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Division I

INFLUENCE OF RECYCLED AGGREGATE ON THE PROPERTIES OF CONCRETE EXPOSED TO ELEVATED TEMPERATURE UP TO 175°C

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ABSTRACT

Concrete structures for nuclear power plant may be subjected to heating action for a long period. Many studies have already reported that the strength of concrete subjected to heating can be retained by maintaining temperature conditions of not more than 65°C under general control standards for nuclear power plant. The effect of the heating should be considered to discuss the long-term safety and the durability of concrete structures. On the other hand, from the viewpoint of environmental consideration, there is a movement to actively use recycled aggregate in concrete. This paper discussed the influence of recycled aggregate on the properties of concrete exposed to sustained elevated temperatures up to 175°C.

INTRODUCTION

With the broadening of their uses, concrete structures are subjected to a wide variety of deteriorative factors during their working life. Heat is one such factor, which alters the strength properties of concrete. For this reason, temperature limits may be set on concrete in service for structures subjected to heat for a long time, such as power generation facilities. The properties of concrete also change in a fire due to high temperature heating. Active investigation has therefore been carried out on concrete affected by heat. It has been reported that compressive strength is changed by increasing heat and the concomitant moisture state, decreasing to a greater extent as the temperature rises. Tensile strength is also reported to decrease with the heating temperature, with the loss being greater than the loss in compressive strength. These changes, which vary depending on the presence/absence and type of aggregate, have been summarized in reports by NRC (2010) and AIJ (2009). On the other hand, from the viewpoint of environmental consideration, there is a movement to actively use recycled aggregate in concrete.

Four kinds of recycled aggregate are specified according to the quality of aggregates in Japan. The recycled aggregates are classified into JASS 5N, JIS A 5021" Class H", JIS A 5022" Class M" and JIS A 5023" Class L". The recycled aggregate of JASS 5N is able to be used as concrete materials of NPP, Class H is applied for architectural buildings. Class M is allowed to be used for building materials in reinforced concrete that do not require the durability of dry shrinkage. Class L is used for unreinforced concrete. And the properties of the concrete with high quality recycled aggregates was presented by authors (2019). Then the properties of recycled concrete with high-quality recycled aggregates produced by 4 types of dry treatment system was almost the same as concrete with original stone.

In this study, the strength properties and fracture properties of concrete with recycled aggregate exposed to sustained elevated temperature up to 175°C for 90 days were investigated.

EXPERIMENT OVERVIEW

Outline of specimens

Table 1 gives the materials, and Table 2 gives the factors and levels. Two types of coarse aggregate, crushed stone and recycled aggregate, were used for concrete. The water-cement ratio was 50% and 60%, and exposure temperature were set to 65, 110, and 175°C. Tests were also conducted on unheated (20°C, 60%R.H.) specimens for comparison. Table 3 lists the mixture proportions. The content of water in concrete was fixed to 178 kg/m^3.

Specimens were cured in the constant temperature room of 20°C for 13 weeks after placing, and demolded, then exposed to heating and testing. Table 4 gives the as-mixed properties of concrete and the strength test results after 13 week-curing.

Table 1: Materials

Materials	Mark	Detail
Cement	MPC	Moderate-heat Portland cement, Density=3.21g/cm^3
Fine aggregate	S	River sand by Kakegawa, Specific gravity=2.58g/cm^3, F.M.=2.72
Coarse aggregate	G	Crushed stone by Oune, Specific gravity=2.64g/cm^3, Absolute Volume=59.1%
	RG	Recycled aggregate, Specific gravity=2.58g/cm^3, Absolute Volume=60.5%
Admixture	Ad	Air-entraining and water-reducing admixture

Table 2: Factors and levels

Factor	Level
Water cement ratio (W/C)	50% (50), 60% (60)
Coarse aggregate	Crushed stone (G), Recycled aggregate (RG)
Exposure temperature	20°C 60%R.H., 65°C, 110°C, 175°C

Table 3: Mixture proportions

Mark	W/C (%)	W (kg/m^3)	MPC (kg/m^3)	S (kg/m^3)	G (kg/m^3)	RG (kg/m^3)	Ad (C×%)
G50	50	178	356	781	960	-	0.012
RG50	50	178	356	781	-	938	0.010
G60	60	178	297	828	960	-	0.015
RG60	60	178	297	828	-	938	0.010

Table 4: Properties of concrete

Mark	Slump (cm)	Air content (%)	Compressive strength (N/mm^2)	Young's modulus (kN/mm^2)
G50	19.5	5.5	44.9	28.5
RG50	19.5	5.9	41.4	28.2
G60	19.0	5.5	37.6	26.1
RG60	20.0	5.3	38.2	28.3

Exposure procedures

Each set of specimens were exposed to different peak temperatures (65, 110 and 175°C). Tests were also conducted on unheated specimens (20°C, 60%R.H.). The exposure term was 90 days. After exposure, specimens were gradually cooled down to ambient temperature, then tested.

