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Review Article
A Review of Methods, Issues and Challenges of Small-scale Fire Testing of Tunnel Lining Concrete

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Abstract
This review compiles the methodologies, issues and challenges regarding small-scale fire tests on tunnel lining concrete. First, this review examines testing, including furnace tests on specimens of actual and reduced dimensions and on site mobile furnace tests. Second is a discussion of the issues surrounding the tests, including the effects of loading, size reduction, inclusion of reinforcement and differences in the properties of actual and laboratory specimens. The major challenge with small-scale testing is there still no reliable theoretical method to predict concrete spalling due to fire exposure. Present contributions to the development of fireproof concrete also support the progress of small-scale fire testing of tunnel lining concrete.

Key words: Tunnel lining concrete, methods, small scale fire test, issues, challenges

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Following major tunnel fires worldwide, the need for effective protection for tunnel lining structures has become a matter of priority for both new and existing tunnels. In the event of fire, the temperature in a tunnel rises extremely rapid within a short period of time. Large-scale fire tests have demonstrated that maximum temperatures of 1200°C or even greater could occur[1]. In recent years, a great deal of study and guideline has been completed internationally to ascertain the types of fire that could occur in tunnel and underground spaces[2-4]. This study and guideline have developed a series of fire curve for the various exposures, as shown in Fig. 1. Assessment of fire in tunnels is based primarily on the risk of the concrete spalling. When tunnel linings are exposed to fire, the structural issues that must be considered are continuous explosive spalling until no concrete remains before the fire diminishes, loss of strength at elevated temperatures and loss of steel reinforcement tensile strength due to high temperatures.

Because no reliable theoretical method yet exists to predict concrete spalling due to fire exposure, assessment is primarily completed through fire tests. Usually, tests are performed on laboratory elements that have been removed from the tunnel structure. In addition, some tests reported here were conducted on laboratory specimens based on the actual concrete mix design used in the tunnel lining structure, self-compacting concrete and polypropylene (PP) fibre concrete. Little study has been completed regarding the use of the Supplementary Cementing Materials (SCMs) such as fly ash, blast-furnace slag and silica fume in tunnel lining structures. However, identical boundary conditions, state of stress and material properties of the assessed structure, which may modify the spalling behaviour are challenging to reproduce in a laboratory.

Recently, various tests have been conducted to determine the extent of fire damage to tunnel lining concrete. The most frequently considered tests are small-scale fire tests using an electric furnace (lab and mobile), which covers the assessment of the passive and active fire protection systems for the structural tunnel lining[2,5-9]. There are many advantages of small-scale fire tests. First, they require only that an electric furnace be used as a fire source to expose the specimen to high temperatures, versus large-scale fire tests that require the massive preparation of the fire source, including the burning of a car, train, wood pallet and other flammable materials. By using the furnace, the time-temperature profile required during the test can easily be set. Additionally, the test can be conducted at any time in a laboratory or site without the difficulties of locating a real tunnel or an abandoned tunnel in which to perform the large-scale fire test. Variable test data can be analysed to predict the results of large-scale fire tests, including examining the unheated surface after exposure to high temperatures and analysing the temperature time profile at the appointed thermocouple locations. Small-scale fire tests are also much less expensive than large-scale fire tests.

However, there are many arguments against small-scale fire tests. First, researchers did not consider the external influences on the structure, such as ground pressure, soil load and ground water pressure[5,6,8,9]. In addition, the small-scale fire tests are conducted without considering the loading from the high-velocity water from the fire fighting rescue operations to the fire damaged structure.

