An Experimental Study on Spalling of High Strength Concrete Elements under Fire Attack

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ABSTRACT

The spalling of high strength concrete under fire attack is discussed in this paper. Two series of fire tests on reinforced concrete elements were carried out in order to investigate the spalling behavior and effect of spalling on the fire endurance of reinforced concrete elements. The results of the fire tests on 30 specimens can be summarized as follows: a) the spalling is significantly affected by the water-cement ratio of the concrete, the permeability of the concrete, the amount of steel reinforcement, the fire intensity and the age of the concrete at fire exposure, b) the addition of polypropylene fiber into concrete is a good measure for the prevention of spalling and can improve the fire endurance of reinforced concrete elements, c) the addition of polypropylene fiber into concrete at a ratio of 1kg polypropylene fiber per 1m^3 concrete reduces the depth of spalling by about 18mm.

KEYWORDS : fire, concrete, spalling, reinforced concrete, column, beam, vapor pressure, polypropylene fiber, unloaded elements, loaded elements, ISO834, DIN4102 part 11

INTRODUCTION

The spalling of concrete under fire attack has been studied by many researchers for a long period of time [1, 2, 3, 4]. These efforts yielded very useful information for structural and material fire safety purposes. However, these results also indicated inconsistent performance of high strength concrete when spalling is concerned. But when a structural fire safety design of reinforced concrete elements and structures is performed, designers must know the degree of spalling, i.e. the depth of spalling of building element surfaces under fire attack in order to estimate analytically how long structural elements can sustain loads, and how long separating elements can contain fire in the compartment.

Moreover, though the effectiveness of polypropylene fiber (PP fiber) in the prevention of spalling has been reported [5, 6, 7, 8, 9], an optimum amount of PP fiber added into concrete mixture has not been clearly established. From the viewpoint of workability of concrete, a lesser amount of fiber is better for the placing of concrete at construction sites.

With the points described above as background, the study shown in this paper focuses mainly on the derivation of data useful in structural fire safety design. The report consists of two main parts:
1) fire tests on unloaded reinforced concrete columns and beams to investigate the degree of spalling (depth of spalling) of elements, and the effectiveness of PP fibers added into concrete to reduce spalling, and
2) fire tests on loaded reinforced concrete beams to confirm the structural advantage of the addition of PP fibers into concrete.

FIRE TESTS OF UNLOADED REINFORCED CONCRETE ELEMENTS

Materials and Mix Proportion of Concrete

The materials used in this study are shown in Table 1. Because of the low-heat of hydration the portland cement used contains more C_2S, which can reduce the internal temperature more during the hardening process, than the ordinary portland cement does, the low-heat portland cement is used for high-strength concrete in many cases in Japan. PP fiber for spalling reduction was subjected to TG-DTA analysis. It was measured that the weight loss of the PP fiber heated in the furnace of a TG-DTA equipment was more than 80% during heating up to 500°C.

The mix proportions and properties of the concrete are shown in Table 2. The mix proportions were designed to study the differences in degree of spalling under different water-cement (W/C) ratios, because it is generally known that the higher the strength of the concrete is, the higher the possibility of spalling. In order to find an optimum amount of PP fibers in concrete, some trial tests were done by testing concrete elements with PP fibers under different W/C ratios as shown in Table 2. PP fibers were added into the base concrete in the agitator of a truck and agitated for 2 minutes under high speed to ensure uniform distribution of the PP fibers in the concrete.

TABLE 1. Material used for concrete

Material	Type	Characteristics
Cement	Low-heat portland cement	Specific gravity 3.20
Coarse aggregate(for column)	Crushed sand stone	Specific gravity 2.65, water absorption 0.80%
Coarse aggregate (for beam)	Crushed sand stone	Specific gravity 2.65, water absorption 0.60%
Fine aggregate (for column)	Land sand	Specific gravity 2.62, water absorption 1.46%
Fine aggregate (for beam)	Land sand	Specific gravity 2.59, water absorption 1.63%
Chemical admixture	Superplasticizer	Principal ingredient : Polycarboxylic acid
Spalling protection	Polypropylene fiber	Diameter 0.1mm, length 12 - 19mm

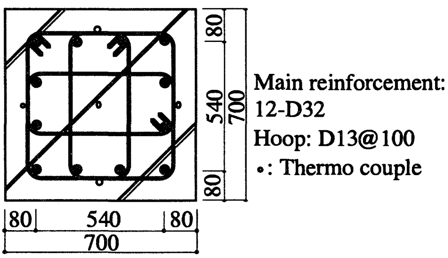
TABLE 2. Mix proportions and properties of concrete

