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APPLICABILITY EVALUATION OF STEEL PLATE REINFORCED CONCRETE STRUCTURE TO PRIMARY CONTAINMENT VESSEL OF BWRS
(1) MECHANICAL AND THERMAL PROPERTIES OF CONCRETE UNDER HIGH TEMPERATURE CONDITIONS

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ABSTRACT

In order to enhance the safety of BWRs and to shorten the period of construction, R&D project for applying steel plate reinforced concrete (SC) structure to primary containment vessel was started in fiscal 2008. As a first step in the development of steel plate reinforced concrete containment vessel (SCCV), the applicability of SCCV was examined from the point of view of structural aspects. In this basic study, mechanical properties (compressive strength, static modulus of elasticity, splitting tensile strength) and thermal properties (thermal strain coefficient, specific heat) of concrete under high temperature up to 300 °C were obtained as the basic data necessary to evaluate the applicability of SCCV under high temperature. The mechanical properties of concrete up to 300 °C are slightly higher than the values of Eurocode, but the decline tendency of mechanical properties against temperature is approximately same. The influence of long term heating on the mechanical properties is not significant. A little difference is observed between the experimental results on thermal properties and the model of Eurocode.

INTRODUCTION

The primary containment vessel (PCV) is one of five physical barriers between the radioactive reactor core and the environment. It contains radioactive materials even when radioactive substances leak from the reactor pressure vessel under accident conditions and reduces the release of radioactivity to the environment. Therefore, the improvement of PCV integrity is directly related to safety in a nuclear reactor power plant.

PCVs have been made using reinforced concrete or steel and the improvement is continued. The steel plate reinforced concrete (SC) structure is one of the new technologies for construction. It is composed of steel plates, tie-bar, stud for connection of steel plate, and concrete. It has flexibility for improving the seismic safety by increasing the thickness of steel plate and increasing the number and/or thickness of ribs connecting the inner and outer steel plate, etc. By applying SC and combining with large module building method, the PCV can be made by installing SCCV modules which are made in the factory and then placing concrete between steel plates at the plant site. It reduces the work in plant construction site, such as reinforcing bar setting work, so that not only the improvement of construction reliability but also the shortening of plant construction period will be realized.

SC structure is already applied in some buildings of nuclear power stations. However, to apply it to PCV, confirmation of its applicability for basic performance of PCV is required, especially the aseismatic and pressure-resistant performances under high temperature conditions.

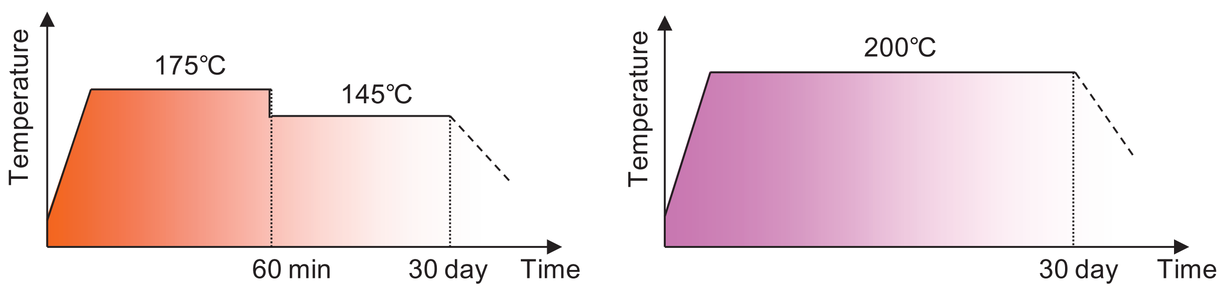
To evaluate the applicability of SC structure to PCV, the basic examination on earthquake resistance and pressure tightness of SC structure was started in fiscal 2008. In the series of papers, the tests and analyses preformed for basic study during fiscal 2008 – 2010 are described.

OUTLINE OF BASIC STUDY

Assumed conditions of study

The purpose of basic study is to understand the basic behaviour of SC structure under high temperature conditions and to confirm the applicability of SC structure to PCV. Figure 1 shows the assumed temperature conditions under design basis accident (DBA) and severe accident (SA).

