EXPERIMENTAL STUDY ON THE THERMAL PERFORMANCE OF FIRE-RESISTANT PLASTER FOR TUNNEL APPLICATIONS

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Abstract: Passive fire protection is a key component of tunnel safety strategies, aiming to delay temperature rise in the concrete lining and limit heat transfer through structural elements. This article presents findings from full-scale fire experiments conducted at the research centre "Zentrum am Berg". The tests were divided into two groups to evaluate the thermal performance of fire-resistant coating under realistic fire scenarios in tunnel environments. The first group examined plaster layers of *maxit ip 160 T* with 4 cm, 3 cm, and 2 cm thickness applied directly to tunnel walls and exposed to moderate heat loads representative of passenger vehicle fires, with varying ventilation settings. The second group involved prefabricated panels with 4 cm *fireprotection plaster maxit ip 160 T* layers subjected to more severe fire exposures using burning magnesium and controlled gas flames. Temperature measurements were recorded on the fire-exposed plaster surface and at various depths beneath using thermocouples. The collected data provide a robust basis for assessing the insulation performance of the tested material. Preliminary results indicate effective thermal protection, supporting the plaster's potential for use in tunnel fire safety applications.

Keywords: Tunnel fire safety, Passive fire protection, Full-scale experiment, Temperature measurement, Thermal insulation material, Tunnel Fire

1. INTRODUCTION

Fires in tunnels represent a distinct and serious hazard due to the confined geometry of these structures and their essential role in transportation networks. A comprehensive understanding of fire effects on tunnel integrity is vital for the development of robust safety measures and the facilitation of efficient post-incident recovery. Consequently, maintaining the structural integrity of tunnels during fire events is of paramount importance.

Past tunnel fires have shown severe damage to structures both during and after the event. Notable examples include the Mont Blanc Tunnel fire in 1999, which caused extensive harm to concrete and steel, leading to long closures and costly repairs (Lacroix, D. 2001), the Tauern Tunnel fire the same year with significant structural deterioration (Leitner, A. 2001), and the Gotthard Road Tunnel fire in 2001 causing partial collapse and extensive reconstruction (Henke, A., Gagliardi, M. 2004). These incidents highlight the risk of fire-induced damage to tunnel linings and reinforcements, emphasizing the need for effective fire resilience and mitigation strategies in tunnel safety.

Elevated temperatures significantly alter the properties of concrete, reducing its strength, stiffness, and deformation capacity through chemical and physical processes (Beard, A., Carvel, R. 2012). A critical hazard is explosive spalling, caused by internal vapor pressure and thermal stresses from restrained expansion and temperature gradients, along with dehydration, phase changes, and microcracking. Chemical reactions such as calcium hydroxide dehydration above 400 °C and limestone decomposition beyond 800 °C increase internal pressure and spalling risk, which can begin at temperatures as low as 200 °C in some concretes. Due to the lack of universal predictive models, experimental evaluation of tunnel lining materials is necessary before application. High temperatures also impair embedded steel reinforcement, with conventional steel losing up to 80% of its strength at 700 °C and showing blue brittleness between 200–300 °C, necessitating protection to limit exposure above 250–300 °C. Additionally, thermal expansion of concrete can cause structural bending and potential collapse, especially in intermediate ceilings and ventilation partitions. While concrete and steel expand similarly up to about 400 °C, their differing behavior beyond this point generates internal stresses that may severely damage composite tunnel structures (Wetzig, V. 2001).

Tunnel fire protection strategies focus on preventing or delaying temperature increases in the concrete lining and reducing heat transfer through structural materials. Passive fire protection is a key element, typically involving secondary concrete or cementitious layers, fire-resistant cladding panels on walls and ceilings, and the use of fibres or additives in concrete to improve fire resistance and reduce spalling risk (Beard, A., Carvel, R. 2012). However, no universal international standard exists for tunnel fire protection levels; requirements vary by country and depend on national regulations, risk assessments, and project-specific conditions.

Structural fire resistance is assessed using standardized "design fire" time–temperature curves that represent thermal loads during tunnel fires (Hurley, M.J., Gottuk, D., Hall, J.R., Harada, K., Kuligowski, E., Puchovsky, M., Torero, J., Watts, J.M., Wieczorek, C. 2016). Common curves include the Standard Fire Curve (ISO 834) for cellulosic fires, the Hydrocarbon Curve (HC) for hydrocarbon fires, and the Rijkswaterstaat (RWS) Curve for severe fuel spill scenarios. A Modified Hydrocarbon Curve (HCM) accounts for tunnel-specific factors like ventilation. National guidelines such as ZTV-ING/RABT and EBA specify rapid temperature rises and cooling phases, with reinforcement temperatures limited to 300 °C. Fire curve selection depends on tunnel type, cargo, fire load, and regulations, guiding fire protection design accordingly.

