Study on the Influence of Minor Constituents in Blast Furnace Slag Rich Cement on the Thermal and Mechanical Properties of Concrete

Toshiaki Mizobuchi¹*, Kohsuke Ishizeki², Takahiro Sagawa³ and Tetsushi Kanda⁴

Abstract

Until now, the influence on the thermal and mechanical properties of concrete of SO₃ and calcium carbonate as minor constituents contained in binder used for concrete made with blast furnace slag rich cement was not clearly known, and neither was the optimum mixing ratio most effective for control of thermal cracking. To evaluate the influence of these minor constituents on the temperature and crack resistance properties of concrete, a simple adiabatic temperature rise test and examination by thermal stress testing machine (TSTM) were carried out in this study. The simple adiabatic temperature rise test evaluated mainly the thermal characteristics of the minor constituents under investigation, while the test using a TSTM, which is a test device that can simulate the behavior inside the member of a real structure, investigated mechanical properties such as creep characteristics, and crack resistance. Further, using the results of the simple adiabatic temperature rise test and the test using a TSTM, thermal stress analysis using a wall structure was carried out to determine the influence of minor constituents on crack resistance. As a result, as determined within the scope of this study, we found that the formation of ettringite and monosulfate accompanying the addition of SO₃ has an influence on the adiabatic temperature rise characteristic and the apparent mechanical properties, and that the addition of calcium carbonate has only a small influence on thermal properties.

1. Introduction

Cracks in concrete structures can significantly impact durability. There are various causes of crack generation, but cracks caused by shrinkage due to volume change at the early age of concrete include thermal cracks caused by the hydration heat of cement, and self-shrinkage cracks. In view of these factors, it is important to devise crack control measures to reduce initial defects in concrete structures and improve the durability of such structures. On the other hand, there are various crack control measures, among which one of the effective means is to use low-heat cement designed for lower heat generation during hydration. However, low-heat cements have problems such as slow strength development. Further, in the case of commercially available blast furnace slag cement, which traditionally is low-heat cement, ground granulated blast furnace slag of high fineness is used to secure strength at an early age. As a result, in hot weather, the temperature inside the member may rise higher compared with concrete using ordinary portland cement under the same proportioning conditions, which in turn can cause issues such as higher likelihood of cracking due to thermal stress, as well as higher coefficient of thermal expansion and higher autogenous shrinkage and carbonation rate than ordinary Portland cement. Nevertheless, blast furnace slag cement is held to have greater long-term strength development as well as excellent seawater resistance and chemical resistance, to effectively inhibit the alkali-silica reaction, and when a large amount of blast furnace slag is added, to effectively inhibit heat of hydration. Further, since it is possible to reduce the clinker dosage, CO₂ emissions can be reduced, which is effective in terms of environmental impact reduction. Moreover, since blast furnace slag itself is an industrial byproduct, the use of ground granulated blast furnace slag also contributes to the effective use of resources.

Based on the above, to solve the above-mentioned problems of blast furnace slag cement, we developed cement with improved resistance against thermal cracking caused by expansion strain at an early age (ECM cement) by using blast furnace slag cement type C, which is high in blast furnace slag, and selecting the appropriate dosages of SO₃ and calcium carbonate (Kanda et al. 2013, 2014, 2015; Mizobuchi et al. 2016; Arai et al. 2016). ECM cement is an abbreviation for Energy CO₂ Minimum (ECM) cement which is such system using blast furnace slag rich cement. The ECM cement refers to a binder material intended to reduce the clinker content approximately 30% of the total binder mass, and to increase SO₃ content to improve early age strength and shrinkage characteristics by means of introducing high

1Professor, Department of Civil and Environmental Engineering, Faculty of Engineering and Design, Hosei University, Tokyo, Japan. *Corresponding author, E-mail: mizobuch@hosei.ac.jp
2Research Engineer, Kajima Technical Research Institute Kajima Corporation, Tokyo, Japan.
3Associate Professor, Department of Civil and Environmental Engineering, Faculty of Engineering, Maebashi Institute of Technology, Gunma, Japan.
4Senior Research Engineer, Kajima Technical Research Institute, Kajima Corporation, Tokyo, Japan.
volume ground granulated blast furnace slag (Yonezawa et al. 2012).