Name [*1]	W/C	Water	Cement	s/a [*2]	Fiber	Compressive strength [*3]	Moisture content [*3]
C27.5	27.5	165	600	40.0	0	88.0 (2) / 118.1 (12)	4.6 (2)
B27.5	27.5	165	600	40.0	0	112.0 (2)	4.7 (2)
B27.5-1.0	27.5	165	600	40.0	1.0	98.7 (2)	5.0 (2)
C30.0	30.0	165	550	48.2	0	97.9 (2)	4.8 (2)
C30.0-1.0	30.0	165	550	48.2	1.0	97.2 (2)	4.7 (2)
C31.7	31.7	165	520	46.0	0	92.4 (2) / 112.4 (12)	4.2 (2)
C37.5	37.5	165	440	48.0	0	77.3 (2) / 82.9 (12)	4.5 (2)
C37.5-1.0	37.5	165	440	48.0	1.0	78.6 (4)	6.0 (4)
C44.9	44.9	175	390	49.0	0	59.5 (2) / 74.4 (12)	4.7 (2)
C48.6	48.6	175	360	49.0	0	52.8 (2) / 62.5 (12)	4.9 (2)
C64.4	64.4	190	295	50.0	0	21.2 (2) / 24.3 (12)	6.1 (2)

*1 : C = concrete used for column specimens, B = concrete used for beam specimens
*2 : s = fine aggregate, a = fine aggregate + coarse aggregate, s/a = volume percentage
*3 : The compressive strength and moisture content of concrete samples were obtained from cylindrical specimens (ϕ10x20cm) sealed during curing under the same conditions of columns and beams which were placed in a laboratory. The numbers in parentheses indicate the concrete ages in months in the test for the properties.

Specimens

The geometries of column and beam specimens are shown in Figure 1. The cover thickness from the surface to the hoop or stirrup is 40 - 50 mm. The height of the column is 1.4m which was decided from the height of the furnace we have used for the tests. The length of the beam was 3.6m, also decided from the length of the furnace. Temperatures in the specimens were measured with thermocouples. Pressures in the beam specimens were measured with stainless tubes (ϕ10mm). One opening of the tube was placed at a measuring point in the specimen, and a pressure transducer was attached to the other opening. Concrete columns without reinforcement were also tested to investigate the effect of reinforcement. Before fire testing, all specimens were cured in a laboratory climate for periods indicated in Table 2.



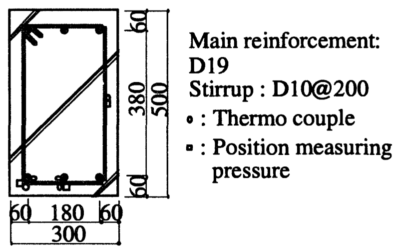


FIGURE 1. Cross section at mid height of column (left) and cross section at mid span of beam (right) (unit : mm)

Experimental Parameters and Test Conditions

Experimental parameters for unloaded specimens are summarized in Table 3. The fire tests with unloaded elements consisted of three series. In the first series, W/C ratio, age of the concrete, fire intensity and reinforcement were the chosen parameters. In general, the higher the fire intensity, the higher the possibility and degree of spalling. The reason for applying the fire temperature - time curve prescribed in DIN4102 part 11 is that most compartment fires in buildings might grow gradually in the early stages of a fire and rapidly grow at the point of flashover. The ISO834 fire simulates a temperature - time curve of a post-flashover fire. For these reasons, it had been assumed that the spalling degree under DIN4102-11 fire could be less than that under ISO834 fire.

In the second series, the amount of PP fibers was the only parameter so as to get data which may establish a mechanism of spalling reduction. The main role of PP fibers in the reduction of spalling is normally attributed to the fact that the fibers produce tubular pores through which pressurized water vapor in the exposed concrete can diffuse and flow out of concrete rapidly [8], because PP fiber tends to melt under a temperature above 100 °C.

In the third series, W/C ratio and the amount of PP fibers were chosen as the parameters in order to find an optimum amount of PP fibers which should be added into concrete.