Calculation of mass loss ratio

Mass loss ratio was calculated by Eq.(1) with the weight measured before and after exposure.

$$\omega_{\mathrm{T}} = \frac{W_0 - W_{\mathrm{T}}}{W_0} \times 100 \quad (1)$$

Here, ω_{T} is mass loss ratio (%), W_0 is weight before exposure (g) and W_{T} is weight after exposure at T°C (g).

Length change rate measuring method

The length change rate was the difference of the length measured before and after exposure with the specimen of 100 × 100 × 400 mm.

Compressive strength testing method

Compression tests were conducted in accordance with JIS A 1108 with the specimen of ϕ100 × 200 mm. Young's modulus was also measured simultaneously using a compressometer (JIS A 1149).

Shear strength testing method

The specimen size for shear tests was 100 × 100 × 200 mm completed fracture toughness test. The measurement span length was 100mm and the load rate was constant at 0.06 N/mm^2 as the rate of increase in strength. Shear strength method was based on "Test method for shear strength of steel fibber reinforced concrete" by Japan Society of Civil Engineers.

Tensile strength testing method

The specimen for tests was 100mm cubic of the central block remaining after shear strength test. This method was performed using the same method as specified in "BS-1881 Part-117 Method for determination of tensile splitting strength".

Fracture toughness testing method

Three-point bending test was conducted to measure the load versus crack mouth opening displacement (L-CMOD) curves. Test conditions followed JCI Standard (JCI-S-001-2003). Specimen size was 100 × 100 × 400 mm. The span length was 300 mm, and notch length was 30 mm. Specimen was loaded with constant displacement control of 0.01mm/min. The test set-up is shown in Fig.1.

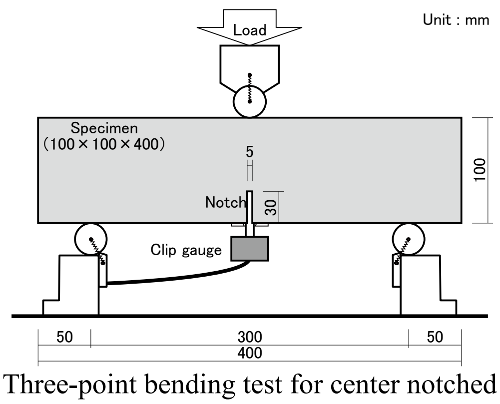

Figure 1. Three-point bending test for center notched specimen

RESULTS AND DISCUSSION

Mass loss ratio

Figure 2 shows the mass loss ratio-exposure temperature relationship of 100 × 100 × 400 mm specimens. Mass loss ratio is greater at the temperature of 50°C and becomes smaller the specimens at 65 to 175°C. Regardless of the water-cement ratio and exposure temperature, the mass loss ratio of concrete with recycled aggregate is greater than the concrete with crushed stone. This is thought to be due to the greater water loss from the mortar adhering to the recycled aggregate.

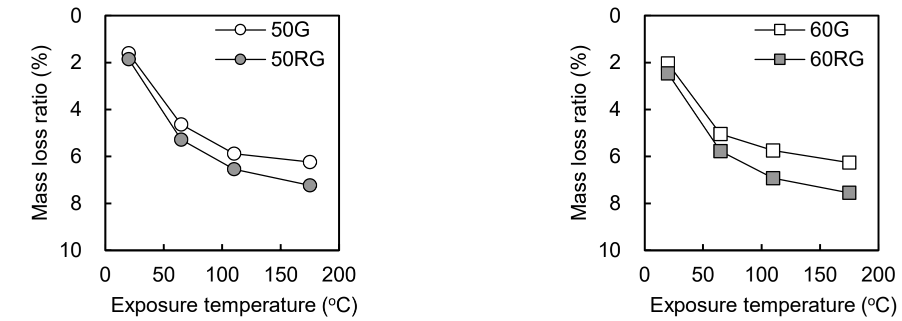

Figure 2. Mass loss ratio-exposure temperature relationship

Length change rate

Figure 3 shows the length change rate-exposure temperature relationship of 100 × 100 × 400 mm specimens. There is no difference in the length change due to differences in water-cement ratio. At 20°C, there is no difference in the length change rate due to the difference in coarse aggregate, but the length change of concrete with recycled aggregate becomes greater as the exposure temperature increases. This is the same trend as in Fig. 2, and the shrinkage is considered to increase as a result of moisture loss.

