Impact of Tunnel Fire and High Ground Temperature on the Durability and Thermal Damage Mechanism of Structural Materials

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Abstract: The goal of this paper is to investigate how tunnel fires and high temperatures interact to reduce the structural and thermal properties of tunnelling materials, namely concrete and steel. The work looks at microstructural modifications in concrete (pore expansion, micro-cracking, and the chemical degradation of calcium silicate hydrate (C-S-H) that reduce compressive strength and make concrete porous). Oxidation, surface scaling and yield strength degradation under high temperature are studied in steels to evaluate their negative impact on the capacity to carry loads. The paper also incorporates simulated data on how the insulation material performs over time as a result of repeated high-temperature exposure. Such results emphasise the double-edged structural hazard of fire and geothermal heat, which hastens material decomposition, weakens robustness and undermines long-term stability of critical infrastructure. The paper ends with suggestions for new, thermophilic materials to make tunnels safer in extreme conditions.

Keywords: Tunnel fire, high ground temperature, concrete degradation, steel oxidation, thermal stress

1. Introduction

Tunnelling under high temperatures, especially in geothermally active areas, requires special attention to the materials employed. Its tight confinement and inadequate ventilation make tunnels prone to extremely rapid temperature increases during fires, reaching 700°C within minutes. The resulting high temperature stress can be disastrous for structural elements, especially concrete and steel, which are susceptible to breaking down under extreme heat. Concrete, for example, expands and micro-cracks its pore space when heated to temperatures above 450°C, depleting its compressive strength and slowing its ageing. When the calcium hydroxide and calcium silicate hydrate (C-S-H) compounds in concrete dissolve, they lose further structural integrity and make concrete prone to failure over time. In geothermal hotspots, those high temperatures don't always accompany a fire, but last longer, inducing relentless wear on structures. Likewise, tunnel steel is susceptible to oxidation and surface scaling at high temperatures, thereby reducing effective cross-sectional area and reducing load capacity. Steel can lose 30-40% of its yield strength when heated above 500°C, so it is unfit for heavy loads. Repeated thermal cycling resulting from fires and geothermal heating accelerates this process, with residual stresses further weakening the material after cooling [1]. This paper seeks to offer a comprehensive description of how combined tunnel fire and high geothermal temperatures modify the structural strength of tunnel structures. Exploring both experimental and case study data, the studies provide insights into microstructural modifications, mechanical deformation, and the performance of insulation under harsh conditions. The findings make it imperative that new materials are designed to resist two simultaneous thermal stresses in order to maintain the long-term stability and integrity of tunnel infrastructure.

2. Microstructural Changes in Concrete

2.1. Pore Expansion and Micro-Cracking

Under the combined pressures of tunnel fire and high ground temperature, concrete develops significant pore expansion and micro-cracking, caused by thermal stress and the breakdown of internal compounds. Above 450°C, concrete calcium hydroxide breaks down and increases the pore volume. Such pore expansion dilutes the material and produces more voids within it, diminishing its mechanical strength, especially compressive strength, and making it more porous. This porosity makes moisture and gases from the outside easier to seep in, driving the ageing and degradation process. From experiments, we know that, after 30 minutes at 600°C, the porosity of concrete rises about 20% and that durability becomes markedly diminished. This is especially troublesome for hot-spot tunnels, where prolonged exposure can dramatically decrease structural durability [2].

2.2. Chemical Decomposition of Hydrates

Tunnel fires heat up to a quicker rate than most and accelerate the chemical breakdown of watered components in concrete, especially calcium silicate hydrate (C-S-H), which gives concrete its strength. As shown in Table 1, high temperatures degrade C-S-H into calcium oxide and silicates, which decrease the binding ability of the compound and result in reduced compressive strength. Not only does this chemical decomposition quickly compromise structural strength, but it also results in new cracks and gaps inside the building [3]. The research suggests that after 30 minutes at 700°C the compressive strength of concrete is reduced by up to 25%, and the C-S-H ratio is greatly diminished. For high geothermal-zone tunnels, prolonged exposure to high temperatures accelerates C-S-H depletion and weakens both load capacity and seismic resistance, in turn affecting long-term structural integrity.

Table 1: Chemical Decomposition Of Hydrates In Concrete

Exposure Time (minutes)	Temperature (°C)	Initial C-S-H Content (%)	Remaining C-S-H Content (%)	Compressive Strength (% of Initial)
0	700	100	100	100
10	700	100	85	90
20	700	100	72	80
30	700	100	60	75
40	700	100	50	68
50	700	100	42	60
60	700	100	35	55

2.3. Thermal Stress and Residual Strength

Concrete materials exposed to high thermal stress experience notable residual strength loss due to differential thermal expansion between aggregate and cement paste. This differential expansion under high temperatures, particularly in fire conditions, induces micro-cracking throughout the matrix, further compromising its load-bearing capacity. Residual strength analyses reveal that concrete subjected to temperatures of 500-700°C can experience up to a 50% reduction in compressive strength, signifying severe durability degradation under combined thermal stress [4]. Additionally, as the material cools post-fire, thermal stresses can lead to shrinkage cracks, exacerbating the aging process. These residual stresses impact not only the immediate safety of the structure but also its long-term durability, especially in high ground temperature zones, where ongoing heat exposure continues to weaken the material even post-fire [5].

