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Effect of moisture content on tunnel fire resistance of self-compacting concrete coated with aerogel mortar

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Self-compacting concrete (SCC) is widely used in tunnel linings that are subject to fire risks. During tunnel fires, personnel and structural safety are commonly threatened by the explosive spalling of SCC due to its high strength and high moisture content. Recent studies have suggested that a coating of fire-resistant material can efficiently prevent SCC from spalling during a tunnel fire. In this study, SCC samples coated with a 6 mm thick layer of silicon dioxide aerogel-cement mortar (SiO₂-ACM) were prepared and compared with uncoated samples. The effects of different moisture contents (0%, 25%, 50%, 75% and 100%) on the fire resistance of SCC were investigated. The results show that SiO₂-ACM exhibited excellent mechanical and durability performances as well as low thermal conductivity. During exposure to mimetic tunnel fire, the degree of spalling of SCC increased as moisture content increased. The SCC samples with the SiO₂-ACM coating exhibited much less spalling than those without such coating. After the mimetic tunnel fire, the uncoated SCC samples had almost completely failed in terms of compressive strength, whereas the residual compressive strength of the coated SCC samples was more than 68.6% even for the SCC with 100% moisture content. Therefore, a SiO₂-ACM coating provides an attractive means by which to enhance the behaviour of SCC during a tunnel fire.

Notation

f_{bending}	bending strength
f_{bonding}	bonding strength
f_c	compressive strength
I	current
K	thermal conductivity
L	length of cupronickel alloy wire
m_0	the mass of samples when the samples reached 0% moisture content
m_{100}	the mass of samples when the samples reached 100% moisture content
m_x	the mass of samples when the samples reached objective moisture content
T	temperature
t	time
U	voltage
ρ_m	moisture content

Introduction

The rapid increase in the rate of industrialisation and urbanisation has led to a great worldwide demand for tunnel development to alleviate the pressure of overland transportation (Ntzeremes and Kirytopoulos, 2018). However, serious tunnel fire accidents are increasing alongside this development, which causes road casualties and massive rehabilitation costs.

For example, in China more than 161 tunnel fire accidents occurred between 2000 and 2016, of which 40 cases caused damage to the tunnel and 27 cases resulted in casualties (Ren *et al.*, 2019). For this reason, the safety of tunnel concrete structures exposed to fire has become a major concern all over the world.

Tunnel fire accidents are often caused by car collisions which result in the burning of organic substances (e.g. gasoline). The maximum heat release rate of a typical hydrocarbon fire (i.e. more than 100 MW) is ten times higher than that of a building fire (Chatris *et al.*, 2001; Mudan, 1984). The temperature can rapidly reach over 1000°C within 10 min of the start of a tunnel fire (Ingason, 2009). The high temperature gradients and the rapid heating lead to a sharp increase in pore pressures due to the explosive formation of water vapour and thermally induced high compressive stresses inside the tunnel concrete structures, resulting in the spalling of concrete from tunnel linings, threatening the integrity of the concrete structure or even leading to the collapse of the tunnel (Donatello *et al.*, 2014; Hertz, 1992; Huang *et al.*, 2017; Zhang and Davie, 2013; Zhao *et al.*, 2017).

The popularity of self-compacting concrete (SCC) has been on a steady incline owing to its superior performance in

tunnel lining applications (Samimi *et al.*, 2019; Sideris and Manita, 2013). However, previous studies have suggested that the performance of SCC during exposure to tunnel fire is deficient (Liu *et al.*, 2008; Xargay *et al.*, 2018a, 2018b). Persson (2004) discovered that at high temperatures the explosive spalling of columns with SCC took place easily. Liu *et al.* (2008) also reported that the spalling issue of SCC after fire was a prevalent problem. In addition, SCC showed a decrease in strength when it was subjected to high temperatures (Uysal and Tanyildizi, 2012). Therefore, techniques to improve the fire resistance of SCC are desirable for its application in tunnel linings.

In recent years, a series of studies have been undertaken to increase the fire resistance of concrete during tunnel fire accidents (Meng *et al.*, 2016; Robert and Colina, 2009; Samson *et al.*, 2016; Sobia and Azmi, 2015). Previous studies have suggested that a protective coating layer has potential to insulate the concrete structures from fire and alleviate spalling (Donatello *et al.*, 2014; Kim *et al.*, 2010; Li *et al.*, 2013; Wang *et al.*, 2017). Bezgin (2015) reported on the required thickness of the cement and volcanic ash-based protection layer for high-strength concrete tunnel segments. Sakkas *et al.* (2014) reported on the fire resistance of potassium-based geopolymer used as passive fire protection for concrete tunnels linings. Ji *et al.* (2013) developed a new fire-resistant technology with nanoclay-reinforced intumescent coating to repair reinforced concrete beams, showing that this coating system could enhance fire resistance. Among all the coating techniques, a cement-based thermal insulation mortar mixed with adiabatic aggregate has been widely considered as a potential coating layer for SCC to increase fire resistance due to its convenience during construction and excellent bonding strength with SCC (Cülfik and Özturan, 2002; Farzadnia *et al.*, 2013; Heikal *et al.*, 2015; Ibrahim *et al.*, 2012).

