ABSTRACT

Although there are many papers concerning the effects of temperature on concrete, those concerning thermal cycles are limited. This paper presents the results of experiments on the effects of cyclic exposure on compressive, tensile, bond strengths and young's modulus of concrete. Un-sealed specimens were subjected to sustained and cyclic temperature of 80°C for 7, 28, 60 days and 1, 7, 28, 60 cycles. After exposure, specimens were tested for weight loss and residual strengths by dry and wet test. Young's moduli were measured on compression test. Tensile strengths were tested by splitting method. Bond strengths were tested by pull-out method.

Compressive strength after 60 day exposure showed 30% increase when tested dry and 10% increase when tested wet, while those after 60 thermal cycles showed 10% decrease when tested dry and 20% decrease when tested wet. Young's modulus after sustained exposure showed 13% reduction when tested dry and 20% reduction when tested wet, while those after cyclic exposure showed 12-13% reduction by dry and wet test. Tensile strengths after sustained exposure showed 10% reduction when tested dry and 15% reduction when tested wet, while those after cyclic exposure showed 13% reduction when tested dry and 20% reduction when tested wet. Bond strength after exposure showed the same tendency as compressive strength. Cyclic exposure was found to cause more deteriorating effects on tensile and bond strengths than on compressive strength.

INTRODUCTION

In Japan, commercial nuclear power plants (NPP) in service stop operation once a year for annual inspection and maintenance. The licensed regular operating term for NPPs are 40 years and the extended operation term is another 20 years when license renewal are permitted by Nuclear Regulation Authority Japan (NRA).

The allowable temperature of concrete components in NPPs subjected to elevated temperatures, such as shielding walls or containment walls, is 65°C for long term except local areas and 175°C for short term, while those at local areas is 90°C for long term and 340°C for short term. Hence concrete components are to be subjected to 60 cycles of thermal cycles up to 65°C at general areas and those up to 90°C at local areas.

Although there are many technical papers concerned with the effects high and elevated temperature exposure on concrete properties, those dealing with the effects of thermal cycles are still limited, and only a few data are available with regard to the degradation of tensile, shear and bond strengths due to thermal cycle other than compressive strength.

D. Campbell-Allen, and P.M. Desai, indicated that compressive, tensile and bond strengths and modulus of elasticity of limestone aggregate concrete reduced after 20 cycles of cycling heating to 65°C.
and that at higher temperature of 200 and 300°C the first thermal cycles caused the largest percentage of damage depending on aggregate type.

V.V. Bettero, and M. Polivka, reported that reduction of compressive strength was 20% after 3 cycles, 30% after 5 cycles and 50% after 14 cycles at heating cycle to 150°C.

D.J. Naus, summarized in a literature review on the effects of elevated temperature on concrete referring above papers that thermal cycling can have deteriorating effects on concrete's mechanical properties even at relatively low temperature of 65°C and that the extent of damage due to thermal cycles at higher temperature was dependent on aggregate type and is associated with loss of bond between the aggregate and cement paste matrix.

However, T. Suzuki, et al., reported that the residual ratio of compressive strength was 150% after 120 cycles for sealed exposure to 110°C indicating 110% for unsealed exposure, and that the residual ratio of modulus of elasticity was 110% for sealed exposure and was 50% for unsealed exposure. And

M. Koba, et al., reported that no difference was found on residual compressive strength and modulus of elasticity between sustained and cyclic exposure to 110°C up to 120 cycles.

There are much discrepancy among the limited data available on the effects of thermal cycles on strength characteristics. However, possible thermal cycles on concrete components in light water type NPPs in Japan would be not so high as Bettero, V.V. et al., Suzuki, T. et al. and Koba, M. et al., reported, but would be moderate elevated temperatures of 65°C at general areas and 90°C at local areas.

In the temperature range around 50°C, long term exposure may cause unusual degradation in compressive, tensile, shear and bond strengths caused by evaporation of free and adsorbed water resulting in increase of pore size and pore volume in cement paste matrix, as presented by K. Kishitani et al., K. Kasami et al.

This paper presents the results of experimental studies carried out in order to make clear of the effects of thermal cycles of 20°C to 80°C on the compressive, tensile and bond strengths and young's modulus.

