Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division I

EFFECTS OF MOISTURE CONDITION ON THE STRENGTH PROPERTIES OF CONCRETE SUBJECTED TO SUSTAINED TEMPERATURE UP TO 300°C

Koichi Matsuzawa[1], Hideo Kasami[2], Takafumi Tayama[3], and Hironobu Nishi[4]

[1] Senior Research Engineer, Dept. of Building Materials and Components, Building Research Institute, Japan
[2] Technical advisor, Japan Association for Building Research Promotion, Japan
[3] Manager, Hachioji Building Material Inspection Center, Japan Association for Building Research Promotion, Japan
[4] Senior Researcher, Concrete Research Laboratory, Flowric., Japan

ABSTRACT

Strength test results on drilled core samples are usually affected by moisture change due to absorption of cooling water during core drilling. However, moisture in massive walls subjected to a gradient elevated temperature, such as shielding walls, does not distribute monotonically with the temperature gradient but shows dry zones on the heating side and outer surface and internal wet zones as shown in past studies. Therefore, it is necessary to consider the effects of moisture in core samples in order to evaluate the concrete strength in structures. This paper presents the results of an experimental study on the effects of the soaking condition of concrete cylinders subjected to sustained elevated temperatures of up to 300°C in order to make clear the effects of moisture condition simulating the strength test of core samples drilled from heated concrete. The results include the following: When subjected to the effect of heating, the compressive strength of concrete with a higher moisture content is lower than that of concrete with a lower moisture content, and the Young's modulus of concrete with a higher moisture content is higher than that of concrete with a lower moisture content. Besides, the compressive strength and Young's modulus of concrete increase with a moisture content of up to 4-5%, but abruptly decrease with a higher moisture content. It was therefore suggested that, when measuring concrete strength in an actual structure, the measured strength may widely vary depending on the core drilling method and the procedure before measurement.

INTRODUCTION

Operation licenses for commercial nuclear power plants (NPPs) in Japan expire in 40 years, unless renewal beyond the 40-year statutory limit is approved by the Nuclear Regulation Authority (NRA) subject to a 40-year special inspection. In regard to the longevity of safety related to reinforced concrete structures of NPPs, the NRA requests concrete tests in the 40-year special inspection for safety-related concrete components, such as reinforced concrete or prestressed concrete containment, shielding walls and pedestals, in which tests for compressive strength, carbonation, chloride penetration and alkali-silica reaction on core samples drilled from the concrete components are required.

Strength test results on drilled core samples are usually affected by moisture change due to absorption of cooling water during core drilling. The standards for core testing, such as ASTM C 42 (2016), "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete" and JIS A 1107 (2012), "Method of Sampling and Testing for Compressive Strength of Drilled Cores of Concrete", recommend a wet test after 40 to 48 hours of soaking. However, moisture in massive walls subjected to a gradient elevated temperature, such as shielding walls, does not distribute monotonically with the temperature gradient but shows dry zones on the heating side and outer surface and internal wet

zones as shown in past studies by England et al. (1977), Takeda et al. (1987) and Ichihara et al. (2013). Therefore, it is necessary to consider the effects of moisture in core samples in order to evaluate the concrete strength in structures. However, there are few technical papers describing the effects of soaking on the strength of concrete subjected to elevated temperature. Kasami et al. (2014) (2015) reported that the compressive strength of cores drilled from model beams subjected to sustained elevated temperatures of up to 175°C and tested after 48-hour soaking were 5 to 15% lower than those tested in a dried condition.

This paper presents the results of an experimental study on the effects of the soaking condition of concrete cylinders subjected to sustained elevated temperatures of up to 300°C in order to make clear the effects of moisture condition simulating the strength test of core samples drilled from heated concrete.

EXPERIMENT OVERVIEW

Outline of specimens

Tables 1 and 2 give the materials and mixture proportions of concrete. Table 3 gives the test factors and levels. Ordinary portland cement, mixed sand, and gravel were used as cement, fine aggregate, and coarse aggregate, respectively. The water-cement ratio (W/C), target slump, and target air content were 53%, 15 cm, and 4.5%, respectively.

