Using a vermiculite-based fire protection mortar to increase the fire resistance of reinforced concrete tunnels

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ABSTRACT: The mechanical properties of reinforced concrete elements tend to be damaged and weakened after they have been exposed to a significant fire, leading to a thinner alkaline protective coating around steel reinforcement, as well as a reduction in the yield and stiffness of the steel. In tunnels, fire can increase the concrete temperature extremely rapidly, as the heat generated cannot escape, resulting in high vapor pressures within the concrete structure, which in turn leads to explosive spalling and a significant loss of strength, potentially endangering human lives. In this study a series of experiments was conducted to evaluate the performance of a specific lightweight fireproofing material in terms of its behavior in fire. Test specimens were produced and tested in accordance with exposure under the RWS fire curve up to a temperature of 1,350 °C as outlined in EFNARC guidelines, then the passive protection provided by the product was evaluated for various layer thicknesses and exposure times. To further substantiate these laboratory findings, a full-scale field test was carried out in an existing reinforced concrete tunnel (Panagopoula twin railway tunnel). The results further contributed to defining and evaluating the parameters in up-scaling this performance under real field conditions, and its influence as a realistic intervention scenario during tunnel service operations.

1. INTRODUCTION

Numerous incidents of fires in reinforced concrete road and rail tunnels have been recorded over the last decades with incalculable and irreversible consequences for both the structural integrity of the infrastructure and mainly for human lives lost and damaged (EFNARC, 2006; Li and Ingason, 2018). At the same time, the significant damage caused to the tunnel's structural concrete lining, means the time and cost of repairs required, creates major disruption and inconvenience directly, and indirectly in adjacent areas, to the road and/or rail traffic, whilst the waste of excessive financial resources is also inevitable (Sakkas *et al.*, 2014). Fires that break out in tunnels can lead to the extremely rapid development of exceedingly high temperatures, due to the nature of the structures and the high-performance, dense, low permeability concrete in a confined environment, with limited ventilation and evaporation ability. Consequently, there can be explosive spalling, which is a phenomenon due to the rapidly expanding water vapor trying to escape, building to a pressure that causes violent detachment of pieces of the concrete surface with a pop or bang, simulating an explosion (Sakkas *et al.*, 2016). Explosive spalling – depending on the density and compressive strength of the concrete – usually happens at a temperature range of between 300 °C and 450 °C (Formosa *et al.*, 2011; Sakkas *et al.*, 2014; Abed and de Brito, 2020).

The need for fire protection of tunnels is usually covered by combinations of relatively complex approaches that include both active and passive fire protection techniques, which are applied in conjunction with modern fire management systems (Chen *et al.*, 2012). Different materials and technologies are used to provide passive fire protection solutions (board systems, insulating blankets, sprayed mortar systems, intumescent coatings, anti-spalling fibers) for upgrading the fire resistance of existing both structural and non-structural concrete tunnel elements. Sprayed fire-resistant mortars are distinguished by their ease of application, and their ability to be applied to almost any given complex substrate geometry, as well as by their high performance. Therefore, when comparing sprayed fire protection mortars to calcium silicate boards for example, mortars tend to be a much easier and more cost-effective solution. Additionally, in recent literature, the possibility has been raised of fire protection boards contributing to higher peak heat release, due to their higher emissions, low heat transfer coefficient and low conductivity, which could lead to interactions with the heat transfer mechanisms, hot gasses, heat feedback and fire plume (Tomar and Khurana, 2019). There are also different types of fire protection mortars, based on their mix design and ingredients, to ensure the desired fire resistance properties of the sprayed mortars. Mortars containing many different types of materials, different binders, powder components and aggregates have been tested. However, today the most widely used materials used in high-performance fire protection mortars are expanded vermiculite, or expanded perlite, as these are widely available, cost effective and efficient in performance.