Silicon dioxide (SiO₂) aerogel is an ideal heat-insulating aggregate with an ultralight density of 0.001–0.5 g/cm³, high porosity of 95–99.8%, super-low thermal conductivity of 0.005–0.018 W/(m K) at 25°C and 1 atm (Jia *et al.*, 2018; Koebel *et al.*, 2011). Ibrahim *et al.* (2014) examined the energy behaviour of multi-layer exterior wall structures covered with different insulating coatings, showing that the silicon dioxide aerogel-based insulating coating revealed better thermal performance than expanded polystyrene and glass wool insulating materials. Silicon dioxide aerogel cement mortar (SiO₂-ACM) also showed excellent thermal insulation performance with low thermal conductivity of 0.084 W/(m K) (de Fátima Júlio *et al.*, 2016a), 0.086 W/(m K) (Liu *et al.*, 2016), 0.085 W/(m K) (de Fátima Júlio *et al.*, 2016b), and proper strength for coating materials. Although the use of SiO₂-ACM as a thermal insulation material has been rapidly increasing in the construction industry (Jia *et al.*, 2018), no study has been reported to date on the performance of SiO₂-ACM exposure to tunnel fire. This important research gap needs to be addressed through additional studies on SCC coated with SiO₂-ACM.

The moisture content of concrete in tunnel linings is always influenced by the environment and climate (Choe *et al.*, 2019; Dauti *et al.*, 2018; Kallel *et al.*, 2017). Van der Heijden *et al.* (2007) suggested that the moisture inside the concrete is a key factor in the spalling mechanism. When the critical value of moisture content is exceeded, explosive spalling can occur at high temperature. Lai *et al.* (2014) indicated that the increasing moisture content of high-performance concrete resulted in the increasing frequency of explosive spalling of the concrete and more severe damage. A similar conclusion was obtained from the experiments of Chan *et al.* (1999) and Ma *et al.* (2018). Therefore, it is important to investigate the influence of moisture content on the behaviour of concrete exposed to fire.

Because of the few explorative and experimental studies reported to date on the behaviour of SCC coated with SiO₂-ACM exposed to tunnel fire, the study presented in this paper investigated the fire resistance of SCC coated with SiO₂-ACM. The paper initially presents a summary of the experimental programme, including material and specimen properties and testing procedures, and then follows this with the results of the experimental programme. Detailed discussions on the results are then presented, in which the behaviour of coated and uncoated SCC samples during exposure to tunnel fire are discussed along with the moisture content of concrete.

Experimental programme

Materials

Ordinary Portland cement was used in this study. Silica fume (SF) and fly ash (FA) were added to improve the performances of the matrix. Table 1 shows the chemical properties and specific gravity of Portland cement, SF, slag and FA. Titanium dioxide (TiO₂) powder was used as a high-temperature infrared inhibitor. Redispersible latex powder (RLP) and cellulose ether (CE) were used to increase the workability of mortar and as a thickening agent, respectively. The physical characteristics of natural sand and commercial silicon dioxide aerogel are shown in Table 2. Polypropylene fibre (length: 12 mm) was used to enhance the crack resistance of mortar. An air-entraining admixture (AEA) was added to improve the workability and density of the mortar.

Table 1. Chemical properties of Portland cement, SF, slag and FA

Component	Cement	SF	Slag	FA
Calcium oxide (CaO)	60.81	0.23	26.46	3.82
Silicon dioxide (SiO ₂)	21.32	86.18	32.36	52.5
Aluminium oxide (Al ₂ O ₃)	7.32	1.08	17.02	28.35
Iron oxide (Fe ₂ O ₃)	3.84	0.93	1.31	3.67
Magnesium oxide (MgO)	1.16	0.78	7.88	0.78
Sulfur trioxide (SO ₃)	2.07	0.84	0.68	0.84
Potassium oxide (K ₂ O)	0.65	—	0.96	1.69
Titanium dioxide (TiO ₂)	0.28	—	0.89	0.87
Manganese oxide (MnO)	0.15	0.78	0.45	0.18
Specific gravity	3.15	2.2	2.84	2.18

Table 2. Physical characteristics of the aggregates

Aggregates	Aerogel	Sand
Maximum size: mm	2	2.36
Fineness modulus	—	2.4
Particle density: kg/m ³	125	2680

Specimen preparation

SiO₂-ACM specimens

The SiO₂-ACM was prepared in a two-step mixing process using a cement mixer. Initially, cement, sand, SF and aerogel particles were mixed in a 5 litre mixing pan for 60 s. Subsequently, the superplasticiser (polycarboxylic acid water-reducer, PCA) was added for another 20–30 s. The mixture was mixed for a total time of 180 s. The mix proportion of SiO₂-ACM is given in Table 3, in which the SiO₂-ACM was designed according to Liu *et al.* (2016).