Table 1: Materials

Materials	Mark	Detail
Cement	C	Ordinary portland cement, Density=3.16g/cm^3
Fine aggregate	S	Mixed sand, Density=2.63 g/cm^3, F.M.=2.82
Coarse aggregate	G	Gravel, Density=2.63 g/cm^3, F.M.=6.95
Admixture	Ad	Air-entraining and water-reducing admixture (lignosulfonate type)

Table 2: Mixture proportions

Slump (cm)	Air content (%)	W/C (%)	s/a (%)	W (kg/m^3)	C (kg/m^3)	S (kg/m^3)	G (kg/m^3)
15	4.5	53	40	174	328	712	1068

Table 3: Test factors and levels

Factor	Level
Heating temperature (°C)	20, 50, 80, 110, 300
Moisture content after heating	Dry, Semi-dry, Semi-wet, Wet (See Table 5)

Cylindrical specimens (ϕ100 × 200 mm) were fabricated for measuring the compressive strength and Young's modulus. Three specimens were prepared for each set of test conditions. The specimens were demolded 24 h after placing and subjected to a curing sequence: fog-curing at 20°C and 100% R.H. until an age of 9 days, curing at 20°C and 60% R.H. until 14 days, and then at 20°C and 90% R.H. until 17 days. These were then heated and tested. Table 4 gives the fresh properties of concrete and its physical properties at different ages.

Table 4: Properties of concrete while fresh and after hardening

Slump (cm)	Air content (%)	7 d, in water at 20°C	Before heating (17 d, in air)		
		Compressive strength (N/mm^2)	Compressive strength (N/mm^2)	Young's modulus (kN/mm^2)	Moisture content (%)
15	4.1	30.4	40.2	33.0	4.4

Test procedures

Figure 1 shows the test flow. The maximum temperatures within the oven during heating (hereafter 'heating temperature') were 50, 80, 110, and 300°C. Unheated specimens (20°C) were also tested for comparison. The maximum temperature was retained for 30 days. The specimens were heated in a program-controlled thermostatic oven at a heating rate of 30°C/h to the specified temperature and kept at that temperature for 30 days. These were then gradually cooled down to 20°C at a cooling rate of 30°C/h. The cooled specimens, with capping on the placing surface, underwent changes in the moisture conditions in four different ways for 2 days before measuring their compressive strength and Young's modulus.

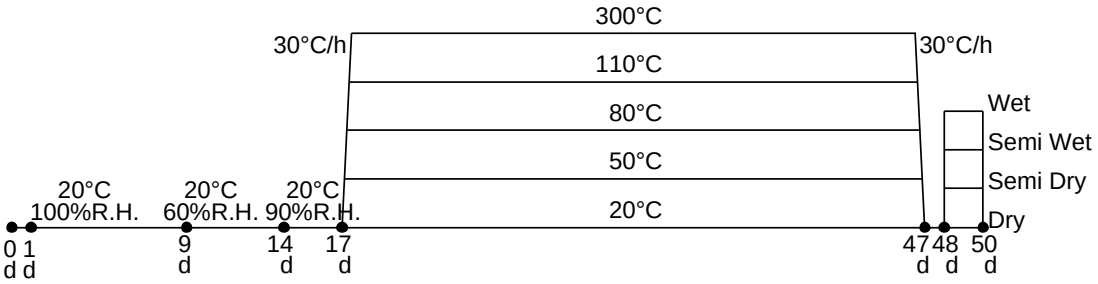

Figure 1. Test flow

Table 5 gives the methods of adjusting the moisture condition of specimens to the dry, semi-dry, semi-wet, and wet conditions after heating. Dry specimens were prepared by being kept in air at 20°C and 55% R.H. for 48 h; semi-dry specimens were immersed in water at 20°C for 30 min and then kept in air at 20°C and 55% R.H. for 48 h; semi-wet specimens were immersed in water at 20°C for 30 min and then kept in air at 20°C and 90% R.H. for 48 h; and wet specimens were immersed in water at 20°C for 48 h.

Table 5: Methods of adjusting moisture conditions

Moisture condition	Method of adjusting after heating
Dry	Keep in air at 20°C and 55% R.H. for 48 h
Semi-dry	Immerse in water at 20°C for 30 min and keep in air at 20°C and 55% R.H. for 48 h
Semi-wet	Immerse in water at 20°C for 30 min and keep in air at 20°C and 90% R.H. for 48 h
Wet	Keep in water at 20°C for 48 h

These moisture conditions were established based on preliminary test results. In the preliminary testing, concrete cylinders ($\phi 100 \times 200$ mm) with a W/C of 60% were immersed in water after heating at the specified temperatures for 1 week to determine the relationship between the water content and immersion time (Figure 2). As a result, the moisture content was found to increase over time at various ratios depending on the heating temperature. Specimens with a lower heating temperature retained a

higher moisture content after heating due to a smaller moisture escape but the increase in the moisture content during immersion was smaller. On the other hand, specimens heated to a higher temperature had a lower moisture content after heating due to a greater moisture escape but the subsequent moisture increase ratio during immersion was greater. As to the relationship between the water absorption after immersion with respect to the post-heating specimen weight and immersion time (Figure 3), the water absorption increased over time similarly to the moisture content, with the ratio varying depending on the heating temperature. A higher heating temperature led to a greater water absorption.

