Development of bottom ash and PP fiber added fire protection coating mortar for NATM tunnel concrete lining

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ABSTRACT: Underground spaces, like tunnels, have confined conditions. So tunnel fires can result in severe human casualties and structural damages. In recent years, in order to prevent these problems, clients are requesting that tunnel linings should be fire-resistant. Fire protection coating on the surface of concrete can give sufficient fire-resistant capacity to tunnel linings, reducing the risk of lining and ground collapse during or after a fire. Also the cost is very sensitive issue in popularizing the material. The newly developed cementitious fire protection coating material contains bottom ash and PP (polypropylene) fibers, which play important role in fire-resisting ability. The newly developed cementitious fire protection coating material has much better strength than the other fire protection materials currently available in the market. This paper describes the results of fire tests of the newly developed cementitious fire protection coating material applied concrete tunnel lining specimens for the application in tunnels.

1 INTRODUCTION

In March 24, 1999, a fire took 39 people's lives in Mont Blanc Tunnel, which connects France and Italy. Underground spaces, like tunnels, have confined conditions, so tunnel fires can result in severe human casualties and structural damages. Therefore, tunnels are enforced with very stringent fire safety requirements and preventive measures, which are gaining great importance in tunnel design. In recent years, in order to prevent these problems, clients are requesting that tunnel linings should be fire-resistant and new and old tunnels are applied with fire protection coating on the surface of concrete tunnel lining.

1.1 *Damage Mechanisms*

When a fire occurs in an unprotected tunnel, the main damage occurs by concrete spalling due to the rapidly increasing temperature. Moreover, in case of burning vehicles, there is a very long duration of the fire with extremely high temperatures of up to 1,200°C. Concrete spalling develops due to various damage mechanisms, resulting from interactions between working loads and thermally induced additional strains.

In the course of the thermo-hydraulic process, the temperature increase causes a transport of mass in the form of water, steam, and air through the pore structure of the concrete. Starting from the fire-exposed concrete surface, the concrete develops multiple zones of a dried-up, a drying, and a quasi water saturated zone. The formation of various zones is due to the steam that not only escapes through the fire-exposed surface, but also makes its way into the concrete. The steam condenses in the cooler zone, which increases the local water content up to the point of water saturation and, thus, brings about an extreme reduction in vapor permeability. Subsequently, the steam pressures generated in front of this zone become extremely high, up to the point where the tensile strength of concrete is exceeded, giving rise to sudden spalling of sections of the concrete.

The thermo-mechanical process describes the impact of thermally generated strains of the stresses and strength of concrete. On the one hand, inherent stresses are caused by a non-linear temperature distribution in the cross section. On the other hand, the different and temperature-dependent properties of the reinforcement and the concrete components give rise to different temperature expansion behavior. The aggregate will expand depending on the type of rock, while the cement matrix is subjected to shrinkage processes caused by drying-out and chemical changes. Further aggregate changes may be triggered by chemical reactions and mineralogical transformations as well as disintegration process.

The first step towards developing a fire-resistant concrete consists in preventing the thermo-hydraulic processes, i.e. the formation of a saturation zone and high steam pressures linked with it. This may be achieved by adding synthetic fibers to the concrete, as these fibers melt at temperatures of 160°C, depending on the type of fiber used. The capillary pores and micro cracks induced this way form the preferred steam transportation path. Theoretical studies corroborate the experimental finding that water vapor transportation and, thus, steam pressure equalization through fine cracks is much more effective than through larger individual cracks.

1.2 *Methods of fire-resistant*

Nowadays, to protect tunnel from the fire, several fire-resisting methods (i.e., spray type, cladding board type and blanket type and so on) are used.

Spray type fire-resistant is spraying the wet fire-resistant materials onto the internal surfaces of the tunnel. Before spraying the materials, the surfaces have to be thoroughly cleaned and steel mesh attached to prevent the sprayed lining from breaking off in pieces. Spray type coatings are very well suited to conforming with irregular shaped linings.

Cladding board type is attaching fire-resistant boards onto the internal surfaces of the tunnel. The boards can be attached either directly against the surface of with a gap, as controlled by the arrangement of attachment bolts.

Fire-resistant blanket types are made of materials such as ceramic fiber and organic fiber. The product is made by electrically melting the raw materials and then spinning them into laminated fibers which are formed into a blanket. The blanket can be applied to the internal tunnel surfaces using some type of framework such as punched metal. The blanket method is well suited for rounded surfaces such as hollows and depressions.

Spray type fire protection coating material is the one of the most efficient way to protect tunnels from the fire. So the fire protection coating material in this paper is also developed for spray type. But fire protection material is coated on concrete linings by hand and tested to confirm the performance of the material.

2 TESTING PROCEDURE

2.1 *Distinctive features of newly developed fire protection material*

Newly developed cementitious fire protection coating material is produced to meet safety requirement of tunnel structure for the fire damage and to facilitate casting and coating on construction site. Especially, this fire protection coating material is developed focusing on improving compressive strength to resist spalling or exfoliation due to severe vibration induced by train and traffic or by wind pressure.

This new coating material is primarily composed of cement, fire proof aggregate, and PP (polypropylene) fibers, which play vital role in fire-resisting ability. Fire protection performance is more strongly dependent on aggregate type than cement type, so type I ordinary Portland cement is used to produce the coating material. For aggregate, bottom ash from coal generated electric power plant is used as light weight fire proof aggregate over shell sand, which is used broadly in Europe and Japan. Bottom ash is 20% of burnt coal ash, which remains at the bottom of coal burner and has porous micro structure. Because of porous micro structure, bottom ash has superior heat insulating characteristic. Also, utilization of bottom ash is environmentally beneficial since it is a waste material which needs to be disposed. Because density of bottom ash is higher than shell sand, it enhances the strength of coating material. In order to minimize the reduction of bond strength during shotcreting due to the increase in density, accelerated setting agent is used. When concrete lining is applied with fire loading, PP fiber melts at temperatures of 160℃~180℃ forming a transportation path for free water steam to be released and prevent catastrophic spalling.

In order to form effective passageway for release of steam, fiber length and thicknesses of 18 mm and 2.1 denier, respectively, are used. This fireproof material is pre-mixing type where shotcreting and on site casting are possible. Material mixture design of cement to aggregate ratio of 1 to 1.5 and the fiber volume ratio of 0.25% are used. Also, acceleration setting agent of 1 volume percent is used to improve bond strength of the material for shotcreting. The water to coating material ratio of 0.395 is used for the mixture design. Since the material emphasizes strength as the main material property enhancement, compressive, flexural, and bond strength experiments are performed. The test datum are compared with the properties of the popular European fire proof coating material for shotcreting and on site casting. Experiment results are shown in Figures 1, 2 and 3.