Koksal et al investigated the effect of expanded vermiculite (153 – 199 kg/m^3) and silica fume (0, 5%, 10% and 15% by cement weight) on lightweight fire protection mortar performance after exposure at elevated temperatures. They concluded that the vermiculite's isolative properties resulted in less C-S-H decomposition, as the inner concrete layers maintain lower temperatures (Koksal, Gencel and Kaya, 2015). Kiran et al also investigated the performance of lightweight mortar containing expanded perlite by exposing protected concrete specimens for 30, 60 and 90 minutes at 821 °C, 925 °C and 986 °C, respectively, concluding that these protective mortar coatings could effectively be used as sacrificial materials that thereby improve post-fire high-strength concrete performance (Kiran *et al.*, 2022). Correia et al studied the ability of a vermiculite/perlite cementitious mortar to efficiently protect glass fiber reinforced polymers pultruded profiles in fire, and also compared this performance with using an intumescent coating system, and a calcium silicate board system. All of the tested material technologies / techniques improved the fire behavior of the specimens, and the vermiculite/perlite mortar system achieved the highest temperature reduction and the greatest reduction in all the tested reaction in fire properties (Correia, Branco and Ferreira, 2010). Caetano et al developed both gypsum- and cement-based fire protection mortars using expanded perlite, expanded clay and expanded vermiculite, concluding that vermiculite gave the optimum results in thermal performance, whilst the reduced particle size distribution of the aggregates used did not benefit thermal behavior of the specimens tested (Caetano *et al.*, 2022). Duan et al used a fire protection mortar coating containing both expanded perlite and expanded vermiculite to protect a large-scale (1/5) immersed tunnel. In comparison with the unprotected tunnel segment, this mortar provided greater fire resistance, as no concrete spalling was observed. Moreover, wire mesh embedded during the mortar application, further increased its performance and fire resistance, by improving its stability and preventing possible cracking (Duan *et al.*, 2021).

The main objective of this paper is to evaluate the performance of a vermiculite-based fire protection mortar under both laboratory and real-world site conditions. A series of tests were carried out by casting test slab specimens and protecting them with this fire protection mortar at different thicknesses. Subsequently, these samples were exposed to an RWS curve in a special laboratory furnace where the fire behavior of the specimen, as well as the performance of the fire protection mortar, could be evaluated. Using corresponding portable equipment, the same test was carried out on site, by exposing a specific square area of the Panagopoula railway tunnel to an RWS curve, after it was prepared, and the fire protection mortar was sprayed to the desired layer thickness.

2. LABORATORY EXPERIMENT

2.1 Materials

The physical and mechanical properties of cement-based, prebagged, dry mixed and wet sprayed, fire protection mortar, Sikacrete®-213 F, for concrete surfaces, are presented in Table 1. To ensure the correct application and bond to concrete surfaces and substrates for the laboratory and on-site tests, 1-component, polymer modified, cement-based bonding bridge primer, Sika MonoTop®-910 Eco, was used.

Table 1. Main physical and mechanical properties of the fire protection mortar used.

Property	Value
Fresh Density	~1,000 kg/m^3
Hardened Density	~450 kg/m^3
Compressive Strength	>1.50 N/mm^2

The specimen slabs used as the substrate for the laboratory tests, were cast in accordance with EFNARC guidelines (EFNARC, 2006). Slabs using for small scale tests were produced using a concrete mix with ~420 kg/m^3 cement and a water-to-cement ratio of 0.40. The compressive strength was ~65 MPa measured in test cubes. Mix design of the specimens for the large-scale test was differentiated as the concrete also contained anti-spalling fibers.

2.2 Sample Preparation & Testing Procedure

The concrete slab small-scale specimens were produced and then sprayed with the fire protection mortar at layer thicknesses of 20 mm and 26 mm, while the same procedure was also followed for large scale specimen, where a mortar layer of 26 mm, reinforced with wire mesh, was applied. By placing thermocouples in the middle of these mortar layers, the alternative scenarios of using protective layers of the mortar at thicknesses of 10 mm and 13 mm were also evaluated. As well as at these points, more thermocouples were located at the interface of the fire protection mortar and the concrete slabs with both 25 mm and 40 mm concrete cover, which again is in accordance with EFNARC guidelines (EFNARC, 2006).

At the Panagopoula railway tunnel test site, thermocouples were installed on the crown / internal roof of the tunnel in the layout described in the EFNARC guidelines for large scale tests (EFNARC, 2006). In total, nine thermocouples (Type K) were fixed on the tunnel crown; four thermocouples were fixed at the interface of concrete and the fire protection mortar, and five thermocouples were fixed 50 mm inside the concrete at the level of the steel reinforcement. After installation of these thermocouples, the fire protection mortar was applied by the wet spray method, to the designed thickness of 15 mm over an area of approximately 125x125 cm2, then the testing was conducted 56 days after the mortar application. With regard to the thermocouples exact locations; TC1, TC2, TC8 and TC9 have been installed at the concrete and fire protection mortar interface, whilst thermocouples TC3, TC4, TC5, TC6 and TC7 have been installed 50 mm below the concrete surface to represent the steel reinforcement position, again all in accordance with EFNARC guidelines (EFNARC, 2006).