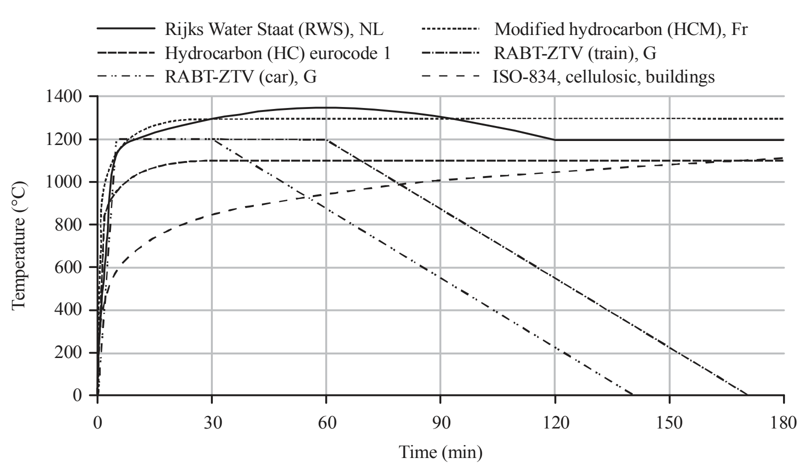

Fig. 1: Fire curves in tunnel

This study reviews the main developments in the field of small-scale fire tests and their key findings. The study is divided into three sections: (1) Methods, (2) Issues and (3) Challenges.

REVIEW

Small-scale fire tests on tunnel lining structures consist of three approaches (Fig. 2), including furnace tests on the actual dimensions of the specimen, furnace tests on the reduced dimensions of the specimen and on-site mobile furnace tests. The objectives of the small-scale fire tests are to determine the physical and mechanical properties of concrete before and after exposure to high temperatures; to determine fire damage to the reinforcement strength, tunnel lining joints, rubber water stops, flexible gaskets and sealing material, to produce fire proof structures and to investigate fire-protection materials.

There are three types of fire exposure commonly used in small-scale fire tests: (1) Cellulosic (ISO 834) fire curve, (2) Hydrocarbon (HC) fire curve and (3) Richtlinien für die Ausstattung und den Betrieb von Straßentunneln (RABT ZTV) fire curve, as shown in Fig. 1. The ISO 834 fire curve begins at the lowest temperature used in normal practice and is based on the burning rate of the materials found in general building materials and contents. The HC fire curve is applicable where small petroleum fires might occur, e.g., car fuel tanks, petrol or oil tankers or certain chemical tankers. The HC fire curve is based on a standardised type of fire, there are numerous types of fire associated with petrochemical fuels. The RABT ZTV fire curve is a series of test programs such as the EUREKA project. In the RABT ZTV fire curve, the temperature rise is very rapid, up to 1200°C within 5 min. The duration of the 1200°C exposure is shorter than in the other fire curves, with the temperature decrease beginning at 30 min for car fires. The decrease for train fires begins at 60 min. The 110 min cooling period is applied to Eureka and RABT ZTV fire curves.

Yasuda *et al.*[5], Caner and Boncu[6] and Yan *et al.*[7] conducted tunnel lining segment fire tests in a furnace using the actual dimensions of the specimen. Yasuda *et al.*[5] conducted a full-scale fire test on the actual dimensions of the Tunnel Boring Machine (TBM) fushimi tunnel composite segment linings to determine the appropriate fire protection measures to shield the TBM tunnel segment during the RABT ZTV fire curve. The objective of that study is to maintain the maximum temperature of the tunnel lining at less than 350°C in concrete and 300°C in steel. The test was performed in the unloaded state. Caner and Boncu[6] performed fire tests based on the HC fire curve on an isolated K segment of an actual shield TBM tunnel with a concrete cover of 40 mm in an unloaded state to investigate the fire damage to the concrete segment (Fig. 3). The concrete was cored and the reinforcement bars were detached on the day of the test for assessment. Yan *et al.*[7] performed full-scale experiments to investigate the fire damage to the Reinforced Concrete (RC) metro shield TBM Shanghai metro tunnel linings exposed to a standard cellulosic fire curve. The test involved 2 L segments and one K segment, connected by two steel joint bolts. Consideration was given to the initial load, bolt type and duration of fire with a concrete cover of 60 mm (Fig. 4). The thermocouples are installed along the joint line in post drilled holes at different depths: (1) Bottom reinforcement, (2) Mid-depth of the specimen, (3) Top reinforcement and (4) Unheated surface.