As for DBA, the highest temperature is 175°C during the initial phase of accident and is 145°C after 60 min. For SA, the temperature is set to 200°C. The period of high temperature is set to 30 days. The highest pressure is assumed to be 310kPa for DBA and 620 kPa for SA and continues for 30 days. The difference in assumptions comparing to existing plants is that the high pressure and temperature continues for a long period duration. For DBA, simultaneous occurrence of accident and earthquake is considered.



(1) Assumed temperature under DBA conditions. (2) Assumed temperature under SA conditions.

Figure 1. Assumed temperature conditions.

Tests and Analyses

The tests and analyses performed in basic study are shown in Figure 2. By testing, the required data are acquired. Material testing obtains the properties of constituting materials of SC structure: concrete, steel plate, stud connector and reinforcing rod (tie-bar). Compressive loading test obtains compressive properties such as load transformation properties and buckling behaviour of steel plate. Shear loading test obtains the properties of SC structure with respect to in-plane shear force to evaluate the seismic safety of SCCV. Horizontal loading test of cylindrically-shaped SC specimens obtains structural properties of cylindrically-shaped SC structure against horizontal load such as load transformation properties and destruction mode.

As for analysis, the simulation analysis is performed for each test to develop a model which reproduces the test results.

In this paper, the concrete material testings are described.

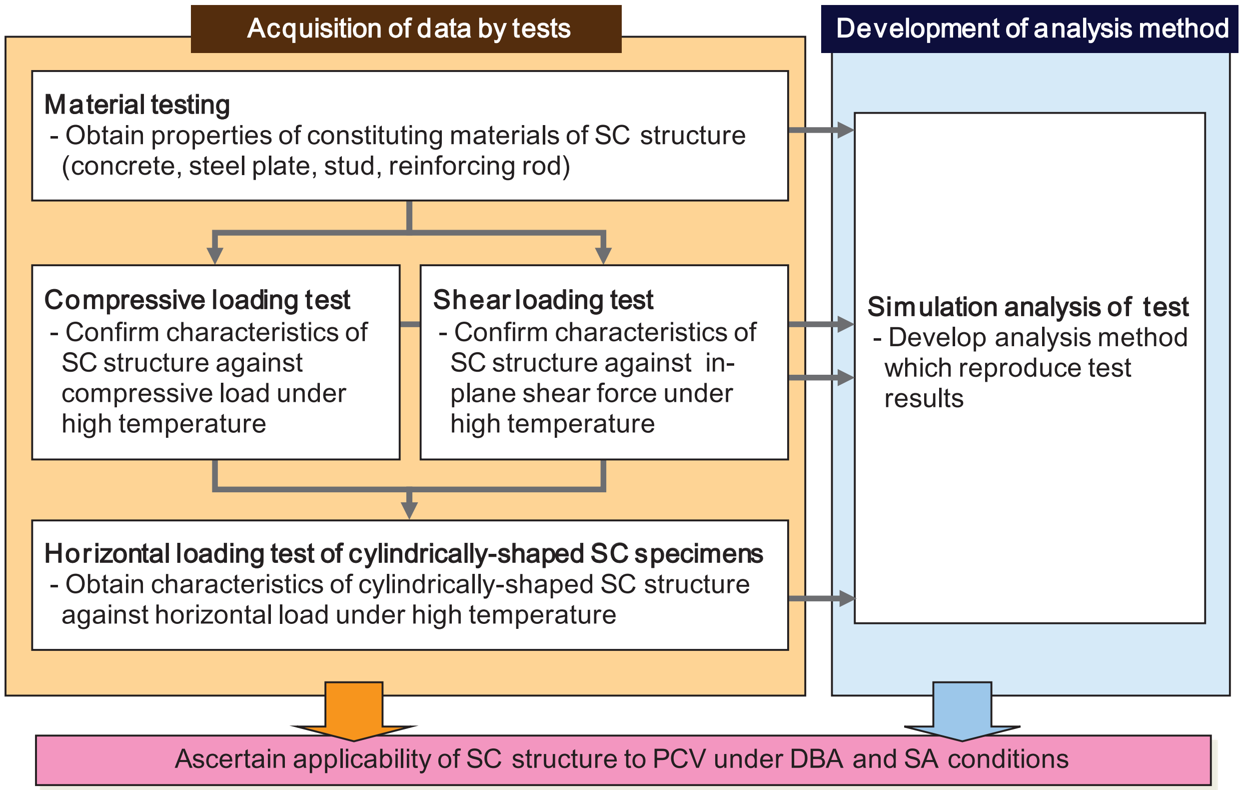


Figure 2. Tests and analyses for basic study.

