Fire-proofing Performance of SFRC Segments with Polypropylene fiber against Explosive Spalling of Lining Concrete of Shield Tunnels

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1 INTRODUCTION

With its excellent strength, ductility and crack-distributing effect, steel-fiber-reinforced concrete makes it possible to prevent spalling of concrete and reduce the amount of reinforcing steel. On other hand, high-fluidity concrete with a self-compacting property not only enhances placeability but also eliminates the process of vibrating compaction in casting concrete, which does not require conventional stiffness of formwork, and reduce production cost as well. For these reasons, shield tunnel lining segments using steel-fiber-reinforced high-fluidity concrete (SFRC lining segments) have been developed and put to practical use in shield tunnel structures. In the event of a large-scale fire in the tunnel, flammable substances and materials such as gasoline, oil and wood might burn in tunnel. The inside of the tunnel, therefore, could soon be exposed to temperatures exceeding 1,000°C. With such high temperatures, explosive spalling of the concrete might occur and concrete strength might lower. Water vapor pressure in the concrete is known as a cause of the explosive spalling. Mixing polypropylene fiber (PP fiber) into concrete is one of the effective measures to release of the water vapor pressure through voids which to be formed after the PP fiber melts and evaporates under high temperature. To prevent the explosive spalling of the SFRC lining segments, the following items are necessary to be confirmed, 1) suitable type of PP fiber and admixture, and 2) proper mix proportion of those materials. We, therefore, have conducted a series of fire resistance tests of SFRC lining segments to verify above-mentioned items. In addition, we conducted a fire resistance test of the full-scale SFRC lining segments under axial force. The results of the verification on fire resistance and cross-sectional temperature distributions are reported in this paper.

2 ADVANTAGES OF SFRC LINING SEGMENTS

SFRC lining segments are produced with high-fluidity self-compacting concrete containing short steel fibers. The followings are advantages of SFRC lining segments.
1) SFRC reduces width of concrete cracks because steel fiber can control uniform distribution of cracks.
2) Steel fiber in the concrete prevents the spalling of concrete, especially in the corners and edges of lining segments, due to impact load during transportation/assembling of the lining segments.
3) The electrochemical mechanism of steel fiber reinforced concrete is effective in preventing the corrosion of reinforcing steel in the concrete, which enhances the durability of the lining segments.
4) The tensile strength and shear strength of concrete improved by steel fiber can reduce the amount of main reinforcement and eliminate distribution/hoop reinforcement. Figure-1 compares cross sections of SFRC and a conventional lining segment. The reduction of those amounts of the reinforcement shortens the construction schedule for placing/assembling of the reinforcing bar.
5) High-fluidity concrete does not require the process of vibrating compaction to the concrete by vibrating tables. It can simplify formwork and production equipments. In addition, elimination of the process of vibrating compaction can reduce environmental impact, such as noise and vibration of vibrating tables.
6) The small environmental impact enables to produce the lining segments at site without transportation from factories. Advantages are a) length and width of segments can be enlarged because there is no limit to segment weight for transportation. b) cost saving due to non-transportation of the segments.
3 FIRE RESISTANCE TEST USING TEST PIECES

3.1 PURPOSE AND TEST CASES

The Purpose of the Fire tests: Finding proper type of materials and proper mix proportion to be effective in preventing the explosive spalling of SFRC lining segments.
Test cases: five (5) types of concrete are used;
1) Medium-fluidity concrete without any admixture,
2) High-fluidity concrete with admixture of limestone powder, 3) High-fluidity concrete with admixture of fly ash, 4) High-fluidity concrete with admixture of blast furnace slag powder, and 5) High-fluidity concrete with cellulose viscosity modifier.
In addition, the PP fiber with five (5) types of aspect ratios (ratio between length and the diameter of the fiber) were used. Table-1 lists the types of PP fiber. Table-2 summarizes the combinations in different test cases.

3.2 PREPARATION OF TEST PIECES

(1) MATERIALS AND MIX PROPORTION

Table-3 lists the materials used in the tests. In all cases, normal portland cement are used.
The followings are Fresh concrete properties. The medium-fluidity concrete has a slump of 18±2.5 cm. The high-fluidity concrete has a slump flow of 55±5 cm. All concrete mixes have an air content of 3.0±1.5%. The design strength was 48 N/mm². The steel fiber content and the PP fiber content are 0.6 vol% and 0.2 vol%, respectively.

