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Development of Fire-Resistant NM-Segment for Road Tunnels

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Abstract

In recent years, tunnel-safety technology, especially fire protection technology for road boring tunnels is needed. We had developed Fire-Resistant NM-Segment that has an ability of protecting concrete and steel structures itself against tunnel fires. This paper reports the results of a fire test done for some reduction and real size models of Fire-Resistant NM-Segment. These results demonstrate that Fire-Resistant NM-Segment has a practical use.

1. Introduction

For road shield tunnels, fire-resistant installations to protect the tunnel lining (segments) from vehicle fires is indispensable. The fire-resistant functions required in a tunnel are to: (1) prevent spalling of the segment concrete, and (2) restrain temperature rise of the steel, concrete reinforcement and joint sealant. In recent years, the tunnel fire-resistance work usually involves the application of refractory (spray mortar, board, fiber blanket, etc.) to the inner surface of the tunnel after assembly of the segments as shown in **Photos 1, 2 and 3**.

Nippon Steel has successfully completed development of the NM segment with refractory ("Fire-Resistant NM Segment")—a steel-concrete NM segment which permits finishing the fire-resistance work at the same time as the segment assembly. With the Fire-Resistant NM Segment, it is possible to cut construction costs and shorten the

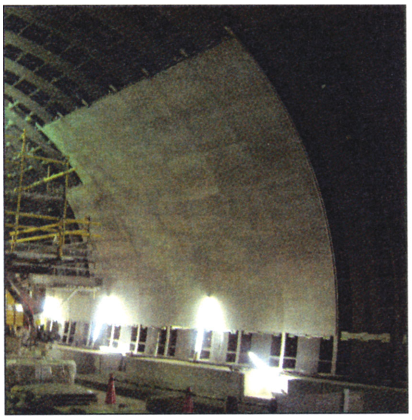

Photo 2 Board type fire refractory

Photo 1 Spray mortal type fire refractory

Photo 3 Fiber blanket type fire refractory with stainless steel

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construction period as compared with fire-resistance work done after segments assembly. In order to confirm whether the newly developed segment can be put to practical use, we carried out heating tests using reduced and full-scale models and physical property tests of the concrete and sealant. This paper describes the results of the tests.

2. Specifications of Fire-Resistant NM Segment

The structure of the Fire-Resistant NM Segment is shown in **Fig. 1**. In terms of the structure, the Fire-Resistant NM Segment is available in two types: (1) a "concrete type" that secures sufficient fire resistance by mixing polypropylene (PP) fiber into the packed concrete (the steel is also covered with PP fiber-added concrete), and (2) a "castable type" in which the packed concrete is PP fiber-added concrete and the steel is covered with castable refractory.

3. Heating Tests with Reduced Models Using Jet Burner

We carried out heating tests using reduced models of the two types of Fire-Resistant NM Segment in order to confirm the fire resist-ance of each of the segment components (packed concrete, piece joint and ring joint) and the performances of the PP fiber-added concrete and castable refractory.

3.1 Models for component heating tests

The three types of models shown in **Fig. 2** were used for the tests to confirm the basic performance of the Fire-Resistant NM Segment.

(1) Concrete model of "packed concrete" to determine whether the concrete spalling depending upon the amount of PP fiber mixed into the concrete and to measure the temperature distribution in the concrete in the depth direction.
(2) Piece joint model of "joint between pieces" to measure the steel and sealant temperatures.
(3) Ring joint model of "joint between rings" to measure the steel temperature and check for exfoliation of the refractory from the steel.

3.2 Component heating tests

3.2.1 Outline of heating tests

As shown in **Fig. 3**, a jet burner owned by Nippon Steel's Refractory Ceramics R&D Div. was used to heat the specimens according to the RABT heating curve (1,200℃ for 60 minutes) specified by the Ministry of Transport (Germany) to check the condition of concrete spalling and measure the temperatures of the concrete, steel and sealant.

