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Exploratory study of ultra-high performance fiber reinforced concrete tunnel lining segments with varying steel fiber lengths and dosages

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ABSTRACT

Ultra-high performance fiber-reinforced concrete (UHPFRC) is an emerging material exhibiting superior mechanical and durability properties. However, its application in precast concrete tunnel linings is lagging due to lack of experimental data and adequate design provisions. This study is a preliminary investigation of UHPFRC tunnel lining segments incorporating various steel fiber lengths and dosages. The mechanical performance of UHPFRC tunnel lining segments was investigated. Flexural and edge-point load tests were conducted on 1/3-scale UHPFRC tunnel lining segments to evaluate its bending and thrust load resistance. The main studied variables were the steel fiber lengths and dosages. Results showed that UHPFRC tunnel lining segments incorporating shorter steel fibers exhibited higher cracking and peak loads compared to that of similar segments made with longer fibers. Furthermore, the shorter fibers enhanced the strain hardening phase, leading to more stable multiple micro-cracks and higher resistance to growth of macro-cracks. Conversely, longer steel fibers better improved the post-peak strain softening of the lining segments, achieving more ductile failure. The load carrying capacity of UHPFRC lining segments linearly increased with higher fiber dosage and followed the rule of mixtures. Moreover, steel fibers enhanced the cracking behavior under both thrust load and concentrated load compared to that of segments without fibers.

1. Introduction

Precast concrete tunnel linings (PCTLs) are becoming more common than conventional cast in-situ tunnel linings due to its easier handling and installation processes. In addition, higher quality and more economical production of PCTL can be achieved since it is fabricated in specialized and controlled precast plants. Normally, PCTL segments are fabricated with normal concrete reinforced with steel rebar cages, with an estimated service life of 100 years. However, various cases (e.g. the London Underground Railway Tunnel, UK; the Koblenz Railway Tunnel, Switzerland; the Michigan Northeast Raw Water Tunnel, USA) had premature deterioration before achieving their respective design lives [1]. This was mainly attributed to corrosion of the steel reinforcement, leading to concrete cracking and spalling, and decreasing load carrying capacity of PCTL over time. Therefore, an alternative material is desirable that can partially or fully replace the conventional steel rebar in PCTL segments to mitigate corrosion problems. Moreover, for the construction of shield driven tunnels in soft soil, the required thickness of a tunnel lining should be around 1/20 of the tunnel's diameter [2]. The circumference of a tunnel lining is directly proportional to the tunnel's diameter. The volume of concrete required increases quadratically with the tunnel's diameter. Therefore, the overall cost of the material and its transportation and assembling process increases for large diameter tunnels. Hence, UHPFRC can be a viable and economical solution for large diameter tunnels owing to its high strength properties and consequently reduced lining thickness.

Ultra-high performance fiber-reinforced concrete (UHPFRC) is an emerging material, exhibiting enhanced compressive, tensile and flexural strengths along with higher durability performance [3,4]. Such superior mechanical and durability properties can be ascribed to its special mixture design and mixing procedure, which ensure a higher degree of material homogeneity and denser micro-structure [5]. UHPFRC exhibits near zero porosity due to its very low water/binder ratio (w/b). However, lowering the w/b also reduces workability, which can be improved using new generation superplasticizers and supplementary cementitious materials [6]. Furthermore, high temperature curing under applied pressure

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further densifies the internal micro-structure of UHPFRC, further enhancing its strength and durability properties [7].

UHPFRC has been successfully employed in various projects around the world [e.g., 2,8–11]. However, its implementation in PCTL, especially in North America, has been scarce. This is due to the lack of adequate design provisions, shortage of qualified contractors and experienced pre-casters, higher initial cost and the requirement of special types of mixers. Also, the dearth of experimental data on the flexural and thrust load capacities of UHPFRC PCTL has impeded its field utilization. Therefore, this research program was tailored to fill the knowledge gap regarding the experimental evaluation of mechanical performance of UHPFRC tunnel lining segments.

2. Motivation and research significance

The use of precast concrete tunnel lining (PCTL) segments has been increasing in comparison with conventional in-situ concrete tunnel linings. Normally, PCTL segments are fabricated using conventional steel rebar reinforced concrete (RC). The conventional RC PCTL segments are more prone to corrosion degradation due to cracking of normal concrete, which allows the penetration of chloride ions, oxygen and moisture. The premature corrosion of RC PCTL segments has led to the development of steel fiber-reinforced concrete (SFRC) tunnel lining segments, thus replacing steel rebar reinforcement. However, the reduced flexural load capacity of normal SFRC PCTL segments is a concern, which hampered its large scale application. Hence, an alternative high strength and ultra-durable material is required to fully substitute for conventional rebar in PCTL segments without compromising structural strength.