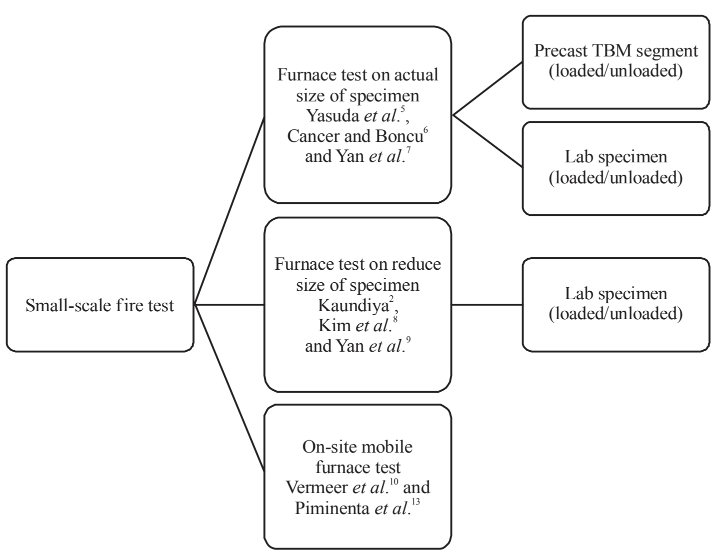

Fig. 2: Small-scale fire test

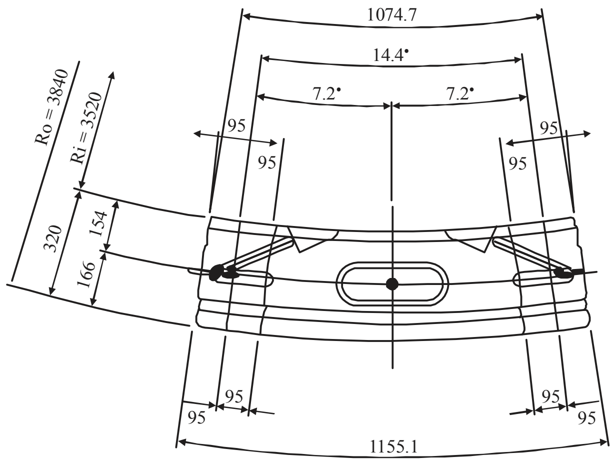

Fig. 3: Actual-scale TBM segment exposed to HC fire curve by Caner and Boncu[6]

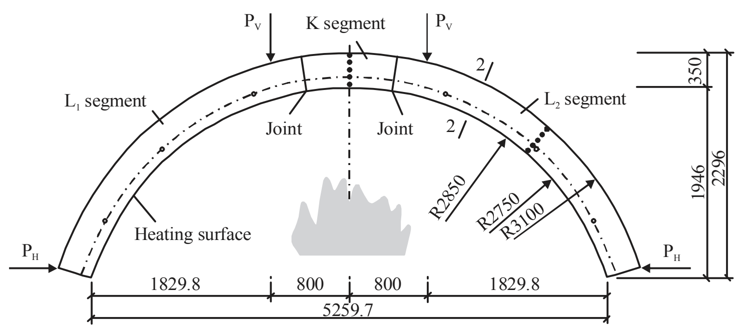

Fig. 4: Actual-scale TBM segment exposed to ISO 834 fire curve by Yan *et al.*[7]

Similar criteria were used in the tests by Yasuda *et al.*[5], Caner and Boncu[6] and Yan *et al.*[7] and the tests were conducted at a temperature greater than 1200°C based on a standard series of fire curve. The nominal concrete cover used during the tests was chosen considering the necessary durability and fire-resistance based on the requirements of BS 8500 and BS 8110. The tunnel exposure conditions can be classified as a severe environment with a nominal concrete cover between 25-40 mm depending on the lowest grade of concrete used. Currently, 60 mm is the standard depth of concrete cover and reinforcement location for tunnel lining[2]. The inner temperature of the concrete is measured by inserting the thermocouples into the post drilled holes, where they are insulated by a fire resistant material placed between the thermocouple and concrete[6,7]. The results indicate that the compressive strength of concrete after being exposed to the highest temperature is reduced between 40-50% from the control specimens[6,7]. However, gaps and differences exist between the tests conducted. Some researchers use factory ready-made TBM segment tunnel lining[6,7], whereas, other researchers reproduce a laboratory specimen by following the actual specification of TBM segmental design[5]. Differences exist between testing either a single segment by itself or jointly testing an entire tunnel segment. In addition, these tests were conducted under both loaded and unloaded conditions.