3.2.2 Test cases

The test specimens used are shown in **Table 1**. Specimens 1 to 3 were to see the difference made by the amount of PP fiber mixed into the concrete; Specimens 4 and 5 were to measure the temperatures of the ring joint and piece joint with steel covered with 60-mm thick PP fiber-added concrete; and Specimens 6 through 9 were to measure the temperatures of steels covered with two types of castable refractory 20 mm in thickness and to compare the two types of castable refractory. The two types of castable refractory used are those which have been applied to the linings of many tunnels.

3.2.3 Test results

(1) Determination of optimum addition of PP fiber to prevent spalling of concrete

With the exception of Specimen 1 to which PP fiber was not added,

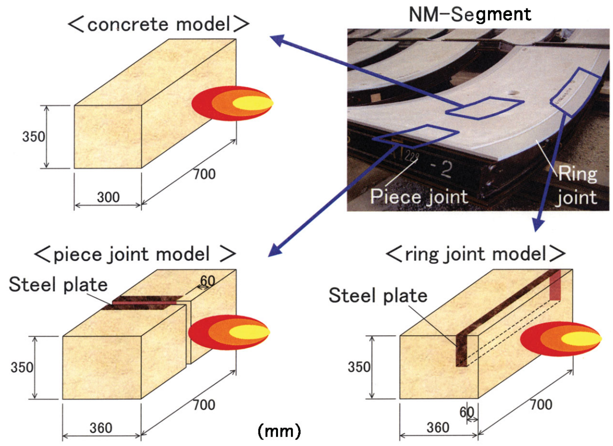


Fig. 2 Specimens of reduction model

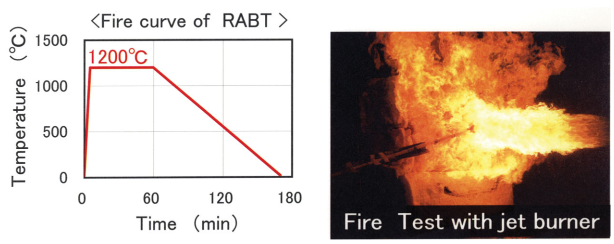


Fig. 3 Fire test for reduction models

Table 1 Test parameter

Specimen No.	Model	Addition ratio of PP fiber (vol%)	Refractories for steel surface	
			Refractory	Thickness (mm)
1	Concrete	0	-	-
2	Concrete	0.1 (0.91kg/m^3)	-	-
3	Concrete	0.2 (1.82kg/m^3)	-	-
4	Ring joint	0.2 (1.82kg/m^3)	PP concrete	60
5	Piece joint	0.2 (1.82kg/m^3)	PP concrete	60
6	Ring joint	0.2 (1.82kg/m^3)	Castable A	20
7	Piece joint	0.2 (1.82kg/m^3)	Castable A	20
8	Ring joint	0.2 (1.82kg/m^3)	Castable B	20
9	Piece joint	0.2 (1.82kg/m^3)	Castable B	20

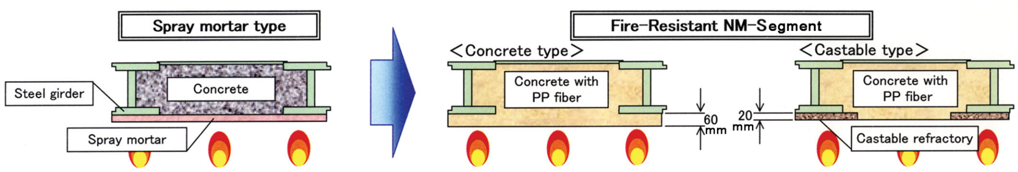


Fig. 1 Structures of Fire-Resistant NM-Segment

all the specimens were devoid of concrete spalling and exfoliation. From this fact, it was found that the addition of 0.1 vol% (0.91 kg/m^3) PP fiber would be sufficient to prevent spalling of the concrete. **Photo 4** shows the conditions of specimens before and after the heating tests.