Applying an insulation layer to the inner surface of the primary lining is a simple and cost-effective passive fire protection method, often using materials like sprayed vermiculite cement (Beard, A., Carvel, R. 2012) (Beard, A., Carvel, R. 2012). Its effectiveness depends largely on the layer thickness, which influences thermal insulation and fire resistance. In Austria, fire protection for road tunnels and the use of such layers are governed by RVS 09.01.45 (Österreichische Forschungsgesellschaft Straße –Baulicher Brandschutz in Straßentunnel 2015) and the ÖBV guideline on protective layers for underground structures (Österreichische Bautechnik Vereinigung 2017), which define fire scenarios based on standard time–temperature curves and technical requirements. Since concrete loses strength around 300 °C (Ryburn, J., Mann, H., Doran, S., Cheung, K. 2025), the ÖBV guideline requires that the temperature at the interface between the protective layer and concrete does not exceed 300 °C after 90 minutes, to maintain structural integrity during fire exposure (Österreichische Bautechnik Vereinigung 2017).

The evaluation of fire-resistant materials under realistic tunnel conditions is essential for improving the resilience of underground infrastructure to fire hazards. The present study examines the effectiveness of a secondary insulating layer applied directly to the tunnel lining under conditions representative of actual fire events. This investigation comprises the development of a conceptual framework, the implementation of full-scale fire tests, and the systematic acquisition of performance data. Emphasis is placed on analyzing the thermal behavior of the fire protection plaster (maxit ip 160) when subjected to realistic fire exposure scenarios.

2. RESEARCH APPROACH AND METHODOLOGY

2.1 EXPERIMENTAL FACILITY

The fire tests were conducted on six separate occasions in 2024 and 2025 at the Zentrum am Berg (ZaB) research facility in Eisenerz, Austria. Operated by Montanuniversität Leoben, ZaB offers a full-scale underground testing environment that enables the controlled simulation of tunnel-related emergency scenarios. The experiments took place in the Western railway tunnel, which is adapted for fire and safety research and features a slight curvature, a length of approximately 400 m, an internal width of 8.3 m, and a height of 7.6 m. The tunnel is lined with shotcrete, offering representative thermal and structural behaviour during fire exposure. The ZaB tunnel system is equipped with two pairs of ceiling-mounted, fully reversible jet fans located in the Western railway and Northern Road tunnels. Each fan is capable of delivering a maximum airflow rate of 31.4 m^3/s, supporting the implementation of various longitudinal ventilation strategies relevant to tunnel fire investigations.

2.2 FIRE SCENARIOS

The fire scenarios were structured into two test groups to allow a gradual increase in thermal exposure. The first group consisted of liquid pool fires simulating burning passenger vehicles, with additional fire sources such as magnesium chips and a gas burner used in later tests to emulate more severe conditions representative of heavy goods vehicle or bus fires.

2.2.1 Controlled Fires with Moderate Thermal Load

The first group of fire scenarios involved controlled pool fires using four square steel pans (1 × 1 m), each filled with 25 litres of a 1:4 gasoline–diesel mixture. The pans were placed on elevated platforms at heights of 2.1 m during the first three test days and 4.1 m during the fourth (Figure 1), aiming to replicate realistic fire conditions and heat transfer dynamics in the tunnel. The fires were maintained for up to 30 minutes to enable detailed observation of fire behaviour and material responses.