Based on the above-mentioned preliminary test results showing that the moisture content and water absorption widely vary depending on the heating temperature, it was decided to adjust the moisture conditions by keeping the curing conditions constant for each level during the time after heating until testing, instead of keeping the moisture content constant for each level (Table 5).

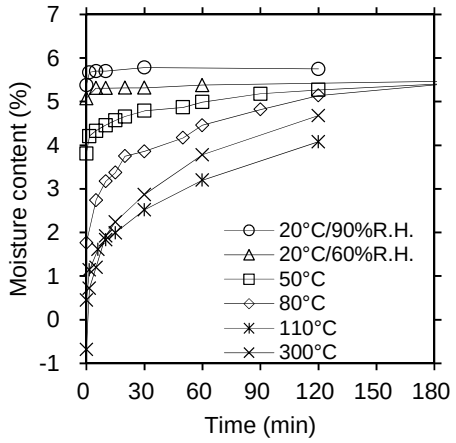

Figure 2. Relationship between post-heating moisture content of concrete and immersion time (preliminary test)

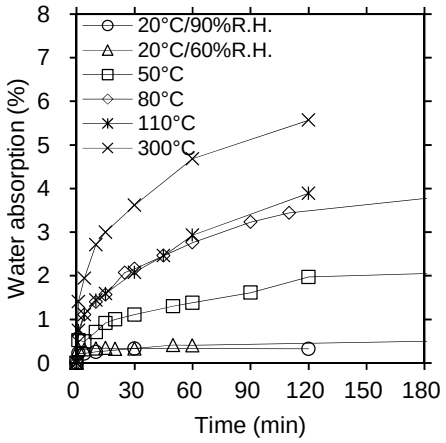

Figure 3. Relationship between post-heating water absorption of concrete and immersion time (preliminary test)

Compression tests were conducted in accordance with JIS A 1108. Young's modulus was simultaneously measured using a compressometer (JIS A 1149).

RESULTS AND DISCUSSION

Moisture condition at the time of testing

Figure 4 shows the relationship between the moisture content and heating temperature at the time of testing, and Figure 5 shows the relationship between the water absorption by moisture adjustment and heating temperature. Note that the moisture content and water absorption were calculated by Eqs. (1) and (2), respectively.

$$w = \frac{W_T - W_D}{W_D} \times 100[\%] \quad (1)$$

$$q = \frac{W_T - W_H}{W_H} \times 100[\%] \quad (2)$$

where w =moisture content, q=water absorption, W_T=weight at the time of testing, W_D=oven-dry weight, and W_H=post-heating weight.

The moisture content of the wet specimens slightly increases from 20°C to 50°C but scarcely changes with higher temperatures. The moisture content of the other specimens decreases as the heating temperature increases, with the drop being greatest between 20°C and 50°C. The reduction rate is greatest in the semi-wet specimens, followed by the semi-dry and dry specimens in this order.

While the dry specimens are not supplied with water, the water absorption of the other specimens increases as the heating temperature increases, with the increase tending to be the largest between 20°C and 50°C. The increase in the water absorption is largest in the semi-dry specimens, followed by the semi-wet and wet specimens in this order.