CONCRETE MATERIAL TESTING

Measured Properties and Conditions

It is required to understand the temperature dependent properties of concrete because the temperature of concrete inside SC structure of SCCV becomes high under accident conditions. To obtain the mechanical properties and thermal properties from room temperature to high temperature, the following tests were performed.

(1) Compressive strength test
(2) Splitting tensile strength test
(3) Thermal strain coefficient test
(4) Specific heat test

As for (1) compressive strength test and (2) splitting tensile strength test, temperature and heating period are set as the test parameter. The maximum temperature for these tests is set to 300°C considering the assumed maximum temperature for accident (200°C) and a sufficient margin. The properties are measured at six levels of temperature as shown in Table 1.

The heating period is also a parameter because the property changes are expected to be caused by the evaporation of water in the concrete during heating. The maximum period of heating is set to 35 days considering the assumed maximum period of high temperature for accident (30 days) and a margin of 5 days. The levels of period is six and a short period of time is divided finer because the changes of properties is considered to be larger

In (3) thermal strain coefficient test and (4) specific heat test, the thermal strain coefficient and specific heat are measured by changing temperature continuously from room temperature to 300°C.

The shape of specimen for each test is shown in Table 1. The specimen shape of (4) specific heat test is determined from the limitation of test equipment and is truncated cone-shaped. As for aggregate, the coarse aggregate with maximum size of 20 mm are used in three kinds of tests (1)-(3). For specific heat test, the coarse aggregate of maximum size of 10 mm are screened by using sifter. For each test, three specimens were prepared. The composition of concrete and the properties of fresh concrete are shown in Table 2 and Table 3.

Table 1: Test conditions.

Kind of test	Specimen shape	Test case
Compressive strength test	φ100×200	Temperature: room temperature, 105°C, 150°C, 200°C, 300°C, heated 200°C and measured after cooled. Period (day): 1, 2, 3, 7, 14, 35.
Splitting tensile strength test	φ150×200	Temperature: room temperature, 105°C, 150°C, 200°C, 300°C, heated 200°C and measured after cooled. Period (day): 1, 2, 3, 7, 14, 35.
Thermal strain coefficient test	φ75×150	Measured continuously from room temperature to 300°C.
Specific heat test	φ19(φ16)×30	Measured continuously from room temperature to 300°C.

Table 2: Mix proportion of concrete.

Kind of test	W/C (%)	s/a (%)	Mix proportion (kg/m^3)								Note
			Water	Cement	Fine aggregate		Coarse aggregate		Admixture		
			W	C	S1	S2	G1	G2	ad1	ad2	
Compressive strength test Splitting tesile strength test	55.0	48.7	175	318	261	610	373	560	3.811	0.633	Duration of heating: 1, 2, 3 and 7days
	55.0	48.7	175	318	261	609	415	507	3.498	0.318	Duration of heating: 14 and 35days
Tharmal strain test	55.0	48.7	175	318	261	609	415	507	3.498	0.318	
Specific heat test	55.0	51.3	175	318	275	643	-	874	3.975	0.954	

W/C: Water-cement ratio, s/a: Sand-total aggregate ratio, C: Ordinary portland cement, S1: Sand, S2: Crushed sand of sandstone, G1: Crushed stone of sandstone (Maximum diameter range 15-20mm), G2: Crushed stone of sandstone (Maximum diameter range 5-15mm), ad1: Air-entraining and high-range water-reducing admixture, ad2: Air-entraining admixture.

Table 3: Properties of fresh concrete.