Meanwhile, Kaundinya[2], Kim *et al.*[8] and Yan *et al.*[9] had completed tests on specimens with reduced dimensions in a furnace. Kaundinya[2] investigated the behaviour and possible application of fireproof concrete in road tunnels based on a RABT ZTV fire curve. The test was conducted for 140 min and involved a 300×300×300 mm^3 concrete cube, 600×500×300 mm^3 unloaded reinforced plate and 600×500×300 mm^3 loaded reinforced plate. The concrete with 2-3 kg m^{-3} PP fibre yielded the best results for concrete spalling. Kim *et al.*[8] performed a fire test with a RABT ZTV fire curve for 180 min on reduced scale specimens based on a common RC tunnel lining used by the Korea Expressway Corporation, as shown in Fig. 5. A specimen with a 60 mm concrete cover was used to develop a new fire protective cement coating material and to determine the variation in fire protection performance at different coating thicknesses

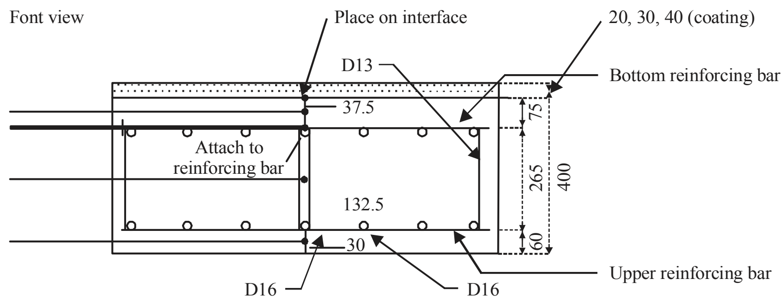

Fig. 5: Reduced-scale RC slab for cementitious coating test by Kim *et al.*[8]

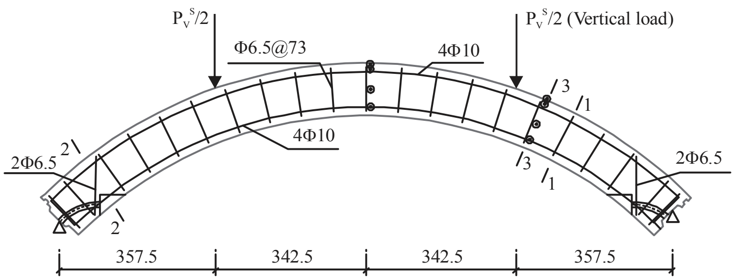

Fig. 6: Reduced-scale TBM segment exposed to HC fire curve by Yan *et al.*[9]

of 20, 30 and 40 mm. The thermocouples were installed along the line and cast together in concrete to record the temperature at different depths: (1) Interface between the concrete and the fire-protective coating, (2) Mid-depth of the concrete coating thickness, (3) Surface of the bottom steel reinforcing bar, (4) Mid-depth of the specimen and (5) Mid-depth of the back concrete lining. The PP fibre was used to release the internal evaporative pressure via melting during thermal loading, providing a pass-through channel.

Yan *et al.*[9] conducted a fire test with a HC fire curve for 60 min on a reduced size specimen of RC and Steel Fibre Reinforced Concrete (SFRC) shield TBM tunnel lining segment, as shown in Fig. 6. The small scale specimen with a concrete cover of 15 mm was employed even though small-scale specimens may not be quantitatively representative of the real large-scale tunnel linings due to possible size effects because the key characteristics and responses of the tunnel linings exposed to high temperatures, such as thermal expansion, variation, redistribution of internal forces and fire damage can be reasonably investigated when the key structural features and thermal-mechanical conditions of the shield TBM tunnel linings are carefully considered in the test. It is also overly time-consuming and cost-prohibitive to perform a comprehensive series of coupled fire tests on the full-scale tunnel linings adopted in a construction project. The thermocouples were installed along the joint line in post drilled holes at different depths: (1) Bottom reinforcement, (2) Mid-depth of a specimen, (3) Top reinforcement and (4) Unheated surface. The thermocouples were arranged at 25 mm intervals along the width line of the structure to avoid interaction.