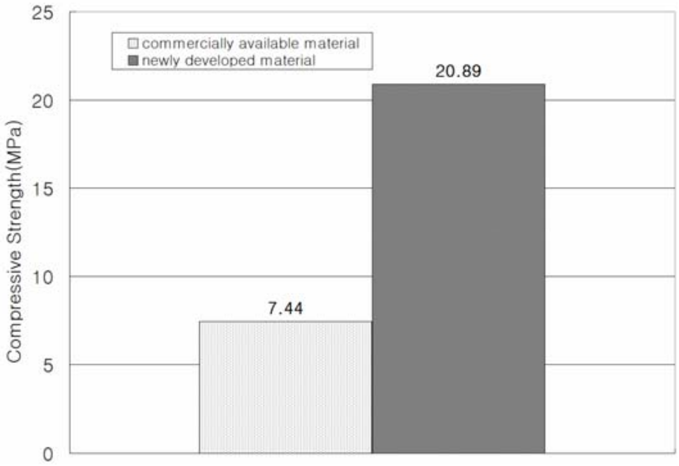

Figure 1. Comparison of compressive strength of commercially available material and new material.

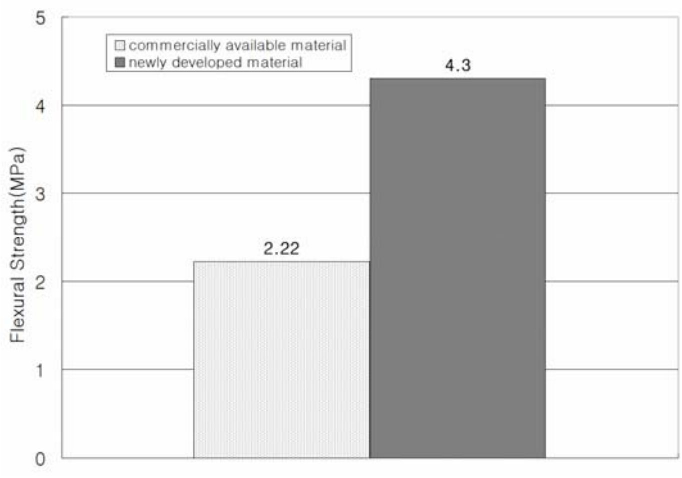

Figure 2. Comparison of flexural strength of commercially available material and new material.

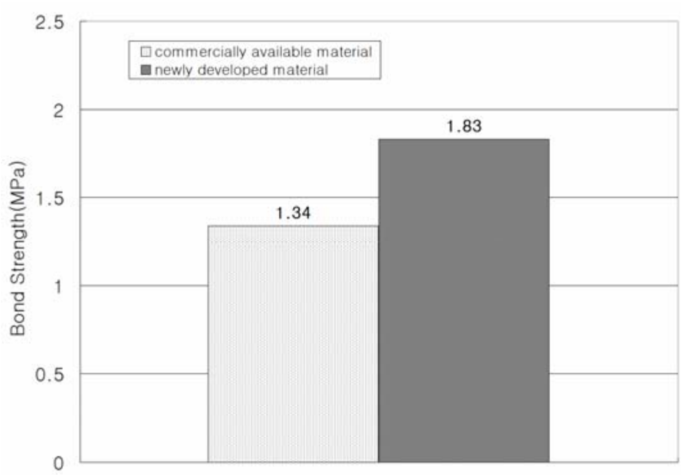

Figure 3. Comparison of bond strength of commercially available material and new material.

As shown in Figure 1, 28 day compressive strengths of the newly developed material and the commercially available material are 20.89 MPa and 7.44 MPa, respectively. Also, as shown in Figure 2, the 28 day flexural strengths of the newly developed material and the commercially available material are 4.30MPa and 2.22MPa, respectively. Finally, as shown in Figure 3, the bond strength of the newly developed material and the commercially available material are 1.83MPa and 1.34MPa, respectively. The improvement in bond strength is due to the usage of bottom ash and accelerated curing agent.

The experimental results confirm the superior strength performance of the newly developed cementitious fireproof coating material.

2.2 *Production of specimens*

In order to evaluate the newly developed fire protection material, the general NATM tunnel concrete lining with the coating material is fire tested. Concrete lining specimens are based on the original RC tunnel lining. The mix design of concrete of Korean Highway Corporation is used to cast original RC tunnel lining. Table 1 shows mixture design contents of concrete of RC tunnel lining.

Table 1 Concrete tunnel lining mix design

Material	Unit
	kg/m^3
Cement	334
Water	167
Fine aggregate	728.33
Coarse aggregate(G)	1025.13
	Unit
	%
Air	4.5
Plasticizer	0.2
AE agent	0.03
	Unit
	mm
G_{max}	25
slump	140

Specimen size and reinforcement type was selected based on typical NATM tunnel lining which is recently constructed. Specimen panel size is 1400mm×1000mm×400mm. D16 and D13 steel bars are used as main reinforcement and hoop reinforcement, respectively.

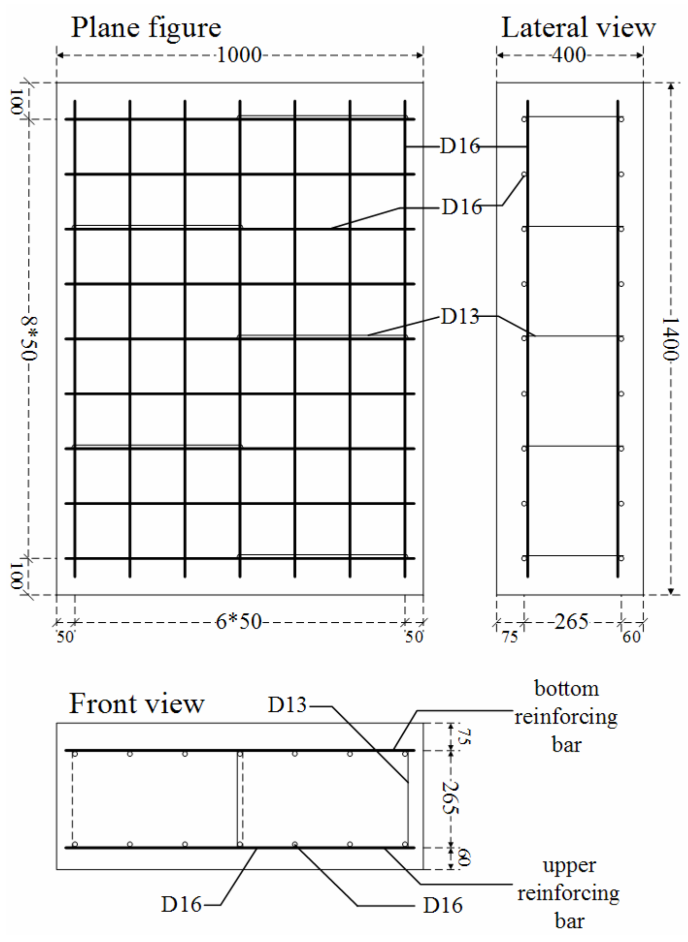

Figure 4. Schematic drawing of reinforcement arranged in the specimen.