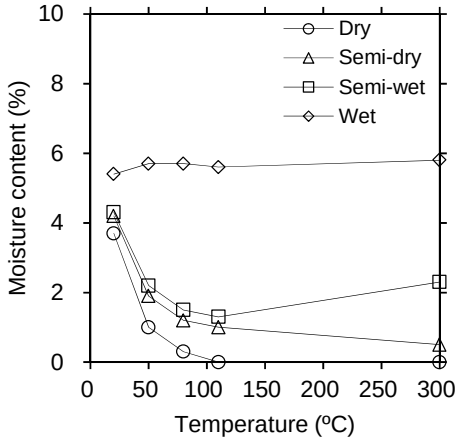

Figure 4. Moisture content-heating temperature relationship

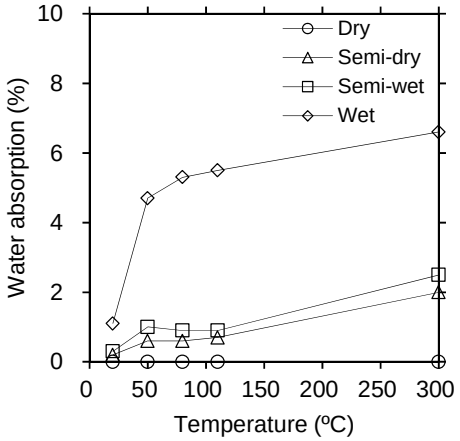

Figure 5. Water absorption-heating temperature relationship

Compressive strength

Figure 6 shows the post-heating compressive strength and the post-heating residual compressive strength ratio with respect to the pre-heating compressive strength, each related to the heating temperature. As to the dry specimens, the compressive strength at 20°C is higher than the pre-heating measurement by around 10%, decreases to 85% for 50°C, increases to 90% for 80°C and 110°C, but decreases again to 80% for 300°C. As to the semi-dry and semi-wet specimens, the compressive strength at 20°C is higher than the preheating measurement by around 10%, decreases to 85% for 50 and 80°C, slightly increases for 110°C, but decreases again for 300°C. As to the wet specimens, the compressive strength at 20°C is slightly lower than the pre-heating measurement, significantly decreases to 70% for 50°C, remains unchanged up to 110°C, and decreases again for 300°C. It should be noted that the compressive strength of the wet specimens is lower than that of the dry specimens, being 88%, 83%, 75%, 75%, and 73% of the latter at 20°C (no heating), 50°C, 80°C, 110°C, and 300°C, respectively. The strength gap thus widens as the heating temperature increases.

The post-heating moisture contents of the dry, semi-dry, and semi-wet specimens are 3.7%, 4.2%, and 4.3%, respectively, at 20°C, being slightly lower than before heating, whereas that of the wet specimens is 5.5%, being higher than before heating (Table 4). This suggests that the reason for the increased compressive strength of the dry, semi-dry, and semi-wet specimens is the subsurface drying of these specimens, which restrains the inside. The compressive strength decreases from 20°C to 50°C regardless of the moisture conditions, presumably due to microcracking and losses in capillary water concomitant with drying during heating. The strength gains of the dry specimens for 80°C and semi-dry

and semi-wet specimens for 110°C can be attributed to the reduction of the single molecular adsorption layer due to additional drying and the hydration of unhydrated cement due to heating. The compressive strength of the wet specimens scarcely changes from 50°C to 110°C. This is presumably because the amount of hydration of unhydrated cement is greater than the other moisture conditions due to the long immersion time after heating. Note that the compressive strength decreases for 110°C and higher, regardless of the moisture conditions, because the losses in the amounts of gel water and interlayer water increase the amount of air voids.

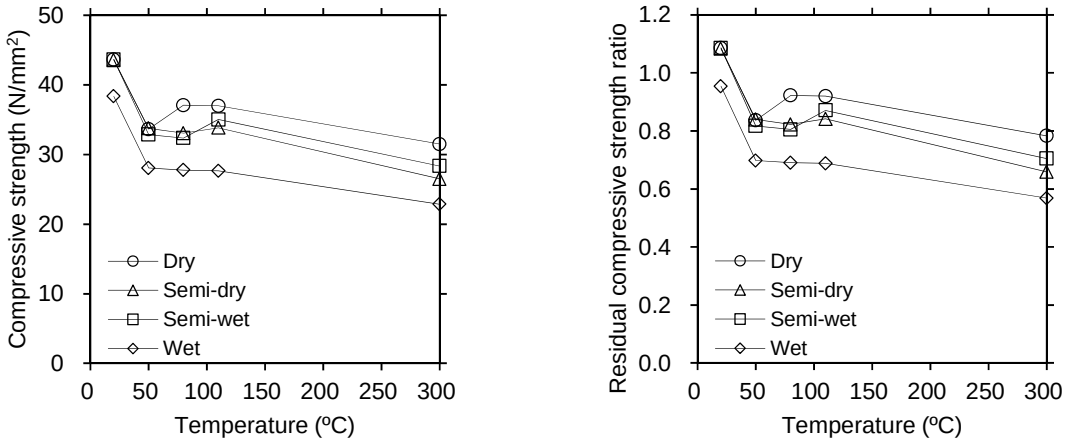

Figure 6. Relationship between post-heating compressive strength and heating temperature