UHPFRC has compressive strength typically higher than 150 MPa (22 ksi) and almost negligible porosity [3]. Thus, it can prove to be a more durable and sustainable material for PCTL fabrication. In addition to improving structural and durability properties, full substitution of steel rebar reinforcement with UHPFRC in PCTL can eliminate the laborious and costly manufacturing of curved shape reinforcing rebar cages, which requires complicated welding and detailing. Furthermore, the cross-sectional dimensions of UHPFRC lining segments can be reduced owing to its high mechanical strength, possibly leading to more economical construction.

Various studies [e.g., 12–16] have examined the flexural and thrust load performance of conventional RC and SFRC PCTL segments. However, so far no detailed studies on the flexural and thrust load resistance of UHPFRC tunnel lining segments could be accessible in the open literature with varying steel fiber length and dosage. Therefore, the present study investigates the suitability of using UHPFRC in precast tunnel lining segments. UHPFRC tunnel lining segments incorporating various fiber lengths and dosages were fabricated in the laboratory and tested under flexural and thrust loads in order to characterize its mechanical behavior. The results can pave the way for tunneling projects relying on UHPFRC precast segments with superior mechanical performance and durability. The findings can also motivate the full-scale use of UHPFRC PCTL segments, leading to significant reduction in PCTL production costs through saving the time and effort of fabricating conventional rebar reinforcement cages, while mitigating costly maintenance and repair of corrosion induced damage.

3. Experimental program

3.1. Materials composition and proportions

The UHPFRC mixtures consist of ordinary portland cement, silica fume, quartz sand, quartz powder and a polycarboxylate based superplasticizer. The compositions of mixture ingredients are listed in Table 1. Various lengths of steel fiber (8 mm (0.31 in.), 12 mm (0.47 in.) and 16 mm (0.62 in.)) with a constant diameter of 0.2 mm (0.0078 in.) were added at different dosages (1%, 3% and 6% by mixture volume). Fibers were copper coated having a tensile strength of 2850 MPa (413.35 ksi). The mixture proportions of the UHPFRC mixtures with a target compressive strength of 150 MPa (22 ksi) are shown in Table 2.

3.2. UHPFRC mixing procedure

The mixing of UHPFRC constituents was performed using a 120 L (32 gal) shear action pan type mixer. The measured amount of superplasticizer (SP) was divided into two halves. One part was included with the mixing water. Initially, the quartz sand and silica fume were added in the mixing pan and dry mixed for 3–5 min. Afterwards, the cement and quartz powder were added and dry mixing resumed for another 3 min. The water containing the SP was added gradually while mixing for an additional 2–3 min. Subsequently, the remaining SP was added over a mixing period of 3 min to increase its efficiency [17]. Steel fibers were then added and mixing continued until proper fiber dispersion. Similar mixing was carried out in previous UHPFRC studies (e.g. [3,18]).

3.3. Fabrication of UHPFRC tunnel lining segments

The length and width of the tested tunnel lining segments were 1000 mm (40 in.) and 500 mm (20 in.) respectively, while their thickness was 100 mm (4 in.) (Fig. 1). The crown height of the tested segment was 100 mm (4 in.) from the horizontal surface (Fig. 1). This was intended to represent a segment taken from a tunnel having a diameter of 1.9 m (6.23 ft). These dimensions represent about 1/3rd the size of normally used full-scale precast tunnel lining segments [19]. The reduced scale was selected in order to simplify the casting, handling and testing of the tunnel lining segments in the laboratory. The segment mold was placed on a vibratory table and UHPFRC was poured at the center of the mold, allowing flow to both mold sides. Similar concrete placement into PCTL segment molds is employed at industrial precast plants. After filling the segment mold with UHPFRC, it was immediately moved to an environment chamber at 45 °C (113°F) and relative humidity (RH) >95%. After 5 h of curing, the segments were taken out from their molds and placed in a moist curing room at RH ⩾95% and 20 ± 3 °C (68 ± 6°F) for another 5 days. Subsequently, segments were stored under ambient laboratory conditions (i.e. 20 ± 2 °C

Table 1
Chemical and physical properties of used materials.

Components	Cement	Silica fume	Quartz sand	Quartz powder
SiO_2 (%)	19.6	95.30	>99.50	>99.80
CaO (%)	61.5	0.49	0.01	0.01
Al_2O_3 (%)	4.8	0.17	0.05	0.05
Fe_2O_3 (%)	3.3	0.08	0.03	0.04
MgO (%)	3.0	0.27	–	–
K_2O (%)	1.2	0.48	–	–
SO_3 (%)	3.5	0.24	–	–
Na_2O (%)	0.1	0.19	–	–
TiO_2 (%)	0.3	0.30	0.03	0.02
Loss on ignition (%)	1.9	1.99	0.11	0.10
Specific surface area (m^2/kg)	371	19530	255	20,000
Specific gravity	3.17	2.12	2.65	2.65
C_3S (%)	55	–	–	–
C_2S (%)	15	–	–	–
C_3A (%)	7	–	–	–
C_4AF (%)	10	–	–	–