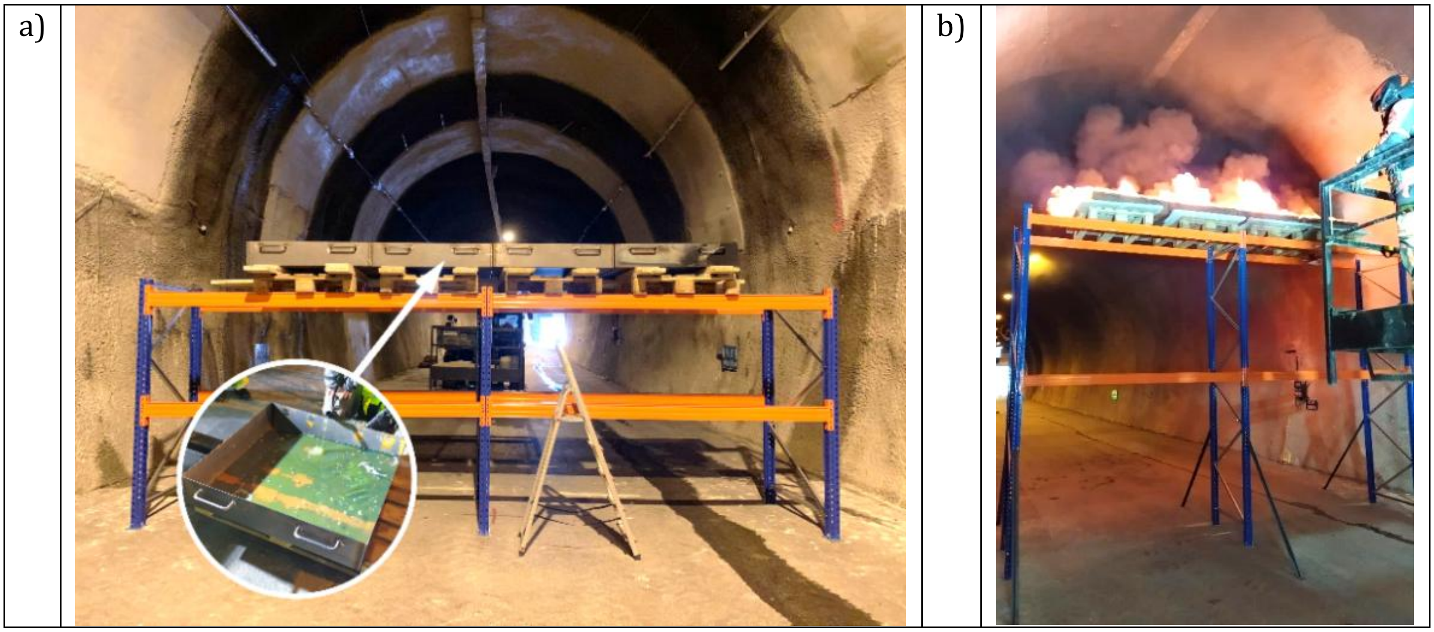

Figure 1: Arrangement of fuel pans on platforms at heights of 2.1 m (a) and 4.1 m (b) above ground

Based on literature correlations and excluding thermal radiation feedback from tunnel walls, the average heat release rate (HRR) was estimated at approximately 5 MW for the four pans (Ingason, H., Li, Y.Z., Lönnermark, A. 2015). This projection does not account for interactions between adjacent fires, which may result in an underestimation of peak HRR values when all pans are fully involved (Borghetti, F., Derudi, M., Gandini, P., Frassoldati, A., Tavelli, S. 2017).

2.2.2 Advanced Tests with Increased Fire Intensity

The first test in the second group involved the combustion of magnesium chips using a specially designed device resembling a grill (Figure 2, a). The fire bed was positioned 0.6 m above ground level and measured 0.85 × 0.7 m. Magnesium chips, packed in cardboard boxes, were incrementally fed into the combustion area to sustain continuous burning.

Magnesium fires produce extremely high temperatures, often exceeding 2000 °C and reaching up to 3000 °C during ignition (Nam, K.-H., Lee, J.-S., Park, H.-J. 2022), far above typical hydrocarbon fire levels. However, their highly reactive and unpredictable combustion makes it difficult to maintain consistent fire intensity and a stable heat release rate.

The second test employed a propane-fuelled gas burner with multiple nozzles arranged in five rows to ensure uniform flame distribution (Figure 2, b). Connected to a supply system of propane cylinders, the setup provided a stable and controllable fuel source throughout the experiment. Propane, known for its efficient combustion and high energy output, can reach flame temperatures of up to 1977 °C in air (Babrauskas, V. 2025), though actual surface temperatures during testing are typically lower due to heat dissipation, burner design, and ventilation conditions.