SCC specimens

In order to study the effect of SiO₂-ACM on the explosive thermal spalling of SCC in tunnel fire, SCC samples were prepared. The mix proportion of SCC was according to Chinese standard JGJ/T 283-2012 (CNS, 2012b), as shown in Table 4. First, the aggregates (sand and gravel) were put into the mixer and dry stirred for 30 s, then half of the water was added and stirred for 30 s next, the cementitious materials (cement, FA, SF and slag) were added and stirred for a further 30 s, before the water-reducing agent and remaining water were added and stirred for a final 30 s. After casting, the SCC samples were filled into cubic moulds (150 × 150 × 150 mm³) and cured in a standard curing room (>95% RH and 20 ± 2°C) for 24 h before demoulding. After demoulding, the samples were cured in the standard curing room for 28 d. The performances of SCC are shown in Table 5.

The different moisture contents of the SCC were controlled. After curing, samples were dried in an oven at 105°C until the mass of each sample reached constant (mass value recorded as m_0). Under this status, the sample reached 0% moisture content. Subsequently, the samples were stored in a water tank for 72 h. Then the samples were taken out, the additional

moisture wiped from the surface, and weighed (mass valued recorded as m_{100}). Under this status, the sample reached 100% moisture content. Then the samples were stored in the oven again until the mass of the samples reached m_x . The moisture content (ρ_m) can be calculated by Equation 1 (Chan *et al.*, 1999; Sideris and Manita, 2013). In this study, samples with 0, 25, 50, 75 and 100% moisture content were prepared. The samples were sealed with plastic film to maintain the moisture when the designed moisture content was reached.

$$1. \quad \rho_m = \frac{m_x - m_0}{m_{100} - m_0}$$

Composite of SiO₂-ACM and SCC

A layer of 6 mm thick SiO₂-ACM was applied the SCC concrete cubes, as shown in Figure 1. Before the thermal spalling tests were performed, the specimens were cured in a standard curing room (RH > 95%, 20 ± 2°C) for another 28 d.

Test methodologies

Properties of SiO₂-ACM and SCC

The bending strength and compressive strength of SiO₂-ACM were tested according to the Chinese standard JGJ/T 70-2009 (CNS, 2009). The prismatic samples (40 × 40 × 160 mm³) were used to test the bending strength, and the cubic specimens (70.7 × 70.7 × 70.7 mm³) were used to test for the compressive strength. The thermal conductivity was measured using the hot-wire method (CNS, 2015). In the thermal conductivity test, cupronickel (Cu/Ni) alloy wire with a length of 73 mm and a diameter of 0.127 mm was used. The thermal conductivity (K) was calculated using Equation 2.

$$2. \quad K = \frac{(UI)/(4\pi L)}{(\Delta T)/\Delta(\ln t)}$$

where U and I are the voltage (1 V) and current (0.23 A), respectively; L is the length of the cupronickel alloy wire; T and t are the temperature (°C) and time (s), respectively.

Table 3. Mix proportion of SiO₂-ACM: g

Aerogel	Cement	Water	Sand	SF	FA	PCA	Titanium dioxide	CE	RLP	Fibre	AEA
12.29	98.04	58.54	81.75	10.89	27.48	2.04	13.65	0.83	2.73	0.41	1.37

Table 4. Mix proportions of C40 self-compacting concrete: kg/m³

Gravel	Cement	Sand	FA	Slag	SF	PCA	AEA	Water
804	318	838	132.5	53	26.5	5.3	0.53	175

Table 5. The performances of SCC

	Workability				f_c at 28 d: MPa
	Slump- flow: mm	J-ring flow: mm	Passing ability: mm	Segregation: %	
Actual	765	720	45	8.71	43

Figure 1. Schematic of SCC coated with SiO₂-ACM

Figure 2. Experimental and HC standard curves of tunnel fire

The SEM analysis was carried out using a scanning electron microscope (SEM, FEI Nova NanoSEM 230) at an accelerating voltage of 10 kV and a working distance of around 5 mm.

The measurement of the compressive strength of SCC was performed according to the Chinese standard GB/T 50081-2002 (CNS, 2002).

Tunnel fire simulation

The side surfaces of the composite specimens were sealed with 50 mm rock wool in order to ensure that a single side of the specimen was subjected to a high temperature, and that the surface with SiO₂-ACM coating was exposed. Then the specimens were put into a bogie-hearth resistance furnace (RTD-45-13, Jiangsu Jinhuan Test Equipment Co., Ltd), heated up to 1100°C in 30 min and kept at this temperature for 2 h. Subsequently, the samples were cooled down to the ambient temperature in the furnace. This mimetic tunnel fire was designed according to the HC standard tunnel fire rising temperature curve (CNS, 2012a). The experimental and HC standard curve are shown in Figure 2.

Results and discussion

Properties of SiO₂-ACM

The mechanical and durable properties of SiO₂-ACM were measured as shown in Table 6. The compressive, bending and bonding strengths of SiO₂-ACM at 28 d were 3.5, 0.8 and 1.5 MPa, respectively. The results obtained were in agreement with the existing literature (Liu *et al.*, 2016), with the exception of Gao *et al.* (2014). Besides this, the measured dry density of SiO₂-ACM was 668 kg/m³, which was about half that ascertained in other research (Liu *et al.*, 2016). Thermal conductivity is one of the main properties of SiO₂-ACM in isolating high temperature. It was measured on the ACM specimens (22 × 32 × 105 mm³) using the hot-wire method. A low thermal conductivity of 0.185 W/(m K) was gained, which was calculated using Equation 1. By contrast, the thermal conductivity of cement mortar without aerogel is as high as 0.533 W/(m K) (Kim *et al.*, 2013). Hence, it can be seen that prepared SiO₂-ACM has excellent thermal insulation properties.