Kind of test	Slump (cm)	Air content (%)	Concrete temperature (°C)	Note
Compressive strength test	20.5 ~ 21.0	4.4 ~ 5.0	20.0 ~ 20.5	Duration of heating: 1, 2, 3 and 7days
	21.5	5.5	20.5	Duration of heating: 14 and 35days
Splitting tesile strength test	20.5 ~ 21.5	4.4 ~ 4.7	20.5	Duration of heating: 1, 2, 3 and 7days
	22.0	5.4	20.0	Duration of heating: 14 and 35days
Tharmal strain test	21.5	5.2	20.0	
Specific heat test	20.5	5.8	20.5	

Test Method

In (1) compressive strength test and (2) splitting tensile strength test, specimen is heated in electric furnace (Figure 3) for predetermined temperature and period. After heating, the specimen is taken out and the test is performed within a short time before the temperature of specimen decreases (Figure 4, 5).

To determine heating time, preliminary tests were carried out using specimen with a thermocouple at the centre of specimen. The starting point for counting heating time is determined as the time when the surface and centre become almost the same temperature based on the measured changes of surface and centre temperatures.

Figure 3. Electric furnace and heating configuration.

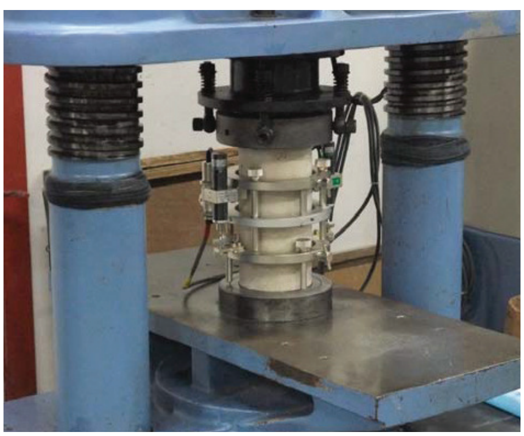


Figure 4. Configuration of compressive strength test.

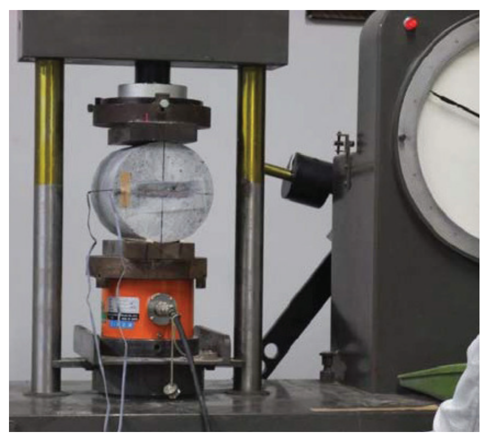


Figure 5. Configuration of splitting tensile strength test.
(Strain gage is only used in room temperature case.)

The temperature of specimen decreases outside the electric furnace during preparing measurement. The preliminary tests were also performed to confirm the influence of temperature decrease upon the strength of specimen. The tests were performed for φ100 and φ150 specimens at heating temperature 210 °C. The centre temperature of φ100 specimen decreases to about 175 °C during the 90 min after taking it out from the electric furnace. It is confirmed that the temperature decrease has little influence to the strength. For φ150 specimen it is also confirmed that the influence of temperature decrease to the strength during the 90 min is small. The measurement is performed within 5 to 10 min after taking out a specimen from the electric furnace and the properties at high temperature are well obtained by the test. Figure 6 shows the change of centre temperature, compressive strength and static modulus of elasticity after taking out the specimen.

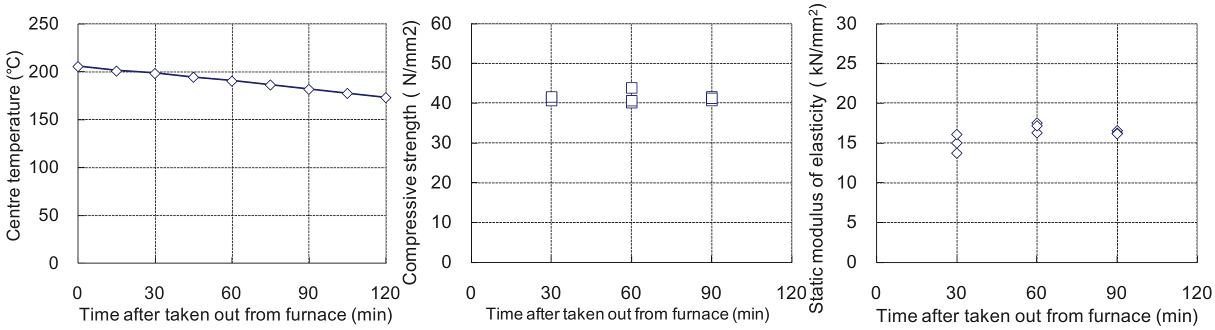


Figure 6. Changes of centre temperature, compressive strength and static modulus of elasticity.

