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Optimum PP Fiber Dosage for the Control of Spalling of High Strength Reinforced Concrete Columns

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Abstract: Spalling is defined as damages to concrete exposed to high temperature during fire, causing cracks and localized bursting of small pieces of concrete. As the concrete strength increases, the degree of damage caused by spalling becomes more serious due to impaired permeability. It is reported that polypropylene(PP) fiber has an important role in protecting concrete from spalling, and the optimum dosage of PP fiber is 0.2%. However, this study was conducted on non-reinforced concrete specimens. The high-temperature behavior of high-strength reinforced concrete columns with various concrete strength and various quantity of PP fibers is investigated in this study. The results revealed that the ratio of unstressed residual strength of columns increased as the concrete strength increased and as the quantity of PP fiber increased from 0% to 0.2%. However, the effect of PP fiber quantity on residual strength of column was barely above 0.2%.

Keywords: spalling, fire resistance, high-strength concrete, polypropylene fiber.

1. Introduction

High-strength concrete has many advantages such as better durability, usability and structure over regular strength concrete, and its application in building and civil engineering structures has been increasing gradually. However, it has a serious shortcoming in that the member becomes brittle with spalling caused by fire. Spalling is manifested as the result of compound reaction of vapor pressure and heat stress. Heat stress is generated due to the temperature difference inside the member during fire. Vapor pressure is formed, when the moisture inside the member is evaporated at the temperature above 100, and kept inside the water-proof concrete. Vapor pressure is reported[1,2] to be the dominant factor of influence on explosive spalling at the early stage of fire, and the spalling problem is more serious for low-ventilating materials such as high-strength concrete. Thus, the research and development of technology[3] to come up with material and structural solutions for this problem has been carried out by investigating the mechanism of spalling of high-strength concrete and identifying the factors of influence on spalling.

There are many practical methods for controlling the spalling of concrete such as (1) a method to deter the rise in temperature of the member during fire by applying fire-resistant cover or fire-resistant paint on the surface of concrete, (2) a method to restrain scattering of concrete by applying steel plate, fiber sheet, metal lath, etc. on the surface of member, and (3) a method to lower the vapor pressure during fire by mixing fiber upon pouring of concrete, etc. Among these, the last one, especially mixing polypropylene (PP) fiber upon concrete pouring, has been reported to be the most efficient method.[4-7] While spalling takes place at the temperature between 190°C~250°C, PP fiber melts typically at 170°C. The melted PP fiber creates microscopic ventilation in the cement matrix for the vapor pressure to pass through, thus lowering the vapor pressure.[1]

The research for using PP fiber as the material to control for the spalling of high-strength concrete has been actively pursued domestically and abroad. Sarvaranta,[7] Sarvaranta and Mikkola[4,5] showed that PP fiber was the most efficient among various fibers in the prevention of spalling. The experiment of Bentz[8] proved that, given the same quantity of PP fiber content, longer length of PP fiber was more advantageous in controlling the spalling. Recently, Japanese researchers have been working on using EVA, PVA, and PP powder[9] instead of PP fiber to solve the difficulty of using it in ultra-strength concrete over 100 Mpa. Examining domestic research, Han et al.[10] investigated the degree of spalling with respect to PP fiber dosage. However, their research was limited to the PP fiber dosage within 0.1%, and no optimum PP fiber dosage was suggested. Kim et al.[11] proposed that the optimum fiber dosage would be within 0.1% and could be derived experimentally based on their results of experiment on PVA fiber. As it has been discussed, the material research to use PP fiber has focused mainly on finding the optimum PP fiber dosage and length based on the experiment using test specimens. Nevertheless, it is the current situation that there is a lack of research at the level of the member to compute the optimum PP fiber dosage while considering the effects of the property change in re-bar being exposed to high temperature, the increase in vapor pressure

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due to the moisture membrane formed by the obstruction of the passage of moisture by tie-bar, and the deterioration in the structural performance due to the damage on concrete cross-section, etc.

Thus, this study aims to carry out fire-resistance test and residual strength experiments on reinforced concrete columns with the experimental variables of concrete strength and PP fiber dosage while observing the spalling process and measuring the residual strength. Then, the spalling property of high-strength concrete (HSC) column by PP fiber dosage is analyzed. Furthermore, the fundamental data to determine the optimum PP fiber dosage is suggested for the design of fire-resistant HSC member.

2. Experiment

2.1 Plan for test specimen preparation and mixing

A total of eleven column test specimens (260 × 260 × 800 mm) were prepared, and the details of the specimen lay-out is shown in Figs. 1 and 2.