Liu *et al.* (2016) successfully developed a kind of insulating aerogel mortar. When the volume content of aerogel was 60%, the density, thermal conductivity, compressive and flexural strengths of aerogel mortar were 1231 kg/m³, 0.1524 W/(m K),

Table 6. Mechanical and durable properties of ACM before and after frost resistance resistance

Mechanical properties: MPa						Durability			
f_c		f_{bending}		f_{bonding}		Water resistance: h	Acid resistance: h	Moisture resistance: h	Frost resistance: times
Before	After	Before	After	Before	After				
3.5	3.0	0.8	0.6	1.5	1.2	≥720	≥360	≥720	≥50

2.15 MPa and 0.45 MPa, respectively. Gao *et al.* (2014) also reported on a lightweight insulating aerogel mortar with a density of 1000 kg/m³, a thermal conductivity of 0.26 W/(m K), and a compressive strength of 8.3 MPa at an aerogel content of 60 vol.%.

Compared to other aerogel insulated mortars, the SiO₂-ACM prepared in this research has lower density, lower thermal conductivity and similar strength. Moreover, all the mechanical and durable properties of SiO₂-ACM meet the requirements of Chinese standard GB 28375-2012 (CNS, 2012a). This confirmed that SiO₂-ACM has the potential to be used as a fire-resistant coating.

Explosive spalling of SCC specimens after tunnel fire

Figure 3 shows the degree of explosive spalling of SCC specimens with 0, 25, 50, 75 and 100% moisture content after mimetic tunnel fire. It can be seen that the explosive spalling of uncoated SCC was severe with an increased moisture content of over 25%. Nevertheless, very slight spalling of SCC with SiO₂-ACM coating was observed with the increased moisture content. Therefore, the SiO₂-ACM coating enhances the resistance of SCC to explosive spalling during tunnel fire.

The relationship between the moisture content of SCC and spalling initiation time, spalling duration, the number of loud voices

(used to categorise the degree of explosive spalling) and spalling initiation temperature was investigated, as shown in Table 7.

It was observed that the spalling initiation time and temperature for spalling occurrence decreased from 11 min to 5 min and from 845°C to 498°C, respectively, when the moisture content of SCC increased from 50 to 100%. Zhao *et al.* (2014) suggested that damage appears when the surface temperature reaches 555.5°C, but no spalling occurs in the whole process of heating up to 600°C. This indicated that the increase in moisture content results in the explosive spalling of SCC occurring at an earlier time and at a lower temperature, due to the build-up of pore pressure by steam (Poon *et al.*, 2003). The vapour pressure is mainly caused by internal free water of concrete (Peng and Huang, 2008). Chan *et al.* (1999) also found that moisture content and strength are the two main factors governing thermally induced explosive spalling of concrete. The spalling duration and number of loud voices increased with the increase in moisture content, while the highest values were at 75% of moisture content. The reason for this is that the explosive spalling of SCC specimens occurred on a large scale when the moisture content of SCC was 100%. As a consequence, although the spalling duration and the number of loud voices were less than that with 75% moisture content, the degree of explosion damage of SCC with 100% moisture content was more obvious (Figure 3).

Figure 3. Images of SCC samples with 0–100% moisture contents after mimetic tunnel fire

Table 7. Explosive spalling parameters of SCC not coated with SiO₂-ACM at different moisture contents

Moisture content: %	Spalling initiation time: min	Temperature for spalling occurrence: °C	Spalling duration: min	Number of loud voices
50	11	845	2	8
75	9	625	14	120
100	5	498	9	59

The explosive spalling of SCC was caused by the production of a large amount of water vapour at high temperature due to the high moisture content in the internal SCC, thus producing

greater vapour pressure in the concrete. Furthermore, the higher the moisture content in SCC, the greater the vapour pressure produced in the specimen at the same temperature.

Figure 4. SEM photographs of SCC uncoated mortar with different moisture contents after mimetic tunnel fire: (a) 0%; (b) 25%; (c) 50%; (d) 75%; (e) 100%

Hertz (1992) also found that the risk of spalling increases with the increase of the heating rate and the moisture content of concrete. When the water vapour in a specimen reached a certain degree, the sample would burst, leading to the explosive spalling of SCC (Zhao *et al.*, 2014). However, the use of SiO₂-ACM as a coated layer on the surface of SCC could solve this problem, as shown in Figure 3.

SEM analysis of SiO₂-ACM and SCC specimens

Figure 4 presents SEM images of the SCC specimens without coating at different moisture contents after being subjected to mimetic tunnel fire with $\times 500$ magnification. It can be seen that more severe cracks and porous structure can be observed with the increased moisture content. When the moisture content of SCC was at 0 or 25%, no visible internal cracks of the sample could be distinguished. When the moisture content was at 50 and 75%, the crack patterns of the SCC samples were more pronounced, and the concrete matrix had strongly deteriorated. A very loose structure was observed when the moisture content was 100%. As Figure 3 shows, compared with uncoated SiO₂-ACM specimens, the SCC samples protected by the SiO₂-ACM maintained high structural integrity, which would lead to low compressive strength of the SCC after tunnel fire. SEM examinations also certified that a high moisture content would cause spalling of SCC not coated with SiO₂-ACM after tunnel fire, because the higher the moisture content was, the looser the SCC structure was. A similar observation has been made in previous studies (Hertz, 1992; Liu *et al.*, 2018).

