An Experimental Study on Thermal Damage and Spalling of Concrete Under Loading Conditions in a Tunnel Fire

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Abstract

While fire outbreaks in tunnels are not as frequent as those in other structures, temperature rises up to over 1,000°C within 5 minutes upon the outbreak of a fire in a tunnel due to its semi-closed structure. Temperature rise in a concrete structure caused by a fire under constant load leads to deterioration in strength, accelerates deformation and finally results in collapse. In this study to identify structural damage caused by a fire in a tunnel, fire tests were conducted using a heating furnace that satisfied the KS F 2257-1 and EFNARC regulations to evaluate the thermal damage to a tunnel concrete lining. The two objects of the test were: 1) to identify the thermal damage to concrete lining associated with fire intensity 2) to evaluate the characteristics of spalling and failure of concrete lining associated with load ratio. The range of thermal damage under the ISO fire, heating rate of 1°C/Sec., MHC fire³⁾ and RWS fire³⁾ was 30mm, 20mm, 100mm and 50mm, respectively. The depth of spalling in the RWS and MHC fires was 30mm. Spalling was observed under unstressed conditions, while it was not observed under 20 ~ 40% loads because of the smooth flow of vapors enabled by micro cracks. Under 70% load, the rapid spread of cracks caused failure during 10 minutes of heating.

Keywords: tunnel fire; heating rate; spalling; fire damage range

1. Introduction

Tunnels are being built longer and the frequency of vehicles' passing through them is also increasing. Gases and heat used to be the main causes of fire outbreaks in tunnels; however, the influence of fire load has emerged as one of the important factors due to the increase of vehicles and diversification of goods associated with technological advance. Upon a fire outbreak in a tunnel, temperature changes more rapidly than forecasted in fire-resistance design, which causes the fire to last longer than expected, resulting in a disaster and tremendous restoration costs. The EURO Tunnel fire (1996, lasting for 3 days), Mont Blanc Tunnel fire (1999, lasting for 53 hours), Moorfleet Underpass fire in Hamburg, Germany (destroying 34m of PSC lining and causing 30cm spalling), Guadarrama

Underpass fire in Spain (Damaging 120m-long lighting, fire-extinguishing facilities and tunnel facilities), subway fire in Daegu, Korea (resulting in 197 casualties and property loss of KW 4.7 billion) and Guma-Dansung Tunnel fire in Korea (generating 600 ~ 900°C water heat and damaging 400m long wall tiles) are examples of large-scale fires in tunnels.¹⁾

Upon the outbreak of a fire in a tunnel, the temperature rises rapidly due to its semi-closed structure, and spalling of the concrete lining causes sectional damage. Therefore, the damage to concrete lining caused by a fire in a tunnel and its thermal characteristics should be closely examined. In this study, the two tests were conducted to identify the thermal damage to concrete lining associated with fire intensity and to evaluate the characteristics of spalling and failure of concrete lining associated with load ratio.

2. Scope of the Study

The selection of test variables is important in clearly identifying the characteristics of spalling upon the outbreak of a fire in a tunnel because spalling is attributable to multiple and various causes. Test variables in this study were selected based on a

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case study consisting of a comparison and analysis of documents covering the influential factors on spalling.²⁾ The damage to concrete lining was analyzed based on the ITA permissible temperature limit since quantitative analysis of the damage upon the outbreak of fire in a tunnel is required in order to decide whether tunnels should be designed for fire-resistance and to what extent they should be fire-protected.³⁾

The test conducted in this study consisted of 2 parts as follows.

The first part was for identifying thermal damage to concrete lining associated with fire intensity. The ISO, MHC (Modified Hydrocarbon) and RWS (Rijks Water Staat) scenarios for fire outbreaks in tunnels provided by the PIARC and the fire scenario with a heating rate of 1°C/sec (maximum of 700°C) were used to analyze the influence of fire intensity on the characteristics of spalling.⁴⁾

The second part was for analyzing the spalling and failure mode of concrete lining associated with different load ratios. Load ratios of 0, 20, 40, 60 and 70% were applied under the condition of the MHC fire to identify the influence of load ratio on concrete spalling and thermal characteristics of the damaged area. Fig.1. shows the process of the study.

3. Heating Furnace Performance

3.1 Features & Details

Photo 2. shows the heating furnace used in the test to secure the implementation of heating curves for each variable.