All test specimens had the cover thickness of 40 mm and reinforcement ratio (ρ) of 1.69%. Moreover, K-type thermoelectric couples were installed at the space of 25, 25, and 80 mm from the surface. Additionally, the space between tie-bars in upper and lower capitals was reduced to one half of the space between tie-bars at the center (100 mm) in order to prevent the failure at the top and bottom ends of the member upon the exertion of loading. Furthermore, a steel rod of ϕ5 mm was embedded to install LVDT for the measurement of displacement in axis direction upon the exertion of loading.

The experimental variables for the test specimens were concrete compressive strength of 27, 60 and 100 MPa, PP fiber dosage of 0.1, 0.2 and 0.3% (the volumetric ratio to the concrete). The mix design for each specimen is shown in Table 1. The compressive strengths of the concrete specimens at 28 days were measured at 32, 60 and 85 MPa. Fly ash of 15% for the concrete mix strength of 27 MPa and 60 MPa and silica hume below 10% for the concrete mix strength of 100 MPa were mixed. Sullivan et al.[12] reported that the use of silica fume below 10% hardly influenced the spalling of concrete. Thus, this study employed 10% silica fume as the admixture.

Although the specific value for optimum PP fiber dosage has not been suggested in Korea, Kalifa et al.[6] carried out a research in this regard. They investigated factors directly related to the spalling of concrete such as the maximum pressure (P_{max}), the temperature at maximum pressure ($T_{P_{max}}$) and the slope of maximum pressure (ΔP_{max}) inside the test specimens. Based on their fire resistance experiment. They found that PP fiber dosage was influential to the control of spalling of concrete up to 1.75 kg/m³ (volumetric ratio of 0.19%) but was not effective in the control of

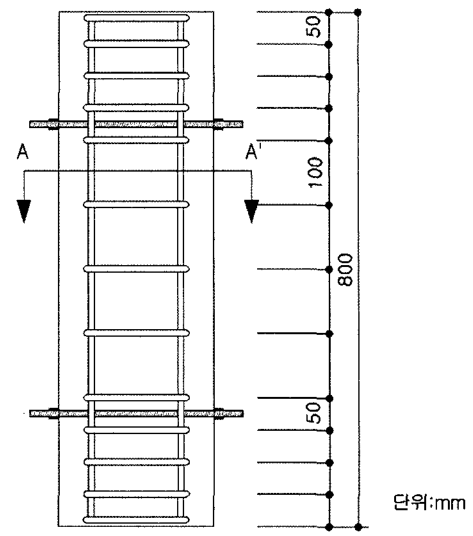

Fig. 1 Detail of specimen.

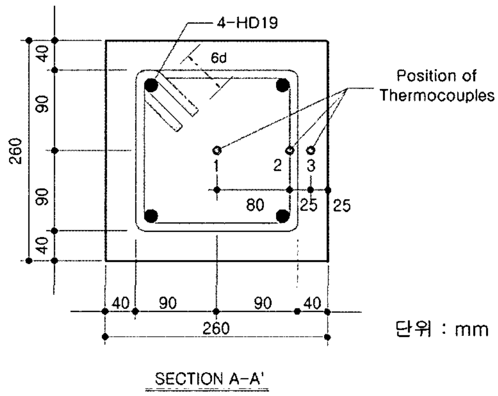

Fig. 2 Section detail and location of thermocouples.

Table 1 Mining proportions for specimens.

f_{ck} (MPa)	f_{28} (MPa)	Binder (kg)	W/C (%)	S/A (%)	Unit weight (kg/m³) W	C	F.A	S.F	S	G	PP fiber	PP fiber dosage (Vol. %)	Fire test	Specimen
27	32	364	48.4	47.6	176	309	55	0	817	906	0	0	×	27-S
											0	0	○	27-F-0
60	60	593	27.5	43.4	163	504	89		705	925	0	0	×	60-S
											0	0	○	60-F-0
											0.9	0.1	○	60-F-1
														60-P-1
											1.8	0.2	○	60-F-2
														60-P-2
											2.7	0.3	○	60-P-3
100	85	706	19.1	36.6	142.5	635		71	557	974	0	0	×	100-S
											0	0	○	100-F-0
s.gravity					1	3.15	2.18	2.15	2.60	2.67	0.9			

spalling above this dosage as shown in Fig. 3. This study prepared a column specimen to verify the optimum PP fiber dosage under the condition of actual structural composition and based on the result of aforementioned material experiment. PP fiber dosage for the experiment was set at 0, 0.1, 0.2 and 0.3%. It was reported that the addition of PP fiber at normal temperature to the concrete mix did not affect the concrete strength. The physical property of PP fiber used in this study is shown in Table 2.

