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A Review on Large-Scale Fire Testing of Concrete Tunnel Lining

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Abstract: This review gathers the methodologies, issues and challenges concerning to large-scale fire experiments on concrete tunnel lining. Firstly, the study reviews fire testing of concrete tunnel lining, large-scale rather than small-scale and effect of tunnel fire on spalling of fireproof concrete. Secondly, issues surrounding the tests, including new fireproof concretes which involves high strength, high performance which normally containing various pozzalanic cementitious materials such as fly ash, silica fume and nanosilica which are very dense and behave explosively during fire are discussed. The main challenge for large-scale testing is that the influences of the specific spalling measures are difficult to predict and compare with others given the distinctions in testing setups and types of fire curves that are applied to obtain results. Current contributions in large scale fire testing are to improve fire-resistant concrete and to support the advancement of the large-scale fire testing of concrete tunnel lining.

Key words: Large-scale fire test, fire-proof concrete, tunnel lining, issues, challenge, support

INTRODUCTION

Tunnels are underground constructions which are located in limited positions where incidental fires may cause dangerous injuries and fatalities to people and structura ldeterioration. The temperature into a tunnel increases rapidly during fire incidents and may reach up to 1200°C or even higher (Radzi *et al*., 2016). The chemical and mechanistic characteristics of tunnel lining such as declining moisture content and decreasing strength can significantly change within the fire incident. These characteristics may be the reason of the construction deterioration of tunnel lining. Several researches have concentrated on the rising temperature and its impacts on the behaviour of tunnel lining by using different fire tests which usually classified as large, medium and small-scale tests.

Large-scale fire tests are used to obtain optimal results and immediate assessment of the behaviour of constructional concrete parts that are exposed to fire (Krzemien and Hager, 2015). Comparison of the utmost surplus gas temperature under tunnel ceiling and temporary information from the full-scale tests provides affirmation of the theoretical examination (Li and Ingason, 2012). Moreover, the observation of concrete spalling considers as an essential aspect which can be usually noted at the aggregate level and cement paste due to its great effect on the lining thickness of tunnel accordingly a considerable variation in construction cost is expected (Du *et al*., 2018). Rijks Water Staat (RWS) standard stated that the spalling should not exceed 50 mm under an exposing temperature for a duration of 180 min.

Scholars used polypropylene fibres to decrease the spalling and provide an efficient resistance against fire, nevertheless, the temperature distribution over the lining thickness is not highly developed (Saadun *et al*., 2016). In specific tunnel, the design safety against fire is focused on a significant assessment of numerous impact factors such as concrete strength. Plain Concrete (PC) and High Strength Concrete (HSC) are usually used to construct the tunnel lining. Researchers attempted to improve thethermal properties of concrete particularly HSC due to its low permeability by introducing new binders as a cement replacement such as fly ash, nanosilica and slag. Ibrahim *et al.* (2012) reported that replacing the Portland cement with 52.5 and 2.5% of fly ash and nanosilica produced a fireproof concrete capable to maintained 94% of its strength at room temperature under an exposing temperature reach up to 700°C. This test and others are usually conducted by using a medium or small scale furnaces. Up to date no final solutions had been obtained to address the spalling of concrete under elevated temperatures. Thus, further investigations should be conducted to integrate this beneficial information into a

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design criterion. In this review, large-scale fire tests on tunnel lining segments are comprehensively discussed.

MATERIALS AND METHODS

Large scale fire testing: Various temperature-time load curves are frequently used during the large scale fire test. RABT fire curve is considered one of these curves which introduced according to German systems for roadway and railway tunnels. The fire test according to RABT curve required a sharp increase of temperature to 1200°C within 5 min and the time of fire should not exceed 30 and 60 min for railway and roadway tunnels, respectively. The ISO834 and RWS curve are also used to conduct the large-scale fire test as shown in Fig. 1 (Maraveas and Vrakas, 2014).

Studies on thermal analyses indicate that the major factors of element design and construction for fire protection depend on the correct selection of the time-temperature curve which cannot be typical of the phenomenon (Maraveas and Vrakas, 2014). The explosion of concrete parts with the unexpected release of energy and loud sounds is the major characteristic of explosive spalling which influences concrete spalling in terms of heating rate, temperature profile, Moisture content. Yan *et al.* (2012) investigated the behaviour of bored tube tunnel linings under a fire via. using standard ISO834 curve with 45 and 90 min heating durations. The results indicated that severe concrete explosive spalling as well as property deterioration occurs under high temperatures.