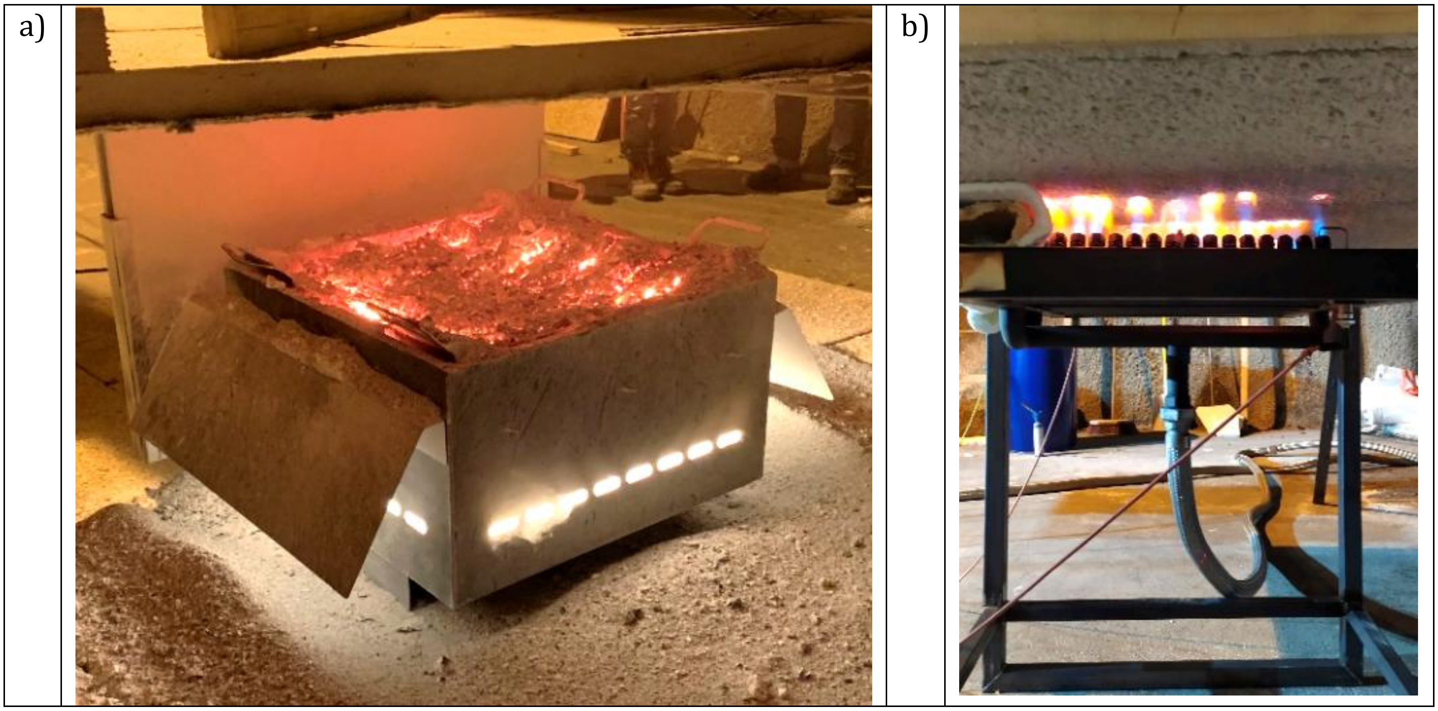

Figure 2: Combustion device for magnesium chip burning (a) and multi-nozzle gas burner (b)

2.3 EXPERIMENTAL CONFIGURATION AND MEASUREMENT METHODS

2.3.1 Assessment of Ventilation Conditions

Ventilation conditions were systematically assessed prior to the fire experiments, as airflow velocity significantly influences both combustion dynamics and heat release rate (Borghetti, F., Derudi, M., Gandini, P., Frassoldati, A., Tavelli, S. 2017). Measurements were taken at six points across the upstream tunnel cross-section using a hot-wire anemometer, with values averaged over 10-second intervals to provide stable and representative airflow data.

Two main ventilation modes were applied during the first group of fire tests. For the first examination, two operating fans in the Northern Road tunnel were utilised, while the second test employed full ventilation, which included two fans from the Northern tube and two from the Western tube. For the second group of fire tests, ventilation conditions were similarly monitored, with both experiments conducted under the operation of two jet fans in the Northern Road tunnel to ensure safe conditions for test personnel. Details of the ventilation scenarios applied are summarised in Table 1.

Table 1: Ventilation modes and measured airflow

	Test Day 1		*Test Day 2*		*Test Day 3*		*Test Day 4*		*Test Day 5*		*Test Day 6*	
	Two fans	*Four fans*	*Two fans*	*Four fans*	*Two fans*	*Four fans*	*Two fans*	*Four fans*	*Two fans*	*Four fans*	*Two fans*	*Four fans*

Average velocity, [m/s]	*0.91*	*1.98*	*0.88*	*1.79*	*0.94*	*1.88*	*1.35*	*2.03*	*1.73*	-	*1.60*	-

2.3.2 Temperature Data Acquisition

In the first group of tests, the investigated plaster material *maxit ip 160 T* was applied to the tunnel shotcrete lining in the Western railway tunnel, forming three test sections with thicknesses of 2 cm, 3 cm, and 4 cm. Each section was 2.8 m wide, with a separation of approximately 4 m between adjacent segments.

Temperature monitoring was conducted at eight locations per cross-section using type K thermocouples, following a predefined test layout (Figure 3). At each location, temperatures were recorded both on the surface of the plaster and beneath it. Surface thermocouples were labelled TC1 to TC8, while those embedded within the insulating layer were designated TC9 to TC16.