(2) TEST PIECES

Figure-2 shows dimension and reinforcement of the test piece. The slab-shaped test pieces measure 0.5 m wide, 1.0 m long and 0.2 m thick. The reinforcement consists of D10 rebars placed at 100 mm intervals at two levels. The concrete cover is 50 mm.
Concrete was mixed in a two-shaft forced action mixer and poured into the center of the form. The medium-fluidity concrete was thoroughly compacted by using internal vibrators, and high-fluidity concrete was poured without any vibrating compaction.
3.3 FIRE RESISTANCE TEST

Figure-3 shows the setup for the fire resistance test. A wall type furnace was used. Four burners installed in the furnace were used to raise the temperature by radiant heat. Two test pieces were attached to the furnace cover, and one side of each test piece was heated. Heat insulation material was installed around each test piece to prevent heat transfer through the surface of 200mm width sides of the test piece. In order to simulate the actual fire in a tunnel, temperature was raised to 1,200°C in 5 minutes after heating was started, and the temperature was maintained for 55 minutes in accordance with the RABT curve (German standard) shown in Figure-4. Temperature in the furnace was measured and controlled by using thermocouples located at a distance of 10 cm from the surface of the test piece to be heated. In the fire resistance test, temperature in the furnace and the time to the occurrence of explosive spalling were measured, and the surface of the test piece was observed with a heat-resistant CCD camera installed at the furnace window and also observed visually through the furnace window. After the fire resistance test, visual observation was conducted and explosive spalling depth was measured with calipers at 50mm intervals on the test pieces. The maximum value among the measurements was defined as the maximum explosive spalling depth, and the average of the measured values at every measurement points was defined as the average explosive spalling depth. The explosive spalling area ratio is given by the following calculation, i.e. the number of points where the explosive spalling were observed divided by the total number of all points at 50mm intervals on the surface of the test piece.

3.4 TEST RESULTS

(1) EXPLOSIVE SPALLING

In all cases, explosive spalling began to occur at furnace temperatures of 500 to 600°C about 2 minutes 30 seconds after heating was started, and then, ended within about 5 to 10 minutes. The circular fragments of concrete surface spalled off with 5 to 10 cm in diameter and several millimeters thick. In heavily damaged test pieces, the explosive spalling continued to occur intermittently. The Spalling areas overlapped each other and widespread damage of spalling occurred in several layers. On the other hand, the explosive spalling was occurred only several times in minor damaged test pieces.

(2) EXPLOSIVE SPALLING DEPTH AND EXPLOSIVE SPALLING AREA RATIO

Table-4 shows measurement results of explosive spalling depth. Figure-5 shows the relationship of explosive spalling area ratio with the maximum/average depth of the explosive spalling.
The maximum/average depth of explosive spalling are correlated with the area ratio, which corresponds with the fact that widespread explosive spalling actually occurred in several layers in heavily damaged test pieces.

Regarding the PP fiber, we found that explosive spalling depth is affected by the type of PP fiber in all test pieces. The depth of the explosive spalling was small in the test pieces with higher aspect ratio of PPD fiber. In test pieces FA-D, VM-D and BS-D which aspect ratio of the PP fiber is 570, the explosive spalling was completely controlled. To the contrary, large values of explosive spalling depth were obtained in SL-B, FA-A and VM-B, which are test pieces with lower aspect ratio of PPD fiber. Test piece FA-E with the highest aspect ratio of the PPE fiber, however, showed that the explosive spalling damage was greater than FA-D.

Figure-6 shows the distribution of the explosive spalling depth. In test pieces FA-A and VM-B with lower aspect ratio of the PP fiber, the widespread explosive spalling damage was observed over the entire surface of the test piece.

Figure-7 shows the relationship between the aspect ratio of the PP fiber and the maximum/average depth of the explosive spalling. Figure-8 shows the relationship between the aspect ratio and explosive spalling area ratio. In the test pieces with aspect ratio at or lower than 570, both the maximum/average depth and area ratio of the explosive spalling decreases with increasing of the aspect ratio. In the test piece with highest aspect ratio (855), however, the depth and area ratio of the explosive spalling are larger than the same in test piece with aspect ration is 570 (PPD). A possible cause is that PP fibers of too high aspect ratio, i.e. too long PP fibers, get entangled easily and become less dispersive in the concrete. Such PP fibers are less effective in release of water vapor pressure. Another possible cause is that because individual fibers are easily bent, the voids after PP fibers melt do not connect continuously from inside of concrete to surface, which also causes less effectiveness in the release of the water vapor pressure.
Table of explosive spalling depth:

<table>
<thead>
<tr>
<th>Aspect ratio of PP fiber</th>
<th>69~114</th>
<th>410</th>
<th>570</th>
<th>855</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midum fluidity Concrete</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
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<tr>
<td>SL-B</td>
<td></td>
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<tr>
<td>BL-C</td>
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<tr>
<td>BL-D</td>
<td></td>
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<tr>
<td>with Limestone powder (LP)</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
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<tr>
<td>LP-C</td>
<td></td>
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<td></td>
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<tr>
<td>LP-D</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>with fly ash (FA)</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>FA-A</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>FA-C</td>
<td></td>
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<tr>
<td>FA-D</td>
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<tr>
<td>FA-E</td>
<td></td>
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<td></td>
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<tr>
<td>with Blast furnace slag powder (BS)</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
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<tr>
<td>BS-D</td>
<td></td>
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<tr>
<td>with viscosity modifier (VM)</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
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<tr>
<td>VM-B</td>
<td></td>
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<tr>
<td>VM-C</td>
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<tr>
<td>VM-D</td>
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</tbody>
</table>