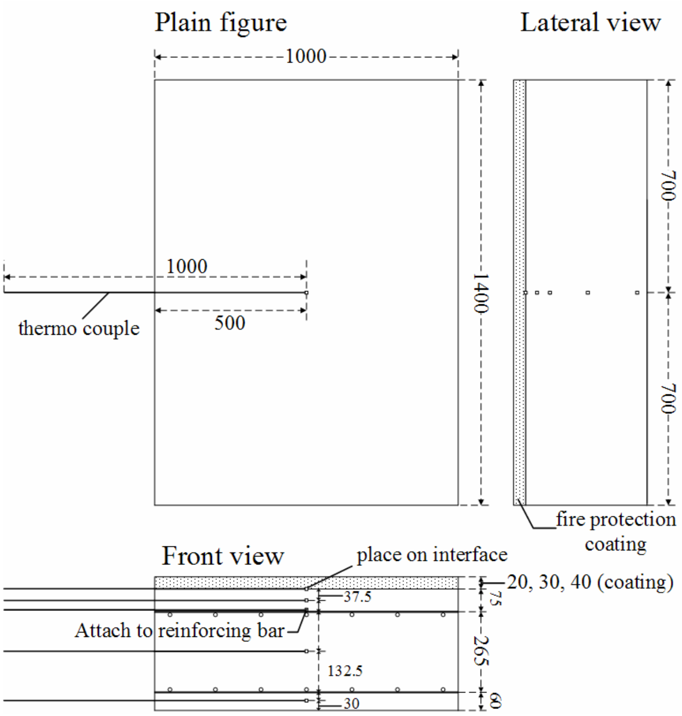

Figure 5. Schematic drawing of sheathed thermocouples locations.

K-type sheathed thermocouples were embedded at specified locations in the tunnel lining specimen to obtain the temperature data. Five thermo couples for fire protection coated specimens and four thermocouples for uncoated concrete tunnel lining specimen are placed at specific locations of specimen to measure temperatures. Thermo-couple locations are ①interface between concrete and fire protection coating, ②mid-depth of concrete cover thickness(37.5mm), ③surface of bottom steel reinforcing bar(75mm), ④mid-depth of specimen(207.5mm), and ⑤mid-depth of back concrete lining(370mm). Figures 4 and 5 show schematic drawing of reinforcement arrangement of the specimen and sheathed thermocouple locations, respectively. Figure 6 shows formwork and reinforcement layout. Figure 7 shows installation setup photo of sheathed thermocouples. Figures 8 show photos of concrete casted specimens.

Figure 6. Formwork and reinforcing.

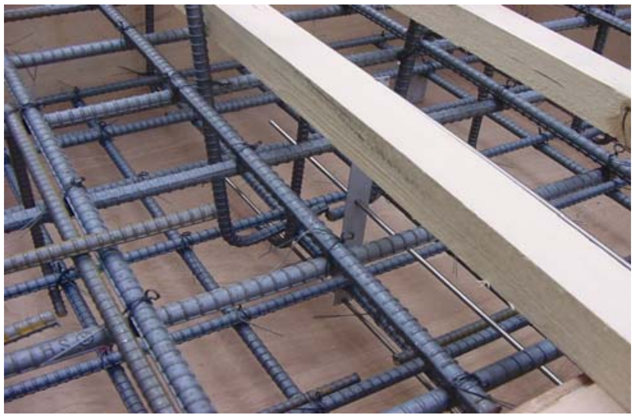

Figure 7. Installation of sheathed thermocouples.

Figure 8. Concrete casted specimens.

2.3 *Coating of fire protection material*

The developed fire protection coating material is applied on the concrete tunnel lining surface. Coating thicknesses of 20mm, 30mm and 40mm were selected to verify the fire protection performance according to the thickness of fire protection coating.

Figure 9. Steel wire mesh.

First, 1400mm×1000mm size of steel wire mesh was fixed to enhance interface bonding between specimen and fire protection coating. And after 28 days, dry cured specimens were coated with fire protection material by hand. Single specimen was produced for each thickness and single non-coated specimen was tested as a control specimen. Figures 9 and 10 are the photos of steel wire mesh to strengthen interface and application of the newly developed fire protection material on the specimen, respectively.

Figure 10. Coating the fire protection material by hand.

2.4 *Fire loading curve and fire test*

Fire test was carried out in KICT (Korea Institute of Construction Technology) after 28 days of dry curing of fire protection material. Fire was applied to the coated face of the specimen using LPG furnace. RABT fire curve was used as control temperature and temperatures obtained from thermo couples were recorded. Figure 11 shows time-temperature curve of RABT fire loading methods.

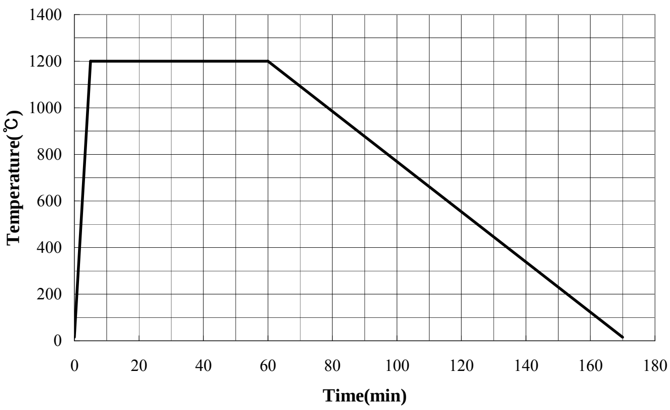

Figure 11. Time and temperature curve of RABT fire loading.

3 TEST RESULTS

3.1 *Concrete lining specimen without fire protection coating (control specimen)*

Figures 12 and 13 are photos of uncoated RC lining specimen setup on the furnace and temperature versus time test result, respectively. Figures 14 and 15 are individual temperature-time curves at mid depth of concrete cover and surface of bottom reinforcing bar, respectively. In all of the test result figures, the furnace temperature-time curve is shown for comparison purpose.

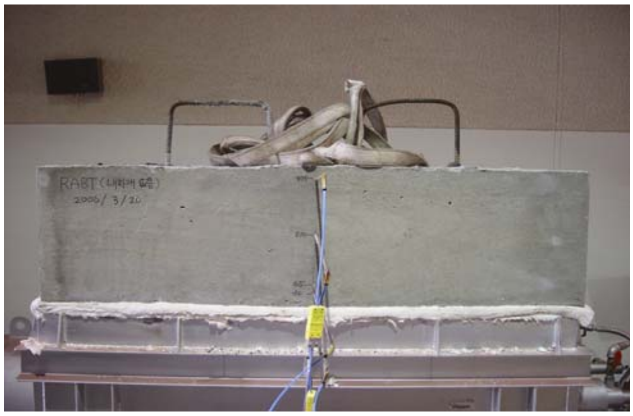

Figure 12. Concrete lining specimen without fire protection coating.