Table 3. Test parameters

Test	Parameters			
Series	Concrete	Conc. age at test	Fire intensity	Reinforcement
1	C27.5, C31.7, C37.5	2 months / 1 year	ISO834 / DIN4102-11*1	Applied / Not applied*1
	C44.9, C48.6, C64.4	2 months / 1 year	ISO834	Applied
2	B27.5, B27.5-1.0	2 months	ISO834	Applied
3	C30.0, C30.0-1.0	2 months	ISO834	Applied
	C37.5, C37.5-1.0	4 months	ISO834	Applied

*1 : tested only for two-month-old specimens

Results and Discussion

Temperature of reinforcement (Series 1) : Average temperatures measured at the steel hoop in the unloaded reinforced concrete columns (see Figure 1) are shown in Figure 2. Temperatures of the two-month-old concrete columns indicate that a lower W/C ratio leads to a higher degree of spalling. The same tendency regarding the temperatures of the columns can be seen in one-year-old concrete. However, comparing elements with the same W/C ratio, temperatures of the one-year-old columns are lower than those of the two-month-old columns. Temperatures measured in the columns exposed to DIN4102-11 fire show the same tendencies in relation to the W/C ratio. Steel temperatures resulting from heating by ISO834 or DIN4102-11 fire indicate that ISO834 fire leads to higher steel temperatures after equal fire exposure time.

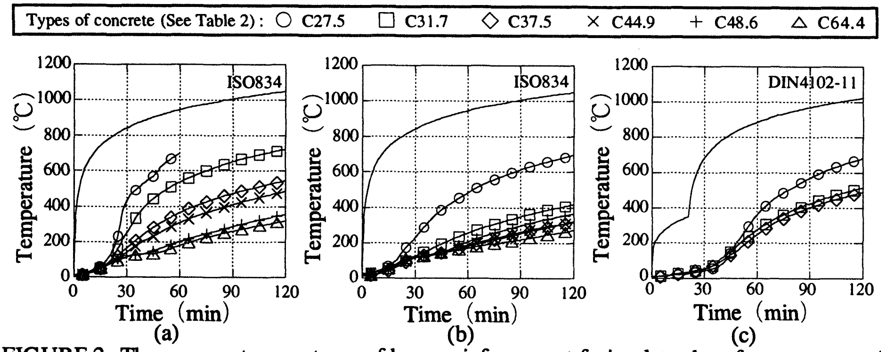


FIGURE 2. The average temperatures of hoop reinforcement facing lateral surfaces, measured at test series 1 ((a): concrete age 2 months, ISO834 fire, (b) concrete age 1 year, ISO834 fire, (c) concrete age 2 months, DIN4102-11 fire)

Depth of spalling (Series 1) : The depths of spalling measured on the lateral surfaces of the unloaded reinforced concrete columns and the concrete columns without reinforcement are shown in Figure 3. Figure 4 shows the specimens after the fire tests. The dotted lines in Figure 3 show the depth at the average depth plus 20mm and the depth at the average depth minus 20mm. The 20mm lines represent the maximum diameter of the coarse aggregate used for the concrete. More than 90% of the test results are scattered within these two dotted lines.

Comparing (a) with (b) in Figure 3, it is clear that a lower W/C ratio of concrete leads to deeper spalling. The spalling depth of one-year-old columns is less than that of two-month-old columns. Spalling does not occur or only slightly occurs in the case of reinforced concrete columns with W/C ratio larger than approximately 50% for two-month-old concrete, and 45% for one-year-old concrete. These results indicate the influences of the strength and moisture content of concrete. Though the moisture content for the one-year-old concrete sample was not measured, it can be assumed that the moisture content of the one-year-old concrete is less than that of the two-month-old concrete, because water in concrete is consumed by the hydration of cement which leads to the growth of strength, and drying from the surface of concrete until the moisture content reaches an equilibrium state. It is generally observed that the lower the moisture content, the lesser the possibility of spalling caused by vapor pressure in concrete.

Comparing (a) with (c) in Figure 3, it is clear that the spalling depths of reinforced concrete columns are deeper than those of concrete columns without reinforcement. Spalling would not occur or would only slightly occur in concrete columns without reinforcement with W/C ratio above 40% for two-month-old concrete. The calculated distributions of stresses and temperatures in a column section are shown in (a) and (b) of Figure 5. In the case of the reinforced concrete column, the compressive stress caused by the restraint of thermal elongation by the main reinforcement is observed in the concrete near the surface exposed to fire. On the other hand, in the case of the concrete column without reinforcement, a very low tensile stress caused by the thermal elongation of the core concrete is observed in the concrete. The reason for the low tensile stresses near the surface is that the strain of concrete is the sum of stress strain, thermal strain and compressive transient creep strain. The transient creep strain grows during heating and is irreversible, it exceeds the thermal strain in the calculation. The difference in degree of spalling between reinforced concrete columns and concrete columns without reinforcement could be attributed to the magnitude of restraint of thermal elongation of the surface concrete exposed to fire. This means that compressive stresses near the surface of elements have an effect on spalling. The compressive stress is dependent on the amount of main reinforcements, external load, internal load (for example : pre-stressed concrete) and so on. The effect of external load on spalling is discussed in [1]. The effect of internal load is discussed in [2]. The information in these studies is reconfirmed by the test results and the calculation results shown in Figure 3 and Figure 5. But, according to fire tests shown [in 9, 11], the influence of external loads is hardly seen. It may be concluded that there is a critical amount of reinforcement, especially main reinforcement. If the amount of main reinforcement exceeds a critical value, the influence of external loads can be ignored.

