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Division I

EVALUATION OF TEMPERATURE, MOISTURE EVAPORATION AND STRENGTH OF CONCRETE SUBJECTED TO SUSTAINED ELEVATED TEMPERATURES UP TO 300 ˚C

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ABSTRACT

This paper presents the results of reconsideration on the authors' previous experiments on the effects of sustained elevated temperature on degradation of concrete investigated for many years, in order to determine correlation between weight loss and residual strength. Results of 3 experiments conducted in 1979, 2001 and 2011 were reconsidered, in which concrete with normal portland cement (NP), moderate heat portland cement (MP), fly-ash cement (FB) and blast furnace slag cement (BB) were tested before and after exposure to temperature of 20 to 300˚C for compressive and tensile strengths and modulus of elasticity and weight loss. In case-1 study in 1979, plain concrete with NP were tested after 10, 100 and 1000 day exposure, and in case 2 and 3, air entrained concrete with NP, MP, FB and BB cements were tested after 91 day exposure.

The results of reconsideration indicated that residual strength can be evaluated by the correlation with weight loss regardless of temperature and term of exposure. Compressive strength showed nonlinear decline with temperature, indicating minimal strength at lower temperature and regain at higher temperature, which were associated with minimal weight loss and maximal weight loss, while tensile strength and modulus of elasticity showed monotonous decline with temperature and weight loss.

Effects of change in characteristic between old NP cement and those at present were discussed, and mechanism of degradation of concretes due to increase of pore size and pore volume are suggested.

1. INTRODUCTION

Although technical papers concerning the strength of concrete subjected to elevated temperature are abundant [1,2] those deal with the strength in massive walls subjected to gradient temperature are limitted.[3,4] In massive walls heated from liner side, moisture migration toward open side causes wetted zone inside walls beside dried zone at liner and open sides due to pore pressure and diffusion.[5] And furthermore concrete strength does not reduce monotonously with exposure temperature. Kasami et al.[6-12] have presented papers indicating minimal residual strength at 50˚C in association with intermediate weight loss as shown in Fig.1. The same phenomena were also found in some other papers[12)-19)] as shown in Fig.2. Therefore, it is difficult to estimate strength of massive concrete subjected to elevated temperature. The authors[20] presented a preliminary estimation of concrete strength in massive wall heated at liner side with the correlation between calculated weight loss and residual strength estimated substituting weight loss for residual strength after exposure obtained from the correlation with weight loss. This paper presents the results of extended research to establish estimation system for strength in massive concrete in aged nuclear power plants through correlation of moisture loss and residual strength. Data in

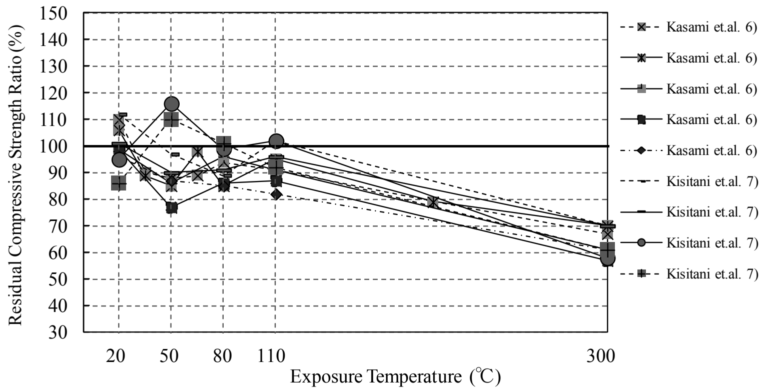


Fig.1 Relation between temperature and residual strength showing minimal by Kasami et al.

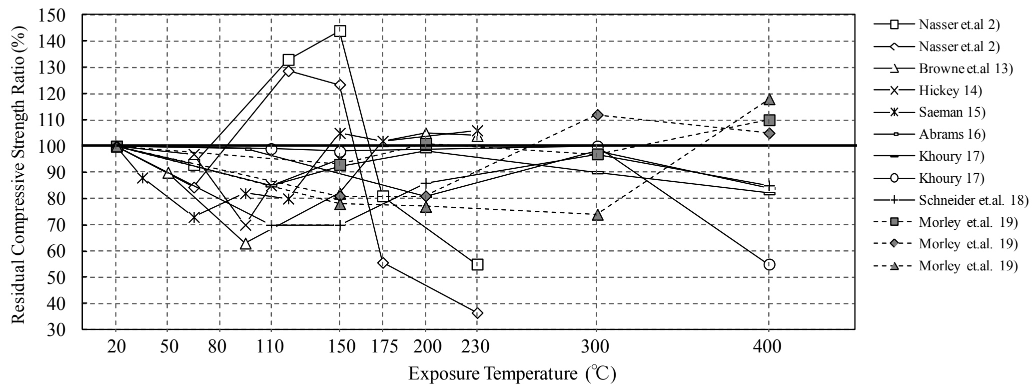


Fig.2 Relation between temperature and residual strength showing minimal in literature

past experiments conducted for a long time by the authors were reconsidered and effects of cement type and quality change were discussed as well as degradation mechanism.