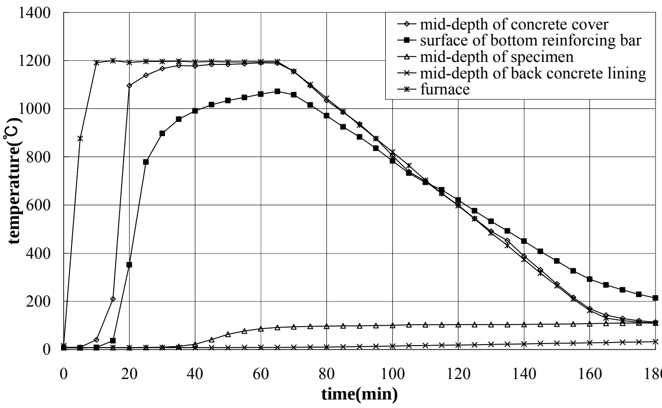

Figure 13. Test result of concrete lining specimen without fire protection coating

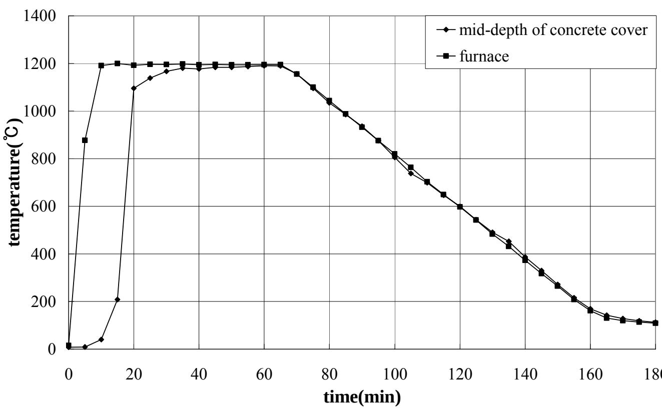

Figure 14. Time-temperature curve at mid-depth of concrete cover.

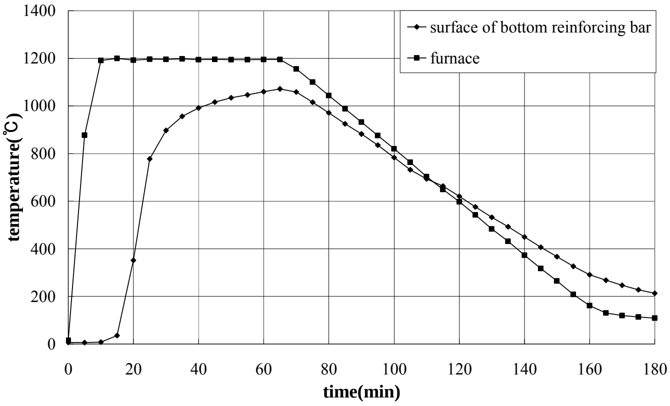

Figure15. Time-temperature curve at surface of upper reinforcing bar.

As shown on Figure 14, when the furnace temperature reaches 1200°C, temperature at mid depth of concrete cover abruptly increased due to the cover thickness spalling caused by high temperature. About 20 minutes after the start of the test, concrete surrounding the reinforcements also spalled off followed by rapid increase in temperature of the bottom reinforcement. On the other hand, Figure 13 shows that the mid-depth of RC lining specimen was not affected by the fire. During the test, water and steam were continuously released from the cracks progressed from the side surfaces of specimen. The cracks were propagated toward the upper part of the specimen at the side surfaces. The highest temperature measured at mid-depth of concrete cover was 1197°C, at surface of bottom reinforcing bar was 1075°C, at the mid-depth of specimen was 111°C, and at the mid-depth of back concrete lining was 33°C. Figure 16 is a photo of concrete lining specimen‘s bottom surface where the fire is applied. After the concrete lining cover was spalled off, exposed surface of concrete and aggregates could be identified. Figure 17 is a photo of cracks and eruption of steam from the cracks. Figure 18 shows surface of concrete lining cover after the test. Concrete lining cover was severely damaged by spalling and main reinforcement bar was exposed.

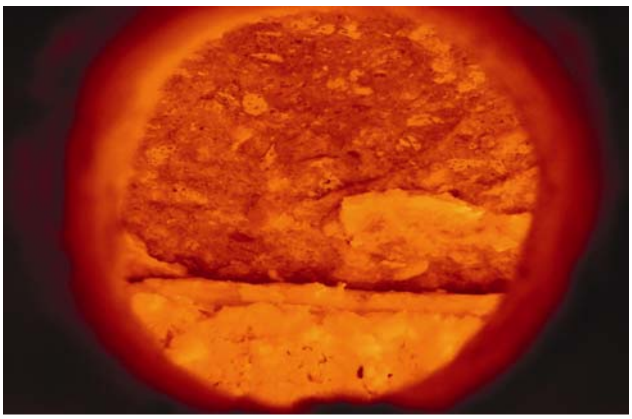

Figure 16. Surface of the specimen inside of the furnace after spalling.

Figure 17. Vapor eruption from cracks of the specimen.

Figure 18. Bottom surface of the specimen after test.

3.2 *Concrete lining specimen with thickness of 20mm newly developed fire protection coating*

Figures 19 and 20 are photos of concrete lining specimen with newly developed fire protection coating material of 20mm setup on the furnace and obtained temperature-time test results, respectively. Figures 21, 22 and 23 are individual time-temperature curve at interface of concrete lining cover and newly developed fire protection coating, mid-depth of concrete cover, and surface of bottom reinforcing bar, respectively.

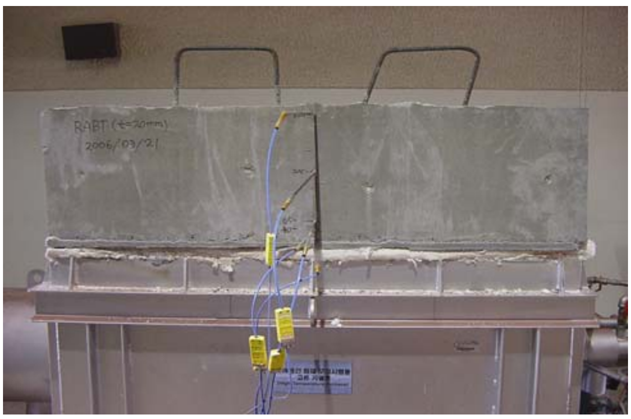

Figure 19. Specimen with 20mm thickness of fire protection coating.