In the laboratory tests, an electrical resistance furnace was used, designed in accordance with EFNARC guidelines for an adjustable square opening (150 – 400 mm), and with the ability to successfully implement the RWS time – temperature curve (EFNARC, 2006). To monitor the temperatures inside, two thermocouples installed in the center of the furnace were able to record temperatures up to 1,600 °C, and within an accuracy of 1.50 °C. This testing procedure was conducted at the National Technical University (NTUA) facilities, in Greece. In addition, for comparison, and to confirm inter-laboratory test repeatability, plus to investigate the effect of the furnace type and specimen scale on the test results, a concrete slab specimen (2100x1900x300 mm^3) protected with a 26 mm thick layer of the fire protection mortar was also produced and tested in the Hagerbach Test Gallery, which is dedicated tunnel materials and equipment testing facility located within a tunnel in the Swiss Alps. Here a gas-fired furnace with a combustion chamber area and volume of 1500x1500x850 mm^3, which was also able to achieve the RWS temperature curve. Six (6) of the type K thermocouples were installed in the following arrangement: two thermocouples (TC1 and TC6) were located at the interface between the concrete and fire protection mortar, two (TC2 and TC3) at a depth of 13 mm in the mortar, and two (TC4 and TC5) at a depth of 25 mm in the concrete slab. For the on-site measurement, a furnace from ENALOS R&D was used, with a combustion area of 100 x 100 cm. The furnace and its set–up, plus the test implementation is clearly shown in Figure 1. In both the laboratory and field tests, the RWS curve, as specified by the Netherlands Ministry of Transport, was followed. During successful testing the temperatures at the depth of the reinforcement, and at the interface between the fire protection mortar and the concrete shall not exceed 250 °C and 380 °C, respectively.

(a) (b)

Figure 1. (a) Application of Sikacrete®-213 F to the tunnel crown and (b) furnace for site fire resistance testing in the Panagopoula twin railway Tunnel.

3. RESULTS AND DISCUSSION

3.1 Laboratory Tests

In Figure 2, temperatures are monitored at the specified points shown, and illustrated to compare with the EFNARC limitations, plus the temperatures at the center of the furnace where the sample is exposed. The mean value from the thermocouples located at the interface between mortar and concrete reached 100 °C and then 200 °C after approximately 20 and 60 minutes, respectively, whilst the corresponding mean values from the thermocouples located 10 mm in the mortar layer reached these temperatures after approximately 10 and 40 minutes respectively. Specimens with 20 mm mortar thickness succeeded in achieving a temperature profile lower than the limit of 380 °C, with a maximum temperature of 364.5 °C after 120 minutes of testing, whilst the thermocouples located at a depth of 10 mm slightly exceeded the 380 °C limit after 120 minutes. At the same time, and as shown in Figure 2, none of the thermocouples located at a depth of 2.5 cm or 4.0 cm in the concrete slab exceeded the acceptable limit of 250 °C, meaning that the embedded steel reinforcement would be able to withstand corresponding exposure conditions. During the test no yielding or explosive spalling phenomena were observed, with the surfaces visually remaining in their original state, specifically in terms of there being no cracking, spalling, or other damage.

In Figure 3, the temperature development on the concrete interface with the fire protection mortar (26 mm thick layer), at 13 mm depth, and with 25 mm and 40 mm concrete cover is plotted for the 120 minutes duration of the specimen's exposure to the RWS fire load curve. Thermocouples located at the mortar and concrete interface (26 mm thickness) reached 100 °C and 200 °C after approximately 30 and 75 minutes, respectively, whilst thermocouples located at 13 mm depth, reached the corresponding temperatures after approximately 20 and 65 minutes.

Thermocouples located at the interface and at 13 mm depth in the mortar all recorded temperatures that did not exceed the 380 °C limit, with maximum values of 314.2 °C and 355.8 °C, respectively, whilst the temperature recorded by thermocouples inside the concrete also did not exceed the 250 °C limit. In these tests also, no damage such as spalling or cracking phenomena were observed. What is clear from all these tests and the criteria fulfilled, is that with Sikacrete®-213 F fire protection mortar applied in thicknesses of 13 mm, 20 mm and 26 mm – the requirements under the RWS curve were met, and so the tests were successful.

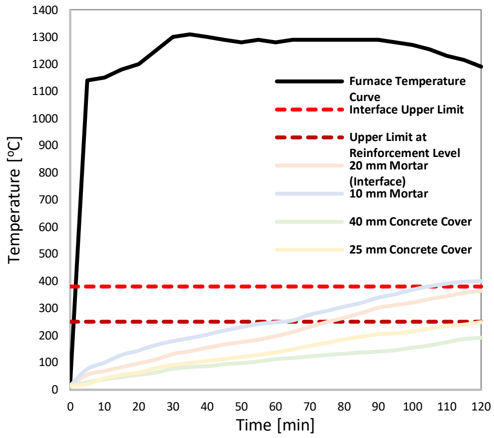

Figure 2. Results of testing under the RWS curve with 10 mm and 20 mm of fire protection mortar (NTUA).

