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The effects of the passive fire protection layer on the behavior of concrete tunnel linings: A field fire testing study

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ABSTRACT

The concrete tunnel lining behavior when exposed to a natural fire loading is very important for the designing of tunnel lining safety. This work presents details of field tunnel fire testing of concrete tunnel linings with and without the fire resistant coatings under a real and natural tunnel fire loading designed using the heat release rate (HRR). This test aims to develop a better understanding of concrete lining behaviors and the effects of the fire resistant coating when exposed to such a fire, rather than the standard temperature-time curves in a furnace as described in most past studies. The results of concrete spalling are shown on both the vault and spandrel areas with a total area of approximate 0.8 m^2 and a maximum depth of 10 mm for concrete lining without the fire resistant coating. The underlying concrete maintains its original nature but with complete failure of the fire resistant coating after the fire as for the concrete lining with the fire resistant coating. The lowest concrete facial strength ratio normalized by the initial average value is 95.2% and 78.9% on the right spandrel, respectively, for concrete lining with and without the fire resistant coating. The smoke and the concrete lining temperatures were also measured. The highest average smoke temperature of 675 °C for the case with the fire resistant coating is higher than the 600 °C for the other case at a same experimental condition but different environments. The concrete temperatures for lining without the fire resistant coating are slightly higher than those for lining with the fire resistant coating. The concrete tunnel lining with the fire resistant coating shows a crucial and strong thermal hysteresis nature, and is useful in avoiding a fast and severe temperature rise, as well as potential spalling. The concrete lining without the fire resistant coating has only slight damage in this test. As a result, the fire resistant coating is not believed to be necessary for a natural tunnel fire with the HRR lower than this test. The results are also expected to a useful complement to concrete tunnel lining fire data.

1. Introduction

Several catastrophic tunnel fires over the past two decades were reported to have caused severe damage to the tunnel linings as well as requiring a significant restoration time. The fire in the Mont Blanc tunnel between France and Italy in 1999 resulted in closing for 3 years, and the Tauern tunnel fire in Austria in 1999 caused a 3 months closure (Lonnermark, 2005). PIARC also reported the highest temperature at the tunnel ceiling reached 1000 °C for a petrol tanker fire (PIARC, 1999).

As a result, the tunnel fire attracted much attention from the international research community in regard to the safety and protection of tunnel linings (ITA, 2005; NFPA, 1998; Haack, 1998). Initially, a lot of studies only focused on the safety of tunnel lining when exposed to fires. Savov et al. (2005) found the collapse of the tunnel in the case of a continuous 3 h stacked car fire load at a spalling depth of 30 cm through a method based on an extension of the "beam-spring" model. Caner et al. (2005) assessed the performance of a concrete and shotcrete tunnel lining by comparing the structural demand and the capacity of the lining using an analysis method. Their following study focused on the structural safety of TBM circular concrete tunnel linings under a hydrocarbon curve (HC) fire (Caner and Boncu, 2009). Pichler et al. (2006) carried out a safety assessment of polypropylene (PP) fibers reinforced concrete tunnel linings under the same HC fire. They reported that no collapse was encountered but the remaining load-carrying capacity of the lining was 16% for a fire exposure of 3 h when PP fibers added to the tunnel lining concrete mix. Yan et al. (2012, 2013, 2015) presented a range of fire experimental tests on reinforced concrete (RC), steel fiber reinforced concrete (SFRC) and hybrid fiber reinforced concrete (HFRC) tunnel segments when exposed to HC and ISO834 fire curve loadings. Their results revealed excellent spalling resistance in SFRC and HFRC segments. But the RC segment performed better than the SFRC and HFRC segments in term of structural performances. Their following study concentrated on tunnel segmental joints

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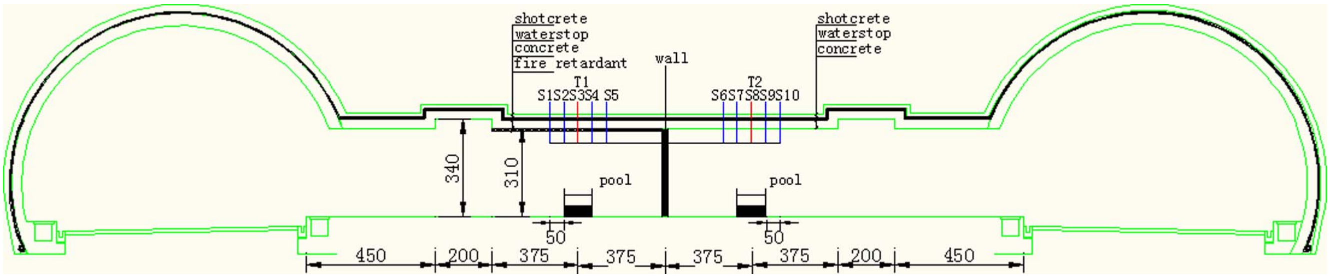

Fig. 1. Sketch of the pedestrian crosswalk in the tunnel, unit:cm.

when subjected to a HC fire (Yan et al., 2016). Zhang et al. (2014) adopted a coupled thermo-hydro-chemo-poro- mechanical model to assess the spalling risk of concrete when subjected a RABT curve fire loading. Their numerical result revealed effects of intrinsic permeability, porosity, saturation and concrete strength on the spalling risk. Choi et al. (2013) developed a new finite element model to simulate the spalling of the concrete tunnel lining structure by eliminating the elements exceeding a pre-determined critical temperature under a RABT fire loading. Experimental fire tests were subsequently carried out to deduce the important parameters needed for the numerical model (Chang et al., 2016).

