- Technical Paper -

MECHANICAL PROPERTY EVALUATION OF HOLLOW-CYLINDRICAL CONCRETE SPECIMEN DESIGNED FOR NEUTRON IRRADIATION EXPERIMENT BY RBSM

Daisuke KAMBAYASHI[*1], Shota UMEKI[*1], Hamza SAMOUH[*2], Ippei MARUYAMA[*3,*4]

ABSTRACT

In order to study the radiation effects on concrete structures in nuclear power plants, irradiation experiments using cylindrical specimens have been proposed. However, due to the high temperature in the center of the specimen caused by gamma-ray, chemical changes in the material must be considered. In this study, a hollow specimen with a hole in the cylindrical specimen was proposed to reduce the internal temperature, and after predicting the temperature distribution of the hollow specimen, the compressive strength and Young's Modulus of both specimens were compared by analysis that takes into account the expansion of aggregate due to neutron irradiation by RBSM.

Keywords: hollow specimen, RBSM, compressive strength, Young's Modulus, aggregate expansion

1. INTRODUCTION

Since the cost of rebuilding concrete structures in nuclear power plants is high, it is important to evaluate the present and future integrity of the structural members.

Concrete is used for the biological shielding walls that support the pressure vessels in nuclear power plants, and there are parts that are affected by radiation (neutron and gamma-ray) over the long term. It has been shown in previous studies [1,2] that neutron irradiation causes expansion of aggregate in concrete, which decreases compressive strength and Young's modulus of concrete. In the same study, it was also shown that the temperature of a concrete specimen of Φ40×60 mm increased up to about 70 °C due to gamma-ray heating even in an environment with cooling water at 55 °C. On the other hand, the structure of the actual one is regulated to have a maximum temperature of 65°C or lower.

In order to investigate the effect on the biological shielding wall, irradiation experiments using cylindrical test specimens have been conducted. However, the temperature of the specimens is higher than that of the actual biological shield (about 71 °C at the center of the specimen) because of the short period of neutron and gamma irradiation, which corresponds to the service period [2]. Although the effect of temperature on the change in physical properties of cement paste (strength change and dimensional change) is not significant, the expansion behavior of aggregate due to neutron irradiation may be sensitively affected by temperature, and this temperature effect should be taken into account in the evaluation of experimental results. Thus, if the temperature distribution is close to the environment of the actual machine, it is possible to evaluate the material without extraneous effects.

Therefore, if the temperature rise inside the specimen can be suppressed by making a hole in the center of the specimen and allowing cooling water to pass through, it may be a more appropriate evaluation. On the other hand, the mechanical properties of the specimen may be changed by making the hole.

In this study, the temperature distributions of the two models were calculated, and then the compressive strength and Young's modulus of the two models were compared by considering the effect of aggregate expansion due to neutron irradiation using a three-dimensional rigid spring model (RBSM).

2. TEMPERATURE DISTRIBUTION ANALYSIS

2.1 Analysis object

The temperature distribution was analyzed for a cross section of a Φ40×60 mm cylinder and that of a cylinder hollowed out from the cylinder with a diameter of 7 mm.

2.2 Analysis model

The temperature distributions in the cylindrical and hollow models were calculated using a discretized equation that takes into account the cross-sectional area based on the one-dimensional heat transfer diffusion equation shown in Equation (1).

$$\rho c \frac{\partial T}{\partial t} \Delta V = k \frac{\partial^2 T}{\partial x^2} + \dot{q} \Delta V \tag{1}$$

Where, T: Temperature (K)
ρ: Density (g/cm^3)
c: Heat capacity (J/g·K)
k: Thermal conductivity (J/cm·s·K)
$\dot{q}$: Calorific value per unit volume (J/s·cm^3)

*1 Graduate student, Graduate School of Environment Studies, Nagoya Univ., JCI Member
*2 Graduate student, Graduate School of Environment Studies, Nagoya Univ., JCI Student Member
*3 Appointed Assistant Professor, Graduate School of Environment Studies, Nagoya Univ.
*4 Prof., Graduate School of Environment Studies, Nagoya Univ., JCI Member