A similarity between increasing temperature and rising HRR is determined. For example, the highest temperatures (>1300°C) are gained with <20 MW, low ceiling heights (4-5 m) and medium ventilation rates. Thus, assessing HRR for underground structures during fires can be conducted through Ingason's method and can be used in experimental events. Several obstacles which may result from difference between the calculated and estimated magnitudes of HRR can occur during tests (Migoya *et al.*, 2011). Many studies conducted on the characteristics of their passive fire preservation parts have focused on the behaviour of strength concrete (Mussa *et al.*, 2018a, b). By contrast, recent studies have proposed that the strength of concrete part affects fire behaviour. Thus, the performance of a preservation concrete parts do not merely follow the characteristics of protected concrete materials (Bezgin, 2015).

The spalling risks of tunnel linings should be estimated by considering different concrete contents and moisture situations to supply designers and tunnel owners with propositions on fire protection and preservation planning. The assessment method is supported by comparing assessment and numeral outcomes to verify the influence and the accuracy of the assessment method. The offered assessment method is applied to a highway tunnel in Austria and the spalling risk is evaluated (Zhang *et al.*, 2017). Spalling occurs from the first minute until 45 min of fire test. Several small slices of concrete fall due to cracks after 122 min test, especially, near the segment edge. Water is cleared from the 11th minute of the test until the test is finished (Robert *et al.*, 2013). Numerous resources (transportation, tools, materials, workers) are necessary for conducting full-scale fire tests, thereby indicating that the number of large-scale fire experiments that have been conducted is limited (Lonnermark *et al.*, 2012; Mussa *et al.*, 2018a, b).

Large-scale fire experiments are conducted on full-dimensioned concrete parts in which the limit

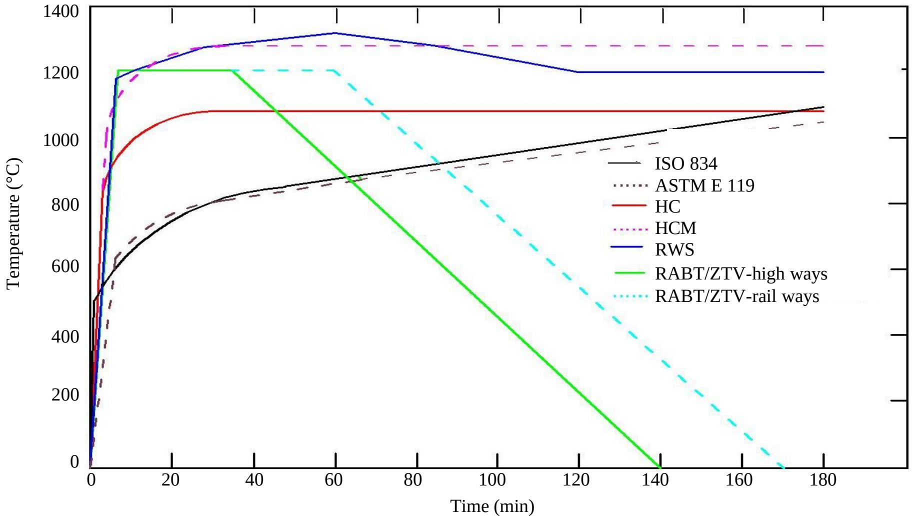

Fig. 1: Types of fire curves (Maraveas and Vrakas, 2014)

Fig. 2: Large-scale fire test (Ibrahim *et al*., 2012)

situations, outer load and conditions agree with design limitations. By contrast, medium-scale experiments are conducted on a section of a slab's surface area which was exposed to fire. Medium-scale experiments are typically applied as a cost-efficient solution to confirm the performance of a specific concrete mix in fire conditions (Krzemien and Hager, 2015; Mussa *et al*., 2017). However, several studies found that a small-scale model can fully comprehend the improvement of a full-scale prototype that will include instructions of the amounts of time and cost. Considerable results from small-scale research are confirmed by actual large-scale models which provide information on the deformation and stress in the tunnel parts and bolts (Standing and Lau, 2017). Figure 2 depicts the setup for large-scale fire tests (Ingason *et al*., 2016).

Experiments were conducted at a temperature up to 1200°C or higher in accordance with a series of fire curves. The fire preservation of the concrete is evaluated on and in concrete samples (Radzi *et al*., 2016). However, gaps and variations exist amongst the experiments. Several tests have been performed with normal concrete samples which are used in factories to define the performance of fireproof concrete (Yan *et al*., 2012; Lonnermark *et al*., 2012; Palm *et al*., 2016), whereas, other tests have been conducted at small scales for new fire-resis ta ntconcrete (Radzi *et al*., 2016). A sufficient fire protection should be implemented in tunnels because these tunnels are important transportation construction for various areas and any difficulty in traffic flow can cause series problems eventually. Several full-scale experiments have been conducted to study the behaviour of specific systems to be assembled in certain tunnels. The studied systems are mostly high-pressure water mist systems. Tunnel fire experiments at model scales have also been performed (Ingason *et al*., 2016). However, in large-scale tests should monitor and evaluate the damages to segments that result from speed cooling for tunnel lining during a fire.