Comparing (a) with (d) in Figure 3, the spalling depths measured for DIN4102-11 fire are deeper than those measured for ISO834 fire. This result can be confirmed with Figure 4 (a) and (d), though the steel temperatures of (a) and (c) in Figure 2 cannot explain those results. According to the comparison of (a) and (c) in Figure 5, there are no obvious differences in temperatures and stresses in the column sections at the time when spalling starts in the fire test. Because of this, it is possible that a higher vapor pressure is attained over a longer period of time in the case of DIN4102-11 fire than in the case of ISO834 fire.

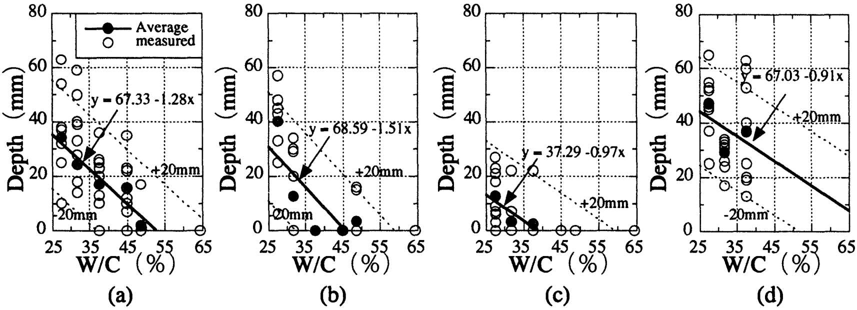


FIGURE 3. Depths of spalling on the lateral surfaces of columns measured in test series 1 ((a) RC column, concrete age 2 months, ISO834 fire, (b) RC column, concrete age 1 year, ISO834 fire, (c) concrete column without reinforcement, concrete age 2 months, ISO834 fire, (d) RC column, concrete age 2 months, DIN4102-11 fire)

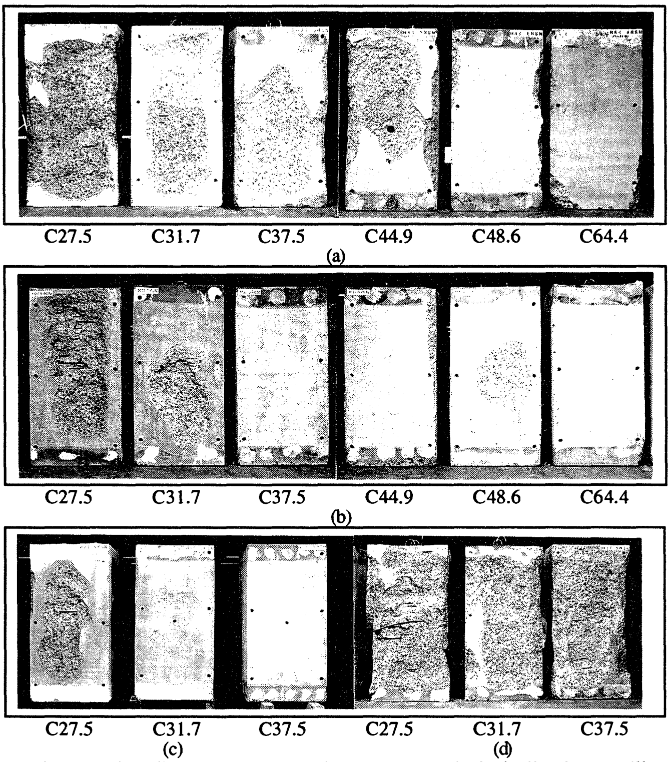
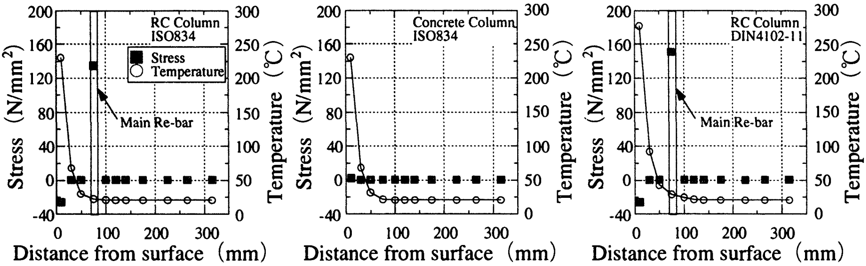