2. EVALUATION OF CORRELATION BETWEEM MOISTURE LOSS AND RESIDUAL STRENGTH OF CONCRETE AFTER ELEVATED TEMPERATURE EXPOSURE

The authors have investigated the effects of elevated temperature exposure and relations between weight loss and residual strength for a long time, using cements made in 1971 to 2011. In the last 40 years. Industrial Standards for Cement in Japan were revised and change in cement production in 1970s's and change in raw materials in 1990s' changed characteristics of cement. As stated in the introduction, results of 3 experimental studies initiated in 1979, 2001 and 2011 were reconsidered in order to clarify the effects of change in cement on concrete properties after elevated temperature exposure and in order to determine the correlation between moisture loss and residual strength. Reconsideration were made on the experimental results presented in reference 7,by K. Kishitani, K. Kasami et al. in case study-1, reference 8,9 by S. Simura, K. Kasami et al. in case study-2 and reference 11,12 by the authors in case study-3. Materials, concrete mixture and outline of experiments are shown in Table 1. Characteristics of normal portland cement used are shown in Table 2. Change of NP cement in fineness, C_3S and SiO_2 content and Hydraulic and Silica Modulus in recent 20 years suggest decrease in long-term strength development and increase in early age strength and drying shrinkage.

Concrete mixtures in case-1 were plain concrete. Mixtures in case-2 and case-3 were air-entrained concrete with water reducing agent. Specimens for compression test were cylinders with 100 mm diameter. In case-1 to 3 experiments, water cured specimens were cured in water until 28 days and stored in air until 91 days. Sealed cured specimens in case-3 were cured as cast for 91 days in lightweight steel moulds sealed with epoxy capping.

Table 1 Procedures of experiments of Case Study-1 to Case Study-3

		Case Study-1	Case Study-2	Case Study-3
Cement	Cement Type	NP	NP, BB, FB	NP, MP, BB, FB
	Vintage Year	1979	2001	2011
Fine Aggregate		River sand	River sand	River sand, Crushed limestone
Corase Aggregate		River gravel	Crushed stone	Crushed sand stone, Crushed limestone
W/C (%)		50%, 60%	50%	50%
Air Entrainment		Plain	Air entrained	Air entrained
Curing before Exposure		28days in water & 56 days in air		
		-	-	91days sealed
Exposure Temperature		20℃, 50℃, 80℃, 110℃, 300℃		
Exposure Term		91days	10, 100, 1000 days	91days
Exposure Condition		Unsealed	Unsealed, Sealed	Unsealed, Sealed

Table 2 characteristics of NP cement used in Case-1 to Case-3

Year	Specific Gravity (g/cm^3)	Specific Surface Area (g/cm^3)	Chemical Composition (%)						Clinker Compound				Cement Factor	
			i.l	SiO_2	Al_2O_3	Fe_2O_3	C_aO	SO_3	C_3S	C_2S	C_3A	C_4AF	Hydraulic Modulus	Silica Modulus
1979	3.17	3260	0.6	22.0	5.4	3.0	64.4	2.0	48.6	26.5	9.2	9.1	2.1	2.6
2001	3.16	3360	1.1	21.3	5.1	2.9	64.2	2.0	55.3	19.4	8.6	8.8	2.1	2.7
2011	3.16	3270	2.2	20.7	5.3	2.9	64.3	2.1	58.6	15.2	9.1	8.8	2.2	2.5