Fire source: The fire source consists of 420 wood pallets located in the middle of the tunnel and the moisture contents of the woods are 15-20%. No additional plastic pallets are used at the test time considering the environmental requests for the Runehamar tunnel. The model-scale study indicates that the 420 wooden pallets can lead to a maximum HRR of approximately 100 MW (Ingason *et al*., 2016). The commodities are placed on particle boards on a rack storage system to simulate an HGV that measures 10.450×2900 mm. The total height is 4500 mm and a 0.5 mm-thick polyester tarpaulin covers the cargo as presented in Table 1 for the load description during a fire in a accordance with Runehamar tests (Ingason *et al*., 2015).

Table 1: Fire load used in large-scale tests Ingason *et al*. (2015)

Test	Description of fire load	Total weight (kg)	Theoretical Energy	Maximum HRR
T0	200 L Diesel in a pool with a diameter 2.27 m	166.4	6.4	6
T1	360 wood pallets measuring 1200×800×150 mm^3 20 wood pallets measuring 1200×1000×150 mm^3 and 74 PE plastic pallets measuring 1200×800×150 mm^3; 122 m^2 polyester tarpaulin	11010	244	202
T2	216 wood pallets and 240 PUR mattresses measuring 1200×800×150 mm^3, 122 m^2 polyester tarpaulin	6853	135	157
T3	Furniture and fixtures (tightly packed plastic and wood cabinet doors, upholstered PUR arm rest, upholstered sofas, stuffed animals, potted plant plastic, toy house of wood, plastic toys) 10 large rubber tyres (800 kg), 122 m^2 polyester tarpaulin	8506	179	129
T4	600 corrugated paper cartons with interiors (600×400 mm×500 mm^3; L×W×H) and15% of total mass of unexpanded polystyrene (PS) cups (18000 cups) and 40 wood pallets (1200×1000× 150 mm),10 m^2 polyester tarpaulin	2849	62	66

Measurement: The measurement of gas temperature in the fire test is conducted by using four thermocouples that are placed approximately at 0.3 m under the ceiling. The cause of the peak temperature below the tunnel roofing is too rising is that the stories are different in an open or a closed fire. Flames and hot gases radiate to the circumference, approximately without heat feedback from the surroundings in open fire. In a closed fire, the heat reactions from the circumference roofing and walls are typically restricted by the large space and may lead to the highest HRR. However, the heat reaction in a large-scale test in tunnels plays a significant part in the heat balance between flames and hot gases and the compelled ventilation improved combustion. A tunnel fire is typically fuel planned in a well-ventilated tunnel. Consequently, the temperatures are higher in the flames and hot gases than in open fire or a fire in a closed building (Yan *et al*., 2015). The thermocouples used to measure the HRR, pressure probes to measure the velocity and a gas instrument to determine the oxygen content in a hot fire. The HRR measurement is based on the methodformulated by Ingason *et al*. (2016). Temperatures are measured by using K type unsheathed and sheathed thermocouples near the fire. The temperatures of gases in the fire are determined 0.3 m beneath the tunnel ceiling and the thermocouples are located at five locations with heights of 0.7, 1.8, 2.9, 4.1 and 5.1 m as demonstrated in Fig. 3 (Ibrahim *et al*., 2012).

A series of K-type thermocouples with approximately 8 mm diameter are used on the vault of concrete lining and air to obtain the thermal distribution in the concrete tunnel lining (Wang *et al*., 2017). Suitable holes are drilled to install thermocouples from opposite surface to fire of the tunnel lining. The holes are cleaned and a small amount of the fine aluminium powder is injected into the hole bottom to generate perfect heat conduction between the concrete and the thermocouples. And then, theholes are padded by cement paste after the assembly of the thermocouples (Yan *et al*., 2012).