The European Federation of National Associations Representing Concrete[4] has produced a guideline for the assessment of a passive fire protection system (surface applied protection and integral protection) based on various standard fire curves for 120 min. The test method consists of two specimen sizes for the fire test: (1) An unreinforced small slab with a minimum size of 400×400 mm^2 and (2) A reinforced large slab with a minimum size of 1500×1500 mm^2, as presented in Fig. 7. The thickness of the slab is dependent on the fire-protection system used and is between 200-250 mm. Type K thermocouples are installed during the casting to record the temperature at different depths: (1) Interface between the concrete and the fire-protective coating, (2) Mid-depth of the concrete coating thickness, (3) Surface of the bottom steel reinforcing bar, (4) Mid-depth of the specimen and (5) Mid-depth of the back concrete lining. A concrete core is taken before and after the fire test to determine the compressive strength. Various parameters are measured and observed during the fire test. The objective of this guideline is to harmonise the test procedures and reporting within Europe and various researchers have used it to investigate the fire damage in tunnel lining structures.

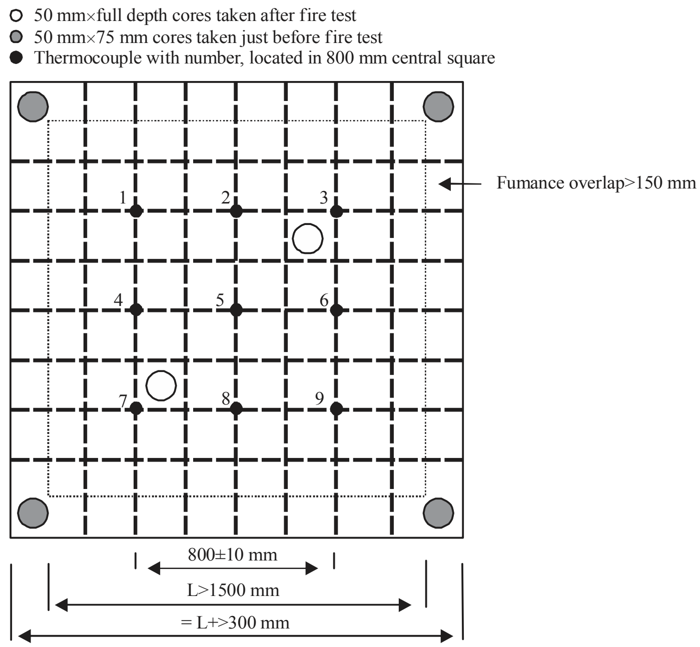

Fig. 7: Specimen preparation by EFNARC[4]

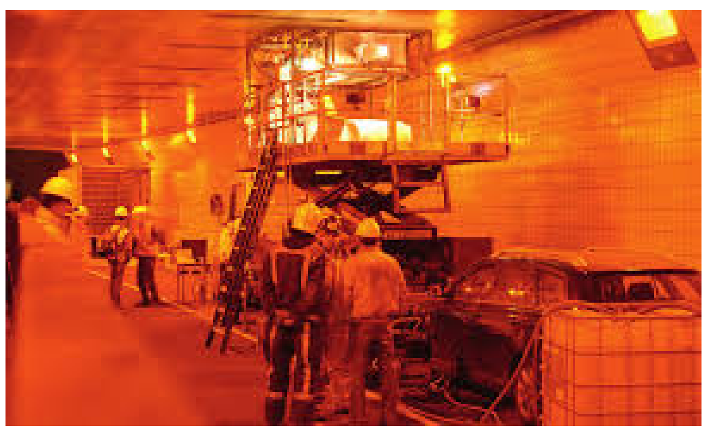

Fig. 8: Mobile furnace test

The reduced-scale specimen tests performed by Kaundinya[2], Kim *et al.*[8] and Yan *et al.*[9] also had similar criteria. Reduced scale specimens have been demonstrated to reflect all the key characteristics and responses of actual tunnel linings when the specifications of TBM segmental design are followed. The nominal concrete cover used for the tests was chosen considering the necessary durability and fire-resistance based on the requirements of BS 8500 and BS 8110. The tests were conducted at a temperature greater than 1200°C based on a standard series of fire curves. The fire protection of the concrete was assessed on and in the concrete specimens. However, gaps and differences exist between the tests. Some tests were conducted with unloaded specimens to determine the behaviour of the fire protective material[2,4,8], whereas, other tests were conducted with loaded specimens to demonstrate the best results for concrete spalling and the real fire damage to the structure[9]. Differences also exist in the duration of the fire test, between 60 and 180 min[2,4,8,9] and in the method of installation of the thermocouples, either by casting them in the concrete or by post drilled holes, insulated using a good heat-resistant material between the thermocouple and the concrete.