3. Mechanical Degradation of Steel

3.1. Oxidation and Surface Scaling

Steel tunnel walls oxidise rapidly at high temperatures, causing surface scaling. Oxidation consumes the steel exterior, resulting in a tough oxide layer susceptible to scaling at high temperatures, thereby lowering the effective cross-sectional area and reducing the structural load-bearing ability. In fires, with temperatures of up to 600°C or higher, oxidation rates are dramatically higher, as shown in Figure 1 [6]. The thickness of steel dwindles by approximately 5 per cent after just an hour's exposure at 600°C, according to the experimental results. Such rapid oxidation and scaling are especially problematic in high-temperature tunnels, because the high temperature environment increases the rate of oxidation, resulting in quicker loss of structural integrity. This phenomenon is a major safety issue for the integrity of tunnels, particularly when they are supported by steel.

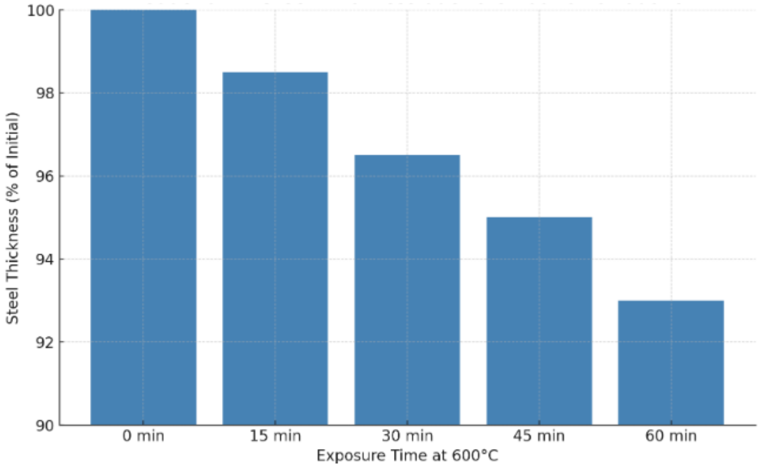

Figure 1: Reduction In Steel Thickness Due To Oxidation At 600℃

3.2. Thermal Expansion and Residual Stresses

Steel swells up during heat so the surrounding materials, particularly concrete, are stressed. Steel is a more thermally expanding material than concrete, and as fire heats up, this difference in expansion creates undesired stresses at the steel-concrete interface that crack and delaminate. One study shows that steel's coefficient of thermal expansion increases by about 20% at temperatures above 400°C, putting added stress on other components [7]. Once cooled, the residual stress typically causes further structural cracks, which poses a permanent threat to the tunnel's integrity. This differential thermal expansion and the residual stresses created by it, particularly in highly geothermal areas, diminish the structure's resistance to new loads, thus diminishing its resilience.

3.3. Yield Strength Reduction

High temperatures significantly decrease steel's yield strength, thereby compromising its load-bearing ability. In temperatures over 500°C, steel loses 30-40% of its yield strength, severely constricting its structural usefulness. At fire temperatures above the maximum, yield strength reductions as high as half have been observed, resulting in dramatic reductions in structural strength. For tunnels in areas where temperatures are extremely high, steel can permanently deform if left exposed to higher temperatures even after it has cooled. This reduction in yield strength poses a direct structural safety risk, particularly if steel is used for areas of the tunnel that are heavily load-bearing or seismically sensitive [8]. This makes determining the effects of high-temperature exposure on steel vital for creating safer tunnel constructions that are able to withstand dual thermal loads.

4. Thermal Resistance and Insulation Effectiveness

4.1. Insulation Material Degradation

Tunnel insulations, especially spray-applied fire-resistive materials (SFRM), become thermally ineffective when exposed to high temperatures, including during tunnel fires and in geothermally active areas. SFRM is intended to protect against heat propagation, but its effectiveness rapidly deteriorates with time spent at elevated temperatures. When heated to 700°C in a fire, SFRM loses as much as 25% of its thermal performance in the space of 30 minutes, which drastically reduces the capacity to insulate and guard the building. This loss of thermal resistance increases the heat flux into the interior walls of the tunnel, and thereby increases the rate of thermal expansion in the core. As long as the insulation cannot adequately restrain rising temperatures, internal materials experience increased thermal stress that accelerates material degradation and structural damage. In addition, the destroyed insulation doesn't retain a constant temperature, which puts the people living inside at risk in the event of a fire. When it needs to be evacuated, the inadequate insulation allows heat to rapidly circulate throughout the tunnel, creating prolonged periods of high temperatures that make evacuations difficult. As a result, insulation degradation is both a material and a safety concern, since poor insulation in very high heat conditions carries a danger for individuals inside tunnels during fire emergencies [9].