As mentioned earlier, thermocouples are used to determine the HRR pressure probes to measure velocity and a gas instrument to acquire the oxygen content of the hot fire gases. The method applied to calculate the HRR is based on Ingason's method by using numerous thermocouples that are separated from the actual cross section (Palm *et al*., 2016; Ingason *et al*., 2015). The masses of samples masses are measured before and after every test. Spalling leads to a mass loss during the tests and dehydration is determined by deducting the mass of the tested samples after cooling from the primary mass of the samples. No difference is identified between mass loss that resulted from the spalling and the mass loss that resulted from dehydration during heating. The present recommendations for reducing the spalling with PP fibres are insufficient to prevent spalling of the tested high-performance concrete mixes (Maluk *et al*., 2017). Swedish studies have been concentrating on plans or potential scenarios that fire services can manage. Full-scale experiments indicate many various methods to fighting a full-scale fire. These methods are used by expert firefighters and the situations are simulated to be nearly actual conditions. Each experiment is closely reported by a team of firefighters with IR image cameras (Palm *et al*., 2016).

Visual monitoring of concrete specimens subjected to a high temperature reveals that surface cracks become apparent when the temperature reaches 600°C. The cracks become clear at 800°C and then clearer when the temperature is increased to 1000°C. Colour image analysis indicates that redness is visible when the temperature reaches 800°C. The outcome of the colour image analysis may be used to evaluate the temperature level applied concrete (Arioz, 2007). The decrease in the compressive strength of concrete is significantly high for specimens exposed to temperatures more than 600°C. This outcome results from the water loss during crystallisation given a reduction in $Ca(OH)_2$ content and the changes in the

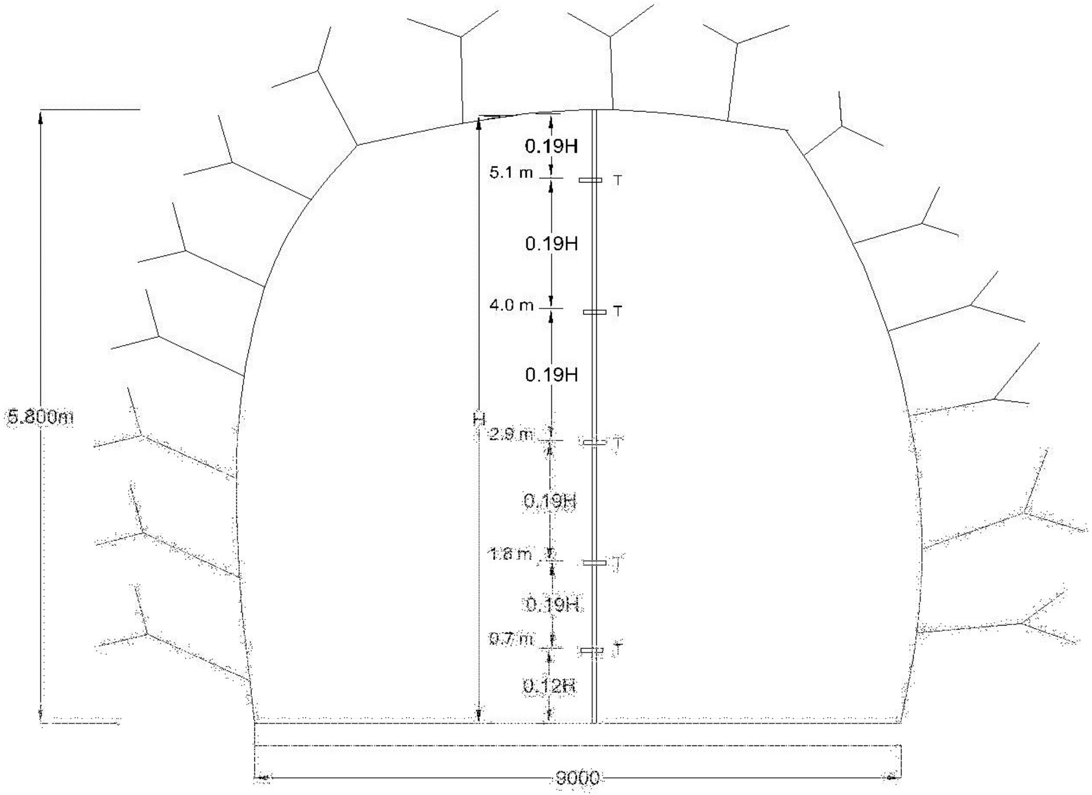

Fig. 3: The thermocouples locations in large-scale fire test (Yan *et al*., 2013)

information of micro cracks and morphologies. Studies have studied the relationship between the compressive strength and colour change of concrete that is exposed to increasing temperatures and the influence of increasing temperature on the mechanistic characteristics and pore structures of high-performance and normal strength concrete (Demirel and Kelestemur, 2010; Ingason *et al*., 2015).