2.2 Heating experiment

There are largely three methods of fire resistance experiment. Stressed test method employs heating and loading simultaneously. Unstressed test method involves no loading during heating process, and then loading is applied to the specimen while maintaining a constant temperature. Lastly, unstressed residual strength test method applies heat to the specimen, and then loading is applied after it is allowed to cool off. The concrete member of existing structure is subjected to loading while being exposed to fire, and the behavior of fire damage such as displacement speed, the time occurrence and degree of spalling, is manifested differently depending on the type and size of loading. Thus, while stressed test is appropriate in delineating the behavior of the member during fire and in fire-resistant performance evaluation, unstressed residual strength test is a method of choice in evaluating the factors of influence to the behavior of fire-damaged member. It is believed that the trend of factors for spalling of the concrete member can be found out through this method and that the fundamental data for the design of fire-resistant member can be finally suggested by a fire-resistant performance evaluation via loading experiment based on the result of this experimental method. Thus, this study conducted unstressed residual strength test in order to evaluate the influence of PP fiber on the structural performance of fire-damaged HSC columns. Heating experiment was conducted pursuant to KS F 2257-1 (fire resistance test method for construction structure member), which is based on the interna-tional standard of ISO 834-1, and followed the time-heating temperature curve as defined by the following eq. (1). Fig. 4 shows the standard heating curve depicting the relationship of time and heating temperature as indicated in eq. (1).

$$T = 345log_{10}(8t+1) + T_0 \tag{1}$$

2.3 Residual strength experiment

A test specimen was installed at UTM of 100 t capacity to measure the residual strength (i.e. the loading strength in the axis direction) of fire-damaged concrete column specimen as illustrated in Fig. 5. The top and bottom ends of the member were wrapped with a ceramic roll prior to heating in order to prevent spalling, and carbon fiber was affixed to prevent the destruction of capital part of the member after heating and prior to loading. In spite of the exertion of center-axis loading, slight eccentricity was observed upon loading due to irregular cross-section caused by random spalling. Nevertheless, the overall pattern of destruction exhibited the same pattern of destruction caused by center-axis

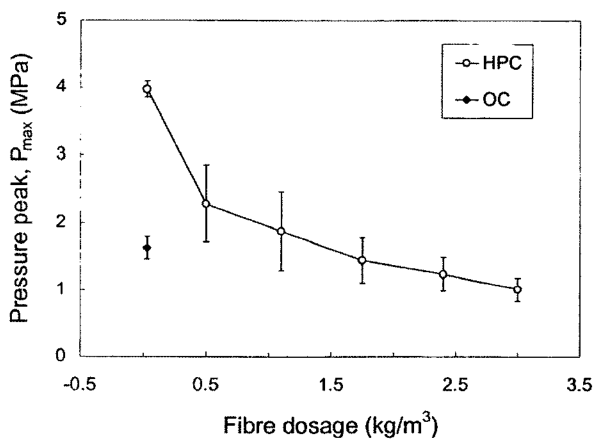

Fig. 3 Pressure peaks versus fiber content.[6]

Table 2 Material properties of PP fiber.

Material	Specific gravity	Length (mm)	Diameter (mm)	Melting point (°C)	Tensile strength (MPa)
Homopolymer polypropylene fibrillated fiber	0.9	19	0.07	162	400~550

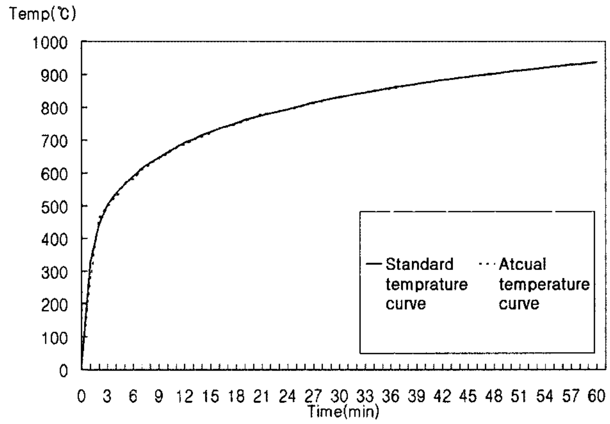

Fig. 4 Temperature curve fire-resistance experiment for 60 minutes.