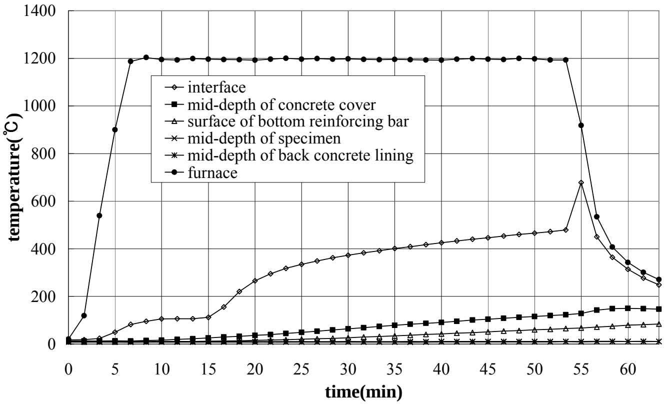

Figure 20. Test result of concrete lining specimen with thickness of 20mm newly developed fire protection coating.

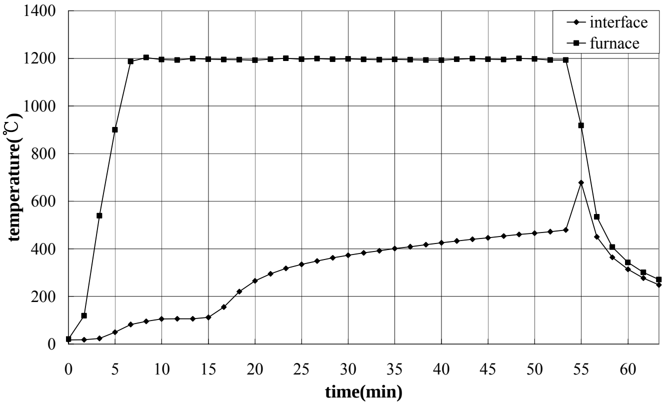

Figure 21. Time-temperature curve at interface of concrete lining cover and newly developed fire protection coating.

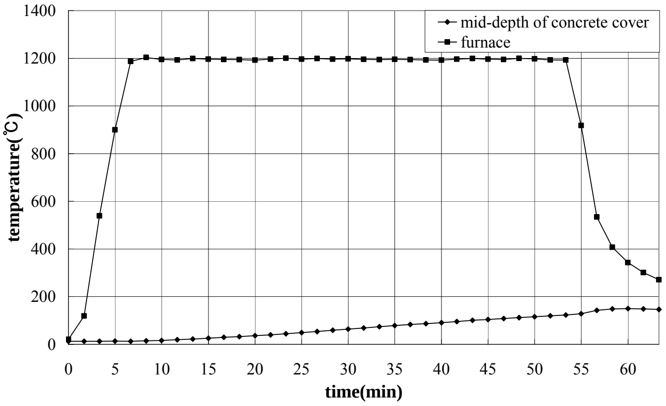

Figure 22. Time-temperature curve at mid-depth of concrete cover.

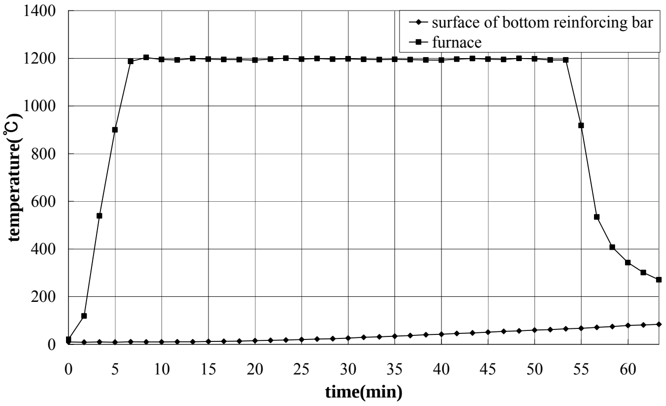

Figure 23. Time-temperature curve at surface of bottom reinforcing bar.

In the test of concrete lining specimen with coating thickness of 20mm, the fire protection coating was exploded abruptly by spalling after 50 minutes from the start of the test. Most of the fire protection coating was spalled off and test was stopped for a safety reason. When the test was stopped, temperatures at all positions were constantly increasing. From Figures 21, 22 and 23, the highest temperature at interface, mid-depth of concrete cover, surface of bottom reinforcing bar, mid-depth of specimen and mid-depth of back concrete lining was 839°C, 151°C, 85°C, 11°C and 12°C, respectively.

Figure 24 is photo of fire protection coating surface in the furnace before explosion of fire protection coating. Figure 25 is bottom surface of the specimen after the test. The figure shows that concrete lining cover and fire protection coating was severely damaged by impact of explosion. And steel wire mesh for strengthening the interface was separated from the specimen.

The spalling of the coated material shows that 20mm thickness is insufficient for resisting RABT fire curve's maximum temperature of 1600□.

Figure 24. Fire protection coating surface in the furnace before explosion.

Figure 25. Separated fire protection coating.

3.3 *Concrete lining specimen with thickness of 30mm newly developed fire protection coating*

Figures 26 and 27 are photos of 30mm coated concrete lining specimen setup on the furnace and obtained temperature-time test results, respectively. Figures 28, 29 and 30 are individual time-temperature curve at interface of concrete lining cover and newly developed fire protection coating, mid-depth of concrete cover, and surface of bottom reinforcing bar, respectively

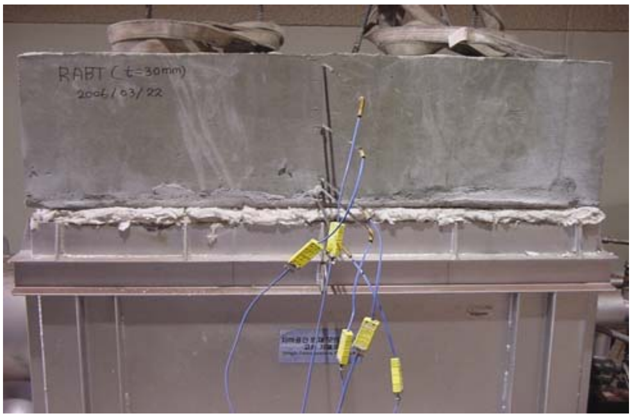

Figure 26. Specimen with 30mm thickness of fire protection coating.