RESULTS AND DISCUSSION

Issues: Many issues arise from the gaps, differences and similarities in conducting full-scale fire tests. The first issue is the variation in the characteristics of the real samples against experimental samples. Yan *et al*. (2012) documented the significance of applying the real samples of TBM lining segment from Shanghai metro line in a fire test to realise the actual impact of the tunnel at the location during the fire. Caner and Boncu (2009) conducted a fire test by applying the real sample of a key tunnel segment to study the material response. A real sample is better than other samples for testing because it is manufactured at a workshop with a high production level and satisfies the design and structural requirements.

The second issue is the concrete spalling which is an extremely complex event and is difficult to estimate and assess through theoretical approaches given to complicated microstructure and multiphase basics of concrete that was subjected to high temperatures (Yan *et al*., 2012). Only a few studies have attempted to simulate the construction loss by spalling and have contemplated modifications in the thermic and mechanical characteristics of concrete and reinforcement at various temperature situations despite numerous studies that have simulated the fire-prompted deterioration of concrete constructions and tunnel lining (Choi *et al*., 2013). The evaluation of the spalling hazard of a fire-laden tunnel lining is a basic section of designing new tunnels and assessing fire protection of current tunnels (Zhang *et al*., 2017).

The third issue is related to the impact of increasing temperature on cement-founded materials, including fly ash and nanosilica which has not been clearly described. Cement is replaced with high-volume fly ash composite and colloidal nanosilica to manufacture mortars with high residual strength even after being subjected to increasing temperatures. Comparison of spalling and deterioration outcomes and fire performance between new concrete (high volume fly ash and nanosilica concrete) and currently produced tunnel lining segments have been not conducted. The 4th issue is that the high-velocity water and unexpected cooling due to firefighting rescue process in actual fire incidents significantly affect the concrete tunnel lining segments because the high-velocity water contributes extra loading on the construction (Radzi *et al*., 2016).

Challenges: The behaviour of actual tunnel linings in a fire test has been documented by just a few large-scale experimental studies. Full-scale tests (either in loaded or unloaded situations) are crucial for determining fire performance and comparing simulat ions and modelling tests. The performance of fire-resistant concrete in large-scale tunnels is limited, the repairing works are costly, also the structure can become unavailable extensively (Yan *et al*., 2012; Lonnermark *et al*., 2012).

A fire-proof concrete is one relatively new and appropriate measurement to prevent the spalling of concrete tunnel lining during a fire. Accurate techniques that determine concrete performance, particularly the spalling hazard, in rapid- fire situations remain completely undetermined and are difficult to estimate through a theoretical approach (Yan *et al*., 2012; Pimienta *et al*., 2010). Explosive spalling of tunnel lining in an actualtunnel fire can become considerable at the beginning of the fire. Spalling is neatly linked to pore pressure foundress into concrete mechanical stresses consider ing differential thermal expansion. Steel fibres significantly aid in enhancing the stresses. The influence of spalling measurement is difficult to predict and compare with others results given the distinctions in testing setups and types of fire curves applied to obtain outcomes (Krzemien and Hager, 2015).

The addition of PP fibres has a noticeable positive influence on minimising the tendency for heat-prompted concrete spalling. On the bases of the parametric study and explanation offered herein, the next inclusive results can be obtained from different factors that might influence PP fibre efficiency at the spalling reduction of the High-performance Self-consolidating Concrete (HPSCC) mixes tested (Maluk *et al*., 2017). A full-scale fire test setup of new fireproof concrete (nanosilica and high amount of fly ash) is aimed at defining the fire performance of concrete tunnel lining at real fire time-temperature curves and compared with a normal product. The influence of the actual high-velocity water within firefighting rescue is also determined. In actual fire incidents, high-velocity water that is generated by firefighting rescue processes into a tunnel influences structural safety (Radzi *et al*., 2016).

CONCLUSION

Large-scale fire tests on tunnel lining construction by actual segments with real dimensions of samples are conducted. New fireproof concrete (high-volume fly ash with colloidal nanosilica) is applied to the tunnel lining segments during the fire test and compare with a normal product which was produced in a factory. Similarities and differences, including the type of fire exposure curve are determined amongst the applied techniques. The issues with large-scale tests include the fire influence on concrete spalling, the behaviour of the concretestructure and the consideration of new materials to be used as tunnel lining structures and high velocity water loading from the firefighting rescue processes. The major difficulty in improving the fire knowledge is the shortage of realisation of naturalistic techniques beyond this type of fire strategy which requires logical large-scale fire tests to be set up and conducted. Future large-scale fire tests must be conducted for reinforcement impacts of fire.

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