(2) Temperature changes of concrete, steel and sealant

The temperature changes of Specimens 2 and 3 at a concrete depth of 60 mm are shown in **Fig. 4**.

At the concrete depth of 60 mm, the maximum temperature reached was about 340℃ (339℃ for Specimen 2 with 0.1 vol% PP fiber and 341℃ for Specimen 3 with 0.2 vol% PP fiber). It is said that the marginal temperature at which concrete's properties (compressive strength, Young's modulus, etc.) remain unaffected is around 350℃. From the test results, it is estimated that the thermal influence of a fire on the concrete at depths of 60 mm or more is minimal. The amount of PP fiber mixed in the concrete did not make any significant difference to the concrete temperature.

The temperature changes at the steel surface of the ring joint models (Specimens 4, 6 and 8) are shown in **Fig. 5**. Although the time in which the maximum temperature was reached was different (166 minutes for concrete with PP fiber and 107 to 108 minutes for castable refractories A and B), the maximum temperature at the steel surface was around 220℃ (220℃ for concrete with PP fiber and 217℃ to 220℃ for castable refractories A and B). Assuming that the marginal temperature at which the steel's properties (compressive strength, Young's modulus, etc.) remain unaffected is approximately 300℃, both the concrete type (steel covered with 60-mm thick concrete with PP fiber added) and the castable type (steel covered with 20-mm thick castable refractory) have sufficient thermal insulation performance.

As shown in **Fig. 6**, the maximum temperatures of the groundside sealants of the piece joint models (Specimens 5, 7 and 9) were around 96℃ (96℃ for PP fiber and 91℃ to 93℃ for castable refractories A and B). It has been confirmed in an experiment carried out separately that the marginal temperature at which the sealant's properties

