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Experimental Study on Long-term Thermal Effects on Concrete

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ABSTRACT

This paper considers the mechanism of heating on the mechanical properties of concrete and the heating effect of 'the member subjected to long-term heating of nuclear power plants' (hereafter 'MNP') from the experimental results of specimens and 'scaled mass model' (hereafter 'MDL') up to 5 years. The effects of the cement type, heating temperature, and moisture dissipation conditions (seal and unseal) on the mineral composition, pore structure, and mechanical properties of concrete were evaluated based on the results of specimen. The mechanism of mechanical properties increase with the progress of hydration and crystallization was considered from the results of the seal specimens. The experimental result of the unseal specimen, whose free water disappearing shows that the gentle hydration progressed and change of mechanical properties are small. From the experimental results of MDL which simulate MNP, which is generally mass concrete and undergoes one-side heating, it was found that the transition of free water is slow and the heating mechanism is similar to the seal specimen, therefore, the mechanical properties increase. Furthermore, unlike the unseal specimen, MDL gave a little decrease in the elastic modulus and the tensile strength even if the moisture content declined. By comparing the heating environment of the MDL and MNP, it is suggested that MNP is in an environment where the strength is improved by the hydration and the crystallization progression than the MDL. This research is planned to be continued for 10 years to expand data.

INTRODUCTION

The concrete structure of the nuclear power plant facility is designed so that the temperature received over a long time period is 65°C or less in general area and 90°C or less in local area. There are many past studies (e.g. [1)]) regarding the physical property change of concrete subjected to long-term heating. Regarding the domestic long-term heating experiment, there is an experiment of 3.5 years by Nagao et al. [2)], but more long-term research is required. The purpose of this research is to conduct concrete heating experiment of 10 years to expand data on physical properties change of concrete subjected to long-term heating.

1. Outline of the Experiment

(1) Experiment series

Two series of 10-year heating experiments are conducted in this experiment. Table 1 shows the purpose and outline of experiment series I and series II.

Experimental conditions of series I are summarized in Table 2. Table 3 shows the symbols for each parameter of series I. Series I experiment is conducted using the cylindrical specimen. The dimension of cylindrical concrete specimen is 100mm in diameter and 200mm in height. The effects of four variables including cement type (Ordinary Portland cement (hereafter 'OPC') with fly-ash; NF, Moderate-heat Portland cement (hereafter 'MPC') ; M, MPC with fly-ash; MF), heating temperature (20 °C, 65 °C and 90 °C), heating period (0 day, 3 days, 7 days, 28 days, 91 days, 1 year, 5 years and 10 years), and water constraint condition (sealed, unsealed) on physical properties of concrete are studied. The specimens are cured for 39 weeks under 20°C sealed condition before heating.

Experimental conditions of series II are summarized in Table 4. Table 5 shows the symbols for each parameter of series II. Series II experiment is conducted using MDL which simulate a mass concrete member of Nuclear Power Plant. The dimension of MDL is 500 mm in width, 530 mm in length and 1,000 mm in height. MDL was made of Moderate-heat Portland-cement. Concrete cores are harvested from MDL by dry core-boring to evaluate the mechanical properties and water content ratio after predetermined heating period. The outline of the heating experiment of MDL is shown in Fig.1. A panel heater is attached to the lower surface of MDL. A steel forms are placed on the lower surface (heating surface) and the four side surfaces, and covered with glass fiber insulation. The upper surface (the surface opposite to the heating surface) is opened to atmosphere which is controlled to 20°C by air conditioner. Core sampling positions are 100 mm, 300 mm, 500 mm, 700 mm, and 900 mm from the heating surface.

Table 1: The purpose and outline of experiment series I and series II.