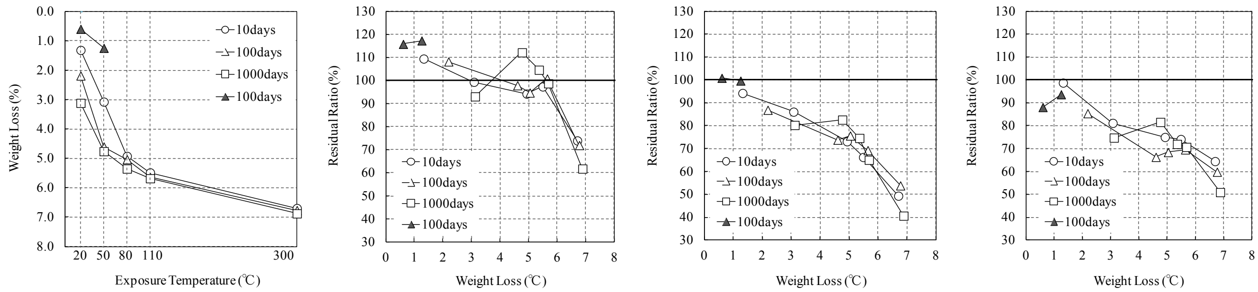
Elevated temperature exposure were made at the age of 91 days with or without seal for 10,100 and 1000 days in case-1 and for 91 days in case-2 and 3. Specimens for sealed exposure to 20 and 50 °C in case-1 were sealed with polyethylene film. Specimens for sealed exposure in case-3 were exposed to 20, 50 and 80 °C sealed as cast in lightweight steel mould and epoxy capping.

Moisture losses, expressed by the percentage of weight loss before and after exposure in original papers were reconsidered to be expressed by percentage of weight at the end of moist curing. Residual strength was expressed by percentage of 91 day strength before exposure as same as the original papers.

Case Study-1 [7)]

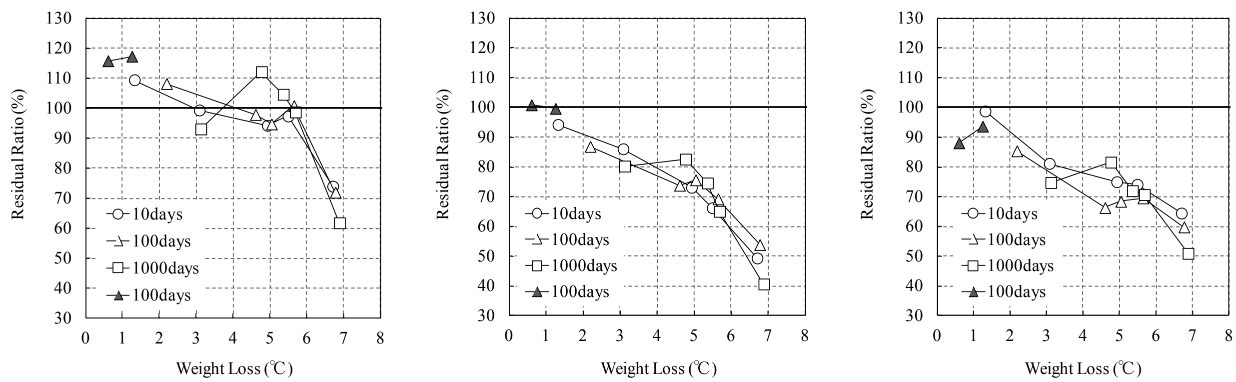
Figure 3 shows the relations between exposure temperature and mean value of 4 mixtures after 10, 100 and 1000 day exposure. Increase of weight loss with exposure term was greater for lower temperature of 20 to 50 °C than that for higher temperatures. Residual compressive strength after 10 and 100 day exposure increased by 10 % at 20 °C and decreased with temperature up to 80 °C indicating minimal and increased again at 110 °C indicating maximal and rapidly decreased up to 300 °C, while those after 1000 day exposure showed different tendency to decrease by 8 % at 20 °C and to increase by 10 % at 50 °C showing maximum and to decrease with temperature rise up to 300 °C, when moisture was allowed to evaporate. Strength reduction with exposure term was found to be greater at 20 °C and 300 °C.Residual modulus of elasticity showed greater decrease with temperature and term of exposure than compressive strength. Sealed specimens indicated smaller weight loss, 15 % increase in compressive strength and smaller reduction in tensile strength and modulus of elasticity.

Figure 4 shows the relations between weight loss and residual strengths. Compressive strength after 10 and 100 day exposure increased at 1 % weight loss and decreased linearly with weight loss up to 5 % weight loss showing minimal and decreased rapidly with the weight loss from 5.5 to 7 %. Although 1000 day exposure specimens showed different tendency, in the range of 0.5 to 4 % weight loss, residual compressive strength can be correlated with weight loss independent of term and Fig.4 Relation



a) Weight loss b) Compressive strength c) Modulus of elasticity d) Tensile strength