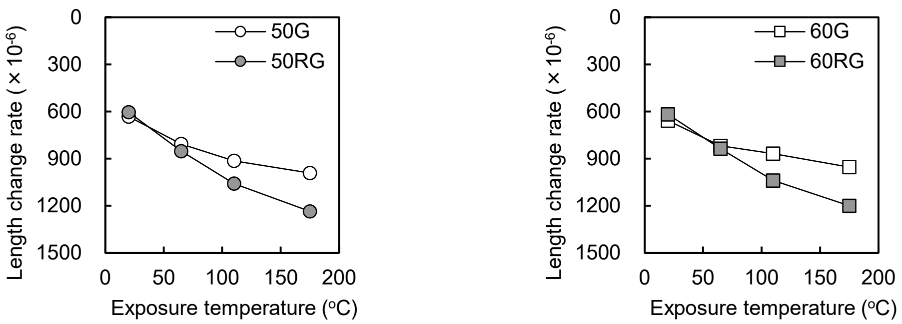

Figure 3. Length change rate-exposure temperature relationship

Compressive strength

Figure 4 shows the compressive strength-exposure temperature relationship. Compressive strength at 50% is higher than at 60% water-cement ratio. Compressive strength, which decreased at a heating temperature of 65°C, increased slightly at 110°C and then decreased again at 175°C. Overall, however, the compressive strength tends to decrease with heating. Although the compressive strength of concrete with recycled aggregate is lower at a water-cement ratio of 50%, the difference is slight, and at a water-cement ratio of 60%, the compressive strengths are equivalent.

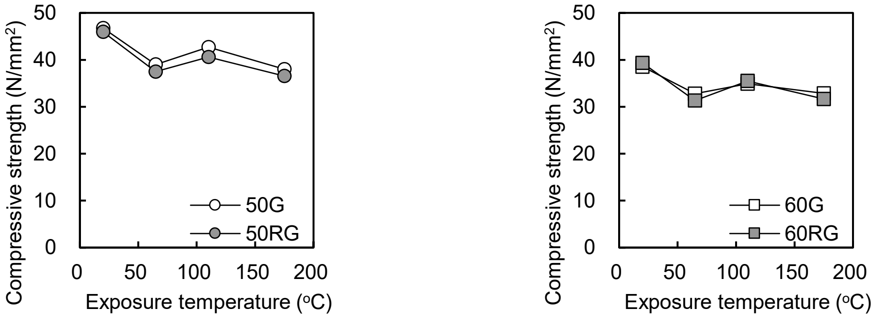

Figure 4. Compressive strength-exposure temperature relationship

Young's modulus

Figure 5 shows the Young's modulus-exposure temperature relationship. Young's modulus at 50% is slightly lower than that at 60% water-cement ratio. Young's modulus remains the same up to 65°C, but decreases at 110 and 175°C. The decrease is independent of the type of coarse aggregate.

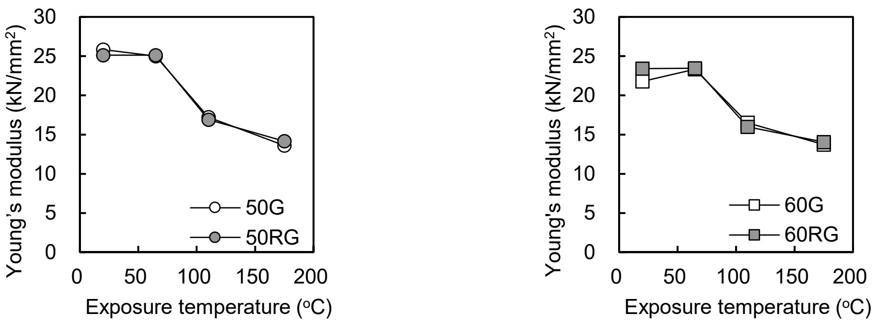

Figure 5. Young's modulus-exposure temperature relationship

Shear strength

Figure 6 shows the shear strength-exposure temperature relationship. Shear strength also decreases with increasing water-cement ratio. As with compressive strength (Fig. 4), shear strength decreases at 65°C, increases at 110°C, and then decreases again at 175°C. The difference in coarse aggregate type is observed at a water-cement ratio of 50%, but the values are similar at a water-cement ratio of 60%.