Series I	purpose	Study on the influence of heating on physical property change of specimen
	outline	10-year heating experiment of specimen is performed. Parameters are heating temperature, cement type, and sealing condition. Mechanical properties, water content, mineral composition and pore structure are measured
Series II	purpose	Study on the influence of heating on physical property change of mass concrete
	outline	10-year one-side heating experiment of MDL is performed. Mechanical properties and water content are measured

Table 2: Experimental plan of Series I

Size of specimen	Cylindrical specimen: 100mm in diameter and 200mm in height
Type of cement	NF: OPC with fly-ash, M: MPC, MF: MPC with fly-ash
Curing before heating	Sealed curing under 20 °C for 39 weeks
Heating temperature	65°C and 90°C
Seal condition	Sealed curing and unsealed curing
Heating period	0 day, 3 days, 7 days, 28 days, 91 days, 1 year, 5 years, and 10 years
Experiment after heating	Compressive strength, elastic modulus, split tensile strength, water content, pore size distribution, X-ray diffraction

Table 3: Experiment case and the symbols of Series I

Cement Type	Heating temperature	Seal condition	Heating period
NF: OPC + Fly ash M: MPC MF: MPC + Fly ash	65: 65°C 90: 90°C	s: sealed us: unsealed	0: No heating 1y: 1-year heating 5y: 5-year heating

Table 4: Experimental plan of Series II

Size of specimen	500mm in width, 530mm in length and 1,000mm in height
Type of cement	M: MPC
Curing before heating	Sealed curing under 20°C for 40 weeks
Heating temperature	20°C and 95°C
Boundary conditions	Lower and side surfaces: sealed condition Upper surface : open to atmosphere
Heating period	0 day, 91 days, 1 year, 5 years, and 10 years
Experiment after heating	Compressive strength, elastic modulus, split tensile strength, water content

Table 5: Experiment case and the symbols of Series II

Scale mass model	Concrete temperature
MDL	72: 72°C (100mm from heating surface) 57: 57°C (300mm from heating surface) 47: 47°C (500mm from heating surface)

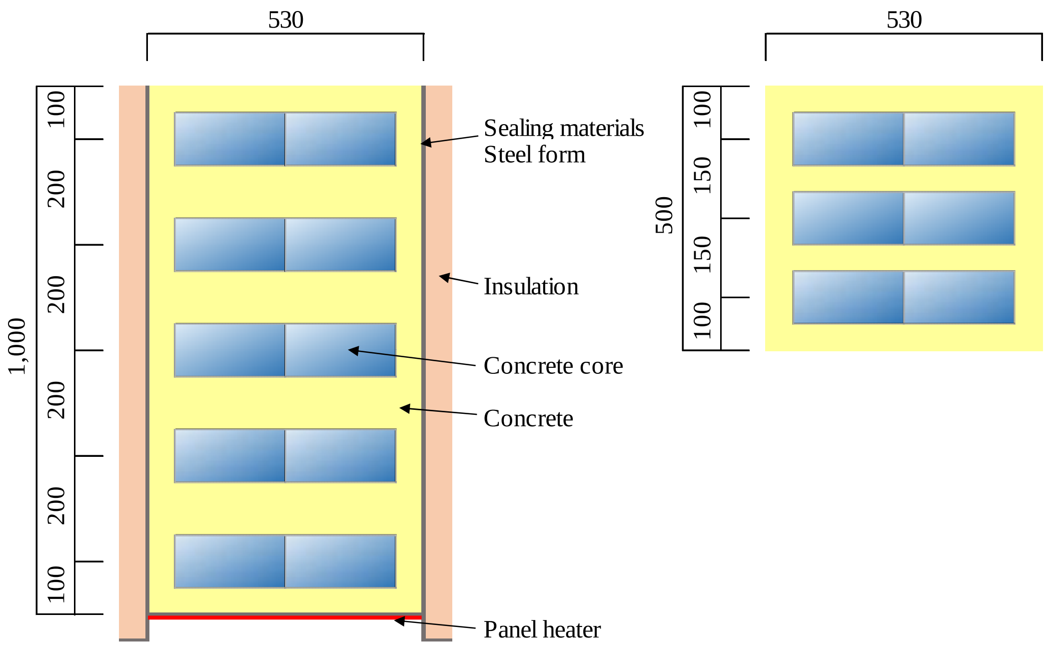

Figure 1. Outline of MDL

(2) Materials and mixture proportion of concrete

Mixture proportion of concrete specimens are same for Series I and Series II. The materials and mixture proportion of concrete specimens are shown in Table 6 and Table 7, respectively. The target slump is 12.0 cm (± 1.5 cm) and the target air volume is 4.0% (± 0.5%).