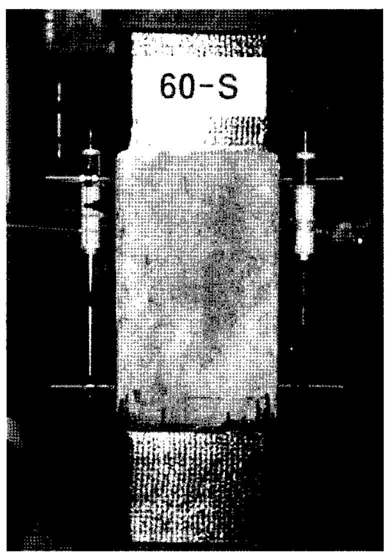

Fig. 5 Specimen setup.

loading. This point was verified by the difference in the measured displacement at both sides of the concrete column.

3. Experimental results and analysis

3.1 Spalling property

The degree of spalling was measured by visual inspection and mass reduction. Visual inspection observed the area and depth of spalling, and the degree of spalling was classified into the following three levels.

·Minor : Spalling occurred only at the concrete surface and did not reach the re-bar.

·Major : Spalling reached re-bar for it to be exposed.

·Severe : Spalling occurred inside tie-bar.

In addition, the degree of spalling was evaluated quantitatively by measuring the weight reduction of the concrete before and after the occurrence of spalling as shown in eq. (2).

$$\text{Spaling degree} = \frac{W_L}{W_C} \times 100 \qquad (2)$$

Table 3 Spalling type and degree.

Specimen	Spalling type	Spalling degree (%)
27-F-0	Minor	6
60-F-0	Severe	25
60-F-1	Major	11
60-P-1	Minor	8
60-F-2	Minor	7
60-P-2	Minor	6.5
60-P-3	Minor	7
100-F-0	Minor	25

Here, W_L indicates the weight reduction of the concrete due to spalling, and W_C represents the weight of concrete column specimen prior to heating. The result of evaluation by visual inspection and the measurement of weight reduction of the concrete is shown in Table 3 for each test specimen.

Examining the degree of spalling by the concrete strength as shown in Figs. 6 and 8, it can be seen that spalling was more severe for HSC columns than for regular strength concrete overall. This is construed due to the fact that permeability decreases as the concrete strength increases. Examination of spalling as shown in Fig. 8 reveals that the test specimen of 100 MPa strength had the cover peeled off evenly while the re-bar was not exposed. On the other hand, the test specimen of 60 MPa strength had the cover peeled off irregularly while the re-bar was exposed partially. Comparing the weight reduction between the two specimens of different strength as exhibited in Fig. 6, there was not much difference between test specimens of 60 MPa and 85 MPa strength. Thus, while it can be expected that the degree of spalling will be more severe for the specimen of 85 MPa due to the decrease in permeability along with higher strength, the silica hume admixture used in the concrete specimen of 85 MPa had the role of reducing the spalling of the concrete specimen.

Examination of the spalling degree by PP fiber dosage revealed that the degree of spalling was significantly reduced as the PP fiber dosage was increased as evidenced in Figs. 7 and 9. Especially, Fig. 7 shows that the degree of spalling was considerably reduced when the PP fiber dosage was over 0.1% and up to 0.2%. However, when the PP fiber dosage was over 0.2%, the reduction in spalling of the concrete specimen leveled off.

This experimental result is similar with the relationship between PP fiber dosage and maximum pressure as reported by Kalifa[6]

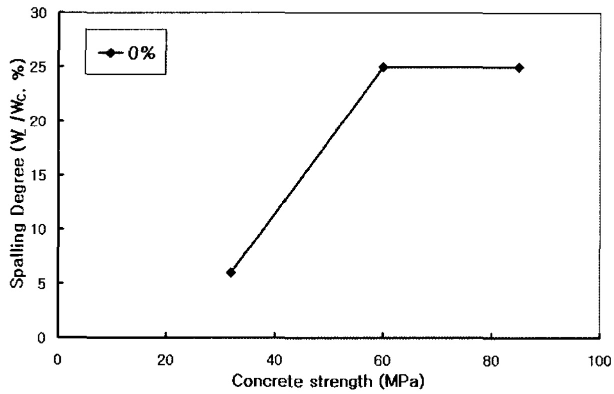

Fig. 6 Spalling degree according to concrete strength (PP fiber content 0%).