The deviation of furnace temperature was set to comply with the KS F 2257-1⁵⁾ and EFNARC⁶⁾ standards in order to secure the reliability of heating capacity in analyzing the behavior of concrete under high temperatures. In order to implement various tunnel fire scenarios, temperature can be adjusted up to 99 points. The internal space of the furnace was protected with fireproof material (ISO Wool Ceramic Fiber 1260 Board) to implement a maximum temperature of over 1,350°C.

Photo 2. The Shape of Fire Test Furnace

R-type thermo couples were set up inside the heating furnace and sheath thermo couples were used to solve the problem of the increase in deviation caused by consecutive operations.

The thermo couples were set up at constant intervals in order to measure average inside temperature near the specimens in compliance with the KS F 2257 and EFNARC standards. In order to prevent thermo couples from being directly exposed to flames inside the furnace, they were set up at least 450mm away from the walls, floor and ceiling of the heating furnace and 102mm away from the heating surface of the specimen in accordance with the EFNARC (100±5mm) and KS F 2257-1 (100±50mm). Cerak -wool was attached between the specimens and heating furnace in order to prevent heat outflow at the back side of the specimens and a thermal expansion confinement condition was provided for the non-heated area of the specimens so that they would adhere to the heating furnace. A pulley was used to place heavy specimens in the heating furnace and a rail was used to move them to the heating surface.

3.2 Verification of heating furnace performance

The calibration of the heating furnace was conducted in accordance with the KS F 2257-1 (ISO 834-1) and EFNARC standards as shown in Table 1. The KS F 2257-1 (ISO 834-1) and EFNARC standards were used to evaluate the performance of heating furnace against the fire curve applied in this test. The limits of percentage deviation in the furnace temperature are as follows.

- a) $5 < t < 10$ minutes: $de \leq 15\%$
- b) $10 < t \leq 30$ minutes: $de = \{15 - 0.5(t - 10)\} \%$
- c) $30 < t \leq 60$: $de = \{5 - 0.083(t - 30)\} \%$
- d) $60 < t$: $de = 2.5\%$

The adjustment test to secure the reliability of heating furnace performance provided a maximum error of 14.2% meaning that it met the performance requirement. Showing a deviation of less than 6% in all sections as shown in Table 1., it also met the requirement of the scenarios for fire outbreaks in tunnels prescribed by the PIARC.

3.3 Loading-Heating linkage

The purpose of this study was to analyze thermal damage and spalling of concrete caused by in-plane compression loads under the most deadly scenario for fire outbreaks in tunnels and find the load ratio at which the deterioration in strength of concrete lining

Fig.1. The Process of the Study

Table 1. Calibration Result of Furnace (%)

Standard (Range)		ISO	MHC	1°C/SEC	RWS
5-10 minutes	Lowest	-2.0	-5.4	-14.2	-6.1
	Highest	0.6	3.4	14.0	-0.4
10-30 minutes	Lowest	-1.8	-4.3	-10.5	-0.01
	Highest	0.2	3.7	9.5	-0.0
30-60 minutes	Lowest	-2.2	-3.5	-4.5	-1.0
	Highest	0.09	2.8	6.6	0.1
After 60 minutes	Lowest	-1.5	-4.3	-4.0	-0.9
	Highest	0.3	3.3	7.3	0.2

attributable to a fire finally resulted in its failure. For this, the heating furnace⁷⁾ shown in Photo 2. was used for the loaded heating test to provide the condition of a fire outbreak in a tunnel characterized by simultaneous attack of load and heat.

4. Test Plan

Table 2. shows the test variables used to analyze the influence of various fire conditions, design compressive strengths and load conditions on thermal damage and spalling of concrete lining.

Table 2. Test Variables of Concrete Lining

Specimen	Fire Scenario	Strength (MPa)	Size (mm)	Thermo-Couple (mm)	Load Ratio (%)
S-1	ISO	40	600×600×200	5,10,20,30,50,100,150	0
S-2	MHC				
S-3	S-1°C-1				
S-4	RWS				
I-M-1	MHC	24	600×600×150	10,20,30,40,50,75	0
I-M-2					20
I-M-3					40
I-M-4					60
I-M-5					70

4.1 Test variables and specimen fabrication

4.1.1 Specimen size

Specimens were manufactured as shown in photo 3 considering sensor locations for each variable. The sizes of the specimens were 600mm x 600mm x 150mm and 600mm x 600mm x 200mm. In order to minimize heat conduction at the loading point of the UTM (Universal Testing Machine), a 100mm distance was provided for each of the 4 sides as a buffer against concrete heat conduction so that heat conduction at the loading point could be controlled at the directly heated area (400mm x 400mm). The configuration of the heated area complied with the small-scale test standards provided by the EFNARC and fire-proofing material was not used in the specimens.