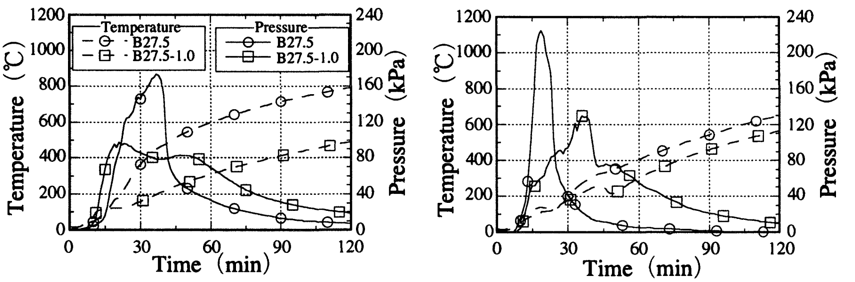
FIGURE 4. Columns after fire tests (Test Series 1, see Table 3) indicating spalling degree ((a) RC column, concrete age 2 months, ISO834 fire, (b) RC column, concrete age 1 year, ISO834 fire, (c) concrete column without reinforcement, concrete age 2 months, ISO834 fire, (d) RC column, concrete age 2 months, DIN4102-11 fire)



(a) (b) (c)

FIGURE 5. Above are the stresses and temperatures of the concrete and main reinforcement in a section of the column at the time when spalling starts in the fire test. The stress distributions are derived from numerical calculations applied with the Morita-Schneider-Concrete model [10], assuming the compressive strength to be $90N/mm^2$ and moisture content to be 4.5% for concrete ((a) RC column, ISO834 fire, at 12 minutes after the start of heating, (b) concrete column without reinforcement, ISO834 fire, at 12 minutes after the start of heating, (c) RC column, DIN4102-11 fire, at 32 minutes after the start of heating)

Effect of polypropylene fiber addition (Series 2 and 3) : The measured vapor pressures at the points about 30 mm from the exposed surface of the beam specimens in Test Series 2 are shown in Figure 6. According to (a) and (b) in Figure 6, the total pressures rapidly increase when the concrete temperature reaches more than 100 °C. The specimen B27.5-1.0 indicates lower pressures than B27.5. This result is important proof that PP fiber is effective in reducing the pressure in concrete exposed to fire and, consequently, in reducing spalling.



(a) (b)

FIGURE 6. Total pressure measured in the section of reinforced concrete beams ((a) measured near the lateral surface of the beam, (b) measured near the corner of the beam)

It is assumed that the higher the amount of PP fiber addition, the higher the reduction of spalling. But a higher amount of PP fiber in concrete leads to a lower workability of fresh concrete. A lesser amount of PP fiber addition is better for workability and for economic reasons. Because of these reasons, it is necessary to find an optimum amount of PP fiber added into concrete for each W/C ratio. The spalling depths obtained from Test Series 3 are compared with those obtained from Test Series 1 in Figure 7. Though the age of C37.5-1.0 in the fire test was four months, the comparison of spalling depth of C37.5 (test series 1, 2 months old) and C37.5 (test series 3, 4 months old) does not indicate any difference. Though the difference of two months in the curing period should have an insignificant effect on spalling, the data of

C37.5-1.0 could be plotted together with other data in Figure 7. It can be said from Figure 7 that a higher water cement ratio needs a lesser amount of PP fiber for reducing spalling. Though in any case much more data is needed for improving reliability, Figure 7 gives useful information for estimating the optimum amount of PP fiber addition for different W/C ratios.

