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Non-destructive testing and temperature distribution of coal mine roadway lining structure under exogenous fire

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ABSTRACT

In order to study the thermal damage of concrete lining under exogenous mine fire conditions, the temperature and P-wave velocity distribution of naturally ventilated concrete roadway lining are investigated through an experiment using a 1/10 reduced-scale roadway model. In this experiment, the lining is composed of concrete cubes, the temperature is monitored with thermocouples installed inside and outside the specimens, and the velocity of concrete specimens is measured before and after the fire. Through the analysis of the results, it is found that the temperature is almost symmetrically distributed on the inner surface of sidewall lining, which corresponds to the stratification of smoke. Moreover, the temperature reaches its maximum value on the inner surface of the lining structure and gradually decreases outward from the inner surface. In addition, the decrease of the P-wave velocity of the concrete is closely related to the fire temperature, while the variation of the P-wave velocity can reflect the damage degree of the concrete lining and thus indicate structural damage and changes in mineral content. Finally, the damage characteristics obtained can provide a basis for the design of roadway linings.

1. Introduction

With the rapid development of the underground coal industry, the mechanization of mines has gradually improved. This increases the risk of mine fires caused by gas explosion, blasting operation, power failure, welding, etc. In particular, the subsurface fires threatening the industry of coal mining widely such as exogenous fires in roadways may result in heavy casualties and economic losses (Hansen, 2017; Lu et al., 2017; Wang, 2007; Zhou et al., 2015; Zhou and Wu, 1996), as shown in Table 1, because exogenous mine fires have the characteristics of sudden occurrence and serious damage. As a consequence of such fires, the concrete lining is damaged and the safety of lining structure is decreased owing to long-time exposure to high temperature (Schrefler et al., 2002; Yan et al., 2013). Therefore, the fire safety of coal mine roadway tunnels has attracted much attention of researchers and a large number of experiments have been carried out to study the damage behavior of the roadway lining under fire (Fan et al., 2013; Gehandler et al., 2014; Nilsen and Log, 2009).

Many researchers have conducted tests on the mechanical and physical properties (e.g., strength, elastic modulus, permeability, porosity, Poisson's ratio, ultrasonic wave velocity) of concrete after exposure to high temperature. They have found that both compressive strength and tensile strength decrease with the increase of temperature in residual strength testing or real-time strength testing (Behnood and Ghandehari, 2009; Chan et al., 1999; Chen and Liu, 2004; Li et al., 2004; Liu and Xu, 2015) and that as the temperature increases, the elastic modulus decreases (Phan et al., 2001; Phan and Carino, 2002) while the permeability increases (Janotka and Bágel, 2002; Noumowe et al., 2009; Poon et al., 2003). In order to set up a non-destructively system to monitor the influence of high temperature on concrete structures, Heap et al. (2013) studied the thermal-stressing on the physical, mechanical, and chemical properties of siliceous aggregate concrete, and reported that the strength, ultrasonic velocity, Young's modulus, and Poisson's ratio decrease with the increase of temperature, while the porosity and permeability increase. Such changes are primarily the result of thermally-induced degradation of cement matrix. In addition, Breugel (1991) and Kalifa et al. (2000) studied the microscopic crack and pore structures of concrete after exposure to high temperature by using SEM to analyze the deterioration process and spalling mechanism.

Among these studies, almost all the concrete structures are heated to target temperatures in a high temperature furnace to simulate fire accidents and the physical and mechanical properties of concrete are explored. However, these simulations are different from actual mine

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Table 1
Exogenous fire accidents in coal mine roadways in China in recent years (Wang et al., 2016).

Accident date	Accident company	Specific location	Direct cause	Deaths
2010-01-05	Li-sheng coal mine in Hu-nan	Vice shaft	Cable fire	34
2010-01-08	Miao-shang coal mine in Jiang-xi	Electrical cavern	Air compressor fire	12
2010-01-22	Mai-wan coal mine in Hu-nan	+650 m west roadway	Explosion	4
2010-03-25	Dong-xing coal mine in He-nan	West connect roadway	Cable fire	25
2010-06-21	Xing-dong No. 2 coal mine in He-nan	Explosive magazine	Explosive fire	49
2010-06-26	Hong-yuan coal mine in Ning-xia	Dark slope 200 m down	Explosive combustion	5
2010-07-17	Xiao-nangou coal mine in Shan-xi	Shaft station	Cable fire	28
2010-07-31	Xin-ling coal mine in He-nan	Intake roadway	Cable fire	8
2011-07-06	Fang-bei coal mine in Shan-dong	Transport roadway	Air compressor fire	28
2012-01-27	Tang-nei coal mine in Guang-xi	Belt roadway	Belt fire	2
2012-05-11	Jia-zhuang coal mine in He-bei	Electrical cavern	Air compressor fire	5
2012-08-29	Qing-nian coal mine in Liao-ning	Intake roadway	Cable fire	5
2012-09-22	Long-shan coal mine in Hei-longjiang	Intake roadway	Cable fire	12
2013-02-28	Ai-jiagou coal mine in He-bei	+750 m intake roadway	Air compressor fire	13