The SEM images of SiO₂-ACM before and after mimetic tunnel fire are shown in Figure 5. It is well known that silicon dioxide aerogel possesses great potential in the field of building insulation because of its ultra-low thermal conductivity, which arises from its unique three-dimensional nano-porous structure (Baetens *et al.*, 2011; Cuce *et al.*, 2014). However, aerogel particles changed to opaque white and atrophied significantly after exposure to tunnel fire, thus leading to the enlargement of the interfacial transition zone (ITZ) of silicon dioxide

aerogel and cement matrix (Figure 5(c)). The atrophy of aerogel particles is primarily caused by the destruction of the three-dimensional nano-porous structure of aerogel (Huang *et al.*, 2017; Li *et al.*, 2016). However, Huang *et al.* (2017) observed that the dehydroxylation of aerogel particles begins occurring when the heating temperature increases to 1100°C for more than 30 min, implying that the structure of aerogel particles could maintain some stability at high temperature, even at tunnel fire temperatures. But as time goes on, the structure of the aerogel particles is destroyed.

For pure silicon dioxide aerogel particles, the pores inside the particles totally collapsed and were fused together at 1100°C for 1.5 h, as referred to by Huang *et al.* (2017). In this case, even though the atrophy of the aerogel particles was still observed, they retained a three-dimensional structure after 1100°C for 1 h (Figure 5(b)). It was deduced that the existence of the cement matrix might postpone the atrophy of the aerogel particles, thus extending the tunnel fire resistance time, which could be verified in further research.

Residual compressive strength of SCC after tunnel fire

The residual compressive strength of SCC with different moisture contents after being subjected to high temperatures is plotted in Figure 6. As a function of moisture content, the compressive strength of SCC showed a downward trend for both coated and SiO₂-ACM-coated SCC. Some researchers (Caetano *et al.*, 2019; Shen and Xu, 2019) have also indicated that moisture content has a significant effect on the concrete's mechanical performance. This is because, as the ambient temperature continues to rise, initially the free water in the SCC evaporates and several chemical and physical transformations of the paste and aggregates under high temperature take place, making the cement particles more tightly bound (Khoury, 2002; Luccioni *et al.*, 2003). Consequently, the steam generated by the combined water and the adsorbed water is more difficult to discharge when subjected to high temperatures. In particular, the internal structure of SCC is dense, and a large vapour pressure is generated inside the concrete at a high temperature,

Figure 5. SEM images of SiO₂-ACM: (a) before mimetic tunnel fire; (b) after mimetic tunnel fire for 1 h; and (c) after mimetic tunnel fire for 2 h

Figure 6. Residual compressive strength of SCC with different moisture content after mimetic tunnel fire

causing cracking of the concrete surface and deterioration in the mechanical properties of SCC.

It is clear that the residual compressive strength of the SCC samples coated with SiO₂-ACM was much higher than that of the uncoated ones (see Figure 6). The residual compressive strength of SCC samples not coated with SiO₂-ACM at moisture contents of 50%, 75% and 100% was considered to be 0 MPa due to the explosive spalling of SCC, whereas the residual compressive strength of SCC samples coated with SiO₂-ACM was more than 68.6% even for SCC samples with 100% moisture content. Furthermore, the residual compressive strength of coated SCC samples was almost twice as great as the uncoated ones at moisture contents of 0% and 25% after high temperature. The above results suggested that the SiO₂-ACM coating provided excellent protection of SCC at high temperature.

Conclusions

- A potential fireproof coating layer, SiO₂-ACM, used in tunnel concrete structures was prepared, of which the dry density was 668 kg/m³, thermal conductivity was ~0.185 W/(m K), and mechanical properties (compressive and bend) were excellent.
- Moisture content had a significant effect on the explosive spalling of SCC under tunnel fire. The degree of spalling of SCC increased as the moisture content increased, when the moisture content was more than 25%. The residual compressive strength of SCC decreased with the increase of moisture content.
- Using SiO₂-ACM as a coating layer on the surface of SCC could play a crucial role in protecting SCC from spalling under tunnel fire. The SCC samples with SiO₂-

ACM coating exhibited much less spalling than those without coating. The residual compressive strength of SCC coated with SiO₂-ACM was more than 68.6% even for SCC with 100% of moisture content.

- SiO₂-ACM coating feasibly offers an attractive means of enhancing the behaviour of SCC in a tunnel fire. However, the thickness of the SiO₂-ACM coating as a protective layer still requires further research.