Until now, the influence of the small amounts of SO₃ and calcium carbonate contained in this ECM concrete on the thermal and mechanical properties of the concrete was not clearly known, and neither was the optimum mixing ratio most effective for control of thermal cracking. To evaluate the influence of these minor constituents on the temperature and crack resistance properties of this ECM concrete, a simple adiabatic temperature rise test and examination by thermal stress testing machine (TSTM) were carried out in this study. The simple adiabatic temperature rise test evaluated mainly the thermal characteristics of the minor constituents under investigation, while the test using a TSTM, which is a test device that can simulate the behavior inside the member of a real structure, investigated mechanical properties such as creep characteristics, and crack resistance. Further, using the results of the simple adiabatic temperature rise test and the test using a TSTM, thermal stress analysis using a wall structure was carried out to determine the influence of minor constituents on crack resistance.

This report summarizes the results of our investigation, including the effects of said minor constituents on the coefficient of thermal expansion, tensile strength, and creep characteristics, which are thought to greatly affect crack resistance.

2. Outline of study

Many of the objects to which ECM concrete is applied are massive concrete members, which tend to have temperature histories that reach relatively high temperatures, so the generation of hydrate products that differ from those generated under standard curing at 20°C or so is expected. Therefore, in this study, it was decided to evaluate crack resistance under the condition of relatively high temperature generation inside members (hereinafter, "mass curing"). What is important here is tensile strength considering temperature dependence, which is the material potential of concrete itself under mass curing, and creep characteristics that mitigate thermal stress and autogenous shrinkage stress in members. Further, as past studies have reported that SO₃ and calcium carbonate influence heat generation characteristics and volumetric change in the initial stage of hydration (JCA 2001; Nito et al. 2010), in this study, we decided to focus on the mechanical properties such as tensile strength and creep characteristics under mass curing closely approximating the internal temperatures in actual mass concrete structures, as well as the initial expansion characteristics and heat generation characteristics that result from the use of minor constituents.

In view of the above, to investigate the influence of minor constituents (SO₃ and calcium carbonate) used in ECM on crack resistance as part of the evaluation of the crack resistance potential of concrete using ECM, this study investigated the crack resistance of ECM by measuring the crack occurrence timing, cracking stress (cracking strength) and strain in a fully constrained state, using a TSTM, which is a test apparatus capable of indoor simulation of the temperature behavior and stress behavior in real structures. In addition, comparison with ordinary Portland cement and commercially available blast furnace slag cement type B, which are used for many concrete structures, was carried out. Further, we conducted thermal stress analysis based on the results of the simple adiabatic temperature rise test and the test using a TSTM, and we also evaluated the influence of minor constituents on crack resistance.

2.1 Structure selected for study

In this study, simulating the internal behavior caused by the heat of hydration of cement in an actual structure with a TSTM, we set up a structure that approximates the assumed target structure type, as shown in Fig. 1. The structure set up in this study was a wall-like structure with a wall thickness of 2.0 m, a wall height of 4.0 m, and a wall length of 20 m, and the behavior at the center of the member was considered. The conditions for the concrete targeted in this study were compressive strength at the control age of 28 days of 40 N/mm² or higher and proportioning conditions that achieve slump of 15 cm and air content of 4.5% (Inaba et al. 2013).

2.2 Outline of study

In this study, a simple adiabatic temperature rise test was conducted to obtain the adiabatic temperature rise formula (thermal characteristics) under the various experimental conditions, and the rate of change in volumetric strain in relation to temperature change was calculated. Next, using the adiabatic temperature rise formula obtained by the simple adiabatic temperature rise test, temperature analysis was performed on the structure under study, and the temperature history (placing temperature of 20°C) at the center of the wall was obtained. Using the calculated temperature history of each case as the set temperature, a test using a TSTM was conducted, the cracking strength and crack occurrence timing were measured, the rate of change in volumetric strain in re-

Fig. 1 Outline of structure under study (1/4 model).
lation to temperature change like simple adiabatic temperature rise test was calculated, and the reduction coefficient of Young's modulus due to apparent creep was calculated, using the results of the mechanical properties tests (compressive strength test, splitting tensile strength test, and Young's modulus test) conducted at the TSTM test.