**OUTLINE OF EXPERIMENTS**

Outline of experimental program is shown in Table 1. Concrete specimens for compressive, tensile and bond strengths were subjected to sustained elevated temperature of 80°C and cyclic temperature of 20°C to 80°C without seal. The exposure temperature was selected as the average of long term allowable temperature at general areas (65°C) and at local areas (90°C).

Term of sustained temperature exposure were 7, 28 and 60 days, and cycles of cyclic temperature exposure were 1, 7, 28 and 60 cycles on a one day cycle.

Weight loss after each exposure was measured on compressive strength specimens. Compressive, tensile and bond strengths and young's modulus were tested on dry and wet specimens.

<table>
<thead>
<tr>
<th>type of test</th>
<th>20°C 20days</th>
<th>20°C 60days</th>
<th>25% 60°C 7days</th>
<th>25% 60°C 28days</th>
<th>25% 60°C 60days</th>
<th>20°C-80°C 1day</th>
<th>20°C-80°C 7days</th>
<th>20°C-80°C 28days</th>
<th>20°C-80°C 60days</th>
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<tr>
<td>Compressive strength</td>
<td>● ○ ● ○ 1)</td>
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<td>Young's modulus</td>
<td>● ○ ● ○ ○</td>
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<tr>
<td>Tensile strength</td>
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<td>Bond strength</td>
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</tbody>
</table>

Note 1) O dry test ● wet test 2) Underwater curing

Table 1 Outline of experimental plan
MATERIALS AND MIX PROPORTION OF CONCRETE

Materials used for concrete are shown in Table 2. Ordinary portland cement, river sand and river gravel were used.

Mix proportion and test results of fresh concrete are shown in Table 3. Water cement ratio was 50% and target slump was 50 mm. The test results of fresh concrete shown are average of three batches.

Table 2 Concrete materials

<table>
<thead>
<tr>
<th>Type of Materials</th>
<th>Ordinary portland cement</th>
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<tbody>
<tr>
<td>Aggregate</td>
<td>Fine River sand: max size: 5 mm, oven-dry density: 2.58 g/cm(^3), absorption: 1.60%</td>
</tr>
<tr>
<td></td>
<td>Coarse River gravel: max size: 20 mm, oven-dry density: 2.64 g/cm(^3), absorption: 0.95%</td>
</tr>
<tr>
<td>Water</td>
<td>Tap water of Tskibya City</td>
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</tbody>
</table>

Table 3 Mix proportion of concrete

<table>
<thead>
<tr>
<th>W/C (x/wt)</th>
<th>Target slump (mm)</th>
<th>Air-content (%)</th>
<th>S/A (x/vol)</th>
<th>Mix proportion (kg/m(^3))</th>
<th>Fresh concrete (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Water</td>
<td>Cement</td>
</tr>
<tr>
<td>0.50</td>
<td>5.0</td>
<td>1.0</td>
<td>47</td>
<td>150</td>
<td>320</td>
</tr>
</tbody>
</table>

(Note) *1: sand-total aggregate ratio by absolute volume *2: oven-dry condition

PREPARATION OF SPECIMENS

Mixing of Concrete

Concrete was mixed with a pan-type mixer in three separate batches, the first batch being for compressive strength specimens, the second batch being for tensile strength specimens and the third batch being for bond strength specimens.

Moulding and Curing of Specimens

Cylindrical specimens with the diameter of 100 mm and weight of 200 mm were prepared for compressive, tensile and bond strengths. Concretes were cast in steel moulds in two layers and were compacted by rodding and tapping. Cylinders for compressive strength were capped on top surface with cement paste. Cylinders for bond strength were embedded with round bars with the diameter of 16 mm vertically, and were capped with cement paste.

Cylinders were stored in mould for two days in mould at 20°C and 80% R.H., and then were removed of steel moulds. Cylinders were cured in water at 20°C until 28 days old.

EXPOSURE TO SUSTAINED AND CYCLIC ELEVATED TEMPERATURE

Cylinders for sustained exposure were subjected to dry air at 80°C and 25% R.H. in a constant temperature and humidity chamber until the prescribed test ages. Cylinders for cyclic exposure were subjected to heating and cooling cycles of 20°C, 45% R.H, to 80°C, 25% R.H, in a constant temperature and humidity chamber with programmed control until the prescribed thermal cycles.

Fig. 1 shows the pattern of heating and cooling cycles. The rate of temperature rise and cooling was 10°C per hour. The thermal cycle was one cycle per one day.
TESTS BEFORE AND AFTER ELEVATED TEMPERATURE EXPOSURE

Tests for Compressive, tensile and bond strengths and Young's Modulus.