Fig.3 Relation between temperature and weight loss and residual strength ratio (Case Study-1)



a) Compressive strength b) Modulus of elasticity c) Tensile strength

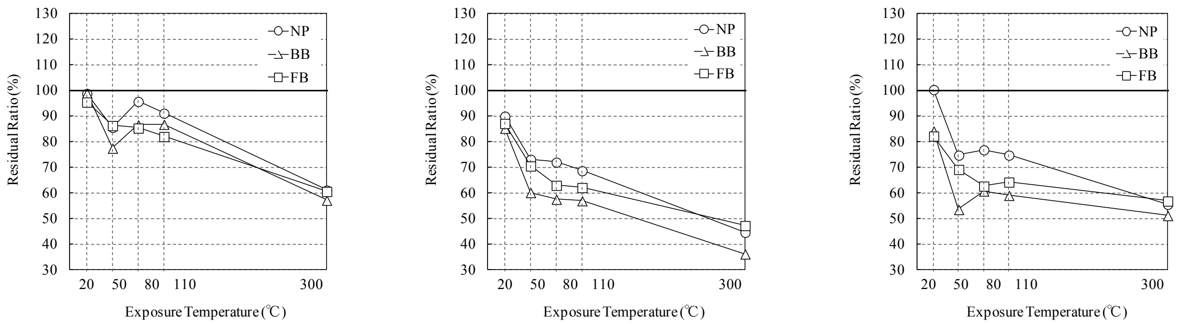
Fig.4 Relation between weight loss and residual strength (Case Study-1)

between weight loss and residual strength(Case Study-1) temperature of exposure. Residual modulus of elasticity decreased monotonously with the increase of weight loss, and can be correlated with weight loss independent of term and temperature of exposure in the range of 0.5 to 4 % weight loss same as compressive and tensile strengths.

Case Study-2[8)9)]

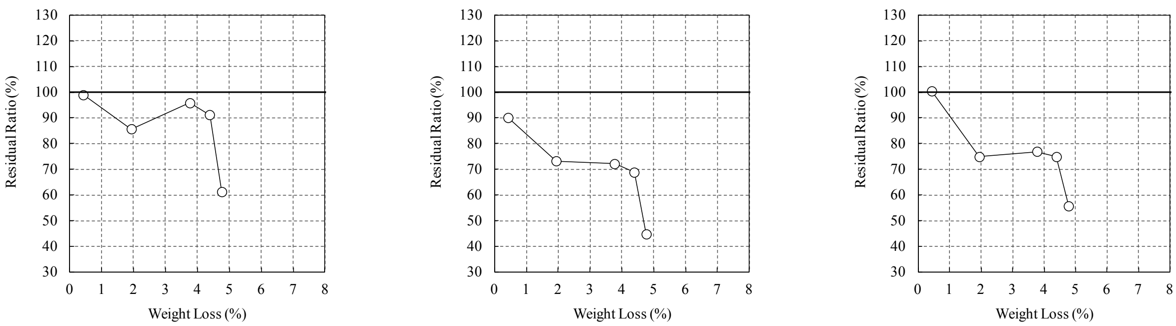
Figure 5 shows relations between exposure temperature and residual strengths of normal portland (NP), type B blast-furnace slag (BB) and type B flyash (FB) cement concrete after exposure. Compressive strength showed 5 % decrease at 20 $^{\circ}$C and rapid decrease by 15 to 20% at 50 $^{\circ}$C indicating minimal and at higher temperature than 80 $^{\circ}$C of maximal indicated linear reduction up to 300 $^{\circ}$C.showing greater reduction than case-1.modulus of elasticity and tensile strength showed similar tendency to reduce with temperature rise, but reduction rate was greater than in case-1.Among 3 type cements, NP cement showed smaller strength reduction, while BB cement showed greater strength reduction. Figure 6 shows the relations between weight loss and residual strengths of NP cement concrete after exposure. Weight loss of NP concrete was smaller than in case study-1. Compressive strength showed minimal at 2 % weight loss and maximal at 4 % weight loss, indicating rapid reduction up to 5% weight loss.

Modulus of elasticity and tensile Strength showed similar reduction pattern with weight loss, though the rate of reduction was more rapid for weight loss. Figure 7 shows the relations between weight loss and residual strengths of FB cement concrete after exposure. Weight loss of FB was greater than NP. Compressive strength decreased monotonously with weight loss without indicating minimal. Modulus of elasticity and tensile strength decreased linearly with weight loss. Residual strengths of FB cement concrete can be correlated with weight loss in good agreement.