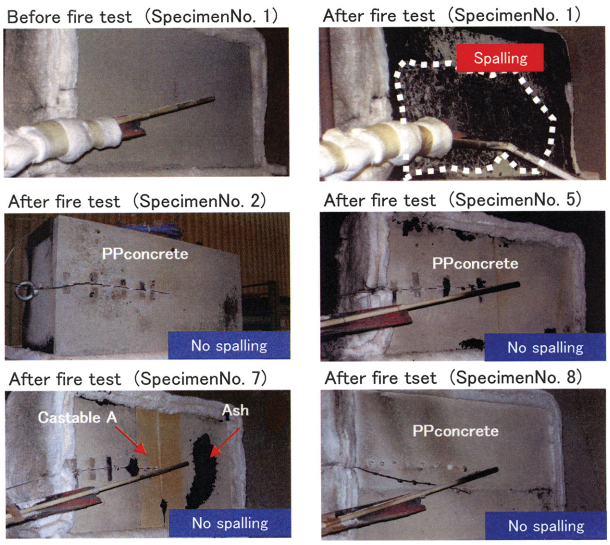


Photo 4 Test results of before and after fire test

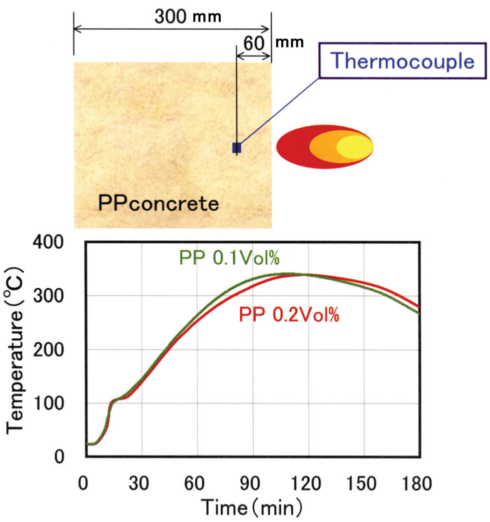


Fig. 4 Temperature of concrete at 60 mm depth

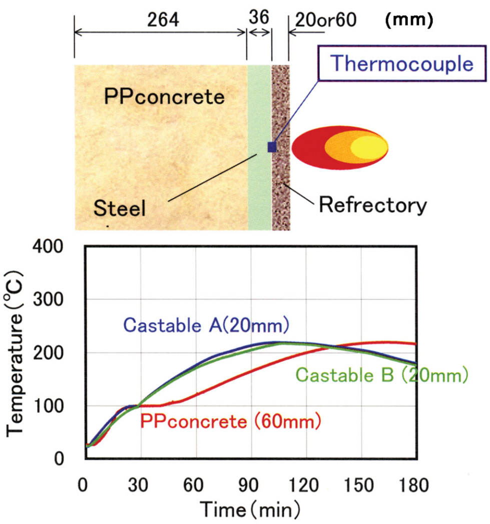


Fig. 5 Temperature of steel surface

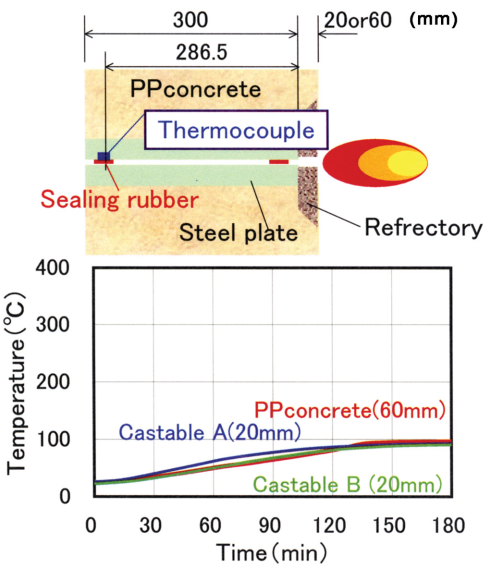


Fig. 6 Temperature of sealing rubber

(rubber performance, etc.) remain unaffected is approximately 120 ℃. Therefore, both the concrete type (60-mm thick concrete with PP fiber added) and the castable type (20-mm thick castable refractory) have sufficient thermal insulation performance for the joint sealant.

3.3 Findings from component heating tests

The following facts were determined from the component heating tests.

(1) The spalling of concrete can be prevented by adding 0.1 vol% or more of PP fiber to the concrete.

(2) As long as the segment is provided with a fire-resistant cover of 60-mm thick concrete with PP fiber added or 20-mm thick castable refractory, each of the concrete, steel and sealant completely meets its marginal temperature requirement in a fire.

4. Heating Tests with Full-scale Specimens in Large Furnace

In the component heating tests described above, it was confirmed that both the concrete type (with steel covered with 60-mm thick concrete with PP fiber added) and the castable type (with steel covered with 20-mm thick castable refractory) had sufficient heat resistance.

Then, we carried out heating tests using full-scale segments.

4.1 Outline of heating tests

The full-scale test specimens used are shown in **Photos 5 and 6**. As shown in **Figs. 7 and 8**, the same types of segments as used in the component heating tests were subjected to the heating test according to the RABT curve (1,200℃ for 60 minutes) at the Building Research Institute—an independent administrative corporation. The concrete used was fire-resistant concrete with 0.2 vol% (1.82 kg/m^3) PP fiber added. As the castable refractory, a material which has been applied for fire-resistance work on many tunnels was used.

In view of the trend toward wider segments in recent years, a segment width of 2,000 mm was adopted. The girder height was 300 mm plus the refractory thickness. A piece joint was reproduced by jointing 1,900-mm long specimens together at the center. The specimens were also provided with sealing rubber. Taking into consideration the ease with which axial force and bending load application can be implemented and the fact that the segment is designed for large-bore tunnels which are free from significant influence of curvature, it was decided to use flat-shaped specimens.