Table 6: Concrete materials

Materials	symbol	specification
water	W	Tap water
Cement	N	Ordinary Portland Cement
	M	Moderate-heat Portland cement
admixture	FA	Fly Ash (Type-II)
Fine aggregate	S1	Crushed sand of hard sandstone (Producing area; Fukui Pref.)
	S2	Land sand (Producing area; Fukui Pref.)
Coarse aggregate	G1	Crushed rock of hard sandstone; grading 2015 (Producing area; Fukui Pref.)
	G2	Crushed rock of hard sandstone; grading 1505 (Producing area; Fukui Pref.)

Table 7: Mixture proportion of concrete

Cement Type	Air	Content per unit volume of concrete (kg/m^3)						
		Water	Cement	FA	Fine aggregate		Coarse aggregate	
	(%)				S1	S2	G1	G2
NF	4.0	170	252	57	479	319	398	598
M	4.0	170	309	-	485	323	404	605
MF	4.0	167	247	56	483	322	402	603

2. Experimental result

(1) Experiment Series I (cylindrical specimen)

a. Change of water content with heating period

In order to investigate the influence of the moisture content on the progress of hydration and crystallization, the moisture content of the specimen after heating was measured. The change of water content of cylindrical specimen with heating period is shown in Fig.2. The water content ratio of cylindrical specimens after 5-year heating period were 13.5 to 14.2 % for 65°C heating and 11.6 to 12.3 for 90°C heating. This result shows that the free water which is necessary for hydration is preserved up to 5-year heating period in sealed specimens. For the unsealed specimen, the free water which is necessary for hydration dissipated in the early stage of heating period. The water content of 65°C heating and 90°C heating on 7-day heating period were 5 to 7% and 1.5 to 3%, respectively.

b. Change of mineral composition with heating period

X-ray diffraction was carried out to investigate the effect of the moisture content of the specimen after heating on the evolution of hydration and the hydration product. Figure 3 shows the results of X-ray diffraction of preheating, 1-year heating, and 5-year heating of the cement type MF. Similar results were obtained for cement type NF and M. Up to 1-year heating period, calcium hydroxide ($Ca(OH)_2$) decreased both by 65°C heating and 90°C heating in the sealed specimens. This results indicate that pozzolanic reaction was caused by $Ca(OH)_2$ and silica which is contained in fly ash. Tobermorite was formed in 90°C heating temperature. Between 1-year and 5-year heating period, Tobermorite was produced both 65°C and 90°C heating temperature. Especially the formation of Tobermorite was remarkable with 65°C heating temperature. In the unsealed specimen, although free water was lost at the beginning of the experiment, gentle CSH formation by pozzolanic reaction was observed up to 5-year heating period.

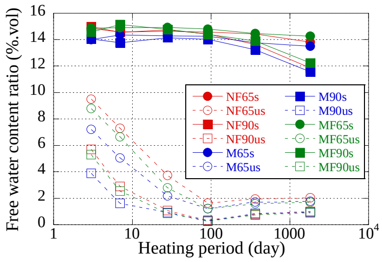

Figure 2. The change of water content ratio

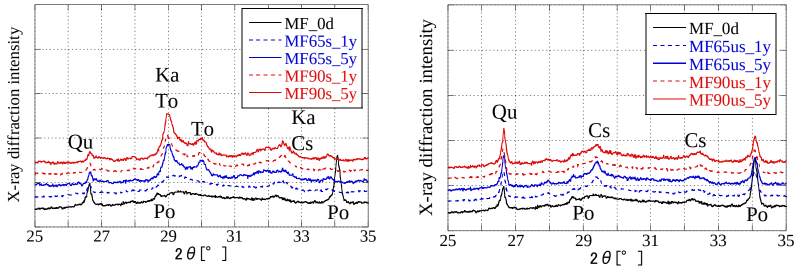

Figure 3. Results of X-ray diffraction
(Po:Ca(OH)$_2$, Cs:CSH, Ka: Katoite, To:Tobermorite, Qu: quartz)