The above studies allow a better understanding of the tunnel lining structural loss when exposed to these standard fires, as well as the emphasis needed for the protection of concrete tunnel linings. One of the effective protective methods is to cover the concrete element by a sufficiently thick fire resistant coating, namely a passive fire protection method. Studies of tunnel lining passive fire protection have been subsequently undertaken by a few researchers. Kim et al. (2010) developed a fire-protection cementitious coating material which was reported to be low in cost and high in strength. This coating material was experimentally evaluated by means of static strength test and RABT fire loading tests using a LPC furnace. The design of a potassium based geopolymer was presented for the fire resistant coating of concrete tunnel linings when exposed to a RWS curve fire in the study of Sakkas et al. (2013, 2014). Its performance was assessed through a concrete slab coated with a 5 cm thick passive fire protection layer and the result showed that this material could help to retain the concrete slab structural integrity, as well as keep the temperature of the geopolymer/concrete interface to 100 °C lower than their test requirement. Bezgin (2015) developed an experimental evaluation method to determine the required thickness of the passive fire protection for high strength concrete tunnel segments under a RABT fire loading. He concluded that the volcanic ash of 30 mm thickness could prevent spalling and limit the development of the reinforcement and concrete surface temperatures to below 160 °C and 300 °C respectively. Additionally, it was considered to be ineffective for limiting the development of the reinforcement temperature for the fire protection layer beyond 55 mm.

Clearly, the above studies have already proved that the passive fire protection material could make a positive effect to prevent a severe spalling of concrete lining when exposed to these standard fire curve loadings in a furnace. However, these standard fire curves are usually not achieved in most tunnels. For instance, heavy goods vehicles (HGV) or tankers are strictly forbidden to pass through some very long highway tunnels in west China. As a results, the use of passive fire protection material in tunnels attracts much attention, with two opposite claims in China. One claim is for the wide use of passive fire protection material in tunnels. The other claim suggests cancelling the wide use of passive fire protection material, except in special tunnels, such as submerged tunnels. They believe the natural fire results in a significantly lower level of spalling for a normal strength concrete tunnel. The most important consideration is the fire protection material dropping from the tunnel ceiling due to its reduced stickiness and durability, which probably causes unexpected accidents. In fact, What happened to the lining when exposed to a natural fire? How much contribution does the fire resistant coating make? What is the criterion for the use of fire resistant coating in a tunnel? These are not clear yet. In the light of this, a detailed field fire experimental study is developed for a natural fire, but with two separated pedestrian crosswalks, one with the fire resistant coating and the other without it, in a road tunnel. It aims to assess concrete lining behaviors and the effects of the fire resistant coating when exposed to a natural fire loading in the tunnel. These findings are expected to be helpful for the designing of tunnel lining safety. Additionally, these test results can be a useful complement to concrete tunnel lining fire data.

2. Test procedure

2.1. Tunnel description

Field testing was carried out at a prescribed pedestrian crosswalk in the Piaoli Tunnel in Guizhou province, China which is a highway road tunnel with a cross-section area of 71.7 m^2 in each tube. The surroundings of the pedestrian crosswalk consist of thick rock of middle weathered limestone of relatively integrity. The surrounding rock is accordingly considered to be sufficiently self-stable. The New Austrian Tunneling Method (NATM) is adopted for the tunnel composite lining design, with 10 cm thick C20 shotcrete covered by 30 cm thick C25 concrete.

The pedestrian crosswalk is 28 m long with a cross-section area of 7.1 m^2. Subsequently, the pedestrian crosswalk is divided into two identical parts, each of 14 m length, where one is coated with a passive fire resistant coating of 10 mm thickness and the other has no fire resistant coating, as in Fig. 1. The non-intumescent passive fire resistant coating is used in this test which mainly consists of volcanic ash. The density is smaller than 800 kg/m^3. The volcanic ash, together with glue and water, is then applied three times after drying each combination on the concrete, in order to make a full bond, as in Fig. 2. The bond strength is greater than 0.1 MPa. The fire endurance is required to meet more than 2 h. The whole process ultimately took one month. The same fire test is therefore implemented in two parts to assess the performance of the passive fire resistant coating as well as the behavior of the concrete lining.

2.2. Natural fire design

This tunnel fire test is essentially motivated by the highway tunnel construction corporation in order to understand the behavior of tunnel linings and the contribution of the passive fire resistant coating when exposed to a natural fire, rather than standard fire curves, such RWS, RABT and so on (BS EN 1991-1-2, 2002; BS EN 1992-1-2, 2004). The natural fire is described using the maximum heat release rate of vehicles in this study. The vehicle composition reveals the maximum heat release rate happens in the case of a general lorry with burning goods on fire, whereas heavy goods vehicles (HGV) or tankers are strictly forbidden to pass through the very long highway tunnels or tunnel groups in west China. Consequently, a 30 MW fire for 2 h is designed for