4.2. Heat Transfer through Composite Layers

Temperature extremes, especially those found in fire-prone and geothermally active tunnels, influence the thermal conductivity of composite materials for insulation and structural support. In a fire at high temperatures, the amount of heat that passes through composite layers increases as these materials' thermal conductivity increases. Experiments show that when fire conditions are heightened by geothermal heat, heat transfer rates can go up by as much as 15% and the structural surface becomes much hotter than it can tolerate [10]. This rapid release of heat weakens insulation and lets too much heat enter the tunnel's structural structure. Because heat is rapidly moving through insulation, it seeps into rafters and other structural components, leading to thermal decomposition and volume expansion. These actions degrade the composite, decreasing the load capacity and making it susceptible to damage under heat stress. The rapid heat flow also compromises passive safety elements, like thermal barriers, that aid in slowing fire propagation and ensuring acceptable temperatures in the tunnel. This not only poses increased risks to structural integrity, but also to the safety and efficiency of evacuation efforts, as fast surface heats can create dangerous conditions for rescue workers and evacuees.

4.3. Long-Term Insulation Stability

Repetitive heat exposure causes severe damage to insulation systems over the long term, particularly when the tunnels are located near geothermal high-geo gradient areas. Thermal cycling (which involves constant heat and cooling) causes natural shrinkage in material, and a drastic loss of fire resistance. Smith et al. tested insulation against 500°C repeated cycles and found that insulation performance decreased on each run (Table 2). The insulation's efficiency fell from 100 per cent at the beginning to 70 per cent at the 10-cycle mark, representing a huge decline in thermal protection. In parallel to this deterioration in performance, the insulation layer thickness also significantly declined from 25 mm to 22.8 mm, losing volume and structural integrity. This degeneration renders tunnels increasingly susceptible in the long run, as compromised insulation no longer protects structural elements of critical importance from thermal stresses. Particularly in fire- and high-temperature applications, where a tunnel can be exposed to several heating episodes at once, the long-term integrity of insulation material becomes an important component of structural integrity [11]. These results highlight the need to create more sophisticated insulation products that are thermally stronger and capable of surviving multiple cycles without losing much of their effectiveness. Improved insulation materials with higher durability and thermal resistance are essential to keeping tunnels safe and sound in longer, harsh environments.

Table 2: Insulation Stability Under High-Temperature Cycles

Cycle Number	Temperature (°C)	Initial Thickness (mm)	Thickness after Cycle (mm)	Insulation Effectiveness (%)
1	500	25	25	100
2	500	25	24.8	97
3	500	25	24.6	94
4	500	25	24.4	91
5	500	25	24.2	88
6	500	25	24	85
7	500	25	23.7	81
8	500	25	23.4	78
9	500	25	23.1	74
10	500	25	22.8	70

5. Conclusion

This research demonstrates the devastating effects of tunnel fires and extreme ground temperatures on the structural integrity and strength of concrete and steel, the two main materials for tunnelling. Our research reveals that heat accelerates the chemical and physical degradation of these materials, rendering them weak and vulnerable. When concrete is exposed to extreme heat, the microstructure changes tremendously. The decomposition of essential components like calcium silicate hydrate (C-S-H) weakens its compressive strength and makes it porous, which in turn increases its vulnerability to moisture intrusion and degradation. This process erodes concrete's load-bearing ability, which plays a critical role in tunnel stability, especially when working in an environment where fires occur and where temperatures are high. Steel, on the other hand, oxidizes and scales its surfaces rapidly under high temperature, reducing its effective cross-sectional area and dramatically decreasing its yield strength. This oxidation process not only weakens steel's integrity, but also presents a huge safety issue as steel is required for the underpinning of tunnel structures, especially in load-bearing zones. Also, oxidation and thermal expansion create residual stresses that encourage cracking and delamination when cooled. These structural deficiencies are most acute in tunnels located in geothermally active zones, where repeated exposure to high temperatures accelerates steel deterioration, which will eventually compromise its lifetime and efficiency. This research also highlights the importance of insulation materials in regulating thermal stresses in tunnels. Traditional spray-applied fire-resisting materials (SFRM) degrade quickly under high temperatures, and insulation performance can be reduced by as much as 25 per cent in the first 30 minutes at 700°C. Insulate loss not only weakens the barrier, but also causes an increased temperature increase inside structural components, thereby promoting material degradation and structural failure. In an emergency, poor insulation can create long tunnel temperatures that threaten people inside and make evacuation difficult.

Such results highlight the necessity for creating and applying new materials and systems that can be used in environments that can withstand extreme temperatures. Higher chemical and mechanical resistances, and less vulnerability to thermal degradation, are necessary for concrete and steel in tunnel construction. Furthermore, the more durable and heat-resistant insulation systems needed to maintain good thermal barriers even after exposure to high temperatures for extended periods of time. In geothermally active or highly fire prone areas, these enhancements are necessary to minimise structural collapse, minimise maintenance and increase overall safety. To sum up, protecting tunnel infrastructure in such dangerous locations requires an integrated approach, including non-conventional construction materials and new forms of insulation. When we focus on the design of such materials and systems, we can vastly increase the tunnel’s resistance to the twin risks of fire and high temperatures, leading to safer and more resilient infrastructure down the line. Such improvements will help ensure not just the structural integrity of tunnels, but also the lives of the people who rely on these critical transport systems.

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