c. Change of pore structure with heating period

In order to investigate the influence of moisture content of heated specimen on the progress of crystallization of concrete, pore structure measurement by mercury intrusion technique was carried out. Figure 4 shows the pore size distribution of preheating, 1-year heating, and 5-year heating of the cement type MF. Similar results were obtained for cement type NF and M. In the sealed specimen, hydration progresses as shown in 'b. Change of mineral composition with heating period', pore volume with pore radius of 0.01 micro or less increased and the pore volume with pore radius of 50 to 2,000 nm decreased with 90°C heating temperature up to 1-year heating period. A similar phenomenon was observed with 65°C heating from 1-year heating to 5-year heating period. The pore radius of 50 to 2,000 nm corresponds to the size of the transition zone around the aggregate, and it has been reported that the correlation with compressive strength is high in the past study [3]. In the unsealed specimen, the pore volume with a pore radius of 50 to 2,000 nm increased up to 1-year heating period. In the unseal specimen, gentle hydration occurred as shown in 'b. Change of mineral composition with heating period', but no significant pore structure change was observed from 1-year heating to 5-year heating period.

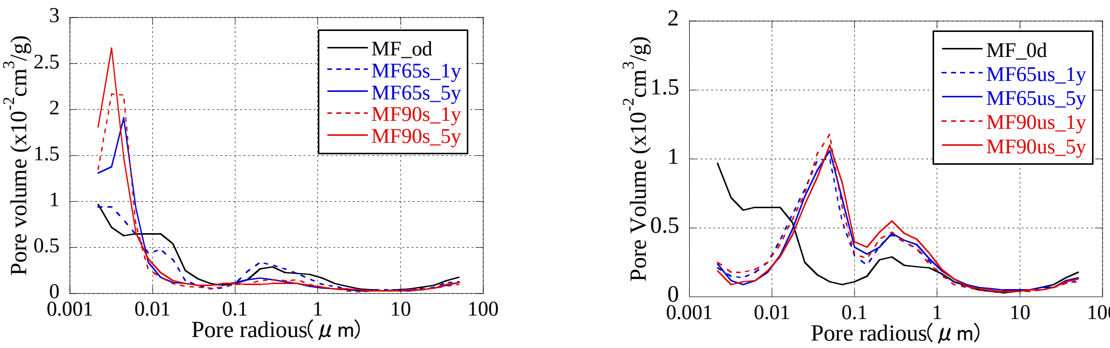

Figure 4. Results of the pore size distribution

d. Change of mechanical properties with heating period

In order to investigate the effect of heating temperature, heating period, and curing condition during heating period on compressive strength, elastic modulus and tensile strength, a mechanical test were conducted. For each mechanical property, the ratio of the value after heating to the value before heating is defined as the residual rate.

1) Compressive strength

Fig.5 and Fig.6 show the residual compressive strength in the sealed specimen and the unsealed specimen, respectively. In the sealed specimen, regardless of cement type and heating temperature, the compressive strength increased with the heating period due to the progress of hydration and crystallization. The residual compressive strength was about 1.6 to 1.8 at 5-year heating. In the unsealed specimen, compressive strength was slightly decreased up to 7-day heating. Thereafter, no change over time was observed, and the compressive strengths at 7 days of heating and 5 years of heating were equivalent. The residual compressive strength of 65°C and 90°C heating temperature were about 0.9 to 1.0 and 0.8 to 0.9, respectively, at 5-year heating.

2) Elastic modulus

Fig.7 and Fig.8 show the residual elastic modulus in the sealed specimen and the unsealed specimen, respectively, up to 5-year heating. In the sealed specimen, regardless of cement type and heating temperature, the elastic modulus increased slightly with the heating period due to the progress of hydration and crystallization. The residual elastic modulus was about 1.1 to 1.2 at 5-year heating.

In the unsealed specimen, residual elastic modulus decreased to about 0.5 up to 28-day heating. Thereafter, no change over time was observed, and the elastic modulus at 28 days of heating and 5 years of heating were equivalent. The residual elastic modulus of 65°C and 90°C heating temperature were about 0.4 to 0.6 at 5-year heating.

3) Tensile strength

Fig.9 and Fig.10 show the residual tensile strength in the sealed specimen and the unsealed specimen, respectively, up to 5-year heating. In the sealed specimen, regardless of cement type and heating temperature, the tensile strength increased with the heating period due to the progress of hydration and crystallization. The residual tensile strength was about 1.3 to 1.7 at 5-year heating.