4.1.2 Selection of fire scenario (fire intensity)

In order to provide various fire intensities, four fire scenarios consisting of the ISO fire, MHC (Modified Hydrocarbon) fire, heating rate 1°C/SEC and RWS fire were used to analyze the damage to concrete as shown in Fig.4.

Based on "ISO Fire" and featuring typical temperature rise, the ISO fire curve is closer to fire outbreaks in buildings than those in tunnels. Mainly used in standard fire tests, it is used as an international

Photo 3. Manufacture of Test Specimen

Fig.4. Fire Scenario of Test

-standard fire curve. In this study, it was applied to the test to provide the condition of a small-scale fire in a tunnel caused by cars. Made by the adjustment of the heating ratio of hydrocarbon, the MHC fire is a scenario to analyze the thermal shock to concrete caused by the rapid temperature rise at the beginning stage. In this study, it was used to analyze temperature distribution associated with pore pressure and the depth of the heated area. The fire curve with 1°C/SEC was used to identify the influence of low heating ratio and constant temperature (680°C) on spalling.

The temperature was raised by 1°C per second to reach 680°C in 11 minutes, after which it remained constant to observe the influence of the heating ratio. The RWS fire curve is the worst scenario of a fire in an oil tanker where 300 MW load lasts for 120 minutes. The PIARC considers it to have the same intensity as the MHC fire. These scenarios for fire outbreaks in tunnels featuring various fire intensities were applied to the experiment to analyze their influence on spalling and the thermal damage to concrete lining.

4.1.3 Thermo couple set up

K-type thermo couples were set up at a depth of 5, 10, 20, 30, 50, 100 and 150mm at the left side and 10, 30, 40, 50 and 75mm at the right side as shown in Fig.5. to measure the temperatures inside the concrete and analyze heat transfer characteristics associated with the depth of the heated area. In order to secure the

preciseness of the thermo couples measurement depth, thermo couple setup samples 45mm x 45mm x 150mm and 45mm x 45mm x 200mm in dimension were manufactured with identical mixing ratio and fixed into a specimen mold to produce specimens.

Fig.5. Installation of Thermal Couple

4.2 Mixing ratio and material properties of concrete lining

4.2.1 Concrete mixing ratio and properties

The fire-resistance of concrete exposed to a fire depends on multiple factors such as aggregate properties, concrete mixing ratio, water content, pore pressure, load, heating method and maximum heat capacity.

The standard for tunnel design provided by the Korean Ministry of Land, Transport & Maritime Affairs prescribes that while concrete with a strength of 21 ~ 24 MPa on the 28th day of curing should be used, high-strength concrete can be also used.⁸⁾ Thus, 24 MPa concrete relatively vulnerable to spalling and thermal damage was mixed with 40 MPa concrete to manufacture specimens for the test. Three kinds of Korean-made rapid hardening portland cement satisfying the requirement of the KS L 5201⁹⁾ Portland Cement Regulation were used. Tables 3. and 4. show the material properties of the aggregates and mixing ratio and material test result, respectively.

4.2.2 Measurement of water-content inside concrete

Moisture content in concrete is the main cause of spalling. The higher the percentage of water content is, the higher the possibility of spalling is because the water inside concrete raises water vapor pressure and pore pressure. The water inside concrete consists of free water and bound water. Since the water vaporizing up to 100 ~ 150°C is mainly free water,

Table 3. Material Properties of Coarse

Aggregate	Density (t/m ³)	Fineness (g/cm ³)	Absorption (%)	Passing 0.08 mm sieve (%)	FM (%)
S	1.57	2.58	1.62	1.9	2.89
G	1.56	2.62	0.65	0.2	6.59

Table 4. Mixing Ratio of Concrete Lining

f _{ck} (MPa)	W/C (%)	S/a (%)	Unit content (kg/m ³)				
			Cement	Sand	Gravel (19)	Water	Super Plasticizer(%)
24	47.2	46.8	341	874	993	161	1.02
40	39.4	39.2	405.7	676.5	1066.1	159.8	6.5

it is the principal cause of spalling. Consequently, the material properties of concrete should be defined through the measurement of water content in it to analyze its behavior upon a fire. In addition, data based on a reliable measuring method should be provided to identify the influence associated with it.