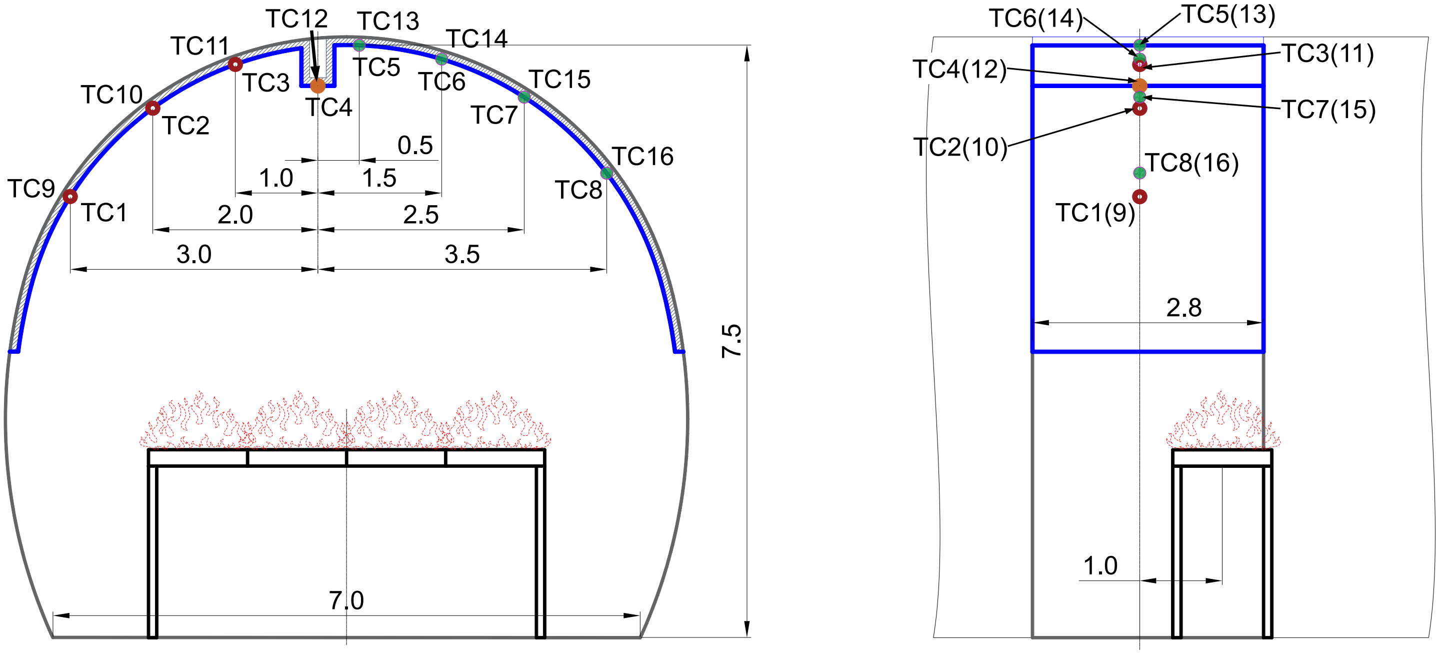

Figure 3: Layout of temperature measurement points

For the second group of experiments, dedicated test panels were produced by casting the fireproof material into wooden moulds, forming square plates measuring 2 × 2 m with a uniform thickness of 4 cm. Four thermocouples were used per panel for temperature monitoring. Two measurement locations (A and B) were chosen near the centre of the panel, aligned along its vertical symmetry axis and spaced 0.2 m apart. Two sensors (TC-A1 and TC-B1) were placed on the heat-exposed surface, while the other two (TC-A2 and TC-B2) were installed on the rear side of the specimen.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 FIRE TESTS WITH MODERATE FIRE LOAD USING A GASOLINE–DIESEL MIXTURE

3.1.1 Fire Source Positioned on 2 m Platform

On the first test day, two experiments were conducted on the tunnel section insulated with a 4 cm plaster layer. The four-square fuel pans were filled with a gasoline–diesel mixture and positioned on a platform elevated 2.1 m above ground level. The first test (Test 1.1) was performed with two jet fans operating in the Northern Road tunnel, while the second (Test 1.2) employed all four fans to establish a fully developed longitudinal ventilation flow.