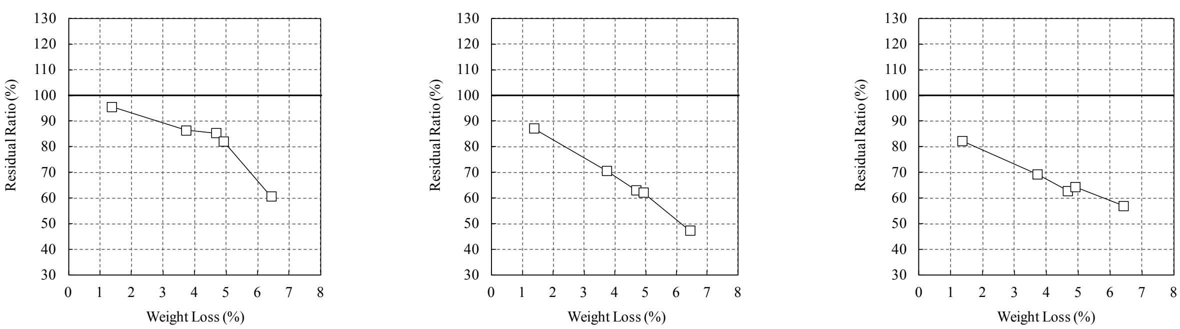
a) Compressive strength b) Modulus of elasticity c) Tensile strength

Fig.5 Relations between exposure temperature and residual strength (Case Study-2)



a) Compressive strength b) Modulus of elasticity c) Tensile strength

Fig.6 Relations between weight loss and residual strength of NP concrete (Case Study-2)

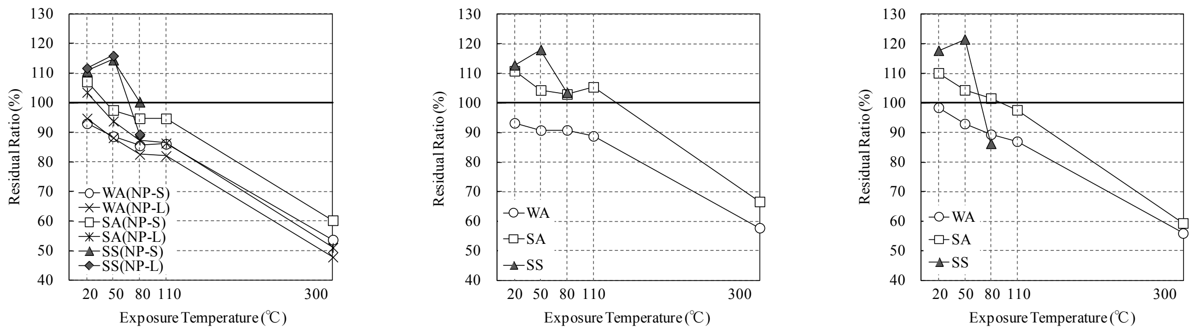


a) Compressive strength b) Modulus of elasticity c) Tensile strength

Fig.7 Relations between weight loss and residual strength of FB concrete (Case Study-2)

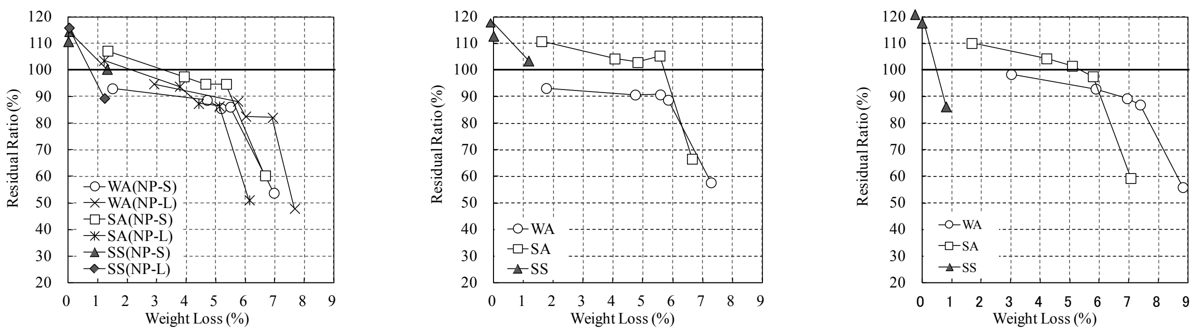
***Case Study*-3**[10)11)]

Figure 8 shows relations between temperature and residual strengths of NP, MP and FB concrete after exposure. Symbols of explanatory notes in the figures indicate as follow, NP-S; concrete made of NP cement and crushed sandstone, NP-L; mixture concrete made of NP cement and crushed limestone, SA; specimens water cured and unsealed exposure, SA; specimens sealed cured and unsealed exposure, SS; specimens sealed cured and sealed exposure. Compressive strength of unsealed specimens showed residual reduction depending on temperature rise without minimal as shown in case study-1, regardless of cement type. NP concrete showed greater strength reduction with temperature than those of MP and FB and those in case study-1. Remarkable difference was found among the curing and exposure method of WA, SA and SS. SS specimens showed 10-20 % higher residual strength than WA at each temperature regardless of cement type.



