Strength Characteristics of Concrete Tested on Drilled Core from Plain and Reinforced Concrete Model Beams after Sustained Exposure to Elevated Temperatures

Hideo Kasami¹, Takafumi Tayama², Toshinobu Maenaka³, Kaoru Inaba⁴, Hirobobu Nishi⁵, Tatsuki Kaneko⁶

¹Technical advisor, Japan Association for Building Research Promotion, Tokyo, Japan and Invited Professor, Quindao Technological University & Quindao Agricultural University, Quindao, China.
²Manager, Hachioji Building Material Inspection Center, Japan Association for Building Research Promotion Tokyo, Japan
³Manager, Power Facilities Engineering Department, Takenaka Corporation, Tokyo, Japan
⁴Chief Researcher, Research & Development Institute, Takenaka Corporation, Tokyo, Japan
⁵Senior research engineer Concrete Laboratory, Flowrick Co.Ltd., Ibaraki, Japan
⁶Research engineer, Technical Research Laboratory, Haseko Corporation, Saitama, Japan

ABSTRACT

Although there are many papers describing the effects of temperatures on the strength of moulded specimens, those describing the strength of cores drilled from structures subjected to elevated temperature are limited.

This paper presents the results of experimental studies on the effects of reinforcement and moisture condition on the strength of cores drilled from model beams subjected to elevated temperatures. Sealed cured cylinders and plain and reinforced concrete model beams were subjected to dry air at 20, 40, 65, 90, 105 and 175°C and moist air at 65°C without seal. After 90-day exposure, cylinders were tested for dry strengths and cores of model beams were tested for dry and wet strengths.

Residual compressive strength of cylinders and cores of model beams did not decline linearly with temperature, but indicated minimal at 3 to 4% weight loss, which associated with exposure to 40°C dry air and 65°C moist air. Wet test core strengths were found to be 20% lower than those of dry test. And dry test core strengths were lower for model beams with reinforcement indicating residual ratio of 90% than for those without reinforcement, which suggested that reinforcement might restrict shrinkage of cement paste or mortar, resulting in micro cracks in cement paste or on the surface of aggregate. On the contrary, residual young's modulus declined monotonously with temperature and those of cores was found to be less affected with reinforcement and little difference was found between dry test and wet test.

INTRODUCTION

It is important to investigate strength of concrete in structure at aged nuclear power plants (NPP) for the evaluation of age related degradation. In Japan, operating license for commercial NPPs expires in 40 years, unless the license renewal beyond 40 years is approved by Nuclear Regulation Authority (NRA). NRA requests concrete tests in the 40 years special inspection at safety-related concrete components such as reinforced concrete or pre-stressed concrete containments, shielding walls and pedestals. Sampled cores are specified to be tested for compressive strength, carbonation, chloride penetration and alkali-silica reaction.

Relating to the longevity of NPP, D.J. Naus reviewed the data on ageing factors, degradation phenomena and remedial measures for concrete components, including the effects of elevated temperature and irradiation as primary degradation factors on concrete strength. With regard to the effects of elevated temperature on concrete, there are much differences among the data on the residual strength after sustained elevated exposure, depending on concrete materials, mixture proportion, age, temperature and term of exposure.
Most of the data available in past literature indicated that strength reduction was small or tolerable in the temperature range below 250°C. Although almost all of those were dealing with the temperature higher than 100°C and limited papers dealing with temperatures below 100°C indicated considerable reduction in compressive strength, indicating minimal strength at 50 to 80°C.

However, the data available relating to the strength of concrete tested on core specimens drilled from structures subjected to elevated temperatures are limited. G.L. England et al., T. Shire et al., T. Takeda et al., and Y. Ichihara et al. investigated non-linear moisture distribution with age in massive shielding wall subjected to gradient temperature, and resulting non-linear strength distribution. Furthermore, apparent strength of drilled core would be affected with the moisture increase during core sampling, cutting and grinding of top and bottom surface, besides the effects of soaking prior to compression tests.

This paper presents the results of experimental studies on the effects of elevated temperature exposure on the strength of drilled cores from model beams with and without reinforcement after sustained exposure to elevated temperatures in the range between 20 and 175°C.