In the test, with axial force and bending load applied to the specimen at the same time by the apparatus shown in **Fig. 9**, the specimen was heated with the inner surface kept compressed so as to reproduce the conditions under which the concrete could explode most easily. Specifically, the specimen was heated with a negative bending moment of 350 kN•m and an axial compressive force of 7,000 kN constantly applied to it to examine the temperature distributions in the steel and concrete, the temperature of the sealant and the condition of occurrence of spalling of the concrete. The jack thrust load

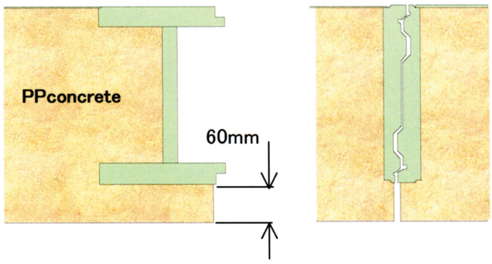


Fig. 7 Section of PP concrete refractory

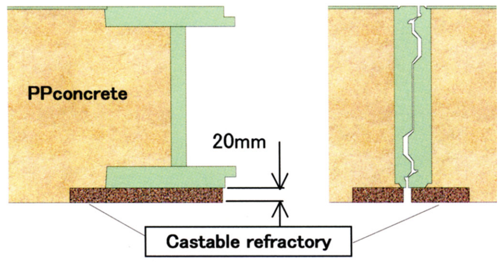


Fig. 8 Section of castable refractory

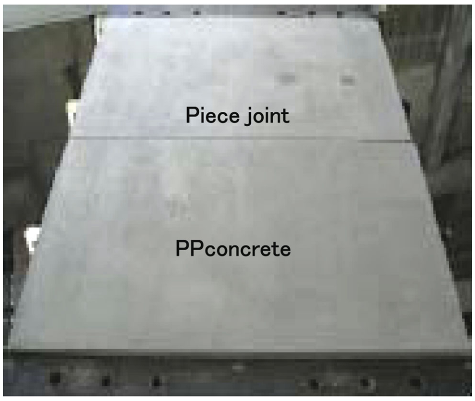


Photo 5 Specimen of PP concrete refractory

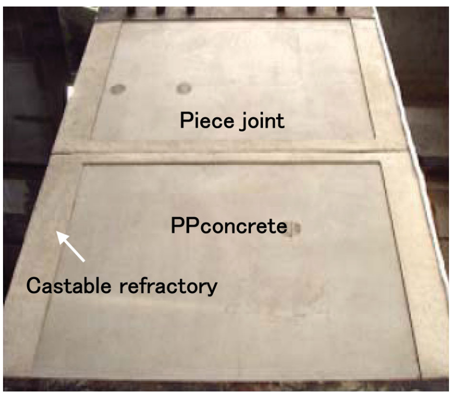


Photo 6 Specimen of castable refractory

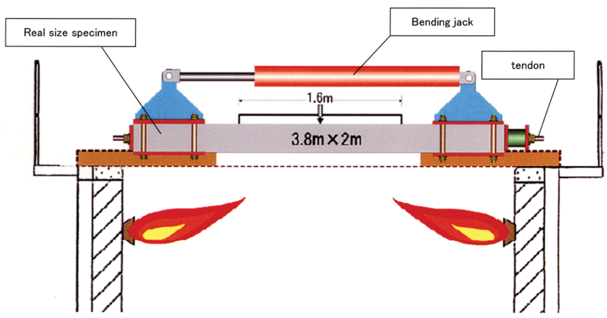
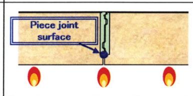
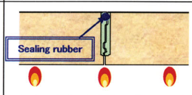
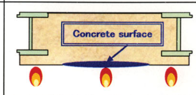


Fig. 9 Fire test with loading jack

Table 2 Target temperatures and phenomena

	Ring joint	Piece joint	Sealing rubber	Concrete surface
Point				
Target temp. & Phenomenon	≦300℃	≦300℃	≦120℃	—
	No exfoliation of refractory			No spalling

was kept constant throughout the heating test.