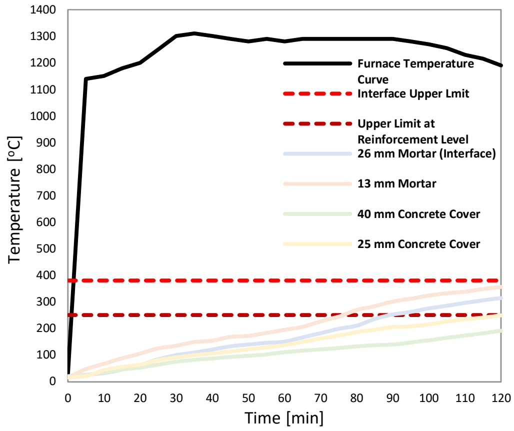

Figure 3. Results of testing under the RWS curve for 13 mm and 26 mm of the fire protection mortar (NTUA).

When it comes to the larger scale specimen that was tested in the Hagerbach Test Gallery, the temperature profiles of the measuring points for the full duration of the test are shown in Figure 4. During this specific experiment and after 120 minutes of exposure under the RWS curve, no excessively high temperatures were observed, and the highest value was 250 °C (TC3), which is well below the 380 °C limit. Following this observation, it was decided to continue the experiment for an additional 60 minutes, keeping the oven temperature constant at 1,200 °C. Even after the total 180 minutes of exposure to this high temperature, the permissible limits were not exceeded, not the spalling point limit (380 °C), or the embedded steel reinforcement protection limit (250 °C). Comparing with the corresponding results presented in Figure 3 regarding NTUA test, improved results could be attributes to the wire mesh, as Duan et al also claim, while the influence of furnace type and sample size should be further investigated (Duan *et al.*, 2021).

3.2 Field Test

The transition from laboratory to real site field test conditions, is complex and always challenging, as many external factors and influences on the concrete elements, such as ground pressure, soil load, ground water pressure, and the internal moisture content of the concrete, can all affect the results of fire testing (Jansson and Boström, 2013; Radzi, Hamid and Mutalib, 2016). The above parameters, and especially the moisture content, led to the occurrence of spalling phenomena at earlier temperature points than the prescribed (380 °C). In the test results shown in Figure 4, spalling occurred after approximately 73 minutes (Figure 5 shows 70 minutes, as the recording frequency of thermocouples was 5 minutes). There was no exceedance of the limit allowed by EFNARC guidelines, which in practice means that the sample did not fail the test after being exposed to the RWS curve. On the contrary, in situ conditions modified the spalling threshold from 380 °C to almost 270 °C (as in Figure 4). Taking this into account, 15 mm of the protection mortar – which theoretically successfully passes the test after exposure to the RWS curve for 120 minutes in laboratory environment, as indirectly shown by Figure 3 – can therefore provide a reinforced concrete railway tunnel with: a real fire protection time of 73 minutes, in situations with a high moisture content measured in the substrate in situ (approximately 73% before testing), and for elements in situations with a lower moisture content (50% ± 10% according to EFNARC), this fire protection would approach the results from laboratory conditions.

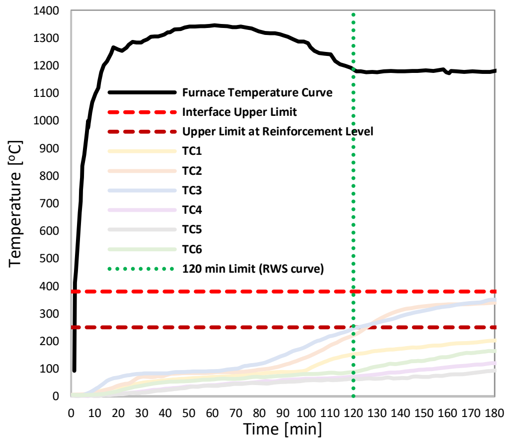

Figure 4. Results of testing under the RWS curve with 13 mm and 26 mm of the fire protection mortar (Hagerbach).