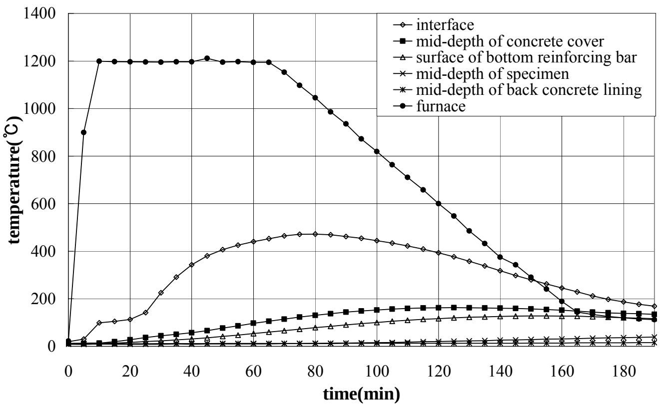

Figure 27. Test result of concrete lining specimen with thickness of 30mm newly developed fire protection coating.

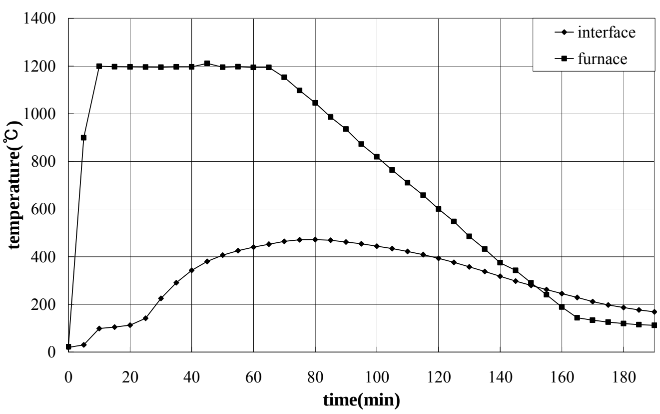

Figure 28. Time-temperature curve at interface of concrete lining cover and newly developed fire protection coating.

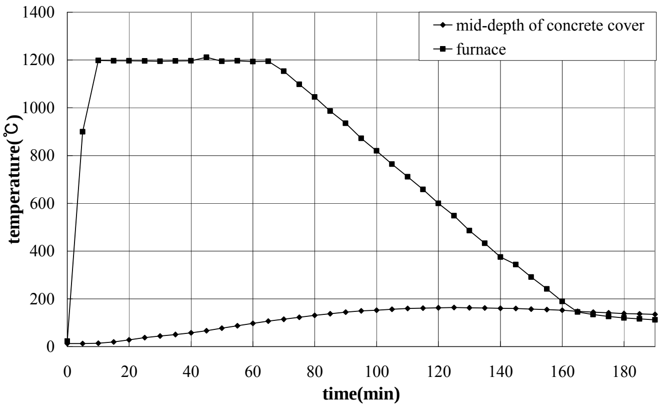

Figure 29. Time-temperature curve at mid-depth of concrete cover.

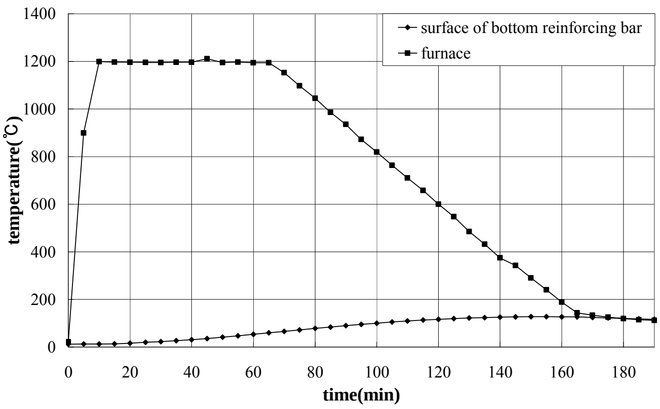

Figure 30. Time-temperature curve at surface of bottom reinforcing bar.

The behavior of concrete lining specimen with thickness of 30mm fire protection coating which was different than that of the specimen with thickness of 20mm fire protection coating, was stable during the test. 20 minutes later after the start of the test, temperature of interface between concrete lining cover and fire protection coating increased significantly. Significant amount of steam is released from the gaps between thermo-couples and specimen and also fire protection coating during the test, but the amount of steam is less than that shown from the specimen with thickness of 20mm coating. There were no cracks found on the specimen. The highest temperature measured at interface were 473°C, at mid-depth of concrete cover was 163°C, at surface of lower reinforcing bar was 129°C, at the mid-depth of specimen was 40°C, and at the mid-depth of back concrete lining was 16°C. Figure 31 is a photo of surface of the fire protection coating in the furnace from window. There were no changes of the surface during the test. Figure 32 shows vapors formed from released steam at the fire protection coating. Figure 33 is fire applied surface of the fire protection coating after the test and showed no significant damages except slight color change. The results show that the newly developed coating material with 30mm thickness is sufficient in resisting the temperature up to 1600°C.

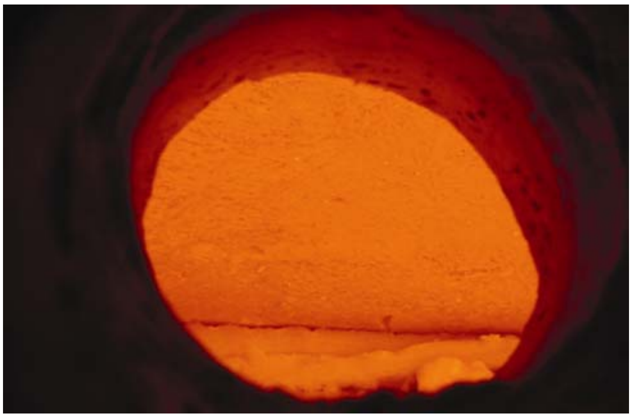

Figure 31. Surface of fire protection coating in the furnace.

Figure 32. Water drops formed on the fire protection coating.

Figure 33. Surface of fire protection coating after test.

3.4 *Concrete lining specimen with thickness of 40mm newly developed fire protection coating*

Figures 34 and 35 are photos of 40mm coated concrete lining specimen setup on the furnace and obtained temperature-time test results, respectively.

Figures 36, 37 and 38 are individual time-temperature curve at interface of concrete lining cover and newly developed fire protection coating, mid-depth of concrete cover, and surface of bottom reinforcing bar, respectively.

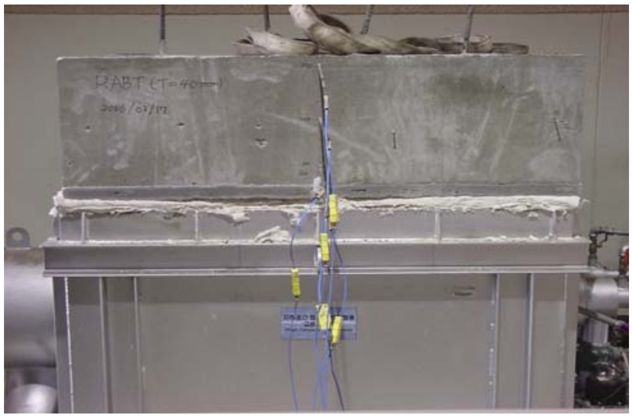

Figure 34. Specimen with 40mm thickness of fire protection coating.