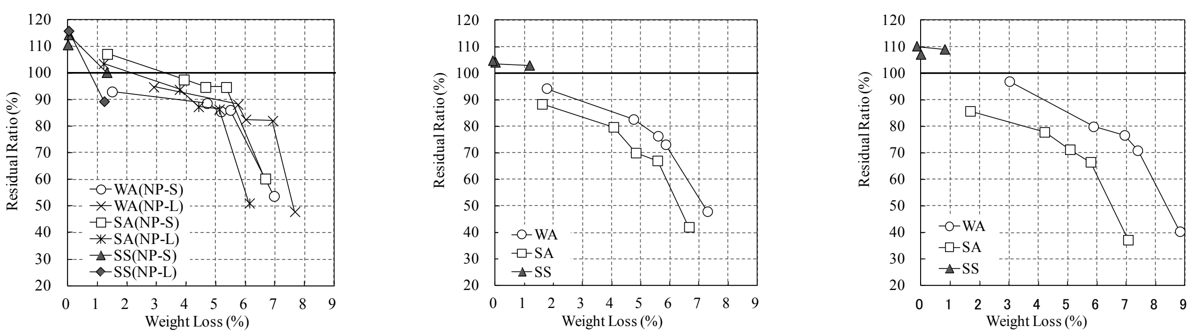
a) NP cement b) MP cement c) FB cement

Fig.8 Relations between temperature and residual strength (Case Study-3)



a) NP cement b) MP cement c) FB cement

Fig.9 Relations between weight loss and residual compressive strength (Case Study-3)



a) NP cement b) MP cement c) FB cement

Fig.10 Relations between weight loss and residual modulus of elasticity (Case Study-3)

Figure 9 and 10 show relations between weight loss and residual compressive strength and modulus elasticity. Compressive strength decreased gradually with the increase of weight loss up to 5 % weight loss and decreased rapidly at weight loss higher than 5.5 % regardless of cement type. Residual strength can be roughly correlated with weight loss, although those of SA were higher than those of WA. Residual modulus of elasticity showed similar tendency to decrease with weight loss.

3. DISCUSSIONS

(1) Evaluation of Correlation between Weight Loss and Porosity

Figure 11 shows relations between weight loss and porosity in cement paste after exposure obtained in case study-1. This figure shows strong correlation between weight loss of concrete and

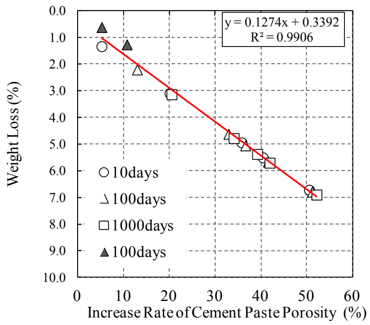


Fig.11 Relations between weight loss and porosity in cement paste in case study-1

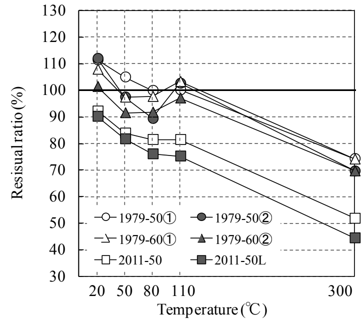


Fig.12 Comparison of relations between temperature and residual strength in case study-1 and 3

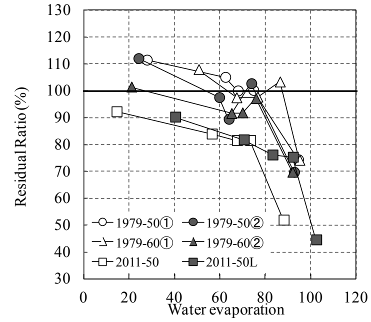


Fig.13 Comparison of relations between weight loss and residual strength in case study-1 and 3

increase in porosity caused by water evaporation after elevated temperature exposure, which suggests that moisture change in cement paste can be expressed with weight loss of concrete.

(2) Evaluation of the effects of change of cement produced at long interval

Figure 12 and 13 show comparisons of relations between temperature and residual strength and between weight loss and residual strength. There are clear differences between 2 groups of relations between temperature and residual strength and between weight loss and residual strength. Although the differences can be affected with the difference in materials other than cement, in concrete mixture and in experimental procedures, change in cement qualities between made in 1979 and 2011 as shown in Table 1 could be the principal causes.