Young's modulus

Figure 7 shows the post-heating Young's modulus and the post-heating residual Young's modulus ratio with respect to the pre-heating Young's modulus, each related to the heating temperature. The Young's modulus of the dry specimens at 20°C and for 50°C decreases to around 80% and 70% of the preheating measurements, respectively, remains unchanged up to 110°C, and then decreases to 40% for 300°C. The Young's moduli of the semi-dry and semi-wet specimens at 20°C and for 50°C decrease to around 90% and 70%, respectively, remain unchanged up to 110°C, and decrease to 40% for 300°C. The Young's modulus of the wet specimens decreases to around 90% at 20°C, then monotonically decreases to 80% and 65% for 50°C and 80°C, and to 40% for 110°C and 300°C. Note that the Young's modulus of the wet specimens is higher than that of the dry specimens up to around 80°C, being 112% and 113% of the latter at 20°C (unheated) and for 50°C, respectively. The modulus of the wet specimens levels that of the dry specimens for 80°C, and then becomes slightly lower with higher temperatures, being 95% and 98% for 110°C and 300°C, respectively.

At 20°C, the Young's modulus of the dry specimens is lower than the other moisture conditions. This is presumably because air voids generated by heating in the concrete are not filled with water due to no water supply after heating. In contrast to compressive strength, Young's modulus decreases as the heating temperature increases, and the effect of moisture conditions tends to diminish with the increase in the heating temperature. This is presumably because reductions in the compressive strength due to post-heating water absorption are offset by reductions in the strain under deformation due to water absorption.

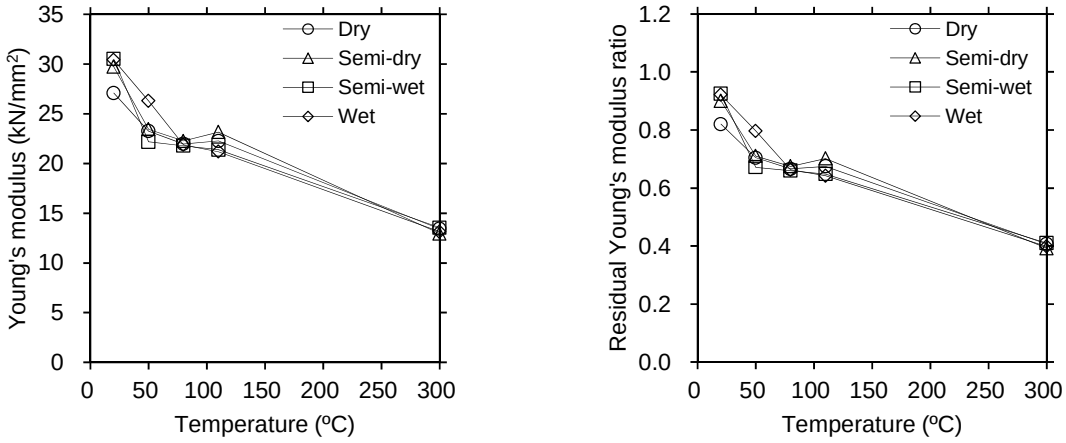

Figure 7. Relationship between post-heating residual Young's modulus and heating temperature

Compressive strength and Young's modulus related to moisture content

Figure 8 shows the post-heating residual compressive strength ratio and residual Young's modulus ratio, each related to moisture content. Though data in the moisture content range of 4.3 to 5.4% are not available in this study, the compressive strength is found to increase to a moisture content of around 4% and abruptly tend to decrease at around 5%. The Young's modulus is also found to increase to a moisture content of around 4%, remain on the same level up to around 5%, and rapidly decrease thereafter similarly to compressive strength.