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REFERENCES

- Baetens R, Jelle BP and Gustavsen A (2011) Aerogel insulation for building applications: a state-of-the-art review. *Energy and Buildings* **43**(4): 761–769, <https://doi.org/10.1016/j.enbuild.2010.12.012>.
- Bezin NÖ (2015) An experimental evaluation to determine the required thickness of passive fire protection layer for high strength concrete tunnel segments. *Construction and Building Materials* **95**: 279–286, <https://doi.org/10.1016/j.conbuildmat.2015.07.130>.
- Caetano H, Ferreira G, Rodrigues JPC and Pimienta P (2019) Effect of the high temperatures on the microstructure and compressive strength of high strength fibre concretes. *Construction and Building Materials* **199**: 717–736, <https://doi.org/10.1016/j.conbuildmat.2018.12.074>.
- Chan SYN, Peng GF and Anson M (1999) Fire behavior of high-performance concrete made with silica fume at various moisture contents. *ACI Materials Journal* **96**(3): 405–409, <https://doi.org/10.14359/640>.
- Chatris JM, Quintela J, Folch J et al. (2001) Experimental study of burning rate in hydrocarbon pool fires. *Combustion & Flame* **126**(1): 1373–1383.
- Choe G, Kim G, Yoon M et al. (2019) Effect of moisture migration and water vapor pressure build-up with the heating rate on concrete spalling type. *Cement and Concrete Research* **116**(August): 1–10, <https://doi.org/10.1016/j.cemconres.2018.10.021>.
- CNS (China National Standard) (2002) GB/T 50081-2002: Standard for test method of mechanical properties on ordinary concrete. China National Standard, Shenzhen, China.
- CNS (2009) JGJ/T 70-2009: Standard for test method of performance on building mortar. China National Standard, Shenzhen, China.
- CNS (2012a) GB 28375-2012: Fireproof coatings for concrete structure. China National Standard, Shenzhen, China.
- CNS (2012b) JGJ/T 283-2012: Technical specification for application of self-compacting concrete. China National Standard, Shenzhen, China.
- CNS (2015) GB/T 10297-2015: Test method for thermal conductivity of nonmetal solid materials – hot-wire method. China National Standard, Shenzhen, China.
- Cuce E, Cuce PM, Wood CJ and Riffat SB (2014) Toward aerogel based thermal superinsulation in buildings: a comprehensive review. *Renewable and Sustainable Energy Reviews* **34**: 273–299, <https://doi.org/10.1016/j.rser.2014.03.017>.
- Cülfik MS and Özturan T (2002) Effect of elevated temperatures on the residual mechanical properties of high-performance mortar. *Cement and Concrete Research* **32**(5): 809–816, [https://doi.org/10.1016/S0008-8846\(02\)00709-3](https://doi.org/10.1016/S0008-8846(02)00709-3).
- Dauti D, Tengattini A, Pont SD et al. (2018) Analysis of moisture migration in concrete at high temperature through in situ neutron