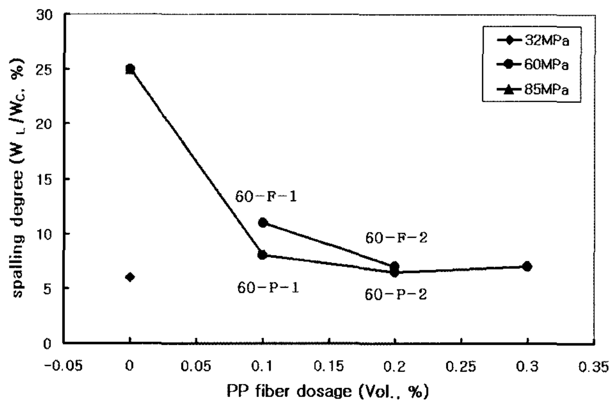

Fig. 7 Spalling degree according to PP fiber content PP fiber content.

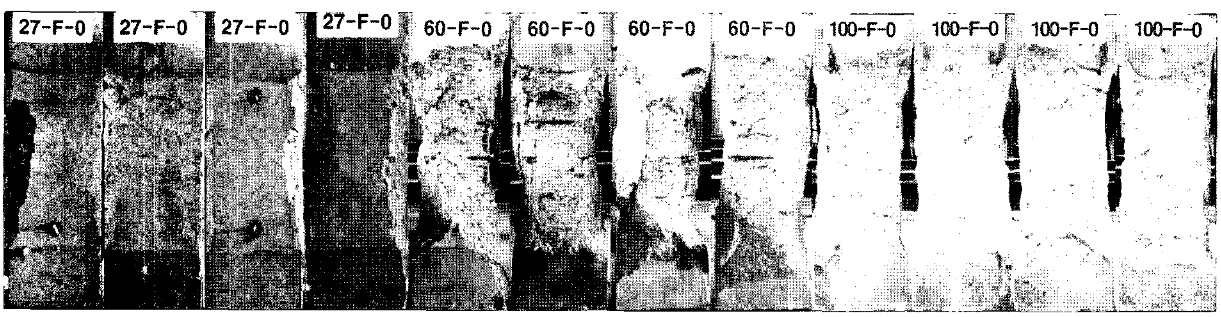

Fig. 8 Comparison of spalling shape according to concrete compressive strength (PP fiber content 0%).

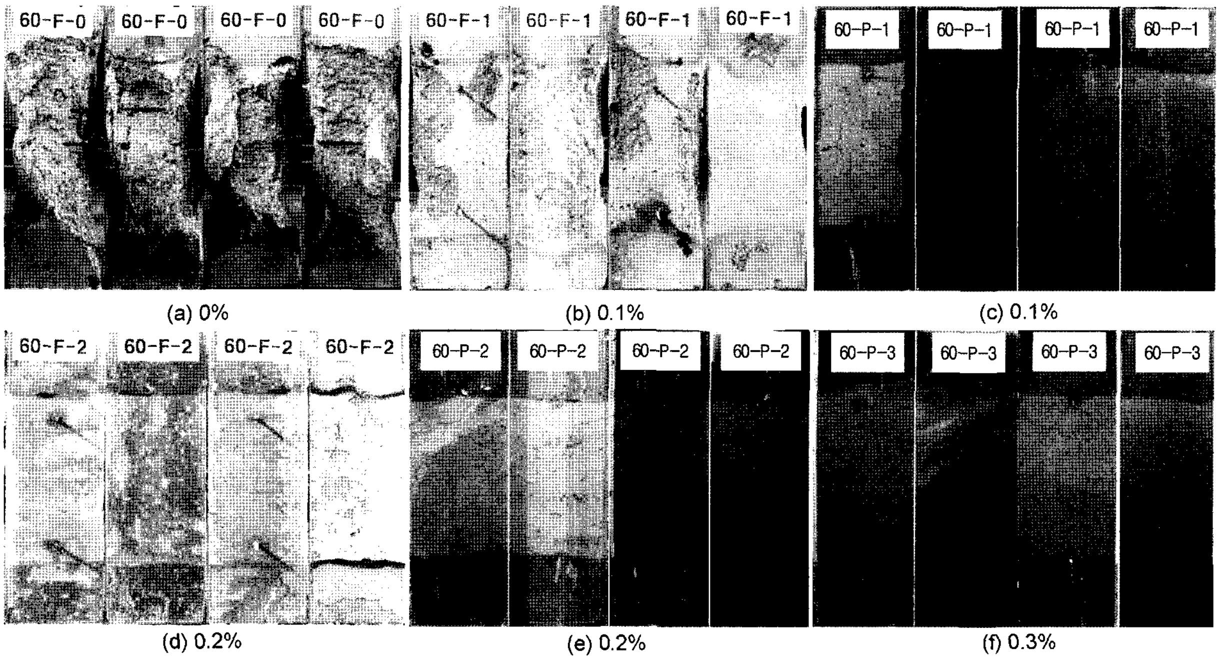

Fig. 9 Comparison of spalling shape according to PP fiber content.

