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Experimental investigation of reinforced concrete and hybrid fibre reinforced concrete shield tunnel segments subjected to elevated temperature

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ABSTRACT

This paper presents a comprehensive experimental study on the comparative behaviour of the reinforced concrete (RC) and the hybrid fibre reinforced concrete (HFRC) shield TBM (Tunnel Boring Machine) tunnel lining segments exposed to fire. The tests were conducted using a newly developed test facility, which is capable of accommodating different mechanical loading and boundary conditions under different fire scenarios. Six RC segments and six HFRC segments were tested to the standard Eurocode HC (Hydrocarbon) curve, while two reference specimens, one for each type, were tested in ambient environment to provide benchmark data. Apart from the spalling resistance, the fire effects on the structural behaviour were investigated under different boundary conditions at the segment ends, including free sliding (no horizontal constraint), total horizontal restraint and controlled horizontal reaction. The vertical load capacities were investigated for both under-fire and post-fire scenarios. The experimental results revealed excellent spalling resistance in the HFRC segments under thermo-mechanical loading, while the RC segments exhibited better structural performance. A combination of RC design (with flexural reinforcement) and the use of hybrid fibres is deemed to be effective in providing good spalling resistance while at the same time ensuring a robust structural behaviour.

1. Introduction

Several major tunnel fire incidents have occurred in the past, for instance the Great Belt Tunnel fire in Denmark and the Mont-Blanc Tunnel fire in France and Italy. As noted in [1,2], tunnel fire has characteristics of high peak temperature, rapid heating rate, long duration and a nonuniform temperature distribution inside the tunnel, thus tunnel fire can result in extensive and complex damages to concrete tunnel linings. Apart from deterioration in the mechanical properties of concrete due to high temperature, severe concrete spalling, as observed from the Mont-Blanc Tunnel fire, is also a major concern over the safety of concrete linings in the event of a tunnel fire. In the case of a metro shield TBM tunnel lining, further complexities arise from the configuration and joint connections of the shield lining segments.

A number of studies have been performed in recent years to examine fire damages to lining concrete and explore effective methods to prevent concrete thermal spalling. Caner and Böncü [3] performed hydrocarbon fire tests on an isolated K segment of a shield TBM tunnel in an unloaded state to investigate fire damage to the segment concrete. The study concluded that the deviation in safety factor of the TBM tunnel widened from soft soil to stiff soil condition for the hydrocarbon fire as the tunnel became more flexible. Yan et al. [4] carried out full-scale experiments to investigate fire damage to reinforced concrete (RC) metro shield TBM tunnel linings tested to a standard ISO834 fire curve. The results indicated that the temperature of the bottom reinforcement (bottom side heated) of the tunnel linings could exceed the failure temperature under the ISO834 curve with duration of 90 min. Yasuda et al. [5] conducted a full-scale fire test on fire protection measures for shield TBM tunnel composite segments under a RABT (Richtlinien fuer Ausstattung und Betrieb von Strassentunneln) fire curve. It was found that spalling of concrete occurred and it reached up to 60 mm when there was no fire protection on the surface.

Steel fibre reinforced concrete (SFRC) has been increasingly adopted in tunnel linings, as evidenced in several precast SFRC

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tunnels built around the world [6,7]. Adding steel fibres to tunnel segments can effectively improve the tensile strength and ductility, mitigate cracking at ambient temperature, and reduce the demand on steel reinforcing bars and the construction time [7,8]. Compared to the RC tunnel lining, the presence of steel fibres also help control the propagation of cracking and thus improve the overall performance of concrete during and after exposure to sustained high temperatures [8,9]. However, in a real tunnel fire, explosive spalling of tunnel lining can become significant in the first few minutes of fire [10]. It is generally recognised that spalling is closely related to the pore pressure buildup within the concrete and the mechanical stresses resulting from differential thermal expansion. Although steel fibres generally help to improve the stress condition, they tend to play a limited role in diffusing the pore pressure buildup in the rapidly heated regions of concrete [11]. Results from Chen and Liu [12] suggest that the presence of steel fibres may only delay the time before spalling occurs. Further studies by Yan et al. [8] on the behaviour of RC and steel fibre reinforced concrete (SFRC) lining segments exposed to a HC curve indicated that the RC segments performed better than segments with only SFRC in terms of the overall fire resistance.