- tomography. *Cement and Concrete Research* **111**(February): 41–55, <https://doi.org/10.1016/j.cemconres.2018.06.010>.
- de Fátima Júlio M, Soares A, Ilharco LM, Flores-Colen I and de Brito J (2016a) Aerogel-based renders with lightweight aggregates: correlation between molecular/pore structure and performance. *Construction and Building Materials* **124**: 485–495, <https://doi.org/10.1016/j.conbuildmat.2016.07.103>.
- de Fátima Júlio M, Soares A, Ilharco LM, Flores-Colen I and de Brito J (2016b) Silica-based aerogels as aggregates for cement-based thermal renders. *Cement and Concrete Composites* **72**: 309–318, <https://doi.org/10.1016/j.cemconcomp.2016.06.013>.
- Donatello S, Kuenzel C, Palomo A and Fernández-Jiménez A (2014) High temperature resistance of a very high volume fly ash cement paste. *Cement and Concrete Composites* **45**: 234–242, <https://doi.org/10.1016/j.cemconcomp.2013.09.010>.
- Farzadnia N, Abang AAA and Demirboga R (2013) Characterization of high strength mortars with nano alumina at elevated temperatures. *Cement and Concrete Research* **54**: 43–54, <https://doi.org/10.1016/j.cemconres.2013.08.003>.
- Gao T, Jelle BP, Gustavsen A and Jacobsen S (2014) Aerogel-incorporated concrete: an experimental study. *Construction and Building Materials* **52**: 130–136, <https://doi.org/10.1016/j.conbuildmat.2013.10.100>.
- Heikal M, Ismail MN and Ibrahim NS (2015) Physico-mechanical, microstructure characteristics and fire resistance of cement pastes containing Al₂O₃ nano-particles. *Construction and Building Materials* **91**: 232–242, <https://doi.org/10.1016/j.conbuildmat.2015.05.036>.
- Hertz KD (1992) Danish investigations on silica fume concretes at elevated temperatures. *ACI Materials Journal* **89**(4): 345–347, <https://doi.org/10.14359/9750>.
- Huang D, Guo C, Zhang M and Shi L (2017) Characteristics of nanoporous silica aerogel under high temperature from 950°C to 1200°C. *Materials and Design* **129**(January): 82–90, <https://doi.org/10.1016/j.matdes.2017.05.024>.
- Ibrahim RK, Hamid R and Taha MR (2012) Fire resistance of high-volume fly ash mortars with nanosilica addition. *Construction and Building Materials* **36**: 779–786, <https://doi.org/10.1016/j.conbuildmat.2012.05.028>.
- Ibrahim M, Biwole PH, Wurtz E and Achard P (2014) A study on the thermal performance of exterior walls covered with a recently patented silica-aerogel-based insulating coating. *Building and Environment* **81**: 112–122, <https://doi.org/10.1016/j.buildenv.2014.06.017>.
- Ingham H (2009) Design fire curves for tunnels. *Fire Safety Journal* **44**(2): 259–265, <https://doi.org/10.1016/j.firesaf.2008.06.009>.
- Ji G, Li G and Alaywan W (2013) A new fire resistant FRP for externally bonded concrete repair. *Construction and Building Materials* **42**: 87–96, <https://doi.org/10.1016/j.conbuildmat.2013.01.008>.
- Jia G, Li Z, Liu P and Jing Q (2018) Applications of aerogel in cement-based thermal insulation materials an overview. *Magazine of Concrete Research* **70**(16): 822–837, <https://doi.org/10.1680/jmacr.17.00234>.
- Kallel H, Carré H, La Borderie C, Masson B and Tran NC (2017) Effect of temperature and moisture on the instantaneous behaviour of concrete. *Cement and Concrete Composites* **80**: 326–332, <https://doi.org/10.1016/j.cemconcomp.2017.03.021>.
- Khoury GA (2002) Effect of fire on concrete and concrete structures. *Progress in Structural Engineering and Materials* **2**(4): 429–447, <https://doi.org/10.1002/pse.51>.
- Kim JHJ, Lim YM, Won JP and Park HG (2010) Fire resistant behavior of newly developed bottom-ash-based cementitious coating applied concrete tunnel lining under RABT fire loading. *Construction and Building Materials* **24**(10): 1984–1994, <https://doi.org/10.1016/j.conbuildmat.2010.04.001>.
- Kim S, Seo J, Cha J and Kim S (2013) Chemical retreating for gel-typed aerogel and insulation performance of cement containing aerogel. *Construction and Building Materials* **40**: 501–505, <https://doi.org/10.1016/j.conbuildmat.2012.11.046>.
- Koebel MM, Aegerter MA and Leventis N (2011) *Aerogels Handbook*. Springer.
- Lai H, Wang S and Xie Y (2014) Experimental research on temperature field and structure performance under different lining water contents in road tunnel fire. *Tunnelling and Underground Space Technology* **43**: 327–335, <https://doi.org/10.1016/j.tust.2014.05.009>.
- Li Q, Li Z, Yuan G and Shu Q (2013) The effect of a proprietary inorganic coating on compressive strength and carbonation depth of simulated fire-damaged concrete. *Magazine of Concrete Research* **65**(11): 651–659, <https://doi.org/10.1680/jmacr.12.00119>.
- Li Z, Cheng X, Shi L et al. (2016) Flammability and oxidation kinetics of hydrophobic silica aerogels. *Journal of Hazardous Materials* **320**: 350–358, <https://doi.org/10.1016/j.jhazmat.2016.07.054>.
- Liu X, Ye G, De Schutter G, Yuan Y and Taerwe L (2008) On the mechanism of polypropylene fibres in preventing fire spalling in self-compacting and high-performance cement paste. *Cement and Concrete Research* **38**(4): 487–499, <https://doi.org/10.1016/j.cemconres.2007.11.010>.
- Liu Z, Wang F and Deng Z (2016) Thermal insulation material based on SiO₂ aerogel. *Construction and Building Materials* **122**: 548–555, <https://doi.org/10.1016/j.conbuildmat.2016.06.096>.
- Liu JC, Tan KH and Yao Y (2018) A new perspective on nature of fire-induced spalling in concrete. *Construction and Building Materials* **184**: 581–590, <https://doi.org/10.1016/j.conbuildmat.2018.06.204>.
- Luccioni BM, Figueroa MI and Danesi RF (2003) Thermo-mechanic model for concrete exposed to elevated temperatures. *Engineering Structures* **25**(6): 729–742, [https://doi.org/10.1016/S0141-0296\(02\)00209-2](https://doi.org/10.1016/S0141-0296(02)00209-2).
- Ma Q, Guo R, Sun Y et al. (2018) Behaviour of modified lightweight aggregate concrete after exposure to elevated temperatures. *Magazine of Concrete Research* **70**(5): 217–230, <https://doi.org/10.1680/jmacr.17.00136>.
- Meng G, Gao B, Zhou J, Cao G and Zhang Q (2016) Experimental investigation of the mechanical behavior of the steel fiber reinforced concrete tunnel segment. *Construction and Building Materials* **126**: 98–107, <https://doi.org/10.1016/j.conbuildmat.2016.09.028>.
- Mudan KS (1984) Thermal radiation hazards from hydrocarbon pool fires. *Progress in Energy and Combustion Science* **10**(1): 59–80, [https://doi.org/10.1016/0360-1285\(84\)90119-9](https://doi.org/10.1016/0360-1285(84)90119-9).
- Ntzeremes P and Kirytopoulos K (2018) Applying a stochastic-based approach for developing a quantitative risk assessment method on the fire safety of underground road tunnels. *Tunnelling and Underground Space Technology* **81**(December): 619–631, <https://doi.org/10.1016/j.tust.2018.08.020>.
- Peng GF and Huang ZS (2008) Change in microstructure of hardened cement paste subjected to elevated temperatures. *Construction and Building Materials* **22**(4): 593–599, <https://doi.org/10.1016/j.conbuildmat.2006.11.002>.
- Persson B (2004) Fire resistance of self-compacting concrete, SCC. *Materials and Structures/Matériaux et Constructions* **37**(273): 575–584, <https://doi.org/10.1617/13980>.
- Poon CS, Azhar S, Anson M and Wong YL (2003) Performance of metakaolin concrete at elevated temperatures. *Cement and Concrete Composites* **25**(1): 83–89, [https://doi.org/10.1016/S0958-9465\(01\)00061-0](https://doi.org/10.1016/S0958-9465(01)00061-0).
- Ren R, Zhou H, Hu Z, He S and Wang X (2019) Statistical analysis of fire accidents in Chinese highway tunnels 2000–2016. *Tunnelling and Underground Space Technology* **83**(December): 452–460, <https://doi.org/10.1016/j.tust.2018.10.008>.
- Robert F and Colina H (2009) The influence of aggregates on the mechanical characteristics of concrete exposed to fire. *Magazine of*