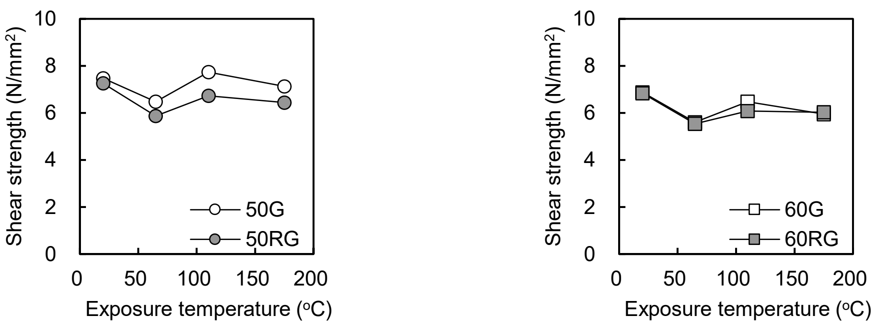

Figure 6. Shear strength-exposure temperature relationship

Tensile strength

Figure 7 shows the tensile strength-exposure relationship. Tensile strength decreased by 0.5 to 1 N/mm^2 at 65°C, followed by smaller decreases at 110 and 175°C. The difference in coarse aggregate type is not observed.

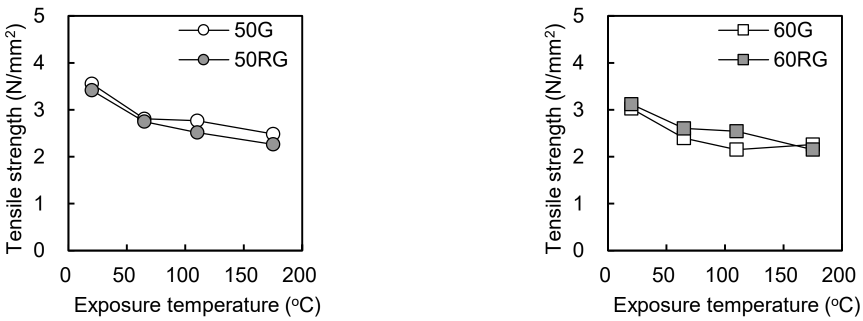

Figure 7. Tensile strength-exposure temperature relationship

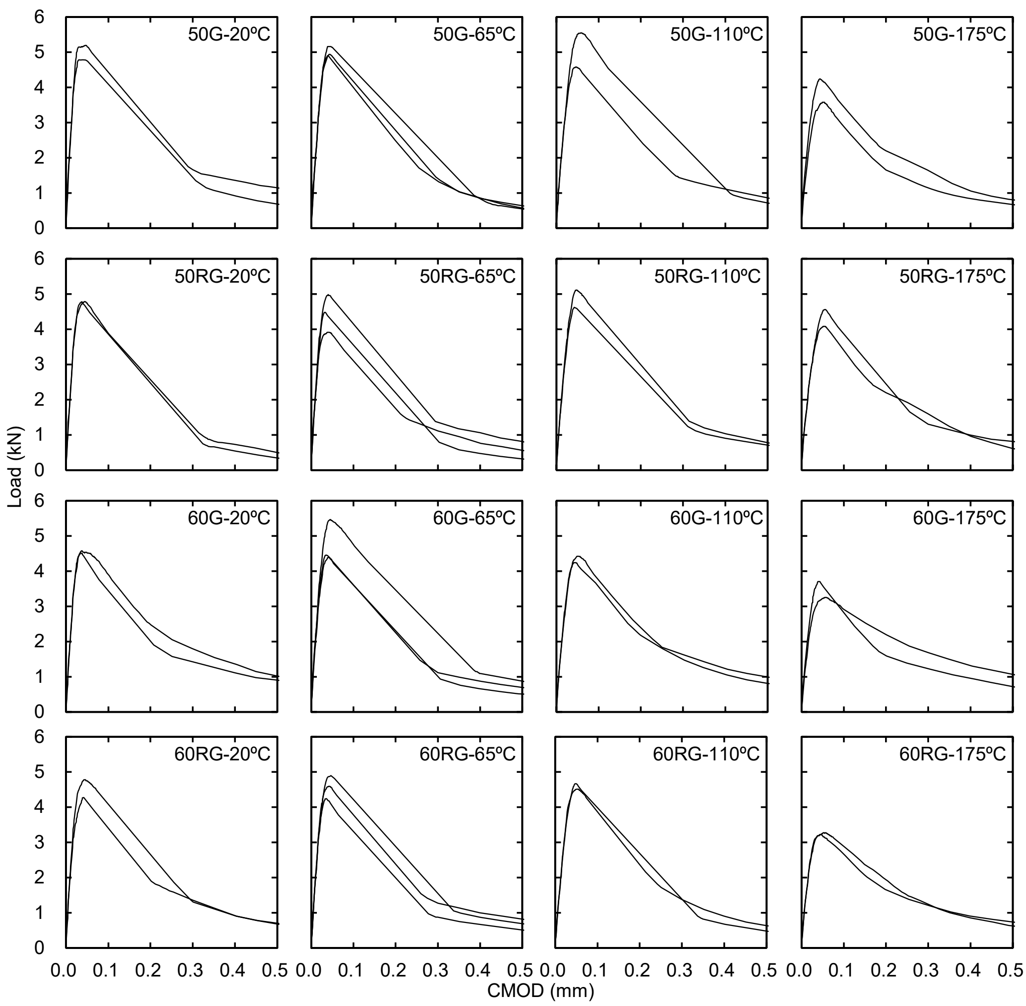

Figure 8. L-CMOD curve

Load-Crack mouth opening displacement (CMOD) curve

Figure 8 shows the load-CMOD curves obtained from three-point bending test. Stable load-CMOD curves were obtained from all specimens heated and unheated, regardless of the exposure temperatures. There are few changes of maximum load up to 110°C regardless of water-cement ratio and coarse aggregate, but decrease at 175°C. It is also noticed that the shapes of the peaks are sharp with lower temperatures but become rounded with higher temperature such as 110 and 175°C, with the post-peak drops being more gradual.

Fracture energy

Figure 9 shows the fracture energy-exposure temperature relationship. Note that the fracture energy was calculated by eq.(2) and (3) according to JCI-S-001-2003. W_0 is the area under the crack opening displacement to rupture of the specimen or 2 mm that was the capacity of the clip gauge.

$$G_{\mathrm{F}} = \frac{0.75W_0 + W_1}{A_{\mathrm{lig}}} \tag{2}$$

$$W_1 = 0.75\left(\frac{S}{L}m_1 + 2m_2\right)g \cdot CMOD_c \tag{3}$$