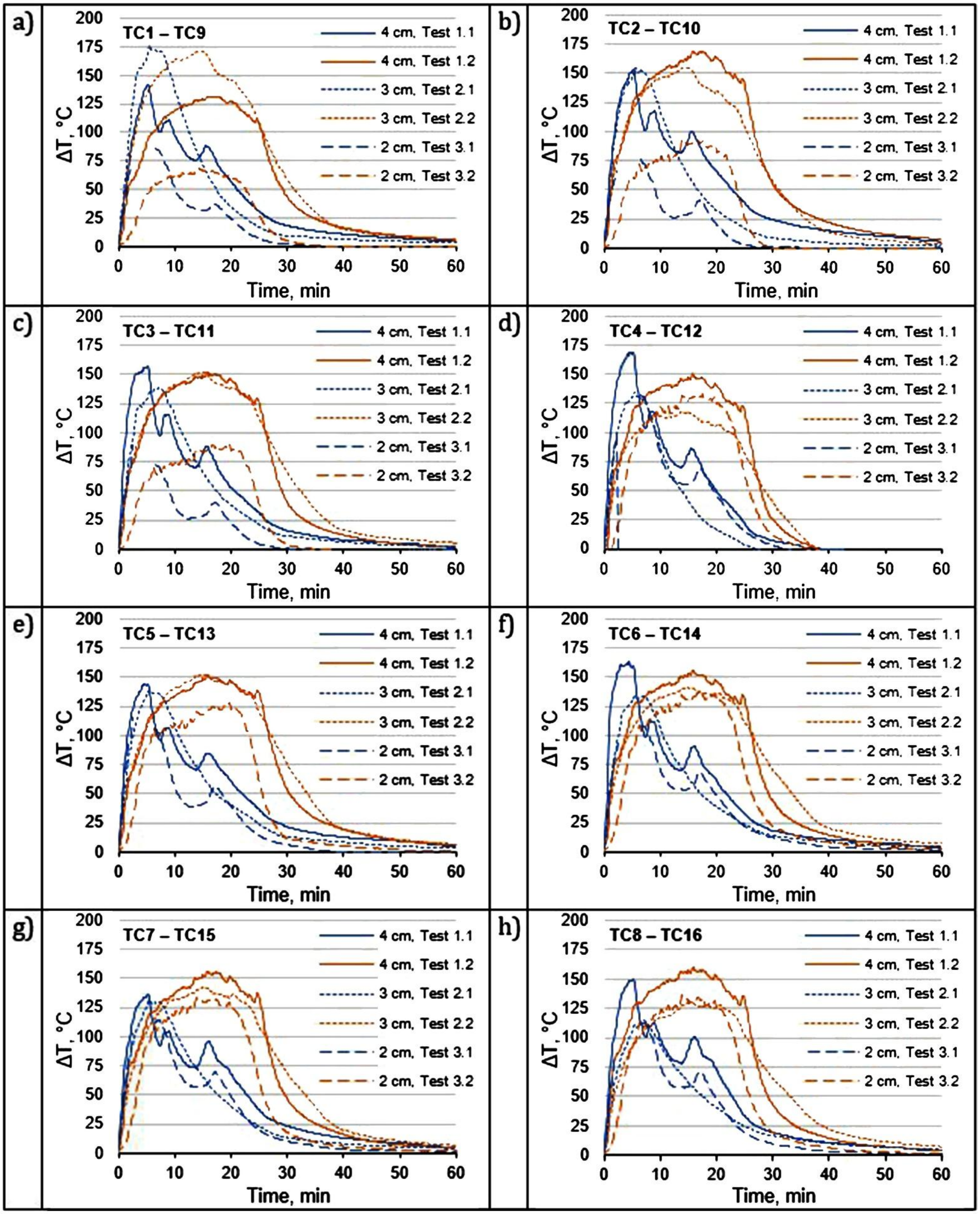

Figure 4: Temperature differences between external and internal thermocouples over the first three test days

A notable effect of the ventilation setup was observed during the experiments, as it significantly affected the fire development and combustion dynamics. In Test 1.1, the limited airflow led to smoke accumulation around the fire source and rapid onset of back layering. In contrast, the increased airflow in Test 1.2 facilitated more effective smoke extraction from the fire zone. Although back layering still occurred, the smoke was considerably less dense than in the first test.

Radiation is the dominant mode of heat transfer in flames with characteristic lengths exceeding 0.2 m (DiNenno, P.J., Drysdale, D., Beyler, C.L., Walton, W.D., Custer, R.L.P., Hall, J.R., Watts, J. M. 2002), consistent with conditions observed in the tunnel. The comparison of temperature profiles from Tests 1.1 and 1.2 reveals a more stable and prolonged heat effect in the latter, attributed to more efficient smoke removal. This enhanced ventilation promoted stronger radiative heat transfer, resulting in a longer duration of sustained heat load and more uniform temperatures on the plaster surface.

During the second (3 cm plaster layer, Tests 2.1 and 2.2) and third (2 cm plaster layer, Tests 3.1 and 3.2) test days, the ventilation protocol remained consistent: the initial test of each pair utilised two jet fans, followed by a second test employing full ventilation with all four fans in operation. The resulting fire behaviour, temperature patterns, and smoke distribution closely mirrored those observed during the first day.

The surface temperatures measured varied moderately across the test days but consistently remained within a comparable range of approximately 140–190 °C. In Test 1.1, thermocouple TC-4 registered the peak temperature of 178.7 °C, increasing to 188.2 °C in Test 1.2 at the same location. On the second test day, TC-1 measured the highest values: 187.4 °C in Test 2.1 and 194.4 °C in Test 2.2. During the third test day, TC-4 recorded a reduced maximum temperature of 150.1 °C in Test 3.1, which then increased to 186.2 °C in Test 3.2. The unusually low maximum value registered in Test 3.1 may be attributed to a brief power failure during the fire outbreak, which resulted in the loss of temperature data for several minutes.