Weight Losses were measured on cylinders for compressive strength tests, and were calculated by the percentage of unheated cylinders at 28 days.

Cylinders for dry tests were stored in air at 20°C, 45% R.H., for 48 hours, and cylinders for wet tests were stored in water at 20°C for 48 hours prior to tests. Cylinders were tested for dry and wet compressive strengths. At compression tests. Compression strain was measured by differential movement transformer and young's moduli were calculated at the stress of 1/3 of maximum stress on the stress-strain curves recorded.

Tensile Strength was tested in accordance with ASTM C78, "Standard test method for splitting tensile strength of cylindrical concrete specimens."

Bond strength against round bar was tested for average bond strength at the beginning of free end slippage, 0.025 mm and 0.05 mm slippage and maximum bond strength.

TEST RESULTS AND DISCUSSIONS

Test Results of Weight Loss and Residual Strengths after Exposure

The test results of weight loss and residual strengths after sustained and cyclic elevated temperature exposure are shown in Table 4. The data are shown in average of test results of each 3 specimens.

![Fig.2 Residual strengths after sustained exposure versus exposure term](image)

- a) compressive strength
- b) young’s modules
- c) tensile strength
- d) bond strength
Weight Loss After Exposure

Weight loss measured on cylinders for compressive strength after exposure at each exposure terms and cycles and after 60 day sustained exposure at 20 C, 45 % R.H. are shown in Fig.4.

Weight loss during sustained and cyclic exposure to 80 C increased rapidly for the first 7 days and 7 cycles, and the rate of weight loss was slowed down between 7 days and 7 cycles to 60 days and 60 cycles. After 60 day exposure, weight loss was 4.8 % for cyclic exposure and 5.1 % for sustained exposure, while weight loss after exposure to 20 C was 2.3 %.

Residual Compressive Strength

As shown in Fig.3, dry test residual compressive strength increased both after sustained and cyclic exposure. However wet test residual compressive strength decreased both after sustained and cyclic exposure. Dry test residual compressive strength did not increase with exposure term or thermal cycles showing minimal strength after 28 days and 28 cycles, and wet test residual compressive strength did not decline with exposure term or thermal cycles, much the same as the minimal strength at around 50 C shown in the previous papers by K.Kishitani et.al. and K.Kasami et.al.

Fig.5 shows residual compressive strength ratio after sustained and cyclic exposure to 80 C versus weight loss. Residual ratio of compressive strength by dry test showed the tendency to increase with weight loss and that by wet test showed the tendency to decrease with weight loss. However minimal points were found at the weight loss of 5 % in dry test and wet test strength ratio.

Fig.6 shows residual compressive strength ratio after cyclic exposure versus those after sustained exposure to 80. Residual compressive strength was found to be lower for cyclic exposure than for
sustained exposure, regardless of dry test or wet test, which indicated the degrading effects of thermal cycles on concrete strength at moderate elevated temperature of 80°C.

**Residual Young's Modulus**

As shown in Fig.3, dry test residual young's modulus decreased with terms and cycles of exposure. Especially residual young's modulus after sustained exposure showed rapid decrease with exposure term.

Fig.7 shows residual young's modulus ratio after sustained and cyclic exposure to 80°C versus weight loss. Residual young's modulus decreased with weight loss especially at higher weight loss than 4%. Fig.8 shows residual young's modulus ratio after cyclic exposure versus those after sustained exposure to 80°C. Residual young's modulus was lower for cyclic exposure than for sustained exposure, the same as compressive strength.

**Residual Tensile Strength**

As shown in Fig.2 and Fig.3, dry test and wet test residual tensile strength decreased with exposure term and exposure cycle monotonously on the contrary to compressive strength.
Fig. 9 shows residual tensile strength ratio after sustained and cyclic exposure to 80°C versus weight loss. Dry test tensile strength after sustained exposure increased up to 3% weight loss and decreased rapidly with the increase of weight loss, while that after cyclic exposure showed increase at 1.5% weight loss and deduced monotonously with increasing weight loss. Wet test young's modulus was remarkably smaller than dry test.

Fig. 10 shows residual tensile strength ratio after cyclic exposure versus those after sustained exposure to 80°C. Residual tensile strength was found to be lower for cyclic exposure than for sustained exposure, the same as that of compressive strength.