On-site mobile furnace testing is an innovation method in conducting small-scale fire tests as shown in Fig. 8. Recently, many European tunnels require testing to ensure they meet more stringent fire safety criteria[6,10-12]. Vermeer *et al.*[10] and

Pimienta *et al.*[13] reported that various tests have been conducted in active and abandoned tunnels. In August, 2012, fire safety testing was performed on the concrete lining of a road tunnel in Paris, France using a mobile furnace. This piece of equipment allowed a fire resistance test up to 1,300°C on a 1 m^2 sample section to be performed on site and in just 2 h, rendering unnecessary labour-intensive testing of concrete samples in a laboratory. In November, 2013, fire resistance tests with a mobile furnace were conducted on an existing Maastunnel tunnel structure in Rotterdam, Netherlands. The results from these fire tests will be used to determine the amount of fire protection needed for the tunnel. As part of a thorough testing procedure, the tunnel ceiling was subjected to a 2 h RWS fire curve and separately, to a 1 h cellulosic fire curve. Fire assessment testing was also conducted on the concrete ceiling of Koningstunnel. The Hague, Netherlands to assess the concrete spalling behaviour of the structure when exposed to a RWS fire curve. Fire assessment testing was also performed on the proposed passive fire protection system of Bevrentunnel, Antwerp, Belgium, to prevent the concrete lining from spalling and to test whether the system would meet the thermal insulation criteria. Another fire-safety test performed is on the proposed fire protection system of Kennedytunnel, Antwerp, Belgium, during a weekend period of closure for renovation work. The objective of the test was to verify that the proposed passive fire protection system could prevent the concrete from spalling and limit the temperatures of the concrete to a certain level. Using the mobile furnace, it is not only possible to perform fire tests in tunnels, but all types of on-site fire resistance tests can be completed at any location, in both horizontal and vertical orientations and using any desired fire curve up to the RWS fire curve.

ISSUES

Many issues were caused by the gaps, differences and similarities in how the small-scale fire tests were conducted. The first issue is the effect of the loaded versus unloaded specimens during the fire tests. Some researchers used loaded specimen to obtain specific, detailed results by considering the actual load of the horizontal and vertical ground pressure and to consider the external influence input data of the structure, such as ground pressure, soil load and earth water pressure[2,7]. During the test, the load was applied as an initial load and the ultimate load was measured to investigate the fire damage to the tunnel structure and tunnel lining joints (joint bolts, rubber water stoppers, flexible gaskets and sealing material). Meanwhile, the unloaded specimens were used in fire tests to investigate the fire damage to the material and the properties of concrete before and after the fire[2,5,8]. The tests were performed in the unloaded state based on the conditions in ACI (2001), in which the preloaded concrete specimen performed better than the unloaded specimens.

The next issue is the differences in the properties of the actual specimens versus the laboratory specimens. Yan *et al.*[7] reported the importance of using the actual specimen of TBM tunnel lining segment from Shanghai metro line 8 in the fire test to understand the real effect of the tunnel lining at the site during a fire. Caner and Boncu[6] conducted a fire test using the actual specimen of a key tunnel segment to investigate the material response. In general, the use of an actual specimen is the best option because it has been produced at factory, with good quality control and meets the design and construction requirements. Actual specimens also include more variables, such as joint bolts, rubber water stoppers, flexible gaskets and sealing material, compared with a laboratory specimen. However, costs incurred, logistics and the availability of the actual specimen may be problematic unless the researcher has an industry collaboration. To obtain precise and accurate test results, the usage of actual specimens is preferable. However, the production of laboratory specimens in previous studies considered all of the key characteristics and responses of the actual tunnel linings[2,4,8,9]. Yasuda *et al.*[5] reported that the specimens are identical to the segment to be used for the fushimi tunnel. By using laboratory specimens, researchers can produce a specimen in different dimension, different materials and install test apparatuses and thermocouples inside the concrete. In the on-site mobile furnace test[10], there are no issues because the test is conducted on the real tunnel structure at the site.