The target values that were used to evaluate the fire resistance of the Fire-Resistant NM Segment are shown in **Table 2**.

4.2 Results of heating test

Fig. 10 shows the changes in temperature of the individual specimens, and **Table 3** shows the maximum temperatures at the main points. All the measured temperatures of the steel (the main girder inner surface and piece joint inner surface) were lower than the target temperature of 300℃, although there was a little difference in maximum temperature. The maximum temperature of the groundside sealing rubber was also lower than the target of 120℃, and the maximum temperature of the concrete of each segment type was lower than 350℃ at depths of 60 mm and more from the concrete surface as shown in **Fig. 11**.

Photo 7 shows the condition of the heated side of the PP concrete-type specimen after the heating test. The specimen was completely free from sectional damage due to concrete spalling or exfoliation, which has an adverse effect on the yield strength of the Fire-Resistant NM Segment. The castable type specimen was also devoid of concrete spalling, etc. which can cause the segment yield strength to decline.

4.3 Results of material deterioration test after heating

Using the specimens that were subjected to the full-scale segment heating test, we measured the concrete strength, the degree of carbonization of the concrete, the scope of burnout of the PP fiber and the degree of deterioration of the sealing rubber.

Fig. 12 shows the ratio of the concrete restitution in the depth direction measured by the Schmitt-Hammer method, compared to the restitution at the non-heated concrete surface. As shown, the restitution ratio increases almost linearly in proportion to the depth from the heated concrete surface, and at depths 40 mm and more, the restitution is nearly equal to that of the non-heated concrete surface.

Table 3 Results of maximum temperature

Notice point	PP concrete type	Castable type	Target temp.
Sealing rubber	76℃	82℃	≦120℃
Girder surface	226℃	206℃	≦300℃
Piece joint surface	130℃	178℃	≦300℃

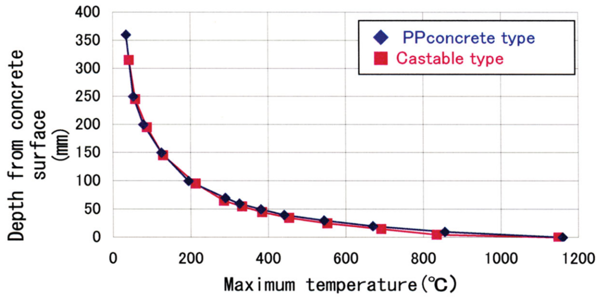


Fig. 11 Maximum temperature-depth curve

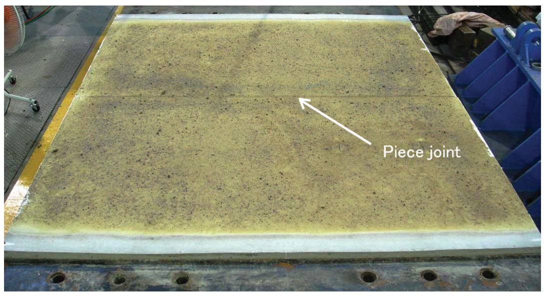


Photo 7 Specimen after fire test (PP concrete type)