For the evaluation of the fire insulation material's performance, the recorded temperature data were used to calculate the temperature differences (ΔT) between the plaster surface and beneath the insulation layer at each measurement location (Figure 4).

These differential temperature curves represent the thermal gradient across the insulation and demonstrate its heat-shielding capacity. Greater temperature differences indicate improved thermal protection by reducing heat transfer through the plaster. The speed at which these differences develop offers insight into the material's thermal response time. This metric is therefore crucial for assessing the insulation's performance under varying thermal loads. The resulting temperature profiles form a robust basis for the subsequent detailed evaluation of the material's fire resistance characteristics.

3.1.2 Fire Source Positioned on 4 m Platform

On the fourth test day, a tunnel section with a 2 cm fire protection layer was investigated. The fire source was positioned on a 4 m-high platform to elevate the flames closer to the tunnel ceiling and sidewalls, thereby promoting increased surface temperatures compared to earlier test configurations. Ventilation conditions were maintained in accordance with the previous test procedures.

The observed smoke propagation patterns were consistent with those documented in previous experiments. In Test 4.1, pronounced smoke accumulation was observed in the vicinity of the fire source. By contrast, Test 4.2 exhibited lower smoke concentrations and a delayed onset of backlayering, which was attributable to the intensified ventilation conditions.

As in the previous tests, a clear distinction in thermal behaviour was observed between the two experiments. In Test 4.1, all thermocouples registered a sharp temperature spike followed by a rapid decline, indicating a brief but intense thermal exposure. Conversely, Test 4.2 exhibited a more gradual temperature rise and an extended period of elevated temperatures, reflecting a sustained thermal load despite marginally lower peak values.

The 4 m platform setup produced considerably higher surface temperatures than those observed in the 2 m platform tests, indicating more severe fire conditions. In Test 4.1, peak temperatures exceeded 300 °C across most external thermocouples, with TC-4 recording the highest value at 407.3 °C. Other notable peak temperatures included 368.8 °C at TC-3 and 359.2 °C at TC-2. In Test 4.2, although the maximum temperatures were slightly reduced, they remained significantly above those measured on previous test days. TC-4 again detected the highest value at 303.0 °C, and several other thermocouples (TC-2, TC-3, TC-5, and TC-7) exceeded 260 °C. The highest temperatures captured by the inner thermocouples occurred during Test 4.2, with TC-10 and TC-11 registering 130.2 °C and 125.4 °C, respectively.

As in preceding tests, temperature differences between internal and external thermocouples were estimated to assess the thermal insulation performance of the fire protection plaster under elevated thermal loads.

3.2 EVALUATION OF PLASTER PANELS UNDER INCREASED FIRE SEVERITY

3.2.1 Performance of Fire Protection Panel in Magnesium Fire Scenario

The fifth test day marked the commencement of the second group of investigations, focusing on the evaluation of the manufactured fire protection panels (Test 5). The first panel was tested under thermal conditions generated by a magnesium fire. It was suspended by chains from the loader boom and positioned above the grill-like combustion device (Figure 2, a).

The recorded temperature data from two thermocouples TC-A1 and TC-B1 on the fire-exposed surface and two TC-A2 and TC-B2 on the rear side are presented in Figure 5, a.