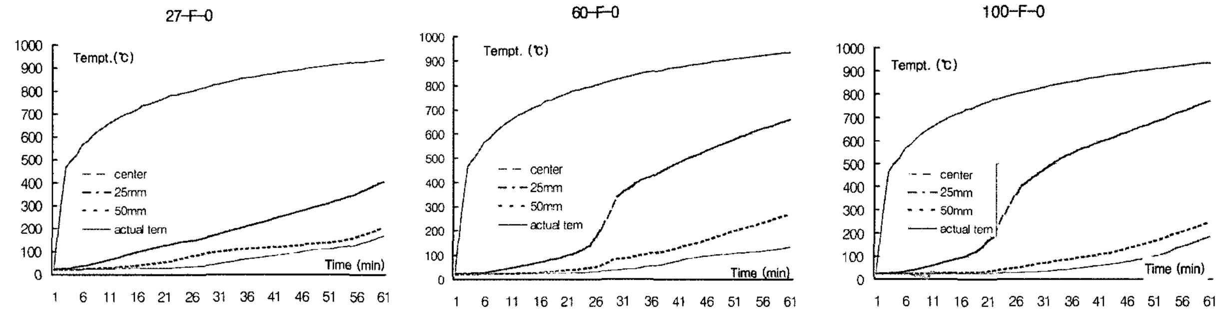

Fig. 10 Time-temperature curve.

based on his fire resistance experiment of the concrete test specimens.

3.2 Time-temperature curve

The time-temperature curve illustrates the distribution of temperature as measured by the thermoelectric couple installed inside the test specimen. Fig. 10 shows the characteristics of temperature distribution by concrete strength for the test specimen without PP fiber mixed in. The figure indicates that there was no part, in which the inside temperature changed rapidly, for the concrete mix specimen of 27 MPa strength. However, the concrete mix specimens of 60 MPa and 100 MPa strength had the temperature rapidly rising at the location closest to and 25 mm apart from the surface when heating was applied for 20~30 minutes to reach the temperature above 100°C . This is explained

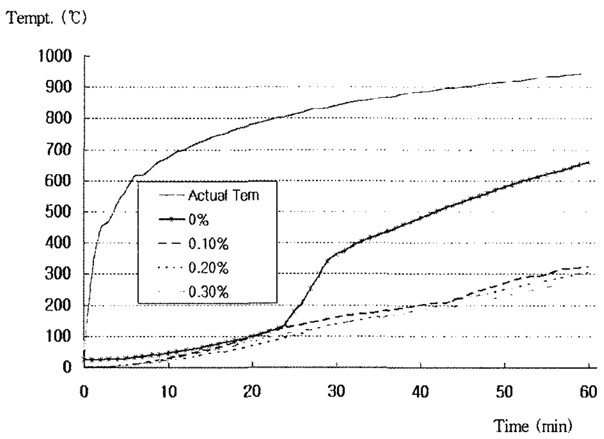

Fig. 11 Time-temperature curve (60 MPa, 25 mm).

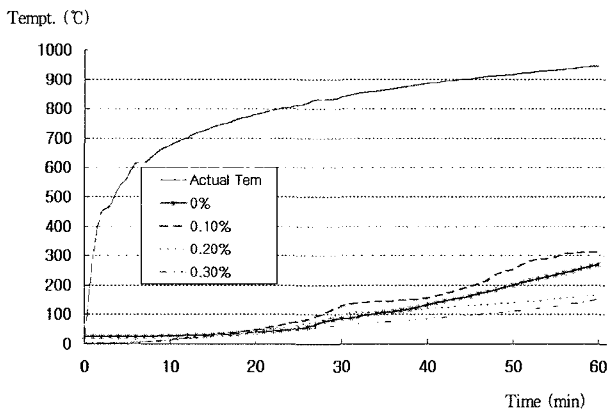

Fig. 12 Time-temperature cuvre (60 MPa, 50 mm).