fires. In an actual fire, the thermal load is characterized by a steep temperature increase during the first few minutes of the fire and a maximum temperature exceeding 1200 °C (Nilsen and Log, 2009). Moreover, under the actual fire conditions, the inside of the lining is exposed to fire, while the outside is surrounded by rock mass. To obtain the damage characteristics of roadway linings from a better simulation of actual fire conditions, the objectives of this paper were to: (1) set up a mine roadway model and choose gasoline as the fire source, to approach the real fire environment; (2) determine the temperature distribution of the roadway sidewall and analyze the temperature penetration into concrete lining near fire; (3) determine the P-wave velocity of concrete lining and evaluate the degradation of lining structure through the damage index established based on P-wave velocity.

In this paper, a 1/10 reduced scale model of coal mine main roadway was set up to study the temperature distribution and the damage of lining structure exposed to fire. In order to better simulate an actual fire, we chose gasoline as the fire source with a heat release rate of 50MW. The results obtained in this paper are very useful for achieving a better understanding of concrete lining exposed to high temperature and thus are helpful to expand the application of concrete in lining structures.

2. Experimental structure

2.1. Roadway model system

The experiment was performed with a 1/10 reduced scale coal mine roadway model, as shown in Fig. 1. The roadway was set to 10 m long, 1 m wide and 0.6 m high. The side walls of the roadway were constructed with bricks and concrete, which is 24 cm thick. In addition, the side walls were plastered with cement mortar to improve air tightness. The roof of mine roadway was composed of a concrete slab of 1 m × 1.2 m × 0.05 m (L × W × H) and four fire-proof plates of 2.5 m × 1.2 m × 0.012 m (L × W × H). The concrete slab was set at the top of fire to ensure ruggedness and heat insulation while the fire-proof plates were distributed at the top of other areas exposed to relatively low temperature. A steel pan of 45 cm × 45 cm × 15 cm filled with gasoline was placed along the centerline of roadway to simulate the fire source (Fig. 2) and the heat release rate in this test was 223.4KW.

The experimental apparatus was built by referring to the Froude modeling, which was widely applied in studies of tunnel fire, and the dimensional relationship between real and model roadway is shown in Eqs. (1)–(3) (Ji et al., 2015):

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

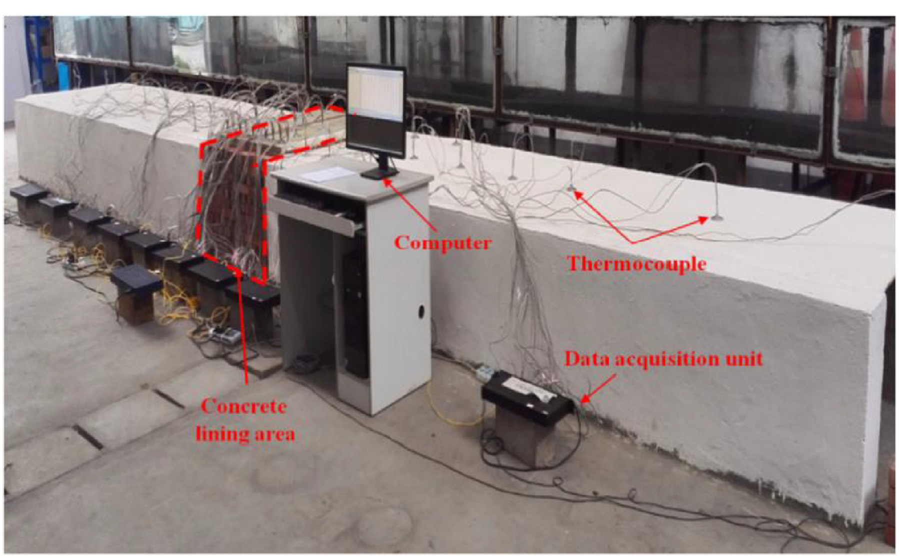

Fig. 1. General view of the reduced-scale coal mine roadway.