Tunnelling and Underground Space Technology 71 (2018) 106–114

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Experimental study on color change and compression strength of concrete tunnel lining in a fire

Sheng Du[a], Yuchun Zhang[a,*], Qiang Sun[b], Weiyi Gong[a], Jishi Geng[b], Kejian Zhang[a]

[a] *Department of Fire Safety Engineering, Southwest Jiaotong University, Chengdu 611756, PR China*
[b] *School of Resources and Geosciences, China University of Mining and Technology, Xuzhou, Jiangsu Province 221116, PR China*

ARTICLE INFO

Keywords:
Tunnel fire
Concrete lining
Color change
Compression strength
Lining temperature

ABSTRACT

In order to investigate the characteristics of tunnel concrete lining after a fire, a 1/10 scale tunnel fire model was constructed to study the color change and strength reduction of the concrete tunnel lining. The compression strength of concrete specimens was measured to quantify the damages and it is observed that the compressive strength of the concrete varied inversely with the EFET (equivalent flame exposure time) values. The surface and inside temperatures of the concrete lining were measured during the fire test, and the color change from applied phenolphthalein was observed and correlated to concrete damages. A tricolor image processing method is used to analyze the concrete color changes, the results indicate that a light red color on the concrete surface demonstrates a deeper neutralization of the concrete material, which can be correlated to the temperature effect during fire test and that the intensity of the red color decreases as the temperature increases. Thus, a low cost and nondestructive evaluation technique based on the tunnel lining color change can be developed.

1. Introduction

Tunnels play an irreplaceable role in traffic and tunnel fires have detrimental effects on the tunnel structures and safety that may result in casualties and loss of properties (Carvel, 2012). Due to the confined space, the heat produced by fire is accumulated in the tunnel, which leads to elevated temperatures and prolonged fire duration (Li et al., 2016). As a result, the tunnel lining structure can be heat-affected to the extent of complete destruction (Boström and Larsen, 2006). For instance, the 1999 Mont Blanc tunnel fire in Italy found maximum temperature exceeding 1000 °C and the total duration of fire was approximately 53 h, which caused substantial damage to over 900 m of the tunnel ceiling (Abraham and Dérobert, 2003).

During fires, the mechanical and chemical properties of concrete tunnel lining may change drastically including decreasing moisture, neutralizing concrete and reducing strength, which could cause the structural damage of tunnel lining. Initially, a lot of studies focused on the behavior of tunnel lining under high temperature. The spalling can be observed at the cement paste and aggregate levels (Zhang 2011). This phenomenon has been extensive studied by many researchers (Chang et al., 2006; Schrefler et al., 2002; Both et al., 2003). Yan et al. (2012, 2015) investigated the fire effects on the TBM tunnel linings which are made by reinforcement concrete in a full-scale experiment. The results showed that significant concrete spalling and strength degradation occurred when the tunnel lining is exposed to very high temperature (of ISO834 standards) within 45 min and 90 min. The behavior of the segmental joints of tunnel lining when exposed to HC fire was studied (Yan et al., 2016). Other concrete mechanical properties of tunnel lining such as compressive strength, tensile strength and elastic modulus has been studied as well, the main regulation is that the mechanical properties deteriorates with the temperature increases during the fire (Felicetti, 2013; Zheng et al., 2012; Chen et al., 2014; Khaliq and Khan, 2015).