**OUTLINE OF EXPERIMENTAL PROGRAM**

Outline of experimental program is shown in Table 1. Cylinders and model beams with and without reinforcement made of normal weight concrete were sealed cured for 91 days. At the age of 91 days, unsealed cylinders and model beams were subjected to sustained elevated temperatures in the range 20 to 175°C. After 90-day exposure cylinders were tested for weight loss and strength at room temperature, and model beams were tested for weight loss and strength of drilled cores by dry and wet tests.

**EXPERIMENTAL PROCEDURES**

*Materials and Mixture Proportion of Concrete*

Moderate-heat portland cement, dune sand, crushed sandstone and an air-entraining water reducing agent were used. Types and qualities of materials used are shown in Table 2. Water cement ratio of concrete was 50%. Target slump was 180 mm and target air content was 4.5%. Mixture proportion and properties of fresh concrete are shown in Table 3.
Concrete Mixing and Specimen Preparation

Concrete were mixed with a pan-type mixer in 5 batches and were re-mixed together with hand shovel on a flat mixing vessel. Re-mixed concrete was sampled for fresh concrete test, and then placed and tamped into φ100x200 mm one time steel molds for cylinders and 150x150x530 mm steel molds for model beams. Cylinders for control were cured in water at 20°C until test ages of 7, 28 and 91 days. The other cylinders were sealed cured in steel molds with plastics sealing. Model beams were wrapped with plastics after removal of molds, and sealed cured at 20°C. Sealed cured cylinders and model beams were stored in constant temperature chamber at 20°C, until test ages or the age of exposure at 91 days.

Elevated Temperature Exposure

Procedures of elevated temperature exposure are shown in Fig. 2. Cylinders and model beams were removed of molds at the age of 91 days and were subjected to temperatures of 20, 40, 65, 90, 105 and 175°C in air-circular type constant temperature chambers for 90 days without seal. Exposure at 20°C was made in constant temperature and humidity chambers at 20°C and 20% R.H. These exposure conditions are defined as "dry" hereafter. Exposure to 65°C and 60% R.H. was made in constant temperature and humidity chambers. This exposure condition is defined as "moist".

Tests on Cylinders before and after Elevated Temperature Exposure

Water cured cylinders were tested at the age of 7 and 28 days after grinding top surface with water-cooling. Sealed-cured cylinders for control tests were removed of steel molds and sealing, and
ground of top surface with air-cooling and were tested for compressive strength and young's modulus in as-cast moisture condition at the ages of 28, 91 and 182 days.

Sealed cured cylinders after 90-day exposure were tested at room temperature for weight loss, compressive strength and young's modulus by dry test and wet test.

**Tests of Model Beams and Drilled Cores after Elevated Temperature Exposure**

After 90-day exposure, model beams were cooled down and measured for weight loss, and then, core samples of φ68x150 mm were drilled from model beams, the quantity of cooling water being limited so as to reduce water absorption. Drilled cores were stored in air at 20 C, 65 % R.H. for 1 day in order to evaporate water absorbed during drilling, then were wrapped with plastic films and stored in room air for another 2 days. Then cores were shaped into the length of 136 ±3 mm and polished on the end surface evenly by grinding polisher. Cores for wet test were ground and polished with cooling water and then stored in water for 48 hours. Cores for dry test were shaped and polished with air-cooling grinder to prevent water absorption. Cores were tested for compressive strength and young's modulus, which were calculated from stress-strain curve measured and recorded with electric extensometer. Numbers of cores were 3 to 6 for dry test and 2 to 4 for wet test.

**EXPERIMENTAL RESULTS**

**Weight Loss and Strength of Cylinders before and after Exposure**

Compressive strength, young's modulus and density of water cured and sealed cured cylinders for control strength are shown in Table 4. Compressive strength of water cured cylinders by "wet test" increased with age up to 91 days. Sealed cured cylinders tested at as-cast condition showed little increase in compressive strength between 91 and 182 days.

Weight loss and strength versus temperature are shown in Fig.3. Weight loss expressed by the percentage of weight loss to the mass before exposure at the age of 91 days, increased with temperature rise for exposure to dry air, while those of moist air at 65 C was less than that of dry air at 40 C.