In the simple adiabatic temperature rise test, the replacement ratio of the mineral admixture (ground granulated blast furnace slag, SO3, calcium carbonate) was set to 70%, and the SO3 and calcium carbonate were added on a cement substitution basis. As SO3, anhydrite (CaSO4) was used, and as calcium carbonate, fine limestone powder (LSP) was used. Further, in this study, the dosage of anhydrite (CaSO4) is expressed as the SO3 amount.

As study cases, using the case with no addition of SO3 and calcium carbonate as the reference case, we conducted experiments split between Series 1, in which the SO3 dosage was varied between 0% and 5% to examine the effect of SO3 addition, and Series 2, in which the standard SO3 dosage of 3.5% was used, and the calcium carbonate dosage was varied between 0% and 3.5% to examine the influence of calcium carbonate addition. We also investigated the case when 5% of SO3 and 5% of calcium carbonate, the respective maximum dosages, were used. The total number of these study cases was 7 cases.

In the test using a TSTM, of the above-mentioned minor constituent study cases, the cases selected for testing were those where the SO3 dosage was varied between 0% and 5% and the case where 5% of SO3 and 5% of calcium carbonate, the respective maximum dosages, were used, for a total of 4 cases. Table 1 lists all the above study cases, further indicating which used a simple heat insulating container and which used a TSTM.

### Table 1 Study cases.

| No. | Test Purpose | Test Item | Cement Type | Target Chemical Composition (%) | Mineral Admixture (Powder) Composition (%) |
|-----|--------------|-----------|-------------|---------------------------------|-------------------------------------------|
| 1-1 | Grasp of adiabatic temperature rise characteristics | Simple adiabatic temperature rise test | Ordinary Portland cement | SO3 0.0 | CaCO3 0.0 | BFS 70.0 | Anhydrite 0.0 | LSP 0.0 |
| 1-2 | Grasp of rate of change in volumetric strain in relation to temperature change (Calculation of apparent coefficient of thermal expansion) | | | SO3 2.5 | CaCO3 0.0 | BFS 65.5 | Anhydrite 4.3 | LSP 0.0 |
| 1-3 | | | | SO3 5.0 | CaCO3 0.0 | BFS 81.1 | Anhydrite 8.6 | LSP 0.0 |
| 1-4 | | | | SO3 3.5 | CaCO3 2.5 | BFS 60.5 | Anhydrite 6.0 | LSP 2.5 |
| 1-5 | | | | SO3 3.5 | CaCO3 0.0 | BFS 61.5 | Anhydrite 6.0 | LSP 2.5 |
| 1-6 | | | | SO3 3.5 | CaCO3 0.0 | BFS 64.0 | Anhydrite 6.0 | LSP 2.5 |
| 1-7 | Cracking strength | Thermal Stress Testing Machine (TSTM) | | SO3 5.0 | CaCO3 5.0 | BFS 65.1 | Anhydrite 8.6 | LSP 5.0 |
| 2-1 | | | | SO3 0.0 | CaCO3 0.0 | BFS 70.0 | Anhydrite 0.0 | LSP 0.0 |
| 2-2 | | | | SO3 2.5 | CaCO3 0.0 | BFS 65.5 | Anhydrite 4.5 | LSP 0.0 |
| 2-3 | | | | SO3 5.0 | CaCO3 0.0 | BFS 61.1 | Anhydrite 8.9 | LSP 0.0 |
| 2-4 | | | | SO3 5.0 | CaCO3 5.0 | BFS 65.1 | Anhydrite 8.9 | LSP 5.0 |