by the reasoning that the path for heat conduction shortened due to the fact that the concrete cover of these HSC specimens was peeled off by spalling. Additionally, the temperature rise was about 5 minutes faster for the specimen of 100 MPa strength compared to the specimen of 60 MPa. This is reasoned that the former had earlier spalling because of its lower permeability. Figs. 11 and 12 compare the time-temperature curves as measured at the locations 25 mm and 50 mm apart from the surface, respectively, for the concrete specimen of the same strength, 60 MPa, in order to examine the influence of PP fiber on the temperature inside the concrete at high temperature. Fig. 11 shows that the temperature at the location 25 mm apart from the surface under the influence of spalling had the temperature rapidly rising due to the spalling of the concrete without PP fiber mixed in. On the contrary, Fig. 12 reveals that the temperature at the location 50 mm apart from the surface, where the influence of spalling is marginal, almost did not change with PP fiber dosage mixed in the concrete specimen. Thus, it follows that PP fiber does not directly affect the change in temperature of the concrete during fire.

3.3 Residual strength

The residual strength of the test specimens is analyzed as follows. The residual axis-strength ratio (P_f / P_s) is obtained by dividing the residual axis-load strength (P_f) of heated specimens after heating by the maximum axis-load of standard unheated test specimens (27-S, 60-S and 100-S). Then, it is compared by the concrete strength and PP fiber dosage. The maximum center axis-load of standard unheated specimens of 27-S, 60-S and 100-S was measured at 1,873, 3,664 and 5,070 kN, respectively.

Fig. 13 shows that the residual axis-strength ratio of columnar specimen increased at the concrete strength of 85 MPa. This is construed by the fact that the axial load strength of fire-damaged concrete column member is not only determined by the concrete strength depending on the temperature but is influenced by a variety of factors including the exposure or non-exposure of the main re-bar due to the spalling and the deterioration degree of the cross section, etc. As seen in Fig. 8, the cross section of the 85 MPa specimen containing silica hume (100-F-0) was deteriorated evenly by spalling, resulting in the higher residual strength ratio against the axial load in the absence of locally concentrated stress. In addition, as shown in Fig. 12, at the location 50 mm apart from the surface and confined by tie-bars at the temperature below 300°C, the decrease in residual compressive strength along with the increase in concrete strength is minimal. On the contrary, as shown in Fig. 11, when the concrete temperature outside the tie-bar at the location 25 mm apart from the surface reaches above 400°C due to the spalling, the reduction in the residual compressive strength along with the increase in the concrete strength is significant. However, it is peeled off due to the spalling so as not to influence the residual axial strength of the concrete column. Because of these reasons, it is found that the residual axis-strength ratio of the concrete column specimen increases at the concrete strength of 85 MPa as shown in Fig. 13. Additionally, although the weight loss due to the spalling is about the same for both 60 MPa and 85 MPa specimens as shown in Fig. 6, it is found that the residual axis-strength ratio is low for the concrete specimen of 60 MPa due to the decrease in the yield strength of the main re-bar exposed to the high temperature by the irregular

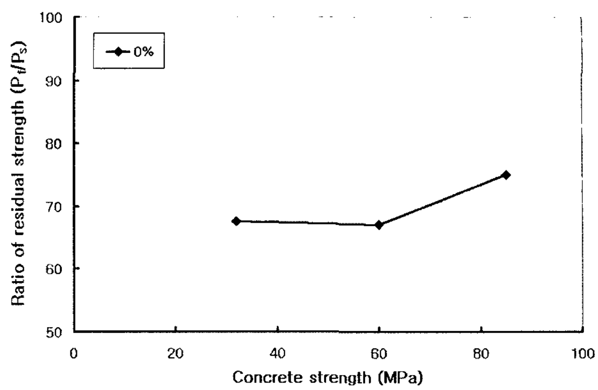

Fig. 13 Ratios of residual strength of columns according to concrete strength.

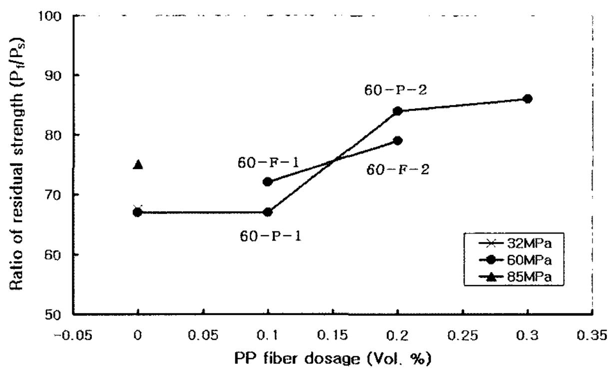

Fig. 14 Ratios of residual strength of columns according to PP fiber content.

spalling and the stress concentrated on the deteriorated cross-section among other factors.