Hybrid fibre reinforced concrete (HFRC) with a mixture of steel and polypropylene (PP) fibres has attracted a lot of attention more recently due to its apparent superior fire performance, particularly in mitigating spalling [13,14]. PP fibres melt at approximately 160–170 °C; although this would result in a certain reduction in the residual strength of the composite material [13], the melting of the PP fibres within the heated concrete is believed to provide key mechanisms for the observed spalling resistance of the concrete. Among other theories (e.g. micro-fracture resulting from the expansion of the molten fibres [15]), melting of PP fibres is understood to produce new expansion channels and connect existing internal channels within concrete material [16], and consequently the accumulated water vapour can escape and the buildup of pore pressure inside concrete is alleviated, thus reducing the chance of spalling [10,15]. In a combined manner, the PP fibres can mitigate the spalling of concrete while the steel fibres provide high ductility and reduce crack propagation for the concrete [17]. This results in a desirable concrete thermal stability [8].

As far as the shield TBM tunnel lining is concerned, however, little has been reported in the literature so far regarding the effectiveness of using HFRC in the shield lining under elevated temperature. To fill in this gap, experimental data on the behaviour of the HFRC shield TBM tunnel linings in comparison with the RC linings under varying thermal–mechanical conditions are particularly needed.

In this paper, we present a comprehensive experimental study on the fire behaviour of RC and HFRC lining segments. The tests were carried out using a specially designed setup allowing a variety of boundary and fire conditions to be simulated. The spalling performance and the general effect of fire on the structural resistance in both types of the lining segments, with the elevation of temperature following the standard Eurocode HC curve, are examined. Beside the comparative observations, the experiments were also intended to provide useful experimental data for the development of improved analytical and numerical models for the coupled thermal–mechanical performance of the shield tunnel linings for engineering applications.

2. Experimental programme

2.1. Overview of test specimens

The test specimens represented shield lining segments at a reduced scale of about 1:3 with respect to the full-size lining units. The specimens were 300 mm in width and 120 mm in thickness, and their average radius was 990 mm. The size of the specimens allowed the composition of the materials in the actual construction to be maintained in the test specimens, thus avoiding any material scaling effect. Fig. 1 shows the dimensions and reinforcement details of the test lining segments. To preserve the key features of the actual metro shield TBM tunnel lining, the hand hole, circumferential tongues, as well as grooves of the lining segment were retained and fabricated in the test models.

Two types of test lining segments, one using normal reinforced concrete (RC), and another using hybrid fibre reinforced concrete (HFRC), were investigated. The mix design for the plain concrete is shown in Table 1. Properties of the PP and steel fibres as provided by the manufacturer are presented in Tables 2 and 3, respectively. The PP fibres and the geometry of steel fibre are shown in Fig. 2. The volume fraction of PP fibre and steel fibre was 2 kg/m^3 and 78 kg/m^3, respectively. The choice of a relatively high steel fibre volume was based on the consideration of ensuring an appropriate level of the flexural strength in the absence of any main reinforcement. According to some previous research on HFRC [18], the volumetric ratio of the steel fibres in the present study may still be considered to be within a practically acceptable limit. The measured standard cube strengths of the plain concrete and the hybrid fibre reinforced concrete at the ambient temperature, and measured at 28 days, are 69.8 MPa and 61.1 MPa, respectively. For the RC lining segments, the main reinforcing bars (hot-rolled) in the circumferential direction were installed with 15 mm concrete cover thickness (cf. Fig. 1). For HFRC lining segments, no reinforcing bars were installed.

To ensure good and consistent quality in the preparation of the test specimens, all construction work, including the concrete mix design and production, casting and curing of the specimens, was carried out by a professional concrete plant. Table 4 lists the concrete age of the specimens at the time of the experimental tests. The age of the specimens varied between approximately 6 and 18 months.

2.2. Test setup and procedure

The overall test setup is illustrated in Fig. 3(a) and (b). The test system was developed at Tongji University for testing tunnel lining segments under both applied mechanical loads and elevated temperatures. This system consists of a mechanical loading frame and a furnace powered by two combustors of industrial grade. The furnace can be controlled by a programmable system to achieve a desired heating up history. The maximum temperature in the furnace can reach 1200 °C and the maximum heating rate is approximately 250 °C/min. A wide range of combinations of mechanical loading and fire scenarios, including high rate heating and high peak temperature in conjunction with diverse mechanical load patterns, can be achieved using this test system. In the present experiment, the furnace temperature was monitored and controlled to follow the standard Eurocode HC curve. Three K type thermocouples, which were threaded through the reserved holes in the cover insulation plates (Fig. 3(b)), were installed at equal distance near the under-space of the segment to measure thermal exposure experienced by the specimens during testing.

The standard Eurocode HC curve which was adopted in the present study to simulate the heating phase [19] is expressed in Eq. (1):

$$T(t) = 20 + 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) \quad (1)$$

where t is time (in minutes) and $T(t)$ is the gas temperature inside the furnace (in °C).

Fig. 3(b) shows a fully insulated specimen mounted on top of the furnace. A closed heating chamber was formed by two