In the unsealed specimen, tensile strength was decreased up to 28-day heating. Thereafter, no change over time was observed, and the tensile strength at 28 days of heating and 5 years of heating were equivalent. The residual tensile strength of 65°C and 90°C heating temperature were about 0.6 to 0.8 at 5-year heating.

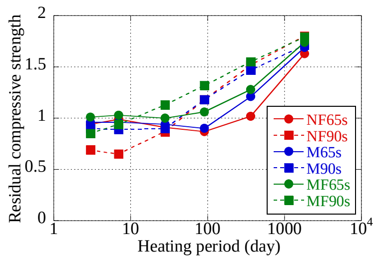

Figure 5. Residual compressive strength of sealed specimen

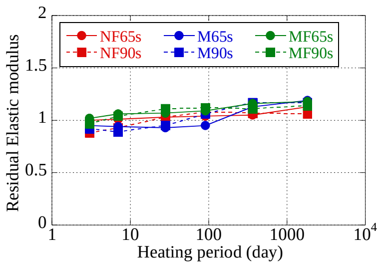

Figure 7. Residual Elastic modulus of sealed specimen

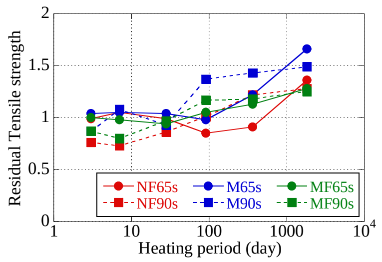

Figure 9. Residual Tensile strength of sealed specimen

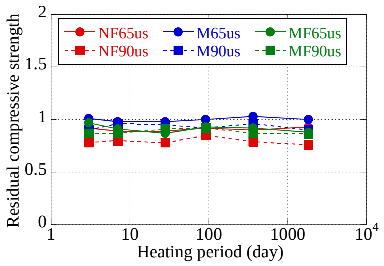

Figure 6. Residual compressive strength of unsealed specimen

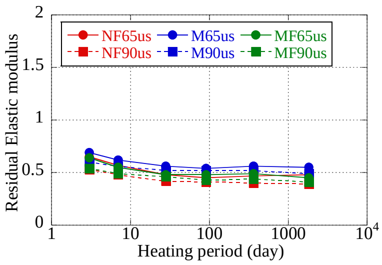

Figure 8. Residual Elastic modulus of unsealed specimen

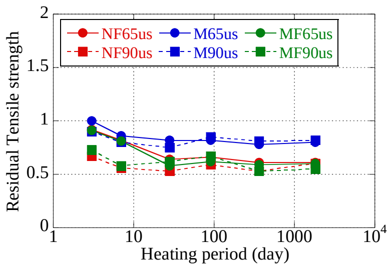

Figure 10. Residual Tensile strength of unsealed specimen

e. Study of the mechanism of heating on the mechanical properties of concrete

Based on the experimental results of both sealed and unsealed specimen up to 5 years of experiment, the heating mechanism for both presence and absence of free water are considered as follows.

1) Mechanism in the presence of free water (sealed specimen)

Changes in mineral composition by heating: Due to the presence of free water required for hydration, hydration progresses by heating and CSH and tobermorite are produced.
Change in pore structure by heating: Crystallization progresses and volume with small pore radius increases due to CSH and tobermorite formation by hydration
Change in mechanical properties by heating: With the progress of hydration and crystallization, the mechanical properties of concrete with 90°C and 65°C heating are enhanced.

2) Mechanism in the absence/escapes of free water (unsealed specimen)

Changes in mineral composition by heating: Although free water dissipates in the early stage of heating, gentle hydration progresses and CSH is produced.
Change in pore structure by heating: As the water content decreases, the amount of pores with a pore radius of 50 to 2,000 nm increases.
Change in mechanical properties by heating: Due to an increase in the amount of pores with a pore radius of 50 to 2,000 nm, the mechanical properties slightly decrease at the beginning of heating, but there is no subsequent change over time.