The elongation is measured by a displacement gauge with a quartz rod, continuously heating the specimen at a rate of 1°C/min and the thermal strain coefficient is obtained. Specific heat is measured by adiabatic scanning calorimetry method which heats specimen of mass M by constant electric power W inside a container of mass M_0 and specific heat C_0 in an insulation status. Specific heat $C_P(\theta)$ at temperature θ is calculated by Equation 1.

$$C_P(\theta) = W \cdot \Delta t / (M \cdot \Delta\theta) - M_0 \cdot C_0 / M, \qquad (1)$$

where Δt is the time required for infinitesimal temperature rise Δθ.

Results and Discussions

(1) Compressive strength test

The changes in the compressive strength and static modulus of elasticity in relation to the heated temperature and period are shown in Figure 7 and 8. The relation between reduction factor for compressive strength and temperature and the relation between reduction factor and heating period are shown in Figure 9 and Figure 10.

As in Figure 9, the compressive strength decreases with the rise of temperature. The decrease is not significant up to 200°C. The influence of heating period on the compressive strength is small (Figure 10). As for the 105°C cases, the strength decreases when the heating period is short and it recovers to the value at room temperature when the heating period becomes long. The strength decrease is considered to be relating to the condition that the evaporable water in concrete does not evaporate enough and the specimen does not reach equilibrium state. For the case of cooled after 200°C heated, the compressive strength is almost the same value as the 200°C case. The value based on Eurocode4[1)] shown in Figure 9 is confirmed to exhibit a similar tendency as the test data.

The static modulus of elasticity decreases when the heating temperature increases (Figure 11). The influence of heating period on the static modulus of elasticity is small (Figure 12). For the case of cooled after 200°C heated, the static modulus of elasticity is almost the same value as the 200°C case. The value for Eurocode4 is calculated based on the secant stiffness at 1/3 strength in stress-strain curve proposed by Eurocode4. The value is confirmed to exhibit a similar tendency as the test data as Figure 11.

These mechanical property changes of concrete by heating are considered to be caused by the alteration of cement paste and the damage in concrete due to the difference of volume change depending on the temperature for cement paste and aggregate.

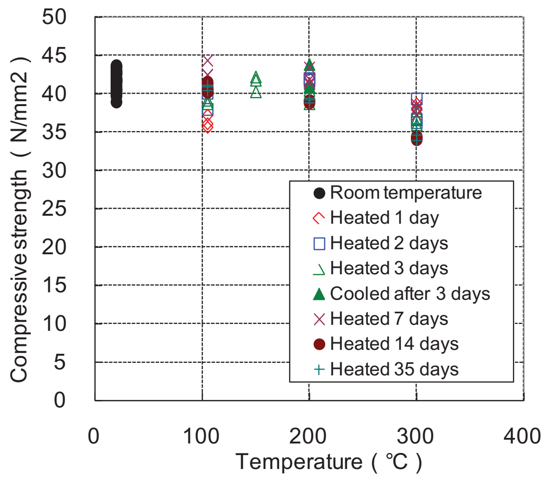


Figure 7. Relation between compressive strength and temperature.

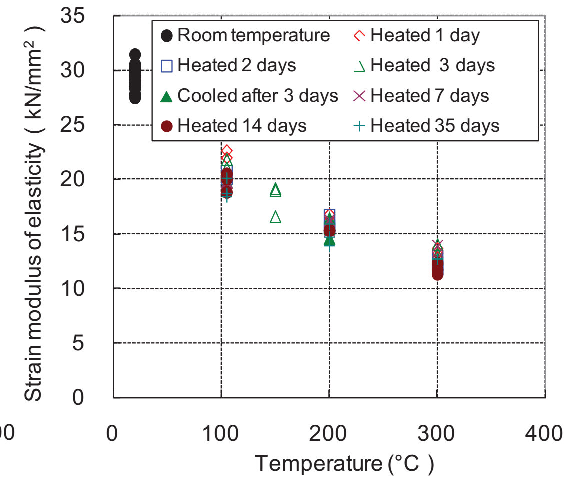


Figure 8. Relation between strain modulus of elasticity and temperature.