Table 1 Characteristics of reinforcements

Density	2.39 g/cm^3	
Heat capacity	2.91 J/g·K	
Thermal conductivity	7.50×10^{-3} J/cm·s·K	
Heat transfer coefficient	2.00×10^{-2} J/cm^2·s·K	
Calorific value	7.00×10^{-2} J/s·cm^3	
Boundary conditions	Inner	Adiabatic (cylindrical)
		Convection (hollow)
	Outer	Convection

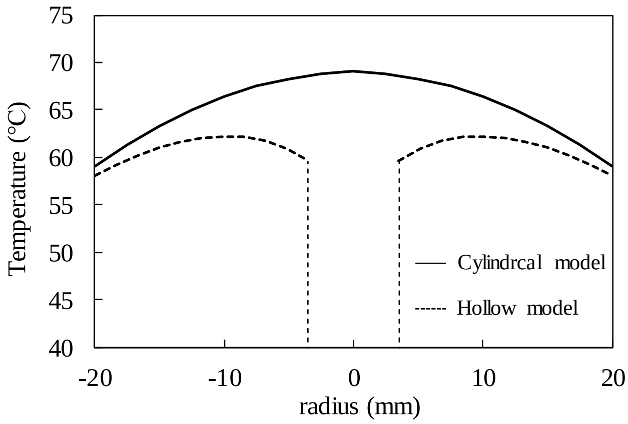


Fig.1 Temperature distribution

The analytical conditions were set as shown in Table 1, referring to the study by Maruyama et al. [2]. At the outer edge and the inner edge of the hollow model, the presence of cooling water of about 55 °C was assumed. The maximum temperature is assumed to be obtained at the center of the cylinder in the vertical direction, so the vertical direction is assumed to be adiabatic and there is no transfer of heat from the outside.

2.3 Analysis result

distributions of the cylindrical and hollow models. In the cylindrical model, the temperature rises to a maximum of 70 °C due to the adiabatic temperature rise inside, while in the hollow model, the temperature rise is suppressed to a maximum of 62 °C.

3. COMPRESSION ANALYSIS USING RBSM

3.1 Analysis outline and object

The Rigid Body Spring Model (RBSM) is a method to discretize an object by assuming that each element is a rigid body when the object is divided into individual elements, and by using springs placed between each element [3]. By imposing a nonlinear constitutive law on the installed spring, it is relatively easy to represent the cracking and fracture behaviors of the analyzed object.

In this study, Φ40×60 mm cylindrical model [2] and a hollow model with a 7 mm diameter cylinder hollowed out from the center of the cylindrical model, as shown in (a) and (b) in Fig.2.

The elements were three layers of aggregate, mortar, and their interfacial transition zone (ITZ), and the arrangement of aggregate was the same in both models. The volume fraction of aggregate was set at about 35%. Fig.3 shows the arrangement of aggregate in each model.

3.2 Material property

(1) Mortar and aggregate elements

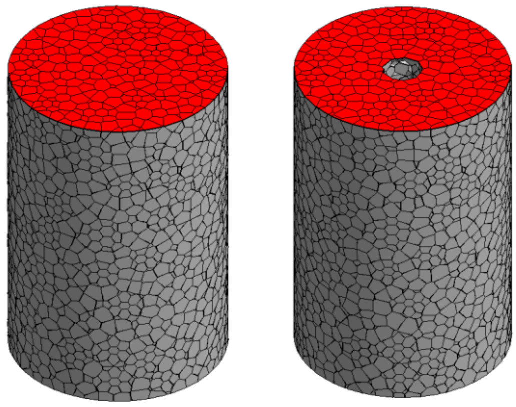
Table 2 shows the mechanical properties of the materials used in the mortar and aggregate elements. The physical properties are based on the experimental data of Maruyama et al. For the fracture energy, the JSCE equation [4] is used. For the vertical and shear springs of each element, the constitutive laws of previous studies [5,6] were used.