Regarding the mechanism of heating on the mechanical properties of concrete, in the case that free water exists, for example sealed specimen, mechanism for increase strength due to hydration and crystallization can be considered. Figure 11 shows the relationship between diffraction intensity change rate of Tobermorite and residual compressive strength. As shown in Fig. 11, the residual compressive strength tends to increase as the diffraction intensity change rate of Tobermorite increases.
Figure 12 shows the relationship between the specific surface area of pores and residual compressive strength up to 5-year heating. Figure 12 indicates that the residual compressive strength increases as the specific surface area of the pores increases. Since the specific surface area of the pores increases with the progress of crystallization by hydration, it is considered that the strength is promoted by the progress of hydration and crystallization.

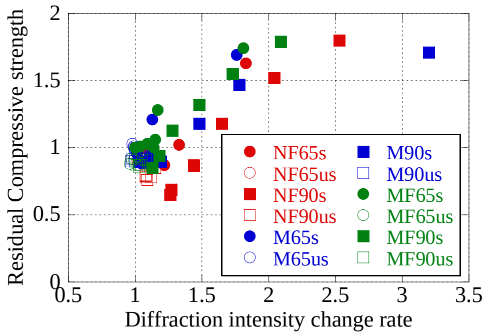

Figure 11. Relationship between diffraction intensity change rate of Tobermorite and residual compressive strength

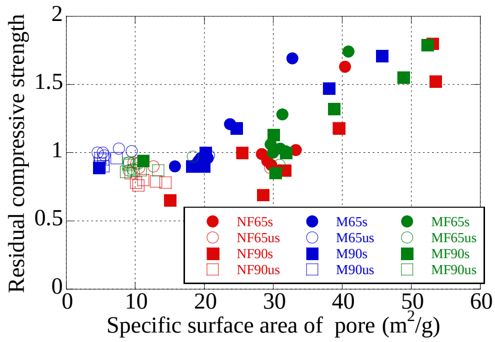

Figure 12. Relationship between the specific surface area of pores and residual compressive strength

(2) Experiment Series II (MDL)

a. Change of water content with heating period

In order to investigate the transition of free water by heating, the moisture content of MDL and the specimen was compared. Figure 13 shows the comparison of the moisture content of the scaled mass model (MDL) and the specimen (M) of the cement type M up to 5 years of heating. Changes of the water content at the concrete temperature of about 72°C which correspond to 100 mm from the heating surface, about 57°C which correspond to 300 mm from the heating surface, and about 47°C which correspond to 500 mm from the heating surface, up to 5-year heating period are shown in Fig.13. The water content ratio at the concrete temperature of about 72°C, about 57°C, about 47°C at five years heating were 7.5%, 14.3%, and 14.0%, respectively. The moisture content of the seal specimen was 11% or more at 5 years of heating and the moisture content of the unseal specimen fell to 5% or less by the 28-days heating.

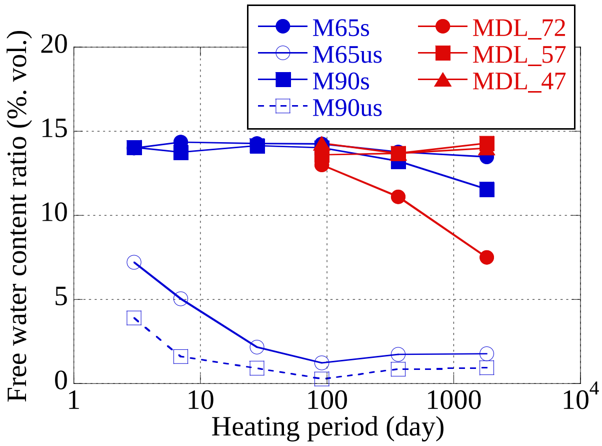

Figure 13. Changes of free water content ratio with heating period

b. Change of mechanical properties with heating period

1) Compressive strength

Figure 14 shows the residual compressive strength of MDL up to 5-year heating. The residual compressive strength of MDL after 5-year heating were about 1.1, 1.5, and 1.3 at the positions of concrete temperature of about 72°C, about 57°C, and about 47°C, respectively. The experimental result shows that the compressive strength of MDL is increased by heating.