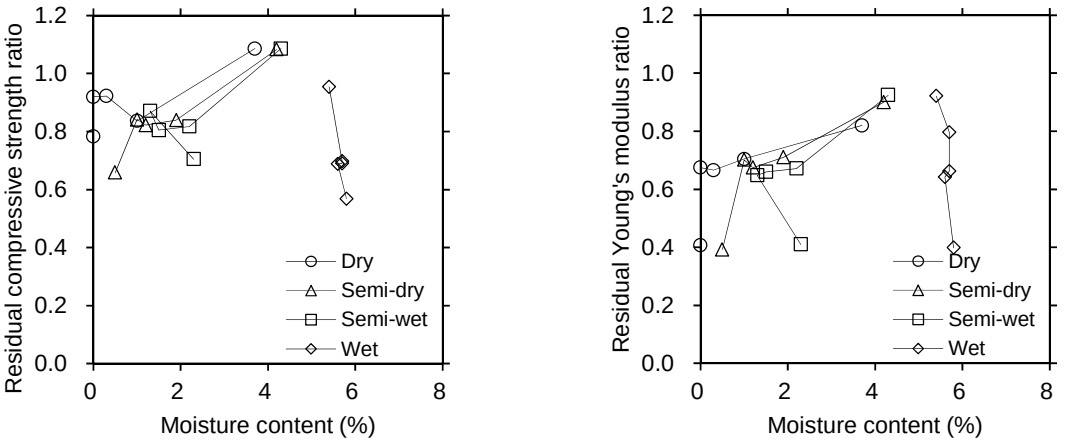

Figure 8. Relationship between post-heating strength properties and moisture content

Compressive strength related to Young's modulus

Figure 9 shows the post-heating residual compressive strength ratio related to residual Young's modulus ratio. The residual compressive strength ratio of dryer specimens at the time of testing is higher, but the residual compressive strength and Young's modulus ratios approach the equivalence as water absorption

increases. When allowed to absorb water for 48 h after heating, the residual compressive strength and Young's modulus ratios are nearly equalized.

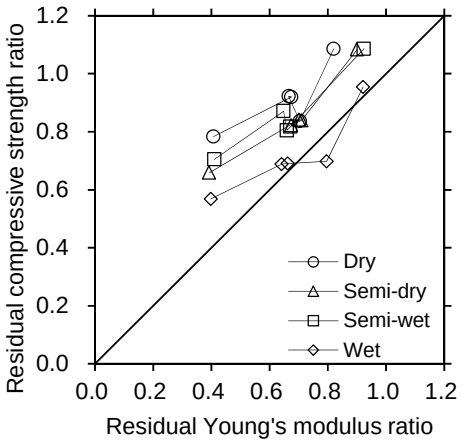

Figure 9. Compressive strength-Young's modulus relationship after heating

CONCLUSIONS

In this study, the effect of moisture conditions at the time of testing on the strength properties of concrete subjected to heating up to 300°C was investigated. Within the range of this study, the following were found:

(1) When subjected to the effect of heating, the compressive strength of concrete with a higher moisture content is lower than that of concrete with a lower moisture content, being as low as around 75%, even with a temperature history of less than 100°C.
(2) When subjected to the effect of heating, the Young's modulus of concrete with a higher moisture content is higher than that of concrete with a lower moisture content, but the difference becomes marginal with a temperature history of over 80°C.
(3) When subjected to the effect of heating, the compressive strength and Young's modulus of concrete increase with a moisture content of up to 4-5%, but abruptly decrease with a higher moisture content.

As stated above, it was demonstrated that the measured strength properties of concrete can vary by 20-30% depending on its moisture content. It was therefore suggested that, when measuring concrete strength in an actual structure, the measured strength may widely vary depending on the core drilling method and the procedure before measurement.

REFERENCES

Chapman, D. A., England, G. L. (1977). "Effects of moisture migration on shrinkage, pore pressure and other concrete properties," *Trans. of Int. Conf. SMiRT-4th*, USA, Vol. H.

Takeda, T., Nakane, S., Nagano, K. (1987). "Experimental studies on characteristics of concrete members subjected to high temperatures," *Trans. of Int. Conf. SMiRT-9th*, USA, Vol. H.

Ichihara, Y. et al. (2013). "Estimation of long-term concrete strength in massive shielding wall subjected to gradient temperature in BWR type nuclear power plant," *Trans. of Int. Conf. SMiRT-22*, USA, Div. I.

Kasami, H. et al. (2014). "On the evaluation of strength characteristics of concrete after elevated temperature exposure, Part 1-4," *Summaries of technical papers of annual meeting, AIJ*, Japan, (in Japanese)

Kasami, H. et al. (2015). "Strength characteristics of concrete tested on drilled core from plain and reinforced concrete model beams after sustained exposure to elevated temperatures," *Trans. of Int. Conf. SMiRT-23*, UK, Div. I.