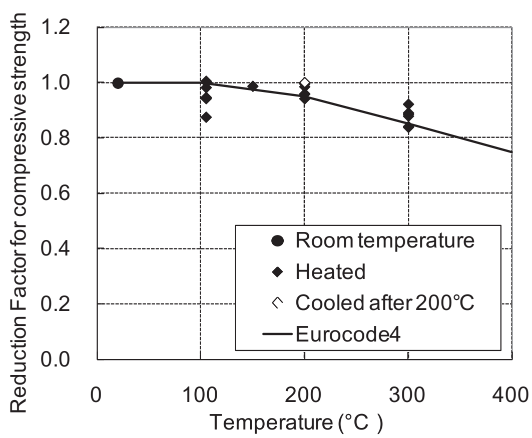


Figure 9. Relation between reduction factor for compressive strength and temperature.

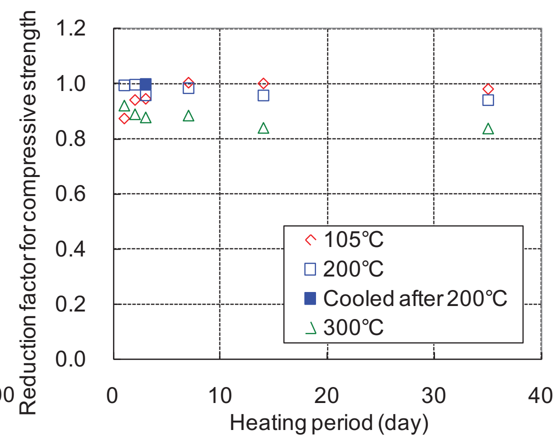


Figure 10. Relation between reduction factor for compressive strength and heating period.

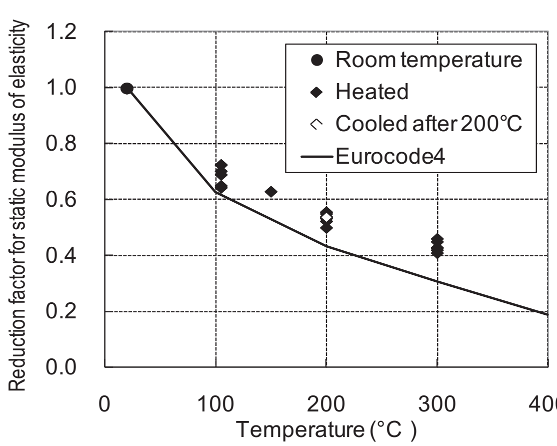


Figure 11. Relation between reduction factor for static modulus of elasticity and temperature.

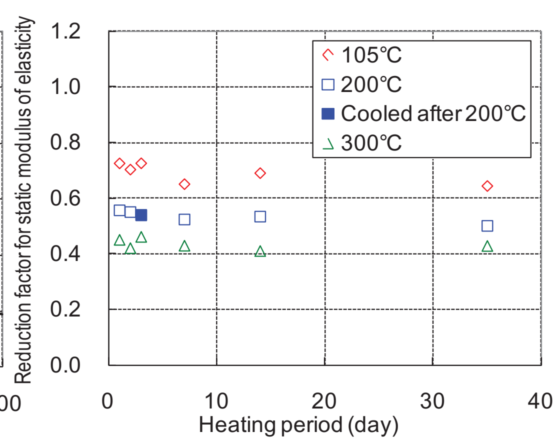


Figure 12. Relation between reduction factor for static modulus of elasticity and heating period.

(2) Splitting tensile strength test

The changes of the splitting tensile strength depending on the heating temperature and period are shown in Figure 13-15. For the splitting tensile strength, the dispersion of the measured data is larger than the compressive strength. The splitting tensile strength decreases with the rise in temperature similarly to the compressive strength. The splitting tensile strength once decreases by short-term heating and recovers with the increase of heating period. The strength decrease at an early stage of heating is considered to be relating to the condition that the evaporable water in concrete does not evaporate enough and the specimen does not reach equilibrium state.
For the case of cooled after 200°C heated, the splitting tensile strength is almost the same value of the 200°C case. It is the same tendency of the compressive strength and static modulus of elasticity. The value based on Eurocode2[2)] is shown in Figure 14. As in the figure, Eurocode2 values are less than the test results except for the vicinity of 100°C.