2) Elastic Modulus

Figure 15 shows the residual elastic modulus of MDL up to 5-year heating. The residual elastic modulus of MDL after 5-year heating were about 1.1, 1.2, and 1.2 at the positions of concrete temperature of about 72°C, about 57°C, and about 47°C, respectively. The experimental result shows that the elastic modulus of MDL is increased by heating.

3) Tensile strength

Figure 16 shows the residual tensile strength of MDL up to 5-year heating. The residual tensile strength of MDL after 5-year heating were about 1.1, 1.3, and 1.2 at the positions of concrete temperature of about 72°C, about 57°C, and about 47°C, respectively. The experimental result shows that the tensile strength of MDL is increased by heating.

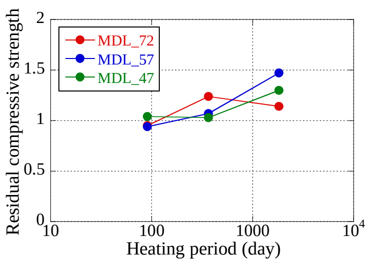

Figure 14. The residual compressive strength of MDL

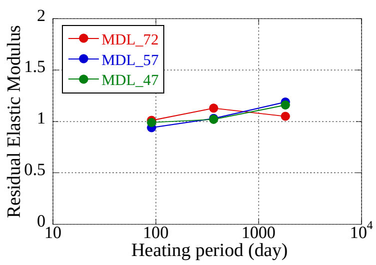

Figure 15. The residual elastic modulus of MDL

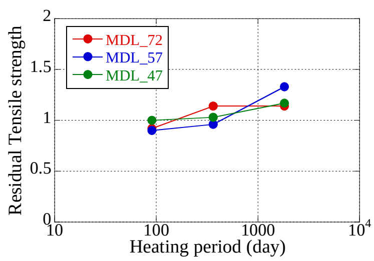

Figure 16. The residual tensile strength of MDL

c. Comparison between MDL and specimens

1) Mechanical properties

Comparisons between the compressive strength, the elastic modulus, and the tensile strength of the high temperature part of MDL and the specimen are shown in Figs. 17, 18, and 19, respectively. As shown in Fig. 17, Fig. 18, and Fig. 19, the residual ratio of compressive strength, elastic modulus, and tensile strength of MDL exceeded 1.0, which was close to the result of the seal specimen. Compressive strength at the position of concrete temperature of 72°C decreased by 8% from 1-year to 5-year heating. The reduction tendency of the compressive strength of MDL is presumed to be in a convergence state, since the residual compressive strength of the cement type M unsealed specimen at 5-year heating as shown in Fig. 6 is 1.0 and 0.9, respectively, at 65°C and 90°C heating.

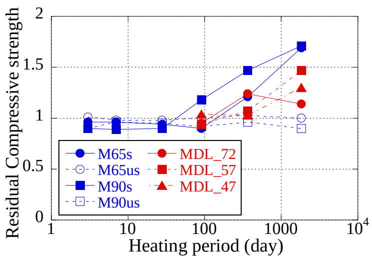

Figure 17. The comparison of the residual compressive strength between scaled model and specimens

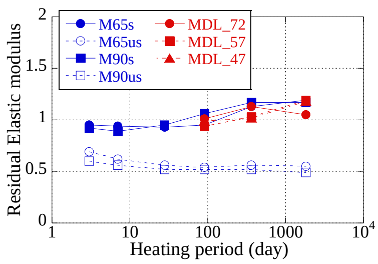

Figure 18. The comparison of the residual Elastic modulus between scaled model and specimens

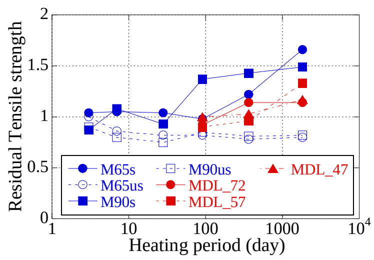

Figure 19. The comparison of the residual Tensile strength between scaled model and specimens

2) Relationship between water content ratio and Elastic modulus and Tensile strength