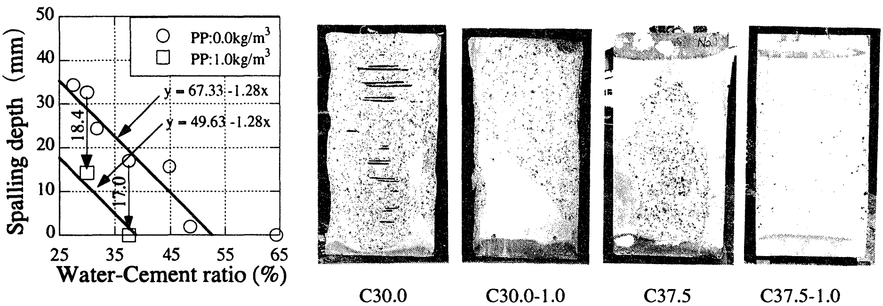


FIGURE 7. Reduction of spalling depth by adding polypropylene fiber into the concrete (Concrete age : C30.0 and C30.0-1.0 = 2 months, C37.5 and C37.5-1.0 = 4 months)

FIRE TESTS OF LOADED REINFORCED CONCRETE BEAMS

Materials and Mix Proportion of Concrete

Materials used for the loaded beam specimens are the same as those for the unloaded column specimens, i.e., low-heat portland cement, crushed sand stone, land sand, superplasticizer and PP fiber. W/C ratios of 27.5, 32.5, 37.5 and 42.5% were applied. In addition to these four types of concrete, two included PP fibers. These had W/C ratios of 27.5% with 2kg of PP fiber per $1m^3$ of concrete and of 32.5% with 1kg of PP fiber per $1m^3$ of concrete. The range in strength of these concrete samples was 63 - $111N/mm^2$ in the fire test. The amount of PP fiber added into the concrete was roughly estimated from Figure 7. According to Figure 7 the spalling depth can be reduced by about 18mm by 1kg of PP fiber per $1m^3$ of concrete. For a W/C ratio of 27.5 %, it was assumed that the spalling depth could be reduced to 0mm by adding 2kg of PP fiber per $1m^3$ of concrete. For a W/C ratio of 32.5 %, 1kg of PP fiber per $1m^3$ of concrete was added, thereby permitting shallow spalling. The mix proportion was planned to investigate the different degrees of spalling and fire resistance of loaded reinforced concrete beams under different W/C ratios and the effect of PP fiber on spalling reduction.

Specimens and Test Apparatus

The geometry of the loaded beam specimen and the test apparatus are shown in Figure 8. The cover thickness of the stirrup reinforcement is 40mm. Temperatures in the specimens are measured with thermocouples at the locations shown in the cross section in Figure 8. The length of the beam is 3.6m and the distance between the pin supports is 3.1m. The beam specimen is loaded at the middle of the span with hydraulic jacks (see Figure 8). Specimens were cured in a laboratory climate for two months until the fire test.

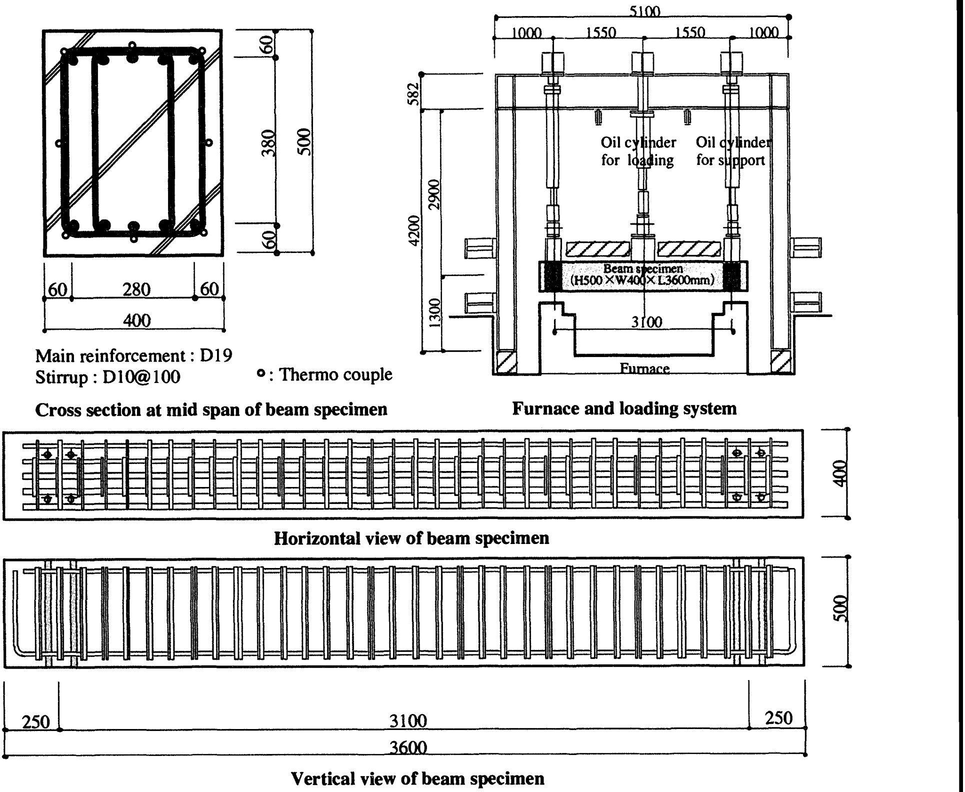


FIGURE 8. Cross section of beam specimen and test apparatus (unit : mm)