Figure-6 Distribution of explosive spalling depth
4 FULL-SCALE FIRE RESISTANCE TEST UNDER AXIAL FORCE

4.1 SPECIMEN

The test specimen used was 1,700 mm wide, 1,900 mm long and 500 mm thick. The specimen was designed as full-scale models of real lining segments. The main reinforcing bars D19 was placed at two levels and every 115 mm intervals. A compressive stress of 15.7 N/mm was applied to the specimen considering a possible axial force on the real lining segments. The compressive stress was loaded with stressing steel bars by the post-tensioning method. Figure-9 shows a test specimen. Figure-10 illustrates the axial loading method.

Concrete mix proportions were determined on the basis of the results of the fire resistance test using test pieces mentioned earlier. 10-millimeter-long PP fiber (aspect ratio: 570) with a fineness of 2.2 dtex were mixed (0.2 vol%) into high-fluidity concrete containing blast furnace slag powder as an admixture. Steel fibers(0.6 vol%) were also mixed into the concrete. The design strength of concrete was 48 N/mm².

4.2 FIRE RESISTANCE TEST

A wall type furnace was used as shown in Figure-10. The RABT curve shown in Figure-4 was applied assuming a temperature in actual tunnel fire. The heating zone measured 1,300 mm (longitudinal) by 900 mm (transverse), and the surrounding area of the specimen and the prestressing steel anchorage zones were covered with heat insulation materials to prevent heat transfer.

In the fire resistance test, temperature in the furnace and the time to the occurrence of explosive spalling were measured, and the surface of the specimen was visually observed from a heat-resistant CCD camera installed at the furnace window and also visually observed through the window. Figure-11 shows the locations of the thermocouples used to measure temperature at the several points of inside concrete. Photo-1 shows the setup for the fire resistance test.
4.3 FIRE RESULTS

(1) EXPLOSIVE SPALLING

Photo-2 shows the surface of a specimen after the fire resistance test. Any explosive spalling did not occur in this test, and even small pop-outs were not observed. Only fine cracks occurred at the surface of concrete and blackened steel fibers were observed at the surface, which do not affect fire-proof performance of the concrete. Photo-3 is a photo taken by CCD camera showing a state in the furnace.

(2) TEMPERATURE OF CONCRETE AND REINFORCEMENT

Figure-12 shows relationship between time and temperature in furnace, concrete temperature, and reinforcement temperature. Figure-13 shows the relationship between the highest temperature at each point of inside concrete and the distance from the heated surface to the measurement points. These results indicate that 1) the highest temperatures at the each measurement point become lower with increasing of the distance from the heated surface, and that 2) the highest temperature of reinforcement (244°C) corresponds with concrete temperature curve, which indicates that the temperature of reinforcement is nearly equal with concrete temperature at the same distance from the heated surface.

As specified BS standard (BS 8110 Part2, 1989), the compressive strength of the concrete and the tensile strength of the reinforcement become lower sharply due to the high temperature more than 350°C and 300°C respectively. Based on those temperatures, it can be assumed that concrete has sufficient strength at a depth of 43 mm or more from the heated surface, and reinforcement has the same at a concrete cover of 54 mm or more.
5 CONCLUSION

In order to determine the proper type of materials and proper mix proportion of SFRC Segments with Polypropylene fiber to improve fire-proofing performance, we conducted fire resistance tests with several test pieces which have different parameters, i.e. 1) fluidity of concrete, 2) concrete admixtures, and 3) aspect ratios of PP fiber. The findings from the fire resistance tests are as follows:

(1) The explosive spalling depth and the explosive spalling area ratio decrease with increasing of the aspect ratio of PP fiber. The highest aspect ratio (850), however, is less effective in preventing the explosive spalling.

(2) Mixing polypropylene fiber with aspect ratio of 570 is the most effective in preventing the explosive spalling for the following SFRC Segments, a) containing fly ash, b) containing blast furnace slag powder and c) containing viscosity modifier.

We confirmed that admixture of blast furnace slag powder and 0.2 vol% of polypropylene fiber with aspect ratio of 570 shall be mixed into the concrete for SFRC lining segments to improve fire-proofing performance.

Fire resistance test was conducted under axial loading with full-scale test specimen prepared with above-mentioned mix proportion. The findings from the test are as follows:

(3) Explosive spalling can be controlled even under axial loading by mixing 0.2 vol% of polypropylene fiber with an aspect ratio of 570 into SFRC lining segment containing blast furnace slag powder. This mix proportion shall be used for SFRC lining segments to improve fire-proofing performance in the future tunnel projects.

(4) We confirmed the relationship between the highest temperatures of reinstatement/concrete of inside concrete and the distance from the concrete surface. The data of those temperatures can be of use to estimate the strength of lining segments after exposure to fire, taking into account a lowering of strength of reinstatement and concrete due to exposure to high temperature of the fire.