(3) Mechanism of degradation of concrete due to elevated temperature exposure

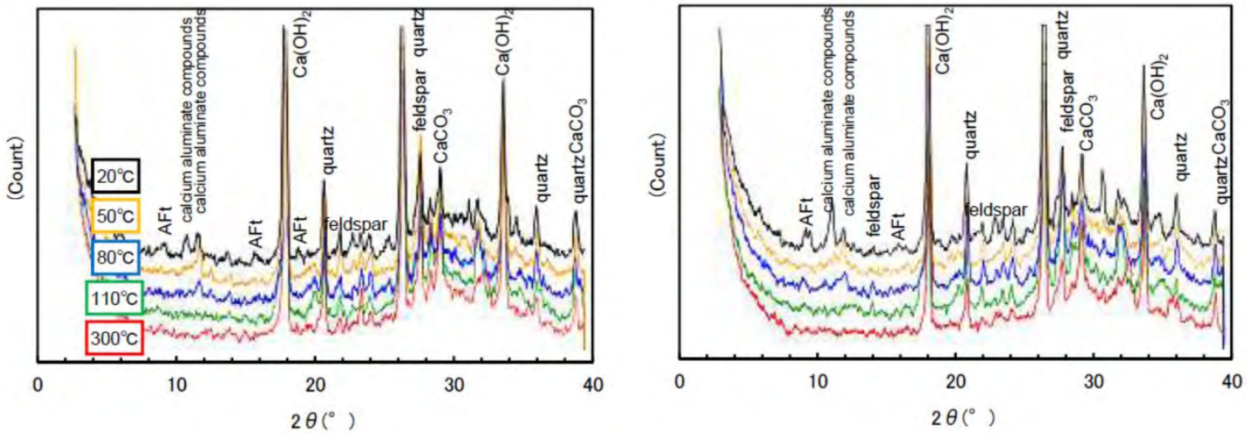
Results of powder X-ray diffraction analysis on concrete after exposure to 20 to 300˚C in case study-3 are shown in Table 3 and Fig.14. Decrease of Aft (Ettringite) and calcium aluminate hydrate at higher temperature were observed, though no sign of chemical change was seen.

Figure 15 shows change in pore size and cumulative pore volume distribution of NP concrete with temperature. Remarkable changes were found between 20 to 50˚C and 110 to 300˚C. Decrease of fine pore and increase of medium size pore between 20 to 50˚C, and decrease of medium size pore and increase of large size pore between 110 to 300˚C were observed. These changes are in good agreement with change in XRD pattern suggests evaporation of combined water between at 50˚C and evaporation of capillary water between 110 and 300˚C. Table 4 shows the relations among exposure temperature, water evaporation and change of pore size distribution. Degradation of concrete due to elevated temperature exposure would be caused by the increase of pore size and pore volume and resulting strength reduction in cement paste and shrinkage crack in cement paste and interface to aggregates.

Table 3 Evaluation of XRD Pattern affected with temperature, cement and aggregate

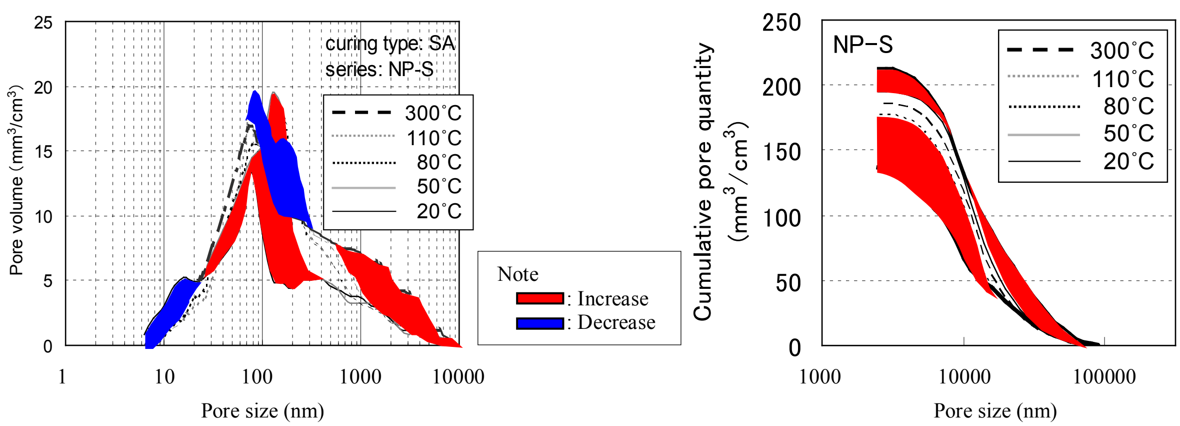
Cel.D	AFt					Calcium Alminate					Porlandite				
Temp.	NP	MP	BB	FB	NL	NP	MP	BB	FB	NL	NP	MP	BB	FB	NL
20˚C	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
50˚C	○	×	○	△	○	○	○	○	○	○	○	○	○	○	○
80˚C	△	×	○	○	△	○	×	○	△	○	○	○	○	○	○
110˚C	×	×	×	×	×	×	×	○	×	×	○	○	○	○	○
300˚C	×	×	×	×	×	×	×	×	×	×	○	○	○	○	○