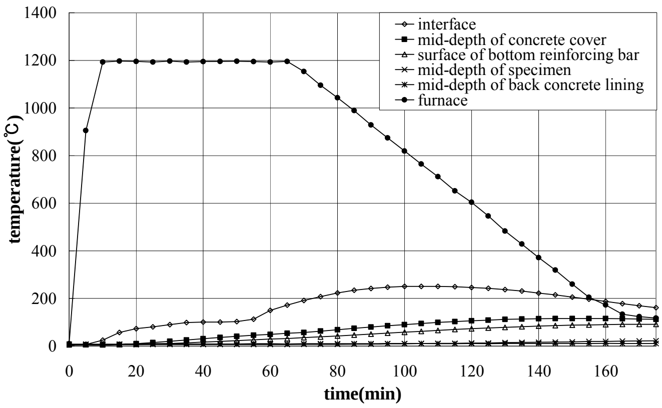

Figure 35. Test result of concrete lining specimen with thickness of 30mm newly developed fire protection coating.

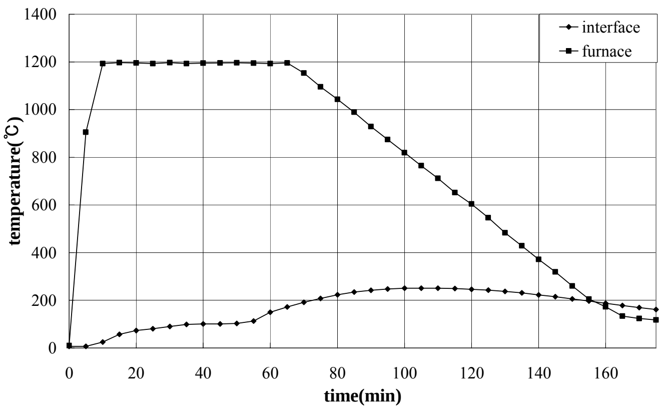

Figure 36. Time-temperature curve at interface of concrete lining cover and newly developed fire protection coating.

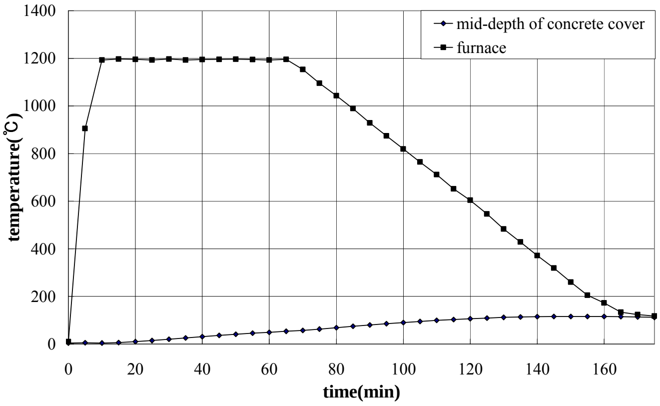

Figure 37. Time-temperature curve at mid-depth of concrete cover.

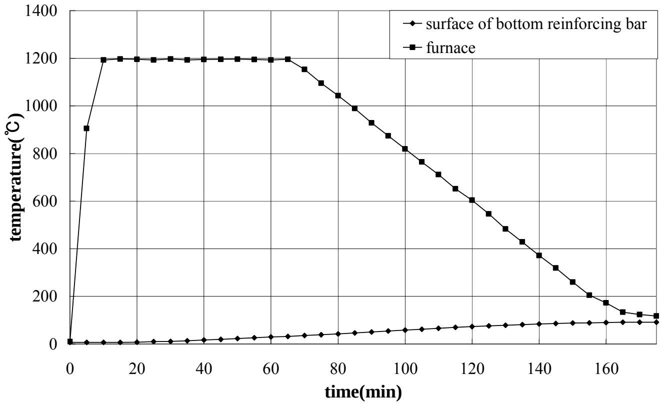

Figure 38. Time-temperature curve at surface of bottom reinforcing bar.

Test result of the concrete lining specimen with thickness of 40mm newly developed fire protection coating shows very similar behavior to that of the specimen with thickness of 30mm fire protection coating. However, the temperatures measured from the thermo couples were lower than that of 30mm coated specimen. Also, lesser amount of steam release was observed from the specimen and fire protection coating. The highest temperature measured at interface were 252°C, at mid-depth of concrete cover was 117°C, at surface of lower reinforcing bar was 93°C, at the mid-depth of specimen was 24°C, and at the mid-depth of back concrete lining was 12°C. Figure 39 is surface of the fire protection coating in the furnace during testing and no special surface changes were not found. Figure 40 is a photo of specimen with moisture stains, which is a evidence of escaped steam from the fire protection coating. Final Figure 41 shows surface of fire protection coating after the test and no significant damages were found. The results show that the newly developed coating material with 40mm thickness is most effective in resisting the temperature up to 1600℃

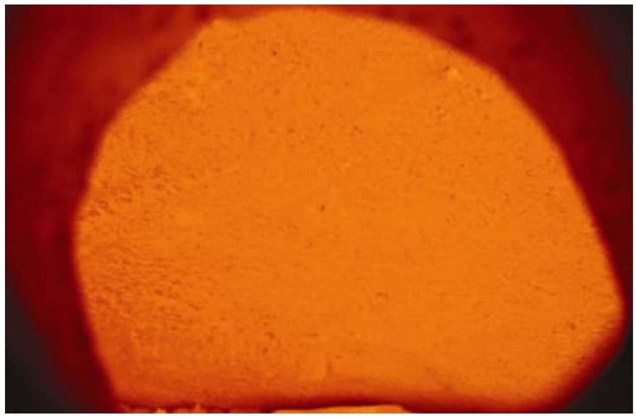

Figure 39. Surface of fire protection coating in the furnace.

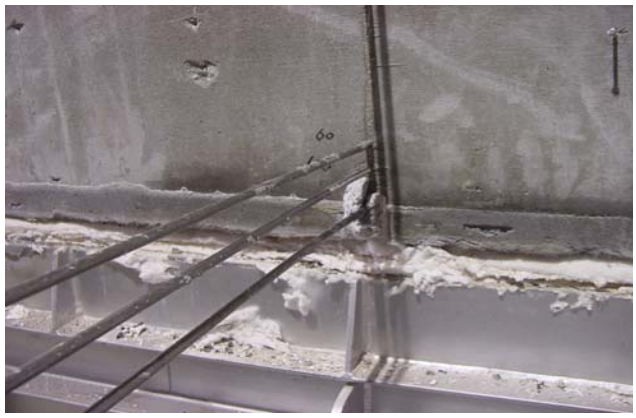

Figure 40. Water steam stain at the interface.