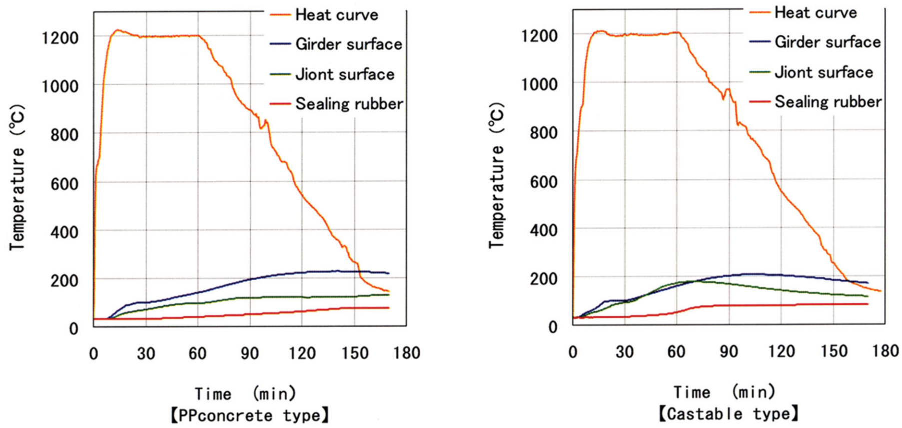


Fig. 10 Time-temperature curve of PP concrete type and castable type

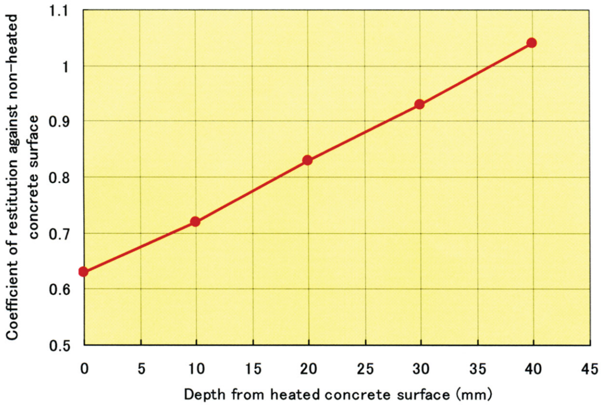


Fig. 12 Coefficient of restitution against non-heated concrete surface

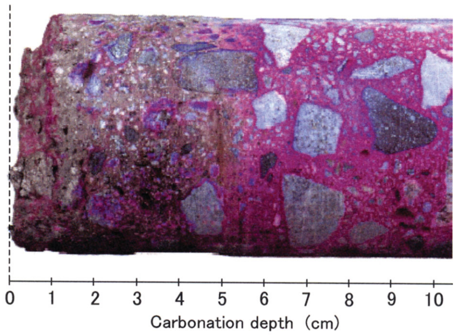


Photo 8 Carbonation after fire test

Therefore, it is considered that at depths 40 mm and more from the heated surface of concrete, the concrete retains strength comparable to that at normal temperature.

Photo 8 shows the range of carbonization observed with the concrete core taken from a heated specimen. The concrete was carbonized to a depth of about 50 mm from the heated surface. This range of concrete carbonization nearly coincided with the range of PP fiber loss observed in an immersion test using a same specimen of the concrete core.

Samples of the sealing rubber collected from heated segment specimens were subjected to a deterioration test. As a result, it was confirmed that the sealing rubber remained completely sound.

5. Conclusion

In order to confirm the fire resistance of the Fire-Resistant NM Segment, we carried out component heating tests, full-scale segment heating tests and material deterioration tests after the heating tests. As a result, it was confirmed that the Fire-Resistant NM Segment was completely devoid of concrete spalling, which has an adverse effect on the concrete yield strength, even in a tunnel fire corresponding to the RABT heating curve (1,200℃ for 60 minutes). It was also confirmed that the concrete, steel and sealing rubber had sufficient heat resistance against fires. Thus, the Fire-Resistant NM Segment can safely be put to practical use.

With the aim of renewing urban areas and utilizing subterranean space, projects to construct road shield tunnels, mainly in large cities, are under way. We believe that in those projects the Fire-Resistant NM Segment will help meet social demand not only for greater tunnel safety against fires, but also for a reduction in construction costs, shorter construction periods and improved structural reliability.

We intend to continue making strenuous efforts to develop new technologies that benefit the project owners, contractors, tunnel users and local inhabitants.

Acknowledgment

We wish to express our heartfelt thanks to the people of GEOSTR Corporation for their generous cooperation in the present development.

References

1) Kawamura, A. et al.: V-597, V-598: 62nd Annual Academic Lecture Meeting, Hiroshima, 2007-9, Japan Society of Civil Engineers