Here, G_{F} is fracture energy (N/m), W_0 is area below CMOD curve up to rupture of specimen or 2 mm (Nm), W_1 is work done by deadweight of specimen and loading jig (Nm), A_{lig} is area of broken ligament 0.003 (m^2), m_1 is mass of specimen (kg), S is loading span 0.3 (m), L is total length of specimen 0.4 (m), m_2 is mass of jig not attached to testing machine but placed on specimen until rupture 0 (kg), g is gravitational acceleration 9.807 (m/s^2), $CMOD_c$ is crack mouth opening displacement at the time of rupture.

Fracture energy varied widely among the two or three specimens, but taking into account previous studies, the fracture energy tended to decrease at 65°C, then increase at 110°C, and then decrease again. The fracture energy is smaller for concrete using recycled aggregate as coarse aggregate, regardless of the water-cement ratio.

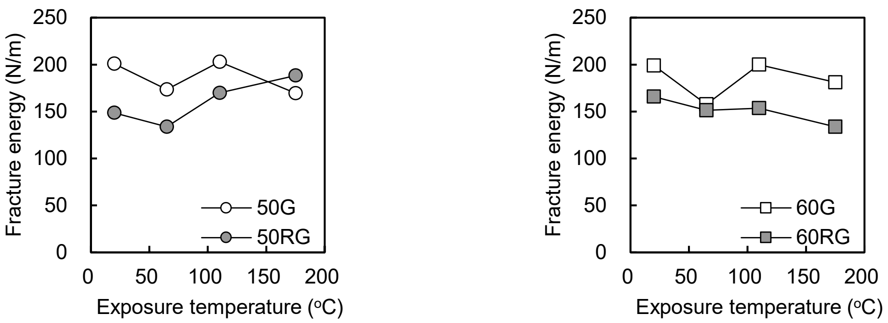

Figure 9. Fracture energy-exposure temperature relationship

CONCLUSIONS

In this study, the strength properties and fracture properties of concrete with recycled aggregate exposed to sustained elevated temperature up to 175°C for 90 days were investigated. Within the range of this study, the following were found:

(1) The mass loss ratio and the length change rate of concrete with recycled aggregate is greater than the concrete with crushed stone.

(2) Although the compressive strength and the shear strength of concrete with recycled aggregate is lower at a water-cement ratio of 50%, the difference is slight, and at a water-cement ratio of 60%, the compressive strengths are equivalent.
(3) The difference in coarse aggregate type is not observed for Young's modulus and the tensile strength.
(4) The fracture energy is smaller for concrete using recycled aggregate as coarse aggregate, regardless of the water-cement ratio.

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