(2) ITZ

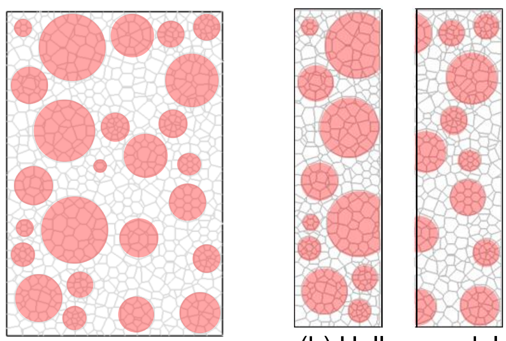
The aggregate-mortar interface has lower strength and Young's modulus than the mortar part, which is important for evaluating the cracking behavior of concrete. Therefore, in this study, the physical properties of the interface are referred to the values of previous studies7). The constitutive law of the interface is shown in Figure 4. In this study, α_{ITZ}=0.5, β_{ITZ}=0.5, and γ_{ITZ}=0.5.

(2) Material parameters

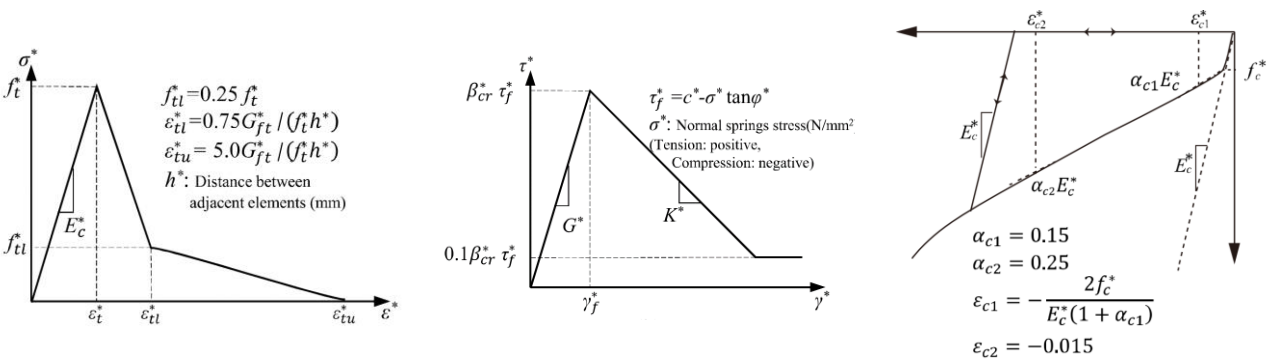
As shown in previous studies [8], RBSM expresses macroscopic material response by the interaction of springs which assumes mechanical behavior and rigid body elements connected by the spring. Hence, the physical properties obtained in the



(a) Cylindrical model (b) Hollow model
Fig. 2 Analysis models



(a) Cylindrical model (b) Hollow model
Fig. 3 Arrangement of aggregate (red part : aggregate)



(a) Tensile model for normal springs (b) Tensile model for shear springs (c) Compressive model for normal springs

Fig. 4 Constitutive law for normal springs and shear springs of mortar and aggregate elements

Table 2 Physical properties of materials [2]

	E_c: Young's Modulus (N/mm²)	f_t: Tensile strength (N/mm²)	f_c: Compressive strength (N/m)	G_{ft}: Fracture energy (N/m)
Mortar	28960	4.63	65.70	0.069
Aggregate	80000	100.0	250.0	1.0

Table 3 Parameters for normal springs

	E_c^*: Young's Modulus (N/mm²)	f_t^*: Tensile strength (N/mm²)	G_{ft}^*: Fracture energy (N/m)
Mortar	$1.45E_{cm}$	$1.0f_{tm}$	$0.4G_{ftm}$
Aggregate	$1.45E_{ca}$	$1.0f_{ta}$	$0.4G_{fta}$

experiment are not necessarily the same as those of the spring. Therefore, in this study, the values in Table 3 obtained by parametric study are used. For parameters not listed in the table, please refer to previous studies [9]. The symbols used in the figures correspond to the symbols used in the table.

3.2 Analysis conditions

In this study, loading tests of cylinders after gamma and neutron irradiation were assumed. The assumed neutron fluences were 0.75×10^{19} n/cm², 1.0×10^{19} n/cm², and 1.5×10^{19} n/cm², and the corresponding aggregate expansions were set to 1200μ, 1746μ, and 3042μ, respectively, by using Bykov's equation [10] to complement the temperatures from the experimental values of Maruyama et al [2]. Since the internal distribution of neutron fluence was not significantly different in the previous irradiation tests [2], it is not considered that the presence of the hole changes the amount of neutron fluence inside of the specimen, and the aggregate was uniformly expanded. The effect of temperature increase due to gamma irradiation was omitted from the analysis in this study because the aggregate expansion was calculated considering the temperature and the temperature strain was considered to have little effect on the aggregate expansion.