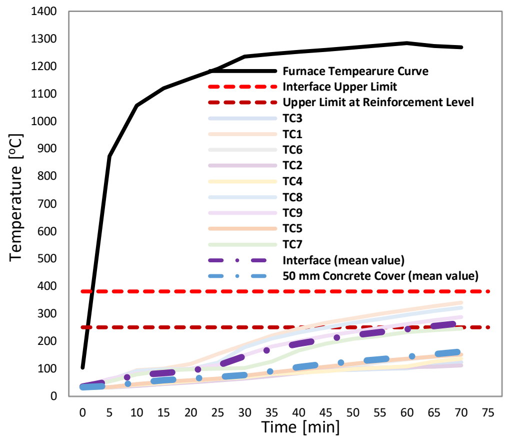

Figure 5. Results of testing under the RWS curve for a 15 mm layer of the fire protection mortar in the Panagopoula railway tunnel.

Additionally, – for an optimized techno-economical approach of the project requirements - a special study was made of the time needed for self-rescue to a safe area by rail passengers by themselves, as well as the intervention times for the emergency response services. The calculations – carried out in accordance with commission regulation (EU) No 1303/2014 - are given in Table 2 and Table 3 (*EU No 1303,* 2014). In Table 2, the estimated data is given regarding the total length of the tunnel, the distance between emergency exits, the number of passengers and on-board railway staff, the worst-case scenario of fire in terms of power, the train evacuation times are summarized, and finally the total estimated time for self-rescue to a safe area is calculated, which was 70.4 and 11 minutes, for passengers and the freight train, respectively. In Table 3, the estimated intervention time by the emergency response services - accounts for 71.5 minutes - has been calculated as the sum of the time need for notifying about the incident, the arrival time of emergency services at the entrance of the tunnel, the approach time to the incident area by firefighters on foot, and the time for deployment of fire hoses. Therefore, even in the worst-case foreseen scenario the experimental fire resistance time - derived from the real scale field test (73 min) - is sufficient for the tunnel to be characterized as safe and acceptable for public use.

Table 2. Estimated time for self-rescue to a safe area by passengers themselves - calculation.

Parameter	Value
Tunnel total length	4.500 m
Distance between emergency exits	500 m
Passenger Train	
Number of passengers and on-board staff	538
Worst-case fire power	25 MW
Train evacuation time	8 minutes
Tunnel evacuation time	70.4 minutes
Freight Train	
Number of passengers and on-board staff	2
Worst-case fire power	52.44 MW
Train evacuation time	2.75 minutes
Tunnel evacuation time	11.0 minutes

To further investigate and confirm the above calculations, a real-time reaction of the emergency services was then timed for an accurately simulated fire incident in the tunnel. After approaches by the emergency services at three different points in the tunnel - east, west and in conjunction with the existing auxiliary tunnel - the measured times amounted to 15, 20 and 16.5 minutes, respectively. Taking the above-mentioned times into consideration, the fire resistance of the concrete tunnel lining with the fire protection mortar is more than sufficient – even in a worst-case scenario - the differences between a laboratory limit (RWS) and a realistic fire scenario are also clearly defined and clarified.

Table 3. Estimated intervention time by the emergency response services – calculation.

Parameter	Value
Time for notification of the incident to traffic control center by on-board staff	9.9 minutes
Time for notifying the incident to emergency services by traffic control center	11.0 minutes
Arrival time for emergency services to the entrance of the tunnel	25.3 minutes
Approach time to the incident area by the pedestrian fire-fighters	23.1 minutes
Time for deployment of fire hoses before use	2.2 minutes
Total intervention time	71.5 minutes

4. CONCLUSIONS

Different tests were conducted for evaluation of the fire protection mortar being investigated, the main conclusions of which are summarized below:

- At layer thicknesses of 20 mm and 26 mm the passive fire protection testing under the RWS curve was successfully completed and passed, without any sign of cracking or spalling phenomena.
- For sample specimens with fire protection mortar thicknesses of 13 mm and 26 mm, the testing was repeated in different laboratories, with different equipment and personnel and with different sample dimensions. Despite these different parameters the testing under the RWS curve was successfully completed and passed.
- When carrying out larger scale field tests on site and testing in situ, different parameters related mainly to the internal moisture content of the concrete substrate adversely affected the results. This was because the high moisture content reduced the temperature point at which the explosive spalling can occur. Therefore, testing carried out on site was interrupted earlier due to the concrete surface spalling. However, the test continued and for the whole time of exposure, the measured temperature points were nowhere near the limits in the regulatory framework.
- After theoretically calculating the self-rescue time and intervention time by the emergency response services, which was also verified in the field, the field measurements of temperature increase clearly showed that the fire resistance of the tunnel surface coated with the fire protection mortar was increased well above the limit and successful.
- More scientific research regarding the furnace type effect, the scale effect, as well as the correlation between concrete moisture content and spalling phenomenon temperature points should be carried out say the authors.

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