Fig. 14 shows the residual axis-strength ratio of the concrete column specimen by PP fiber dosage. It shows that, as the PP fiber dosage increased from 0% to 0.2%, the residual axis-strength ratio increased constantly. However, the residual strength ratio almost stopped to increase with the PP fiber dosage above 0.2%. This point is construed by the fact that the reduction in the cross-section due to weight loss appeared uniformly without a significant change in the spalling pattern as the PP fiber dosage increased.

4. Conclusions

The following conclusions are derived from the experimental results.

1) The reduction in the concrete weight due to spalling of high-strength concrete columns was not proportional to the residual axis-strength ratio of the concrete column member. This is reasoned that not only the cross sectional reduction by the weight loss but also other factors such as the exposure of main re-bars in accordance with the spalling pattern and the localized cross sectional loss have influenced the residual axial strength of the member.

2) The result of this research revealed that the amount of weight loss of the concrete column member due to spalling remained almost the same when the concrete strength increased from 60 MPa to 85 MPa. However, the residual axis-strength ratio of the member increased about 10%. This is reasoned that silica

fume has affected the spalling behavior of the member.

3) When PP fiber dosage was increased from 0% up to 0.2%, the residual axis-strength ratio increased from 68% to 85%. However, when it kept increasing from 0.2% to 0.3%, there was almost no change in the residual axis-strength ratio. Thus, it follows that this experimental finding can be used as fundamental data for the computation of optimum PP fiber dosage.

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References

1. Bazant, Z. P. and Kaplan, M. F., *Concrete at High Temperatures : Material Properties and Mathematical Models*, Prentice Hall, 1996.

2. NIST, *International Workshop on Fire Performance of High-Strength Concrete*, Md Gaithersburg, Feb., 1997.

3. NIST IR 5934, *Fire Performance of High-Strength Concrete : A Report of the State-of-the-Art*, NIST, Dec., 1996.

4. Sarvaranta, L. and Mikkola, E., "Fiber Mortar Composites in Fire Conditions," *Fire Material*, Vol.18, 1994, pp.45~50.

5. Sarvaranta, L. and Mikkola, E., "Fiber Mortar Composites under Fire Conditions: Effects of Ageing and Moisture Content of Specimens," *Material Structure*, Vol.27, 1994, pp.532~538.

6. Kalifa, P., "High-Temperature Behaviour of HPC with Polypropylene Fibers from Spalling to Microstructures," *Cement and Concrete Research*, Jun., 2001, pp.1487~1499.

7. Sarvaranta, L., Jarvela, E., and Mikkola, E., "Fiber Mortar Composites Under Thermal Exposure," *Pluralis(Ed.), Proceedings of 2nd International Symposium on Textile Composites in Building Construction*, Lyon, France, 23-25 June 1992, pp.47~56.

8. Bentz, D., "Fibers, Percolation and Spalling of High Per-Formance Concrete," *ACI material Journal*, Vol.98, No.2, 2000, pp.351-359.

9. Kim, M. H., Yoon, H. D., Yoo, J. C., Kang, S. J., and KIm, G. Y., "Status of Research Trend and Performance Evaluation on Fire Resistance of Ultra-strength Concrete by Japanese Construction Companies," *Journal of Korea Concrete Institute*, Vol.17, No.5, 2005. (in Korean)

10. Han, C. G., Yang, S. H., Lee, B. Y., and Hwang, I. S., "Investigation of Spalling of High Performance Concrete in Response to Various Aggregate Types and Various Quantity of Polypropylene Fiber," *Proceedings of Korea Concrete Institute*, Vol.11, No.5, (53rd issue), 1999, pp.69~78. (in Korean)

11. Kwon, Y. J., Chang, J. B., Na, C. S., and Kim, M. H., "Trend of Research on Spalling of High-strength Concrete and Counter-Measures," *Special Issue of Korea Concrete Institute*, Vol.17, No.3, (86th issue), 2005. (in Korean)

12. Sullivan, P. J. E. and Sharshar, R., "Performance of Concrete at Elevated Temperatures (as Measured by the Reduction in Compressive Strength)," *Fire Technology*, Vol.28, No.3, August, 1992, pp.240~250.