The boundary conditions during expansion were completely fixed at the bottom of the model, free deformation in the vertical direction on the top surface during aggregate expansion, and fixed on both sides during loading. The sides of the model were assumed to be free to deform.

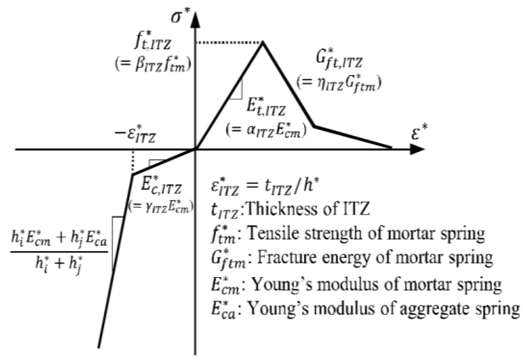


Fig. 5 Constitutive law for ITZ

3.2 Analysis result

Figure 6 shows the cracks at the time of fracture in each model. In both models, micro-cracks were observed around the aggregate, and these cracks were connected to form large cracks in the diagonal direction of the specimen. As the amount of aggregate expansion increased, micro-cracks appeared all over the specimen. In the hollow model, fine cracks are observed along the hole, especially at the expansion of 3042μ, but the effect is small and the fracture properties are almost the same in both models.

The stress-strain relationship of the two models is shown in Fig.7 for each expansion amount of coarse aggregate. Although the behavior after softening was different, it was confirmed that the behavior of the

