenyang in China, using sectional analysis. Concerning the analysis of the most unfavorable design condition – the soil pressure during the service stage, the calculation was performed with the commercial code ANSYS. The lining rings were simulated, considering the load-structure interaction and the possible presence of water. Specifically, the worst case scenario was analyzed. The design values of bending and axial forces obtained for the service stage were $M_d = 202$ kN·m and $N_d = 833$ kN, respectively, with the latter the most adverse in terms of the design of the mixed reinforcement.

To satisfy the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS) together with an integral study of the associated costs, the optimum solution for the mixed reinforcement had been determined. The initial design procedure for the SFRC tunnel segments was based on the MC 2010 [19]. The simplified post-cracking constitutive law of SFRC used in the design procedure is shown in Fig. 1. To evaluate the flexural properties of SFRC, beams 150 × 150 × 150 mm were tested in accordance with EN 14651. Table 3 shows the values of residual flexural strength and strain used to simulate the post-cracking behavior of the SFRC.

The segments were initially designed with a minimum amount of reinforcement consisting of 8φ12 in each side (see Fig. 2) and

Table 2
Properties of used steel fibers for manufacturing SFRC tunnel segments.

Parameters	Description
Length, mm	60
Diameter, mm	0.75
Aspect ratio	80
Type of steel	Carbon
Shape and cross section	Hooked and circular
Ultimate tensile strength, MPa	1800
Young's modulus, GPa	210