Methods to measure the percentage of water content inside concrete include the ASTM method, nuclear magnetism method, supersonic method and electro-magnetic method¹⁰⁾. In this study, the ASTM C 566¹¹⁾ was used to measure the percentage of water content and the VAISALA was used to measure the relative and absolute humidity of 3. Table 5. is the summary of water content and relative humidity.

Table 5. Moisture Content of Concrete Lining

Measurement	Item	Result
ASTM C 566	Water vaporization (g)	142
	Water content (%)	3.73
VAISALA HM 44	Absolute humidity (kg/m ³)	11.7
	Relative humidity (%)	98.5

4.2.3 Measurement of the Inner Pore Pressure of the Concrete

The authors carried out a verifying test to discover whether the inner pore pressure changed in the different depths of the heating surface of the concrete, and the correlativity between the time and the temperature at the point of maximum pressure. Table 6. shows the results. In the case of the ISO Fire, spalling appeared at an internal temperature of about 150~200°C, and the maximum pore pressures of 0.821 MPa and 0.756 MPa were measured at a depth of 20mm and 30mm. In the case of the MHC Fire, a relatively higher temperature appeared around a depth of 20mm from the heating surface compared with that of the maximum pore pressure.

Table 6. Results of Pore Pressure

Fire Intensity	Depth (mm)	Maximum Pressure (MPa)	Time (minute)	Temperature (°C)
ISO Fire	20	0.821	23	157
	30	0.756	53	185
	40	0.496	61	163
	50	0.574	58	168
MHC Fire	20	0.176	25	301
	30	0.205	18	170
	40	0.79	35	234
	50	0.368	29	176

5. Fire Test with Variables

5.1 Thermal damage and spalling associated with fire intensity

5.1.1 Influence on the depth of spalling

Photo 6.(a) shows the concrete exposed to the ISO fire. The maximum depth of spalling was 10mm. Photo 6.(b) is the concrete exposed to the MHC fire. The depth of spalling was 30mm. It is deduced that rapid rise in temperature at the early stage of a fire caused sectional damage and deeper spalling. While pore pressure was the greatest at 40mm, the deepest spalling was 30mm. As shown in Photo 6.(c), spalling of concrete was not observed when it was exposed to the 1°C/SEC fire seemingly because the heating ratio was relatively low and the temperature remained constant at 680°C after the 11-minute point. Photo 6.(d) shows the concrete exposed to the RWS fire. The deepest spalling was 30mm as in the MHC fire, seemingly because while the temperature in the RWS fire did not rise as rapidly as in the MHC fire, their temperature rise curves were similar to each other.

Photo 6. Spalling Condition after Heating

5.1.2 The range of thermal damage to concrete

The ITA (International Tunneling Association) provides tunnel standards in terms of heat emission and fire duration to protect structures from fire outbreaks in tunnels. It suggests a permissible temperature limit of 380°C to prevent deterioration in the capacity of PC panel lining. Accordingly, the range of thermal damage to PC panel lining in each fire intensity (scenario) was obtained based on the standard as shown in Table 7.

In the ISO fire, the concrete temperature at a depth of 5 ~ 20mm rose rapidly in 20 ~ 30 minutes. The highest pore pressure observed at a depth of 20mm at this point in time indicated that concrete spalling occurred then. As the temperature rose over the ITA's permissible

Table 7. Fire Damage Range of Concrete Lining

Lining	Fire Scenario (2 hour)	Spalling Depth (mm)	Fire Damage (380°C, mm)
40 MPa	ISO	10	0 ~ 30
	MHC	30	0 ~ 100
D-200 mm	S-1°C-1	0	0 ~ 20
	RWS	30	0 ~ 50

limit (380°C), the range of capacity deterioration was 0 ~ 30mm as shown in Fig.7.

In the MHC fire, rapid temperature rise caused spalling up to a depth of 30mm seemingly at approximately the 10-minute point. A rise in pore pressure at a depth of 40mm from the heating surface indicated the formation of a vapor zone at a depth of 30 ~ 40mm, which caused spalling. As shown in Fig.8., capacity deterioration seemed feasible at the 100mm point from the heating surface where the temperature was over the ITA's permissible limit of 380°C.

Fig.7. Fire Damage Range by ISO Fire (380°C)

Fig.8. Fire Damage Range by MHC Fire (380°C)

In the 1°C/SEC fire, concrete spalling was not observed due to the relatively low heating ratio and low temperature in the furnace. As shown in Fig.9., although the temperature rose over the permissible limit of 380°C in the range of 5 ~ 20mm from the heating surface, spalling did not occur thanks to relatively slower temperature rise.