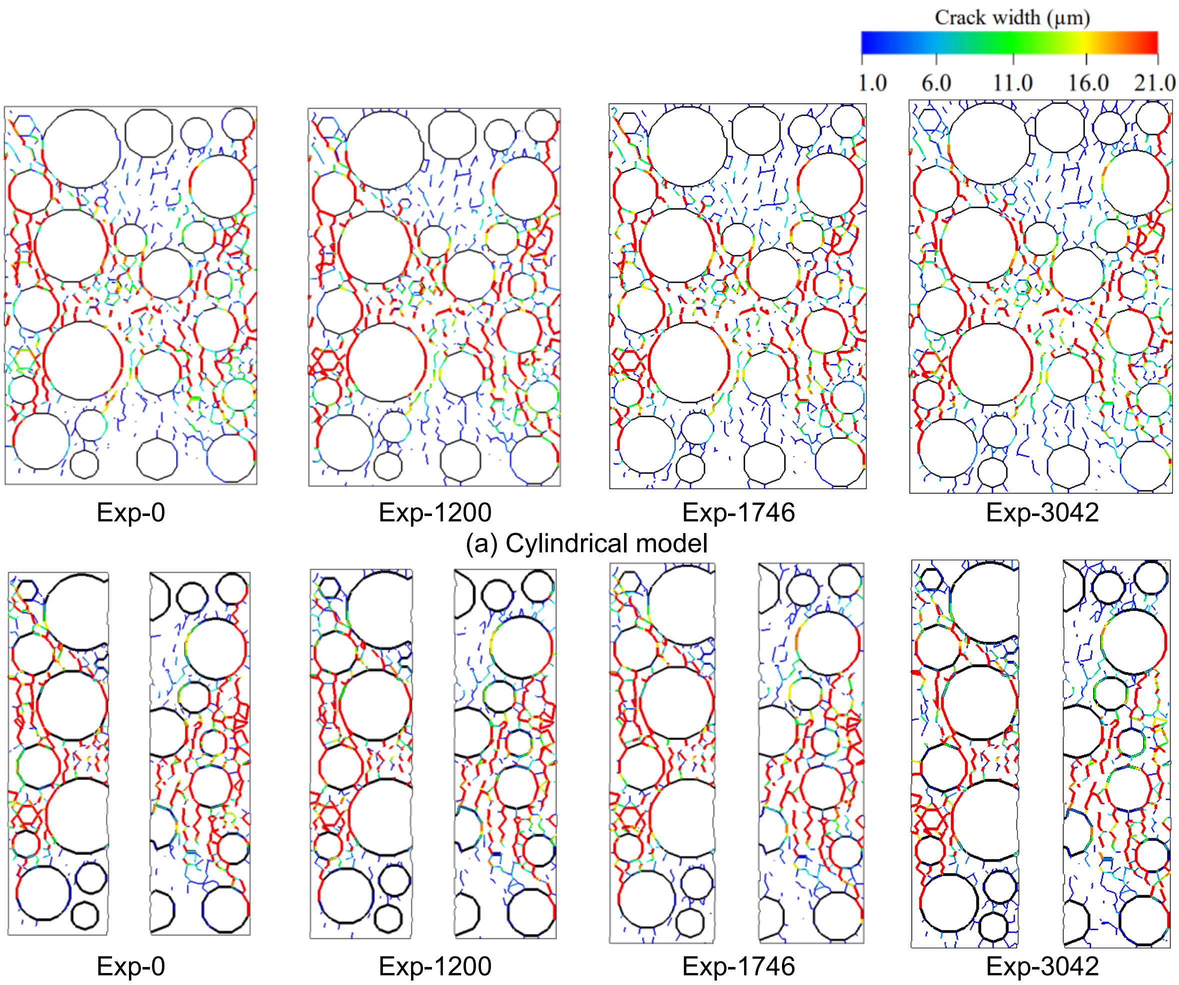


Fig. 6 Cracks at fracture

cylindrical and hollow models was similar until the strength was reached, and there was almost no difference in the compressive strength and Young's Modulus.

Fig 8 shows a plot of the compressive strength and Young's Modulus ratios at each irradiation amount. The results show the same tendency as in the previous study [1] that the compressive strength and Young's modulus decrease with the increase in the amount of expansion.

From the above results, it is inferred that the presence or absence of a hole with a diameter of about 7 mm made in the center of the specimen of Φ20×60 mm has no significant effect on the compressive strength and Young's modulus of the specimen under the condition of aggregate expansion caused by neutron irradiation.

4. CONCLUSIONS

In this study, the temperature distribution of a cylindrical model of Φ20×60 mm and a hollow model with a hole of 7 mm in diameter were analyzed assuming the existence of gamma heat generation and cooling water, and then the mechanical properties of both models were compared by compressive loading analysis considering the expansion of aggregate due to neutron irradiation using RBSM. The results are summarized as

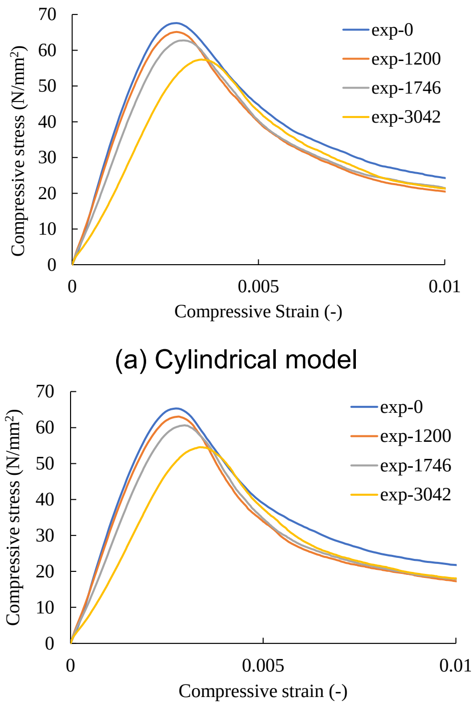


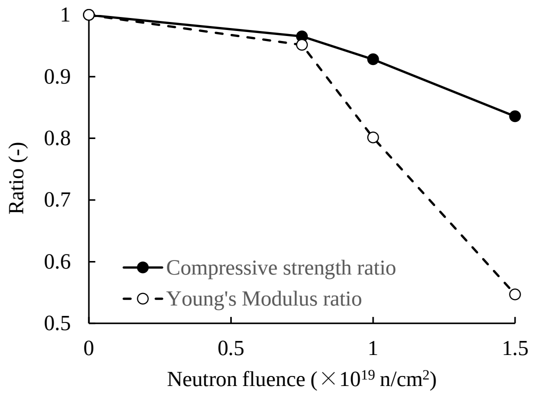
Fig. 7 Stress-strain relationship

follows.