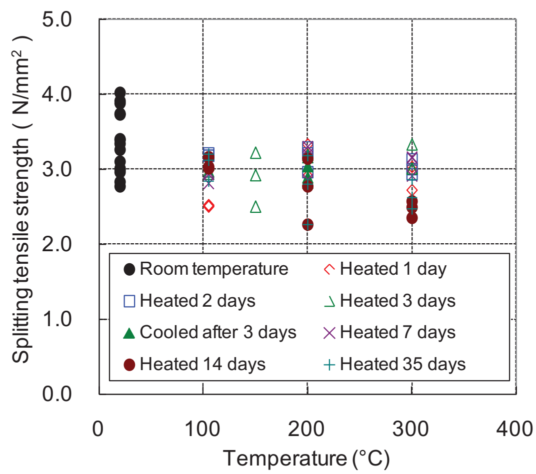


Figure 13. Relation between splitting tensile strength and temperature.

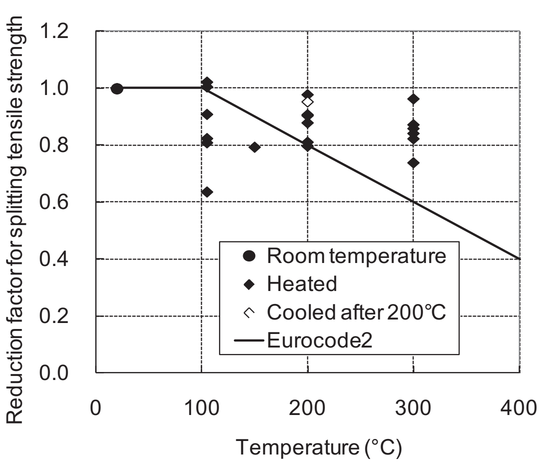


Figure 14. Relation between reduction factor for splitting tensile strength and temperature.

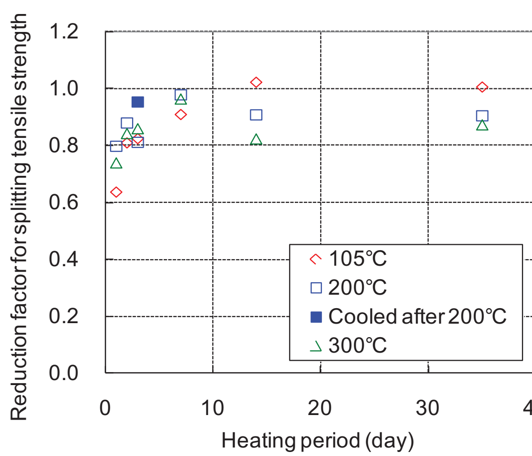


Figure 15. Relation between reduction factor for splitting tensile strength and heated period.

(3) Thermal strain coefficient test

The relation between the thermal strain and temperature is shown in Figure 16. The change rate of the thermal strain becomes low when the temperature exceeds 100°C. It is caused by drying shrinkage. To measure the thermal strain excluding the drying shrinkage effect, the tests were performed using the specimen dried for one week in drying furnace. As shown in the figure, the thermal strain increases in proportion to the temperature rise.

The evaporable water content of SCCV changes depending on rate of temperature rise, etc. so that it is required to consider which coefficient value should be used depending on SCCV statuses. Eurocode4 shows the same tendency as the result of dried specimen. The coefficient is about 10 – 12 μ/K which is the value generally used in the design stage.