Figure 41. Surface of fire protection coating after test.

4 COMPARISON OF TEST RESULTS

(comparing the temperature at each location according to thickness of fire protection coating)

4.1 *Temperature at lining and coating interface*

Figure 42 is the test result comparison of temperature – time curve measured at the coating and lining interface.

For 20mm thickness coated specimen, the coated layer abruptly spalled off at approximately

20minutes after the start of the test. For safety reasons the test was stopped for this specimen. For 30mm and 40mm specimens, even though the coating thickness increased by 1cm, the temperature difference was two times larger in 30mm specimen than 40mm specimen. This proves that there is optimum coating thickness for fire protection of this newly developed material. Figure 42 shows that the maximum temperatures at the interface are reached at few minutes. After the furnace temperature descended from 1200℃, this trend means that the material is able to absorb the heat there by proving the effectiveness of the porous bottom ash usage in the material.

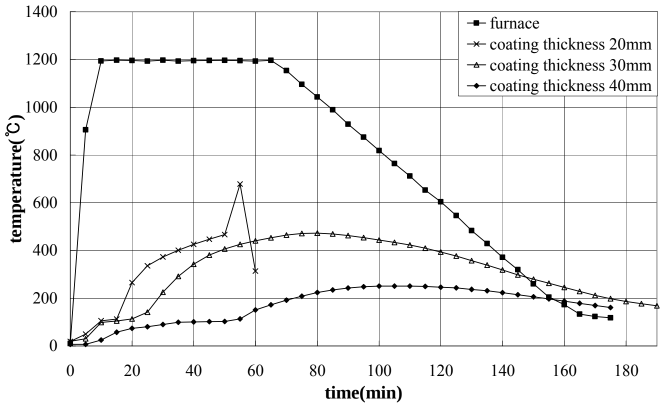

Figure 42. Test result of temperature at interface according to thickness of fire protection coating.

4.2 *Temperature at mid-depth of concrete cover*

Figure 43 is the test result comparison of temperature – time curve measured at mid-depth of concrete cover.

Obviously, the maximum temperatures at the mid-depth of concrete cover are lower than the maximum temperatures at the interface. This means that the applied fire was effectively resisted by the coating material since the maximum temperature was less than 200℃ for 40mm coated specimen. Between 30mm and 40mm coating thickness, the maximum temperature for 30mm thickness is approximately 139% than that of 40mm thickness. In any case, the damage from RABT fire curve is prevented using coating material.

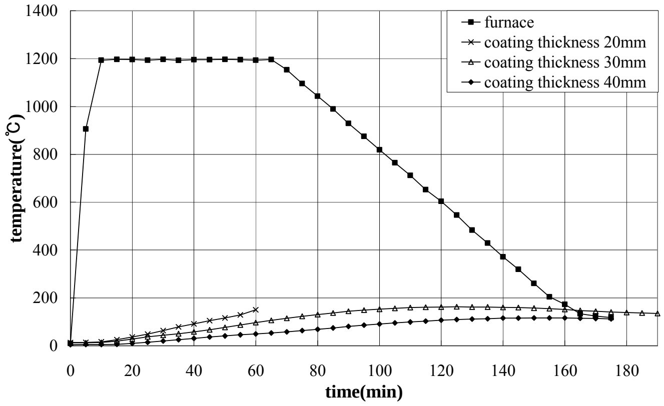

Figure 43. Test result of temperature at mid-depth of concrete cover(37.5mm) according to thickness of fire protection coating.

4.3 *Temperature of surface of bottom reinforcing bar*

Figure 44 is the test result comparison of temperature – time curve measured at surface of bottom reinforcing bar.

The maximum temperatures measured at this location were slightly less than the temperature measured at mid-depth of concrete cover, once again showing the effectiveness of the coating material in resisting fire damage. Since the maximum temperature at this position is approximately 129℃, the fire will not affect the reinforcing bars performance. Between 30mm and 40mm thickness coated specimen, the differences are very small and negligible.

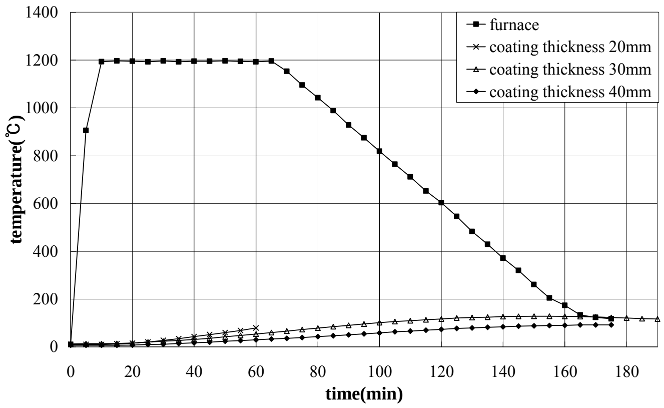

Figure 44. Test result of temperature at surface of bottom reinforcing bar(75mm) according to thickness of fire protection coating.

5 CONCLUSION AND SUMMARY

▪ During the test, concrete lining specimen with thickness of 20mm newly developed fire protection coating is destroyed because of the spalling induced high temperature.

▪ concrete lining specimen with thickness of 30mm newly developed fire protection coating showed ordinary performance with no spalling effect but little high inner-temperature of the specimen.
▪ concrete lining specimen with thickness of 40mm newly developed fire protection coating showed no spalling effect and lower inner-temperature of the specimen than specimen with thickness of 30mm fire protection coating. Therefore, this thickness of 40mm coating specimen showed best performance among all three specimens.

There were not any special damages in concrete lining specimens with newly developed fire protection coating thickness of 30mm and 40mm except spalled specimen with coating thickness of 20mm by high temperature. And also, there were few damages in coating. But unfortunately, specimens with fire protection coating thickness of 30mm showed very high temperature at the interface between coating and concrete lining which is nearly 500°C. When inner-temperature of concrete lining increases, concrete lining itself will have much probability to be failed by spalling caused high temperature and tension of reinforcement. So, in substance fire protection coating thickness of 30mm is insufficient for protecting concrete lining from the fire. On the other hand, fire protection coating thickness of 40mm has best performance. Coating thickness between 30mm and 40mm will be suitable choice considering economical aspects.

Therefore, this test proved that the newly developed fire protection coating material has enhanced fire protection ability and the thicker coating has more performance to protect concrete lining from fire events. Using bottom ash which has many minute holes in it, when produce fire protection material, makes fire protection ability higher. Moreover, industrial wastes from coal generated electric power plant are decreased and this is very beneficial effect for environment.

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