In above studies, the concrete was heated at a specific heating rate by an electric furnace or oil-burning furnace, which is different from a real-life tunnel fire. Some experiments have been performed to study the behavior of real tunnel linings in a fire. The fire effects on tunnel linings and fire protection measures have been investigated in the EUREKA program, and the study shows that the damage of a tunnel lining is related to the fire loading (Haack, 1992). Yasuda et al. (2004) found that fire protection measures could effectively reduce the temperature of the inner lining segments. Chang et al. performed a series of fire experiment to study the effect of initial temperature gradient and maximum temperature on the structures and heat transfer coefficient of concrete tunnel linings (Chang et al., 2016). In addition, some studies were concentrated on the fire protection and damage evaluation to the concrete tunnel linings. Wang found that the fire resistant coating can protect the tunnel lining from being damaged in fires (Wang et al.,

---

[*] Corresponding author.
E-mail address: zycfire@swjtu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.tust.2017.08.025
Received 5 April 2017; Received in revised form 17 August 2017; Accepted 17 August 2017

2017). These studies focused on the failure behavior of tunnel lining when exposed to a real fire, and how to effectively protect the safety of tunnel lining to avoid the fire damage.

In order to effectively repair and maintain the damaged tunnel linings after a fire, it is important to develop fast and nondestructively methods and technologies to evaluate the mechanical properties and damage degree of concrete tunnel lining. Short et al., Felicetti and Caner and Böncü studied non-destructive testing techniques, such as color image analysis, drilling resistance, ultrasonic testing and concrete carbonation depth testing (Short et al., 2001; Felicetti, 2006; Caner and Böncü, 2009). However, in these studies, the concrete tunnel linings were heated by electric furnace and the researchers analyzed the physical properties directly. In real fire, the color change of concrete tunnel lining is affected by fire smoke and the lining is single-face-heated. Therefore, the existing methods to evaluate fire damage to tunnel linings are either difficult to operation on site, or are destructive in nature, which reduce their applicability and increase the costs.

When tunnel lining is exposed to high temperature, concrete is usually neutralized (Wu, 2016). Therefore, damage of tunnel lining could be estimated by determining the degree of neutralization of the concrete. This paper presents a physical test of a scaled tunnel under fire to study on color change and compression strength of concrete tunnel lining. In the test, the concrete tunnel lining was heated on one side. The appearance characteristics and the compressive strength are investigated under a real fire. According to the test results, the authors developed a relationship between the color change and the tunnel lining strength reduction. A fast and nondestructive test method to analyze the fire effects on tunnel lining is also suggested.

2. Experimental setup

The experiment was performed on a 1/10 reduced scale road tunnel model, as shown in Fig. 1. The dimensions of the tunnel are 1000 cm long, 100 cm wide and 60 cm high. The left wall is 1000 cm long and the right wall is 900 cm long, with an additional 100 cm replaced by the length of concrete blocks placed in the middle. In addition, the side wall was plastered with cement mortar to improve the air tightness of the wall. The concrete ceiling was located in the center of the tunnel, composed of two concrete plaques of 50 cm long, 120 cm wide and 5 cm thick. The concrete slab was set up directly above the fire area to ensure ruggedness and heat insulation, while fire-proof plaster plates were placed above adjacent areas which have a relatively low temperature. A 45 cm × 45 cm × 15 cm steel pan was placed along the center-line of the tunnel to simulate the fire source (Fig. 2) and the heat release rate in this test was 158.11 KW (Karlsson and Quintiere, 2000). Before ignition, gasoline was poured into the fire pan through the ignition holes using a special funnel designed in advance. The experimental apparatus was built by referring to the Froude modeling, which was widely applied in tunnel fire studies, and the dimensional relationships between a life-sized tunnel and the model tunnel are given as (Li et al., 2011):