Compressive strength increased after exposure to dry air at 20 to 105 C, with the minimal point at 40 C and maximal point at 65 C, and showed minimum strength at moist air of 65 C. At higher temperature range of 90 to 175 C, compressive strength declined linearly with temperature rise. While, young's modulus after exposure to dry air declined linearly with temperature rise, except that after exposure to moist air at 65 C, which showed remarkable increase. Typical stress-strain curve of cylinders are shown in Fig.4. At higher temperature of 105 and 175 C, strain increased and stress decreased, resulting in reduction in young's modulus. While after exposure to moist air at 65 C, both stress and strain decreased but reduction in strain was greater than in stress, resulting in increase in young's modulus.

Fig 5 (a) shows residual compressive strength ratio versus weight loss. The minimal point was found at 3.8 % weight loss associated with 65 C moist air, and the maximal point was at 5 to 6 % weight loss associated with exposure to dry air at 65 and 90 C. Fig 5 (b) shows residual young's modulus versus weight loss. Young's modulus decreased rapidly with the increase of weight loss higher than 5 %.

**Table 4  Control Strength of Standard and Sealed Cured Specimens**

<table>
<thead>
<tr>
<th>model beams</th>
<th>moisture condition of specimens</th>
<th>compressive strength (MPa)</th>
<th>young's modulus (GPa)</th>
<th>Density at the time of test (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>water cured</td>
<td>sealed cured</td>
<td>sealed cured</td>
</tr>
<tr>
<td></td>
<td></td>
<td>test age (days)</td>
<td>test age (days)</td>
<td>test age (days)</td>
</tr>
<tr>
<td>100 cylinders</td>
<td>Wet</td>
<td>21.3</td>
<td>42.9</td>
<td>55.5</td>
</tr>
<tr>
<td></td>
<td>As cast</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Weight loss of model beams after Exposure

Fig. 6 shows weight loss of model beams versus temperature. Unfortunately, measured data on 20, 65 and 90°C were lost by accident, hence the lost data were estimated with the relations of cylinders and model beams and inserted as shown in Fig. 6(b) and (c).
Residual Strength of Cores Drilled from Model Beams

Fig. 7 shows residual compressive strength of cores drilled from model beams without and with reinforcement, (non-RC) and (RC), by dry test and wet test. Residual compressive strength of cores drilled from plain concrete model beams by dry test showed the similar tendency as those of cylinders, indicating minimal point at 40°C and maximal point at 65°C. However, difference of exposure to dry air and moist air at 65°C was smaller than that of cylinders. Wet test strength was 20% lower than dry test.

Residual strengths of cores drilled from RC beams was lower than those from plain concrete beams by 20%, indicating the same minimal and maximum point at 40 and 65°C. Difference between dry strength and wet strength was smaller for RC model beams than for plain concrete model beams.

Fig. 8 shows residual young's modulus versus temperature. Young's modulus declined linearly with temperature rise and difference between dry test and wet test was smaller than in compressive strength. Figs. 9 and 10 show stress-strain curves of dry cores drilled from model beams. Stress-strain curves in wet tests indicated decreased compression stress and strain, which may explain the reason why the difference of young’s modulus between wet test and dry test.

Figs. 11 and 12 show residual ratio of compressive strength and young's modulus versus weight loss. Fig. 11 indicated the minimal strength at 3% weight loss and maximal strength at 4% weight loss regardless of reinforcement and moisture condition. Although dry test compressive strength increased by 10% at 3 to 5% weight loss except minimal point, wet strength were 20% lower and residual ratio were 90% at 3 to 4% weight loss except minimal point where residual ratio was 80%. Fig. 12 shows residual ratio of young's modulus versus weight loss. Young's modulus of cores from non-RC beams showed practically no change up to 3% weight loss and decrease rapidly with the increase of weight loss, while, those of non-RC model beams showed rapid reduction with the increase of weight loss.
DISCUSSIONS

Effects of exposure temperature on residual cylinder strength

The relations of residual compressive strength of cylinders versus exposure temperature indicated minimal strength at 40°C dry air and 65°C moist air associated with 3% weight loss as shown in Figs. 3 and 4, although the authors' previous paper indicated minimal point at 50°C. However, the minimal point at 35°C were observed in a previous paper by Kishitani, Kasami et al., conducted at 20, 35, 50, 65, 80, 110, 200 and 300°C, as shown in Fig. 13a and (b), which were in good agreement with the present experimental results.