In the RWS fire, rapid rise in temperature in the 5 ~ 30mm range from the heating surface caused spalling and the damage to the overall concrete surface resulted

Fig.9. Fire Damage Range by 1°C/SEC Fire (380°C)

Fig.10. Fire Damage Range by RWS Fire (380°C)

in a temperature rise even at the 50mm point from the heating surface. Spalling was observed mainly at around 10 minutes. As shown in Fig.10., capacity deterioration was feasible at a depth of 50mm from the heating surface where the temperature rose over the ITA permissible limit of 380°C.

5.2 Thermal damage and spalling associated with load ratio

A fire test for 24MPa concrete was conducted as follows to identify the influence of load ratio on spalling and find the ultimate load ratio causing the deterioration in concrete strength and the failure of concrete lining.

5.2.1 Influence on spalling and cracks

Before the heating test, load was applied to a 150mm x 600mm sectional area of each specimen at a speed of 30 N/min until the target load ratio was reached. Load remained constant after that. The MHC fire was applied for 120 minutes to one side direction. It is deduced that the appropriate load generates micro cracks and promotes moisture flow to control spalling, whereas too heavy load causes strength deterioration and spalling. Under a load ratio of 70%, concrete lining was destroyed as soon as heating was applied.

Table 8. shows spalling and crack details. The result in which spalling occurred under a load ratio of 0% while not under a load ratio of 20% and 40% corresponds to that of the study conducted by the

Table 8. Test Results of Spalling and Crack

Specimen	Strength (MPa)	Spalling depth (mm)	Crack (mm)
I-M-1	24	16	2.0
I-M-2		0	0.5
I-M-3		0	0.3
I-M-4		24	1.0
I-M-5		Fracture	-

authors of this study.¹²⁾ In addition, the findings on the relation between load and spalling also correspond to those of the study carried out by Phan L.T.¹³⁾ and Harada K.¹⁴⁾

5.2.2 Influence on temperature rise

In the I-M-1 specimen which was under a load ratio of 0%, moisture vaporized into gas in 10 ~ 18 minutes after heating. Intensive fire caused spalling, the thermo couple at a depth of 10mm was exposed and the temperature rose to 1,182°C. At a depth of 75mm, the temperature rose to 388°C. Fig.11. (a) shows temperature rise in the unstressed heating test. In the I-M-2 specimen, which was under a load ratio of 20%, micro cracks played the role as a passage of moisture, controlled spalling and prevented surface damage. Consequently, temperature rise was not significant. The highest temperature at a depth of 10mm from the heating surface was 943°C as shown in Fig.11. (b), which was lower than that of 1038°C observed at a depth of 20mm in the I-M-1 specimen.

In the I-M-3 specimen, which was under a load ratio of 40%, spalling did not occur and the temperature rise pattern was similar to that in specimen I-M-2. In the I-M-4 specimen, which was under a load ratio of 60%, spalling was observed and the temperature rose to 1,064°C. Temperature rise pattern in the specimen was similar to that in the I-M-1 specimen seemingly because of surface damage caused by spalling.

6. Conclusion

The conclusion of the test conducted with variables of fire intensity, compressive strength and load ratio to analyze the thermal damage and spalling of concrete lining is as follows.

1) In the ISO fire, the depth of spalling of the PC panel lining was 10mm and thermal damage was caused at a depth of 30mm from the surface exposed to a fire. Maximum pore pressure was observed at a depth of 20mm, spalling occurred at the 20 minute point after heating and the temperature rose to 150 ~ 200 °C.

2) In the MHC fire, the depth of spalling of the PC panel lining was 30mm as in the RWS fire and thermal damage was caused at a depth of 100mm from the surface exposed to a fire. Pore pressure inside concrete, the cause of spalling, was the strongest at a depth of 40mm. Spalling occurred at the 15 ~ 30 minute point after heating when the temperature was 150~ 250°C.

Fig.11. The Result of Fire Test (Loading: 0 % ~ 70%)

3) In the 1°C/Sec. fire, while the depth of spalling of the PC panel lining was 0mm, thermal damage was caused at a depth of 20mm from the surface exposed to a fire.

4) In the RWS fire, while the depth of spalling of the PC panel lining was 30mm, thermal damage was caused at a depth of 50mm from the surface exposed to a fire.

5) Appropriate load ratio generated micro cracks inside concrete, lowered pore pressure and mitigated spalling.

6) Increase in load ratio accelerated temperature rise. Load ratio of over 70% of the sectional strength of concrete lining caused rapid rupture.

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