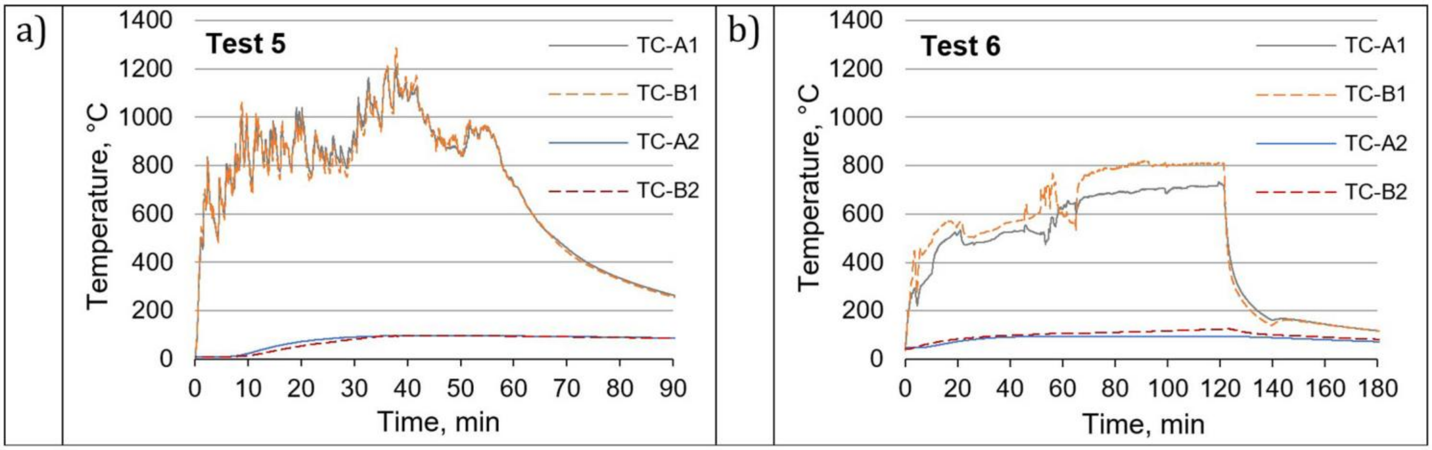

Figure 5: Temperature profiles from the magnesium fire scenario (a) and the gas burner fire scenario (b)

The temperature development on the exposed surface showed a rapid increase shortly after ignition, reaching around 700 °C and remaining at approximately 900 °C for 15 minutes. This was followed by a rise to an average of 1100 °C, with peak values of 1209 °C and 1287 °C recorded by TC-A1 and TC-B1, respectively. In contrast, the rear side of the 4 cm plaster layer heated up more slowly, eventually stabilising at around 96 °C. High-frequency temperature fluctuations, reaching up to 200 °C, were caused by the irregular combustion of magnesium, which was manually fed in intervals, resulting in variable flame intensity and turbulent burning behaviour.

3.2.2 Thermal Response of Fire Protection Panel under Gas Burner Exposure

Test day 6 focused on evaluating the fire protection panel under thermal loading produced by a gas burner (Test 6). Similar to the preceding setup, the panel was suspended from a loader and positioned directly above a multi-nozzle gas burner (Figure 2, b). Following the established instrumentation strategy, thermocouples TC-A1 and TC-B1 were attached to the exposed surface of the panel, while TC-A2 and TC-B2 monitored temperatures on the rear side. The recorded temperature data are presented in Figure 5, b.

Thermocouples TC-A1 and TC-B1 on the exposed surface showed fluctuating temperatures due to manual adjustments of the specimen position and the burner-to-panel distance. Initially positioned 10 cm above the burner, the panel was later realigned to better target hot zones, resulting in temperature differences between the sensors. At 65 minutes into the test, TC-B1 was repositioned to a hotspot, after which the external thermocouples began to exhibit an approximately linear temperature increase. During this period, TC-A1 reached 733.8 °C, while TC-B1 recorded 819.9 °C, reflecting intensified local heating. Concurrently, internal thermocouple TC-B2 reached 125.4 °C, while TC-A2 remained relatively stable below 95 °C.

The cooling behaviour of the panel followed the expected trend, with only a brief temperature rise caused by repositioning the specimen. Once thermal equilibrium was re-established, temperatures continued to decrease steadily, confirming consistent thermal performance during the post-combustion phase.

4. CONCLUSIONS

This study examined the thermal performance of fire protection plaster applied to tunnel walls and prefabricated panels through ten full-scale fire experiments conducted in a railway tunnel at the research centre “Zentrum am Berg”. Experimental data were obtained under realistic tunnel fire conditions, providing insight into the material’s ability to limit heat transmission.

The experiments, specifically designed for this study, were structured into two distinct groups. The first group involved moderate fire loads generated by gasoline–diesel pool fires, simulating the thermal effects of a burning passenger vehicle with an estimated heat release rate of approximately 5 MW. The insulating material was applied directly to the inner surface of the primary tunnel lining, forming three test sections with plaster thicknesses of 2 cm, 3 cm, and 4 cm *maxit ip 160 T*. Each section was tested at least twice under varying configurations, enabling evaluation of the plaster’s behaviour under different thermal exposures. The second group addressed high-intensity fire scenarios by exposing prefabricated 4 cm-thick *maxit ip 160 T* plaster panels to a magnesium chip fire and a propane gas burner, replicating more severe fire events. In all tests, temperatures were systematically recorded on the fire-exposed surface and at specified depths beneath the insulating layer. This methodology facilitated a detailed assessment of heat penetration and the material’s insulating performance.

The results indicated that variations in fire-resistant coating thickness had a measurable influence on thermal performance. In all cases, the reference temperature of 300 °C on the underlying concrete lining was not exceeded. Notably, even under severe fire exposure, the maximum temperature recorded on the rear side of the 4 cm plaster panels remained relatively low, reaching 96.5 °C during the magnesium chip fire and 125.4 °C during the propane gas burner test.

Overall, the obtained temperature data provide a solid empirical basis for the subsequent evaluation of the fire resistance properties of the tested material. The preliminary results indicate effective performance across a range of fire intensities and test configurations. These initial findings support the potential practical application of the investigated fire protection method in tunnel environments and offer valuable input for ongoing engineering assessments and regulatory considerations.

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