Test Conditions and Procedure

The vertical load at the middle of the span of the beam specimens was 44 kN. This load level was derived from a general bending moment in the middle of the span of beams in high-rise residential buildings (about 30 stories) of reinforced concrete structures in Japan. Though the supports of beams of this kind of building are generally of a fixed condition, pin supports were applied in this study considering the most severe bending condition for the beam specimens. The vertical load was applied to the beam specimens prior to heating and kept constant during heating.

The beam specimens were heated from both sides and the bottom according to the fire temperature - time curve prescribed in ISO834. The heating duration was 180 minutes. Residual strengths of the high temperature beams just after heating were measured by increasing the vertical load level with the rate of 5 kN/min for the specimen of W/C ratio of 37.5% and the rate of 20 kN/min for the other specimens.

Results and Discussion

Temperature of reinforcement : The averages of temperatures at three measuring points located near the soffit of the cross section of the beams (see Figure 8) are shown in (a) of Figure 9. The steel temperature - time curves of the beams of concrete without PP fiber indicate that a lower W/C ratio leads to a higher degree of spalling. The same tendency can be seen in Figure 2 for unloaded reinforced concrete columns. It can be reconfirmed that the lower the W/C ratio of concrete, the higher the degree of spalling. Comparing LB27.5 (W/C 27.5%) with LB27.5P (W/C 27.5%, PP fiber added with the ratio of 2kg/m^3), and LB32.5 (W/C 32.5%) with LB32.5P (W/C 32.5%, PP fiber added with the ratio of 1kg/m^3), it is significant that the addition of PP fiber into concrete can keep steel temperatures lower, which is resulted from the reduction of spalling depth.

Deformation : The vertical deformation measured in the middle of the span of each beam specimen during heating is shown in (b) of Figure 9. The deformation - time curves of the beams without PP fiber addition indicate that a lower W/C ratio leads to a greater vertical deformation. This tendency can be easily understood by comparing the steel temperatures shown in (a) of Figure 9. The higher the steel temperature is, the greater the vertical deformation. Comparing LB27.5 with LB27.5P, and LB32.5 with LB32.5P, it is very clear that the addition of PP fiber into concrete leads to smaller vertical deformations, which is resulted from the reduction of spalling depth.

Residual strength : The vertical deformation measured at the middle of the span for each beam specimen during loading just after heating is shown in (c) of Figure 9. It should be noted that the beam specimens indicated 'collapse' in (c) of Figure 9 were ruptured in bending. The deformation curves of the beams without PP fiber addition indicate that a lower W/C ratio leads to less residual strength, because the cross sectional area of low W/C ratio concrete beams becomes smaller, and main reinforcements are more exposed and lose their tensile strength depending on high temperatures. From the comparison of LB27.5 with LB27.5P, and LB32.5 with LB32.5P, it is clear that the addition of PP fiber into concrete leads to a higher residual strength, because the spalling depth can be reduced by adding PP fiber.

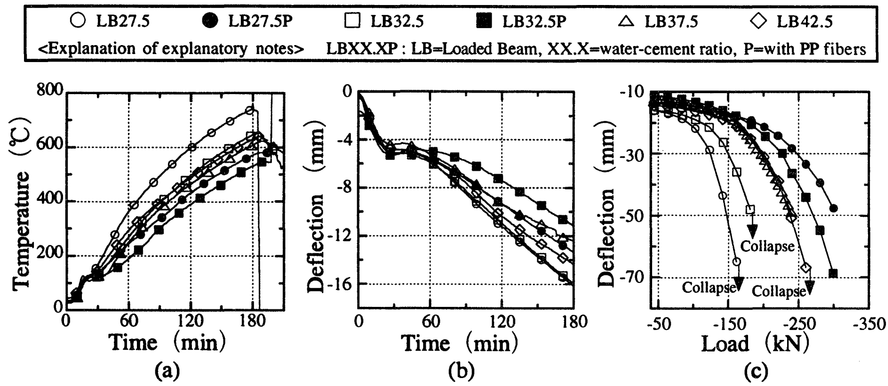
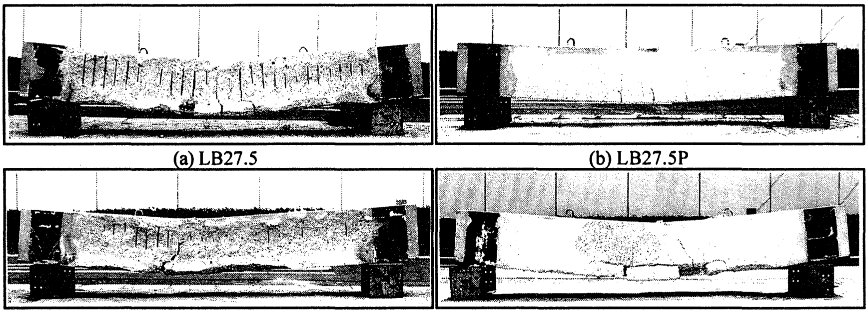