**Residual Bond Strength**

As shown in Fig. 2 and Fig. 3, dry test residual bond strength against round bar increased with the increased regardless of exposure terms and exposure cycles. However, those after 60 day and 60 cycle exposure were lower than that after exposure to 20°C by 10%.

Fig. 11 shows residual bond strength ratio after sustained and cyclic exposure to 80°C versus weight loss. Dry test bond strength after exposure increased with the increase of weight loss up to 3.5% weight loss, on the contrary to compressive and tensile strengths. The residual bond strength ratio was higher for cyclic exposure than for sustained exposure to 80°C.
Fig. 12 shows residual bond strength ratio after cyclic exposure versus those after sustained exposure to 80°C, which also indicated that dry test residual bond strength was higher for cyclic exposure than for sustained exposure.

Effects of Thermal Cycles

The deteriorating effects of thermal cycles even at moderate temperature of 80°C are evident, as shown in the experimental results and discussions mentioned above. In order to evaluate the extent of degradation effects of thermal cycle, the relationship between residual strengths after cyclic exposure and those after sustained exposure shown in Figs. 6, 8 and 10 are summarized in Fig. 13.

Compressive strength shown in Fig. 13(a) showed 10-15% lower strength ratio for cyclic exposure than for sustained exposure, regardless of moisture condition of test specimens. Fig. 13(b) for Young's modulus and Fig. 13(c) for tensile strength indicates similar tendency.

While bond strength shown in Fig. 12 and Fig. 13 showed different tendency indicating higher strength after cyclic exposure. Increase of residual bond strength after cyclic exposure can be due to drying shrinkage of concrete surrounding round bar and repeated differential movement between round bar and concrete. Bond strength against deformed bar may show different tendency, considering bond to deformed bar is associated with shear strength of concrete.

The data obtained in this experiment indicated that tensile strength of concrete was most affected with thermal cycles. Change in the ratio of residual tensile strength ($F_{trw}$ for wet test residual tensile strength, $F_{trd}$ for dry test residual tensile strength) and bond strength ($F_{brd}$ for dry test residual bond strength) to standard water cured 28 day compressive strength ($F_{c28w}$) versus exposure term or exposure cycles are shown in Fig. 14, in order to evaluate the extent of degradation effects of thermal cycles on tensile strength.

The value of $F_{trw}/F_{c28w}$ and $F_{trd}/F_{c28w}$ after cyclic exposure decreased with thermal cycles up to 28 cycles rapidly especially by wet test, indicating lower values than sustained exposure. Reduction in $F_{trd}/F_{c28w}$ and $F_{trw}/F_{c28w}$ was not so large, in the range of 8 to 9% after 60 cycles, but $F_{trd}/F_{c28w}$ may reduce to 6% with the increase of compressive strength. Hence, it may cause over estimation to evaluate tensile strength or shear strength by residual compressive strength.

With regard to bond strength $F_{brd}/F_{c28w}$ increased from 7% to 9% after sustained and cyclic exposure and to 10% after exposure to 20°C, 45% R.H., while $F_{brd}/F_{c28w}$ reduced rapidly to 4%. The ratio of bond strength to compressive strength after sustained exposure to 20°C was 8% by dry test and 5% by wet test.

Wet test always gives lower strength than dry test by approximately 20%. or dry test always gives higher strength than wet test. Therefore, it may be important to select wet or dry tests for compressive strength of drilled core from concrete components subjected to elevated temperature in aged nuclear power plants.
CONCLUSIONS

The following conclusions can be drawn from the experimental studies, simulating the thermal cycles on concrete components in nuclear power plants.

1) Thermal cycles may cause considerable deteriorating effects on compressive and tensile strength and young's modulus of concrete, even at moderate elevated temperature of 80°C.
2) Deteriorating effects of thermal cycles were greater for tensile strength than for compressive strength and bond strength against round bar.
3) Dry tests for residual concrete strength may under estimate the deteriorating effects of thermal cycles, and may over estimate residual strength in existing structure.
4) Residual strengths did not change monotonously change with thermal cycles, indicating minimal or maximal value at intermediate thermal cycles, except young's modulus, which decline with thermal cycles and with weight loss.
5) Ratio of tensile or shear strength to compressive strength tested at 28 days on saturated specimens may cause greater reduction by wet test after within 60 thermal cycles.

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