Note ○:strong peak. △:weak peak. ×none



a) NP cement b) FB cement

Fig.14 Change in XRD pattern with exposure temperature of SA specimens (Case Study-3)



a) Pore size distribution b) Cumulative pore volume

Fig.15 Change in pore size distribution with temperature of SA specimens (Case Study-3)

Table 4 Relations among temperature, pore size and water evaporation

		56days Air curing	Exposure temperature				
			20℃	50℃	80℃	110℃	300℃
Evaporated Water (%)		6	14 - 40	17 - 44	4 - 13	6 - 10	9 - 20
XRD pattern	AFt (Ettringite)	—	○	○	△	×	×
Case-3:SA	Calcium Aluminate	—	○	○	○	△	×
Pore size	Smaller than 20nm	—	↘		—	→	
distribution	20nm-70nm		↗		—	→	
Case-3:SA	70-300nm		→		—	↘	
Cumulative pore volume		—	↗		→	↗	
Source of Evaporated Water		Free Water	Capillary Pore		Gel Pore		Adsorbed or Combined Water

Peak Intensity → ○:Strong , △:Weak , ×:None

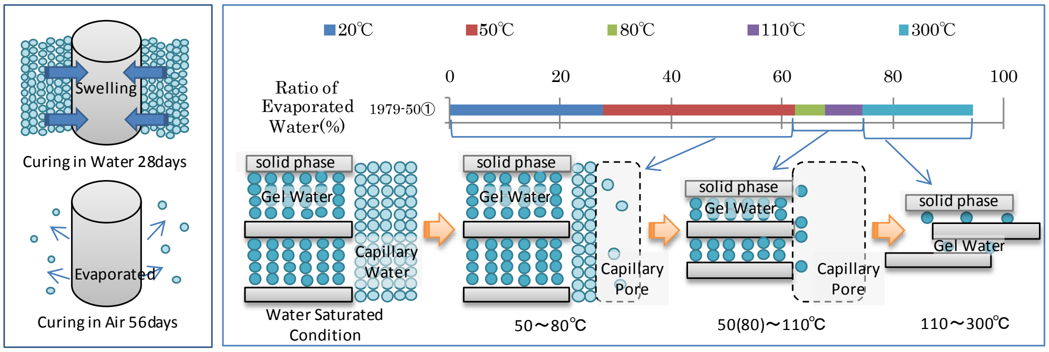


Fig.16 Schematic drawing of dehydration hardened cement

Fig.16 shows schematic drawing of describing the relations among exposure temperature, water evaporation and possible change in the structure of hydrated cement paste, based on the above mentioned phenomena.

4. CONCLUSIONS

Based on the reconsideration on the authors' previous experimental results described above, the following conclusions were obtained.

1) Exposure to elevated temperature higher than 50˚C causes degradation of concrete when moisture is allowed to evaporate.
2) Reduction in tensile strength and modulus of elasticity were greater than that in compressive strength.
3) Relations between temperature and residual concrete strengths are affected with type of cement used as well as curing and exposure conditions such as sealed or unsealed.
4) Reduction in concrete strength after elevated temperature exposure is smaller for moderate heat portland cement and fly-ash cement, and greater for blast-furnace slag cement than that for normal portland cement.
6) Concrete with normal portland cement made in 1979 showed smaller strength reduction than those with recent normal portland cement.
7) Reduction of compressive strength with exposure temperature is not monotonous, indicating minimal strength associated with intermediate weight loss.
8) Residual strengths of concrete after elevated temperature exposure can be correlated with weight loss or moisture loss regardless of term and temperature of exposure.
9) Degradation of concrete due to elevated temperature can be due to increase in pore size and pore volume in cement paste and due to resulting strength reduction of cement paste.

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