FIGURE 9. Values measured in the fire tests of loaded reinforced concrete beams ((a) average temperature of three lower measuring points in a cross section of the beams, (b) deflection at mid span during heating, (c) deflection during loading just after heating)



(a) LB27.5 (b) LB27.5P

(a) LB32.5 (b) LB32.5P

FIGURE 10. Beams after fire test indicating different spalling effects on concrete with and without PP fibers

Consideration of spalling : The amount of PP fiber added into concrete with W/C ratios of 27.5% and 32.5% were roughly decided from the test results shown in Figure 7. The beam specimens, LB27.5, LB27.5P, LB32.5 and LB32.5P, after all tests are shown in Figure 10. The concrete at the corner of soffit of LB32.5P was not lost by spalling, but by loading just after heating. The beam specimens after the fire tests shown in Figure 10 reveal that an optimum amount of PP fiber for preventing spalling could be derived using the relationship between W/C ratio, amount of PP fiber and spalling depth shown in Figure 7. The effect of reinforcement should be taken into account in the near future, too.

CONCLUSIONS

The spalling of high strength concrete under fire attack is discussed in this paper. It should be noted that spalling is not only affected by parameters applied in this study but it depends also on the kind of aggregate and other factors. Relationships obtained in this study would mainly be applicable for concrete with crushed sand stone as coarse aggregate. The results of the study are briefly summarized as follows :

a) The W/C ratio of concrete has a significant effect on spalling. The lower the W/C ratio, the higher the degree of spalling. Spalling does not occur or only slightly occurs, if the W/C ratio exceeds 50% for two-month-old concrete, and 45% for one-year-old concrete.
b) The concrete age at the time of fire exposure has a significant effect on spalling. The spalling depths of one-year-old concrete elements are less than that of two-month-old elements. Though the concrete age affects the strength and moisture condition of the concrete, it is generally observed that the lower the moisture content, the lesser the possibility of spalling caused by vapor pressure in the concrete.
c) The amount of steel reinforcement, especially main reinforcement, has a significant effect on spalling. Spalling does not occur or only slightly occurs in the case of concrete columns without reinforcement with W/C ratio exceeds 40% for two-month-old concrete.
d) The different degrees of spalling between reinforced concrete columns and concrete columns without reinforcement is caused by the level of restraint of thermal elongation near the surface of the concrete exposed to fire. The compression stresses near the surface of elements exposed to fire is dependent on the amount of main reinforcement, external load, internal load and so on. It may be concluded that there is a critical amount of main reinforcement, which if exceeded, the influence of external loads can be ignored. The investigation on the critical amount of reinforcement will be performed by the authors in the near future.

e) Though it had been assumed that the spalling degree under DIN4102-11 could be less than that under ISO834, because DIN4102-11 fire grows gradually for the first 20 minutes of the fire duration, the spalling depths measured for DIN4102-11 fire are deeper than those measured for ISO834 fire. According to numerical structural calculations, the comparison between ISO834 fire and DIN4102-11 fire shows that there is no obvious difference in temperatures and stresses in the column section at the initiation of spalling. Thus, it is possible that a higher vapor pressure is attained over a long period of time in the case of DIN4102-11 fire compared to the case of ISO834 fire.

f) The addition of polypropylene fiber into concrete is a good measure for preventing spalling and can improve the fire endurance of reinforced concrete elements. According to the results of fire tests on unloaded reinforced concrete columns with W/C ratios between 30 % and 37.5%, spalling depths can be reduced by about 18mm by adding 1kg of PP fiber per 1m^3 of concrete. By interpolating and extrapolating the results, it is possible to find an optimum amount of PP fiber to be added into concrete for spalling protection.

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