The experimental results of the unsealed specimen show that the decline in the elastic modulus and tensile strength is greater than the compressive strength due to the decrease in water content ratio. On the other hand, in MDL, although the water content ratio decreased at the position of the concrete temperature of about 72°C, the reduction ratio of the compressive strength and the elastic modulus was equivalent. Fig. 20 and Fig. 21 show the relationship between the water content ratio and the residual elastic modulus, and the relationship between the water content ratio and the residual tensile strength, respectively. As shown in Fig. 20 and Fig. 21, the residual ratios of the elastic modulus and the tensile strength of MDL exceeded 1.0 even the water content ratio decreased to about 7%. This result seems to indicate that in the influence of the water content reduction on the mechanical properties of MDL is small and the elastic modulus and the tensile strength of the members of the nuclear power plant undergoing one side heating do not suffer from a large decrease due to the water content reduction. The reason why the elastic modulus and the tensile strength of MDL do not decrease even if the water content decreases is considered that the moisture escaping occurs entirely on the specimen over a short period of time in the unseal specimen, whereas moisture escaping of MDL gently occurs over a long period of time. Therefore, it is considered that the elastic modulus and the tensile strength do not decrease remarkably in the mass concrete member subjected to one side heating even if the water content decreases.

3. Consideration on the thermal effect of concrete at nuclear power plants

Regarding the mechanism of heating on the mechanical properties of concrete, it is revealed from the results of present experiment that, when free water exists, hydration and crystallization proceed and the mechanical properties increase with heating. In addition, by comparing the water content ratio and the mechanical properties of MDL and the specimen, it is found that the transition of free water is slow at the high temperature part of MDL, and the change in the mechanical properties with heating is close to the sealed specimen. The transition of free water of MDL of this study is considered to be faster than the concrete which receives long-term heating in the nuclear power plant, as the following reason.

- While the heating temperature in this study is 90 °C, the maximum temperature of concrete in the general part of a nuclear power plant is 65 °C or less.
- While the thickness of MDL in this study is 1 m, the thickness of concrete subjected to long-term heating in a nuclear power plant is the same as or more than MDL.

From the consideration of this study, it is considered that the mass member of nuclear power plant is in an environment where the hydration and crystallization progress by heating and the mechanical properties increase as compared with MDL of this research.

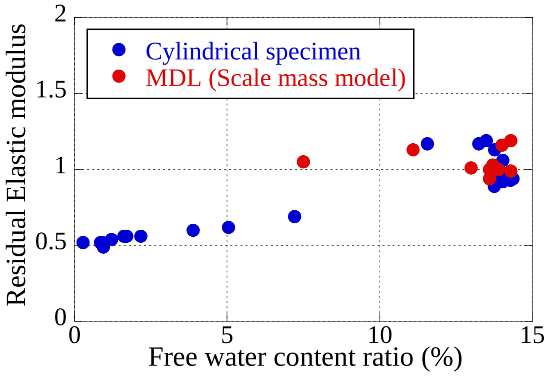

Figure 20. Relationship between the water content ratio and the residual elastic modulus

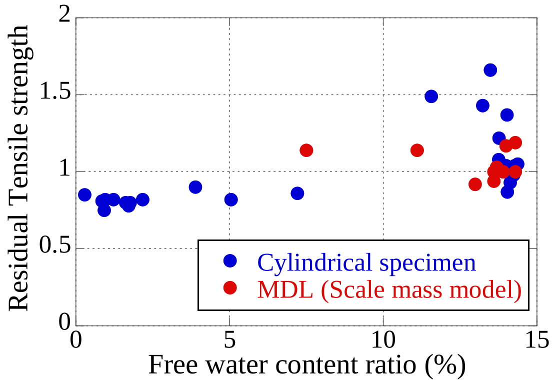

Figure 21. Relationship between the water content ratio and the residual tensile strength

4. Conclusion

- Based on the experimental results of moisture content, mineral composition, pore structure and mechanical properties of the specimen, the mechanism of heating on the mechanical properties of concrete was discussed.
- Since transition of free water of scaled mass model is slow, the heating mechanism is similar to the sealed specimen, and it is considered that the mechanical properties are increased by the progress of hydration and crystallization.
- Comparing the heating condition of MDL of this study and the environment of the member subjected to heating in the nuclear power plant, it is suggested that the nuclear power plant is in an environment where the hydration progresses and the mechanical properties are improved.

Acknowledgments

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