Another issue related to the small-scale fire test is the reduced size of the specimen. In the studies performed by Yasuda *et al.*[5], Caner and Boncu[6] and Yan *et al.*[7], the dimensions of the specimen were based on the size of the door opening and the accessibility of the furnace. Larger specimen size requires a larger furnace opening. However, because it is time-consuming and cost-prohibitive to complete the study on a larger specimen, the smaller specimen size is required. Although small-scale specimens may not be quantitatively representative of the real large-scale tunnel linings due to the possible size effects, a reduced specimen size is employed because the key characteristics and responses of the tunnel linings to exposure to high temperatures, such as thermal expansion, variation, the redistribution of internal forces and fire damage can be reasonably investigated when the key structural features and thermal-mechanical conditions of the shield TBM tunnel linings are carefully considered in the test.

The next issue is the effect of reinforced versus unreinforced specimens during the fire test. The EFNARC guidelines[4] state that the unreinforced small-scale method can be used for development work, for the provision of indicative performance data regarding propriety products and for quality monitoring during product production and during a contract. The reinforced large-scale test method can be used to demonstrate that the protection system fulfils all of the requirements of the job specifications. In previous studies[2,6-9], reinforced specimens were used in fire tests to assess fire damage to reinforcement strength. Steel begins to lose strength at a temperature of 300°C, with losses of 50% and 75% occurring at temperatures of approximately 560°C and 700°C, respectively[14]. If conventional rebar is to be used in the concrete structure, then this should also be included in test samples, as the presence of steel reinforcement will influence the degree of spalling experienced in a fire scenario. Concrete has relatively low thermal conductivity and high density, providing good insulation for reinforcing bars. Protecting the reinforcement is important to maintaining the load-bearing capacity of the concrete. Any reduction in cross-section due to fire spalling could potentially significantly reduce the fire resistance[12,15].

CHALLENGES

There is still no reliable theoretical method to predict concrete spalling due to fire exposure and the assessment is mainly performed through fire tests in which the researchers and industries must conduct both large and small-scale tests depending on the time-consuming and cost-prohibitive factors. Presently, for small-scale fire tests, EFNARC[4] has produced guidelines for the assessment of a passive fire protection system (surface applied protection and integral protection) based on various standard fire load curves. In the future, there will likely be improved specifications and standards for fire tests of tunnel lining structures.

Few studies have been conducted on fire tests of new materials used as tunnel lining structures. In previous studies[6,2,11,13,14], researchers have focused on improving the fire performance of tunnel structures during production by choosing better coarse and fine aggregates and by adding PP fibres. The PP fibres, when uniformly distributed within concrete, play an active role in improving the spalling resistance of concrete that is induced by elevated temperatures by reducing the plastic shrinkage and cracking and delaying the cracking initiation time[16]. Currently, there are many studies contributions to the development of fireproof concrete that can be used as tunnel lining structures. Ibrahim *et al.*[17] describes how fireproof high-strength concrete can be produced using high-volume fly ash with nano-silica. The test proved that this material has good fire resistance and higher compressive strength after exposure to high temperatures. The use of high-volume fly ash nano-silica concrete could reduce carbon dioxide emissions versus all-cement concrete[18].

In real fire events and fire fighting rescue operations inside a tunnel, high-velocity water is used on the affected structure. The high velocity of the water will significantly contribute additional loading to the structure. This loading should be considered during small-scale fire tests.

CONCLUSION

Small-scale fire tests on tunnel lining structure include furnace tests on the actual dimensions of the specimen, furnace tests on the reduced dimensions of the specimen and on-site mobile furnace tests. There are similarities and differences among the methods used, including the type of fire exposure curve, the material and size of specimen, the duration of testing and the external loading to the specimen. The issues with small-scale tests include the effects of loaded versus unloaded specimens, the properties of the actual specimens versus laboratory specimens, the reduced size of the specimens and the effects of reinforced versus unreinforced specimens. Future development of a reliable theoretical method will be significant for the performance of small-scale fire tests on tunnel lining structures at lower costs. In addition, future small-scale fire tests will consider new materials used as tunnel lining structures and high-velocity water loading from fire fighting rescue operations.

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