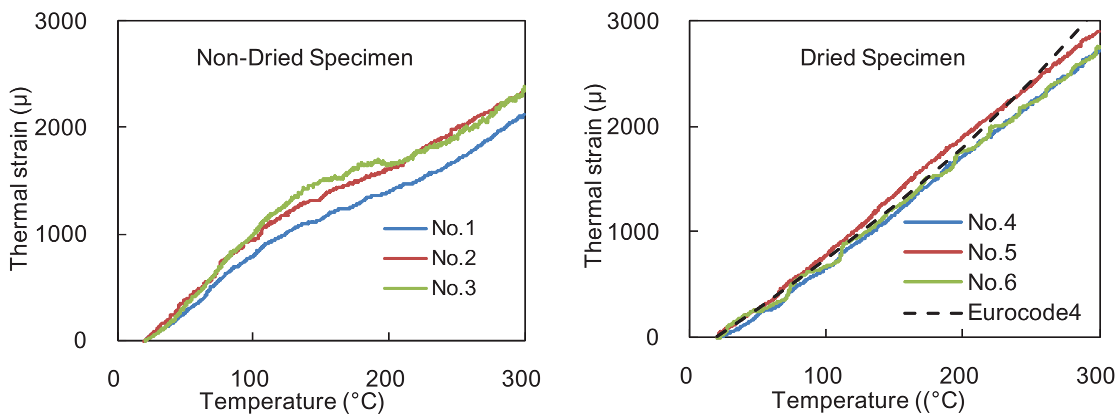


Figure 16. Relation between thermal strain and temperature.

(4) Specific heat test

To confirm the influence of latent heat, the tests were performed twice under the same conditions. Figure 17 shows the relation between the specific heat and temperature. In the first test, a peak exists in 100 – 140 °C. In second test the specific heat increases in proportion to the temperature rise. The peak in the first test is considered to be caused by the latent heat of free water to evaporate.

In the adiabatic scanning calorimetry method, the specimen is small and the coarse aggregate of maximum size of 10 mm are used. The aggregate status was confirmed to be uniformly distributed inside a specimen by cross-sectional observation. The results of specific heat also show the dispersion of specimen is small.

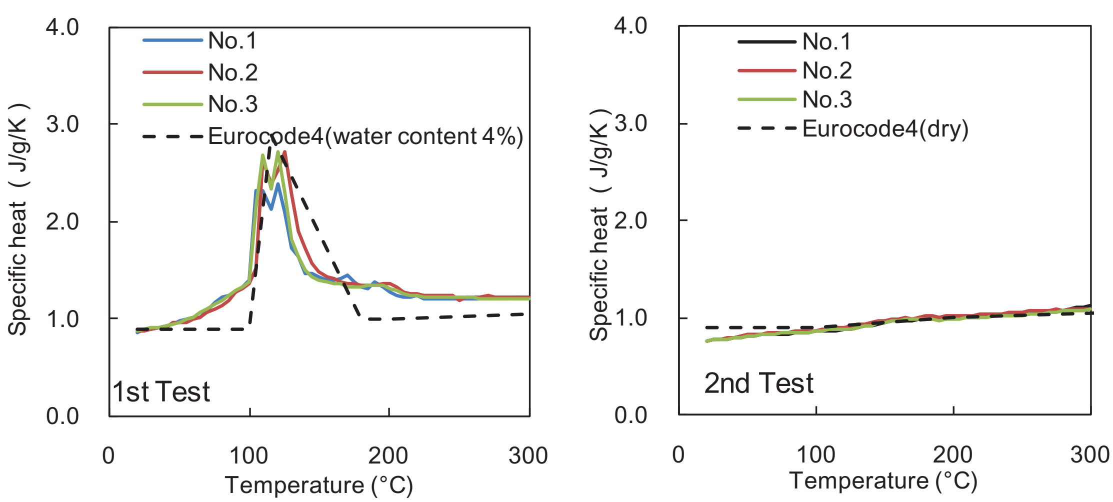


Figure 17. Relation between specific heat and temperature.

CONCLUSION

To evaluate the applicability of SC to PCV of BWRs, tests and analyses were performed as basic study to confirm the feasibility under DBA and SA conditions. In the paper the properties of concrete depending on the temperature and heating period are described.

The properties of high temperature concrete were obtained up to 300 °C. After the basic study, accident occurred in Fukushima Daiichi power station at March 11, 2011. The investigation of accident revealed that the temperature in PCV rose up to about 400 °C and the local maximum temperature was about 600 °C. After the accident, the assumed maximum temperature under SA conditions were changed to 300°C and applicability and designing method were evaluated based on the new assumptions.

As for the properties of concrete, test conditions were broadened to include the maximum temperature of 700°C and the continuing period over 100°C of 7 months. The tests have been finished in fiscal 2014 and the test results are being analyzed.

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