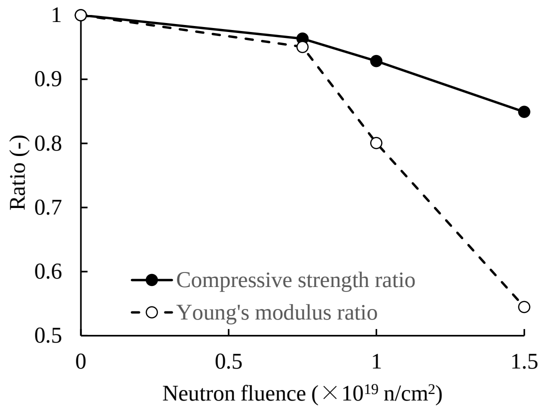
(1) The results of the temperature distribution analysis show that the temperature rise in the cylindrical model is about 70 °C due to the adiabatic temperature rise at the center, while the temperature rise in the hollow model is suppressed to a maximum of 62 °C by the cooling water.

(2) The loading analysis after aggregate expansion by RBSM showed that the compressive strength and Young's modulus of aggregate in concrete decreased when the aggregate expanded due to neutron irradiation, as in previous studies. In both models, cracks were observed around the aggregate, and the cracks connected to each other to reach failure. From the comparison between the cylindrical and hollow models, the presence or absence of a 7 mm diameter hole in the cylindrical specimen of Φ20×60 mm does not have a significant effect on the compressive strength and Young's modulus.

(3) The hollow model does not need to take into account the chemical change of the material and its effect due to high temperature, and its mechanical properties are the same as those of the cylindrical model, so it can be used in experiments to evaluate the effect on the bio-shielding wall more appropriately.



(a) Cylindrical model



(b) Hollow model

Fig. 8 Compressive strength and Young's Modulus ratios

ACKNOWLEDGEMENT

A part of this study was the results from the "Japan Concrete Aging Management Program on Irradiation Effects (JCAMP)" sponsored by METI in Japan.

REFERENCES

[1] Maruyama et al.: A Numerical Model for Concrete Strength Change under Neutron and Gamma-ray Irradiation, Journal of Advanced Concrete Technology, Vol.14, pp.14-162, April.2016

[2] Maruyama et al.: Development of Soundness Assessment Procedure for Concrete Members Affected by Neutron and Gamma-Ray Irradiation, Journal of Advanced Concrete Technology, Vol.15, pp.440-523, September.2017

[3] Kawai, T.: New discrete models and their application to seismic response analysis of structures, Nuclear Engineering and Design, Vol.48, No.1, pp.207-229, June.1978

[4] JSCE.: Standard specifications for concrete structure 2002, inspection, 2002

[5] Yamamoto, Y., Nakamura, H., Kuroda, I. and Furuya, N.: Analysis of compression failure of concrete by three-dimensional rigid body spring model, Journal of Japan Society of Civil Engineers, Vol.64, No.4, pp.612-630, 2008

[6] Yamamoto, Y., Nakamura, H., Kuroda, I. and Furuya, N.: Crack propagation analysis of reinforced concrete wall under cyclic loading using RBSM, European Journal of Environmental and Civil Engineering, Vol.18, No.7, pp.780-792, 2014

[7] Sasano, H. and Maruyama, I.: Sensitivity analysis on the impact of aggregate and ITZ strength on the concrete properties by RBSM, Japan Concrete Institute, Vol.41, No.1, pp.389-394, 2019

[8] Bolander, J.E. and Saito, S.: Fracture analysis using spring networks with random geometry, Engineering Fracture Mechanics, Vol.61, No.5-6, pp.569-591, 1998

[9] Kambayashi et al.: Numerical Analysis of a Concrete Biological Shielding Wall under Neutron Irradiation by 3D RBSM, Journal of Advanced Concrete Technology, Vol.18, pp.617-632, October.2020

[10] Bykov et al.: Effect of irradiation temperature on the radiation expansion of quartz, Soviet Atomic Energy, Vol.51, No.3, pp.593-595, 1981