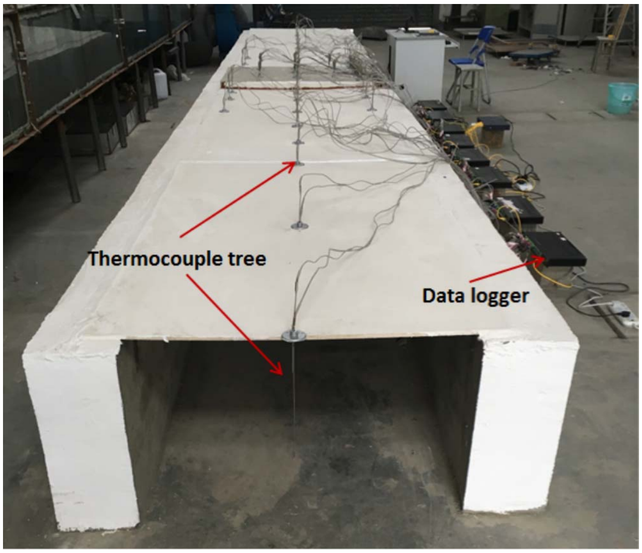

Fig. 1. General view of the reduced-scale tunnel (Scale Ratio: 1:10).

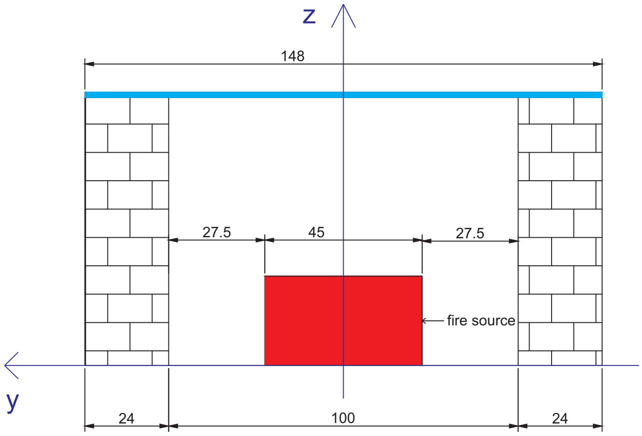

Fig. 2. The cross section of the model tunnel (unit: cm; scale ratio: 1:10).

$$\frac{Q_m}{Q_f} = \left(\frac{L_m}{L_f}\right)^{5/2} \tag{1}$$

$$T_m = T_f \tag{2}$$

$$\frac{V_m}{V_f} = \left(\frac{L_m}{L_f}\right)^{1/2} \tag{3}$$

where Q is the heat release rate (HRR), T is the temperature, V represents the velocity, L denotes the model size, L_m/L_f represents the similarity ratio, Q_m/Q_f is the heat release rate ratio between real and model fires, respectively, and the subscripts 'm' and 'f' stand for the model tunnel and the full-scale tunnel, respectively.

In the center of the right wall of the tunnel model, a one-meter-long concrete lining consisting of 60 concrete cubes of 10 cm × 10 cm × 10 cm, was built as the subject matter (Fig. 3). The concrete cubes were made of Portland cement (P.O 42.5) and fine aggregates (river sand of 0.025–0.05 cm dia.). The water-cement ratio was kept at 0.78 and the mixtures were placed at room temperature, using tap water, with a mix proportion of 1:3.54:1.28 (cement:fine aggregate:water). The concrete cubes were set for 24 h before being demolding and cured at 20 ± 2 °C for 28 days. In order to reduce heat loss and improve the effect of thermal insulation, the gaps between the cubes were sealed with fire clay and the outside of the concrete lining was covered with bricks, as shown in Fig. 3b.

The real-time temperature data of the tunnel was collected by installing thermocouples (K-type stainless steel sheathed thermocouples of 3 mm dia.) connected to a temperature acquisition system. A thermocouple tree was placed in the middle of the center-line to monitor the temperature changes over time. Ten thermocouple trees, each containing six thermocouples, were distributed along the inside surface of the concrete lining (Fig. 4). All thermocouples were tightly placed at the center of the concrete cubes. In addition, for the concrete cubes at the center of the lining, several other locations were selected and had thermocouples inserted, to monitor the temperature variations inside the lining. The depths of the inserted thermocouples were 8 cm, 5 cm and 2 cm, respectively. The depths are corresponding to the distances between the inner surface of the tunnel lining and the thermocouples at 2 cm, 5 cm and 8 cm, respectively.