- Concrete Research* **61**(5): 311–321, <https://doi.org/10.1680/mac.2007.00121>.
- Sakkas K, Panias D, Nomikos PP and Sofianos AI (2014) Potassium based geopolymer for passive fire protection of concrete tunnels linings. *Tunnelling and Underground Space Technology* **43**: 148–156, <https://doi.org/10.1016/j.tust.2014.05.003>.
- Samimi K, Kamaragi GRD and Roy R (2019) Microstructure, thermal analysis and chloride penetration of self-compacting concrete under different conditions. *Magazine of Concrete Research* **71**(3): 126–143, <https://doi.org/10.1680/jmacr.17.00367>.
- Samson G, Lanos C and Phelipot-mardelé A (2016) A review of thermomechanical properties of lightweight concrete. *Magazine of Concrete Research* **69**(4): 201–216, <https://doi.org/10.1680/jmacr.16.00324>.
- Shen J and Xu Q (2019) Effect of moisture content and porosity on compressive strength of concrete during drying at 105°C. *Construction and Building Materials* **195**: 19–27, <https://doi.org/10.1016/j.conbuildmat.2018.11.046>.
- Sideris KK and Manita P (2013) Residual mechanical characteristics and spalling resistance of fiber reinforced self-compacting concretes exposed to elevated temperatures. *Construction and Building Materials* **41**: 296–302, <https://doi.org/10.1016/j.conbuildmat.2012.11.093>.
- Sobia AQ and Azmi I (2015) Elevated temperature resistance of ultra-high-performance fibre-reinforced cementitious composites. *Magazine of Concrete Research* **67**(17): 923–937, <https://doi.org/10.1680/mac.14.00134>.
- Uysal M and Tanyildizi H (2012) Estimation of compressive strength of self compacting concrete containing polypropylene fiber and mineral additives exposed to high temperature using artificial neural network. *Construction and Building Materials* **27**(1): 404–414, <https://doi.org/10.1016/j.conbuildmat.2011.07.028>.
- van der Heijden GHA, van Bijnen RMW, Pel L and Huinink HP (2007) Moisture transport in heated concrete, as studied by NMR, and its consequences for fire spalling. *Cement and Concrete Research* **37**(6): 894–901, <https://doi.org/10.1016/j.cemconres.2007.03.004>.
- Wang F, Wang M and Huo J (2017) The effects of the passive fire protection layer on the behavior of concrete tunnel linings: a field fire testing study. *Tunnelling and Underground Space Technology* **69**(March): 162–170, <https://doi.org/10.1016/j.tust.2017.06.021>.
- Xargay H, Folino P, Nuñez N *et al.* (2018a) Acoustic emission behavior of thermally damaged self-compacting high strength fiber reinforced concrete. *Construction and Building Materials* **187**: 519–530, <https://doi.org/10.1016/j.conbuildmat.2018.07.156>.
- Xargay H, Folino P, Sambataro L and Etse G (2018b) Temperature effects on failure behavior of self-compacting high strength plain and fiber reinforced concrete. *Construction and Building Materials* **165**: 723–734, <https://doi.org/10.1016/j.conbuildmat.2017.12.137>.
- Zhang HL and Davie CT (2013) A numerical investigation of the influence of pore pressures and thermally induced stresses for spalling of concrete exposed to elevated temperatures. *Fire Safety Journal* **59**: 102–110, <https://doi.org/10.1016/j.firesaf.2013.03.019>.
- Zhao J, Zheng J, Peng G and van Breugel K (2014) A meso-level investigation into the explosive spalling mechanism of high-performance concrete under fire exposure. *Cement and Concrete Research* **65**: 64–75, <https://doi.org/10.1016/j.cemconres.2014.07.010>.
- Zhao J, Zheng J, Peng G and Sun P (2017) Spalling and cracking modelling of high-performance concrete exposed to elevated temperatures. *Magazine of Concrete Research* **69**(24): 1276–1287, <https://doi.org/10.1680/jmacr.16.00139>.

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