Effects of weight loss on residual strength of cylinder and core

Weight loss due to water evaporation is affected with specimen’s size, hence, effects of elevated temperature exposure should be evaluated with weight loss or mass of evaporated water. Fig. 14 shows of residual ratio of compressive strength of cylinders and cores versus weight loss, the residual compressive strengths were found to be at intermediate weight loss of 3 to 4%, regardless of specimen type, moisture condition and reinforcement. However, the maximal point was affected with specimen type, indicating maximal at 5 to 6% for cylinder strength and at 3 to 4% for core strength. Reduction in compressive strength at lower temperature of 40 to 65°C and intermediate weight loss might be due to increase in pore
size and pore volume, as Kasami et al. explicated chemically in previous papers. Residual young's modulus declined monotonously with the increase of weight loss without showing no minimal nor maximal point regardless of test conditions.

Effects of moisture condition on core strength

Comparison of residual strengths by wet test with those by dry test is shown in Fig.15. Residual compressive strengths was found to be smaller for wet cores than for dry cores by 20% at most. However residual Young's moduli were not affected with moisture condition of cores, although both of stress and strain were affected with weight loss and moisture condition at the time of strength tests.

Effects of Reinforcement of Model Beams on Core Strength

Fig.16 shows the comparison of compressive strength of cores from RC model beams with those from plain concrete model beams. Cores from model beams with reinforcement were 10% smaller than those from model beams with out reinforcement at higher temperature than 40 C, possibly due to the restriction of drying shrinkage with reinforcement and resulting increase in voids in cement mortar or on aggregate surface.
CONCLUSIONS

Following conclusions were drawn from the experimental results.

(1) Residual compressive strength did not decline monotonously with temperature rise, indicating minimal point at 40°C, and maximal point at 65°C.

(2) The minimal point of residual compressive strength was at the intermediate weight loss at 3 to 4%.

(3) Unusual strength reduction at lower temperature of 40 to 65°C and at intermediate weight loss might be due to increase in pore size and pore volume in cement matrix.

(4) Strength reduction at minimal point might be 20% equivalent to the effects of exposure to higher temperature of 175°C.

(5) Strength reduction of cores by wet test was found to be 20% or more at minimal point and higher exposure temperature.

(6) Strength of cores drilled from beams with reinforcement was lower than those without reinforcement and molded specimens, which suggests that experimental results tested on molded cylinders or cube might be under estimate concrete degradation.

ACKNOWLEDGEMENTS

The experimental studies presented above were conducted by the collaboration of our organizations to which the authors belong. The authors would thank to many researchers who participated in the experimental works. The authors also would thank to Professor M. Abe at Kogakuin University, Professor Y. Kitsutaka and Mr. K. Matsuzawa at Tokyo Metropolitan University for their helpful advises.
REFERENCES

Browne, R.D., Bemforth, P.B. (1975), "The Long Term Creep of Wylfa P.V. Concrete for Loading Ages up to 12.5 Years", Vol.H/8, *Trans. of Int. Conf. SMiRT-3rd*, USA


Kasami, H., Okuno, T., Yamane, H. (1975), "Effects of Sustained Exposure to Elevated Temperatures up to 300°C on Concrete Properties", Vol.H/5, *Trans. of Int. Conf. SMiRT-3rd*, USA

Kasami, H., Kaneko, T., Shimura, S., Quan, H. (2012), "Deterioration of Concrete Exposed to Sustained Elevated Temperature", Paper C11/1, pp.1-12, *Proc. of Int. Congress on Durability of Concrete*, Norway


Nasser, K.W., Marzouk, H.M. (1979), "Properties of Mass Concrete Containing Fly Ash at High Temperature", *ACI Journal*, American Concrete Institute, USA

Naus, D.J. (1986), "Concrete Component Aging and Its Significance Relative to Life Extension of Nuclear Power Plants", *NUREG/CR-4652, ORNL/TH-10059*, Oak Ridge National Laboratory, USA

Naus, D.J. (2005), "The effects of Elevated Temperature on Concrete Materials and Structures Literature Review", *NUREG/CR-6900, ORNL/3005/553*, Oak Ridge National Laboratory, USA