(1) Overview of the TSTM

The TSTM consists of an unrestrained specimen that can expand and contract freely (unrestrained specimen) and a specimen that can be subjected to an arbitrary degree of restraint. It faithfully reproduces the heat generation process of concrete caused by the heat of hydration of cement, and using the strain generated by the unrestrained specimen, it is possible that the restrained specimen freely change the degree of restraint from fully restrained to fully unrestrained, which makes it possible to measure stress from concrete placing to crack occurrence, as well as the strain history (Springenschmid et al. 1994; Schoppel et al. 1994; Lokhorst et al. 1995). Further, when reinforcing bars are embedded, it is also possible to assess the development of crack width after the occurrence of cracks. Moreover, since the TSTM enables strain and stress control at a constant temperature, it is also possible to measure creep and autogenous shrinkage (Mizobuchi et al. 2000).

The TSTM itself is an apparatus that simulates stress behavior under uniaxial restrained condition, the structure that can be simulated are wall-like structures where stress is dominant in the wall length direction.

As shown in Fig. 2, the shape of each specimen is a rectangular parallelepiped, and at the start of the test, the bolts supporting the form surface are loosened so as to minimize as much as possible surrounding restraint. The restrained specimen is a dogbone-shaped specimen, so that no stress concentration occurs in the gripping portion during tension. Each specimen was covered with a polyethylene sheet to prevent moisture escape during the test.

To control the temperature history of the targeted structure to the unrestrained specimen and restrained
specimen, warm water was made to flow through water pipes arranged in the formwork, and the temperature of the water was controlled so as to obtain the desired temperature history. Also, as shown in Fig. 2, five thermometers were installed in the restrained specimens and three in the unrestrained specimen to ensure that there would be no difference between the temperature measurement result of each specimen and the set temperature. The strain of each specimen was obtained based on the displacement measured from the displacement gauges (measuring length of 750 mm) installed on both side faces of the specimen. The test was initiated at the start of initial setting (Senba et al. 2015; Arai et al. 2016).

(2) Simple adiabatic temperature rise test

In the simple adiabatic temperature rise test, concrete with diameter of 250 mm × height of 200 mm was placed at the center of the simple heat insulating container shown in Fig. 3, and ten specimens with diameter of 100 mm × height of 200 mm were arranged around the central specimen. A thermocouple and an embedded strain gauge (apparent modulus of elasticity: 40 N/mm²) were placed on the central specimen for temperature and strain measurement. The specimens placed around the central specimen were used for the compressive strength test and Young's modulus test. The measurements were carried out 14 days after concrete placement and the measurement interval was set to 6 minutes.

(3) Hydration reaction analysis

In this study, hydration reaction analysis of the minor constituents was carried out. The preparation and testing of specimens for hydration analysis are described below.

![Fig. 3 Outline of heat insulating container for simple adiabatic temperature rise test.](image-url)
mm thick slices as the specimens used for analysis, immersed in acetone for 3 hours to stop hydration, and then subjected to analysis.

XRD measurement and Rietveld analysis were performed on the specimens (Sagawa and Nawa, 2014; Kim et al. 2017). XRD measurement was performed using a rotating specimen stage and high-speed solid state detector, using as conditions target CuKα, tube voltage of 40 kV, tube current of 15 mA, scanning range of 5 to 70 deg. (2θ), and step of 0.02 deg. For the Rietveld analysis, SIROQUANT Ver. 3 was used (Sagawa et al. 2014).

2.3 Constituent materials and mix proportions

The materials used in this study are listed in Table 2, and the constituents of each mineral admixture are listed in Table 3. The ordinary Portland cement (OPC) used in this study does not contain fine limestone powder as a minor constituent. The mix proportions of each case are listed in Table 4. The proportioning conditions in this study were target slump of 18 cm, target air content of 4.5%, and constant water-binder ratio.

3. Experimental results and discussion

3.1 Adiabatic temperature rise characteristic

Figure 4 shows the temperature history of each case as obtained by the simple adiabatic temperature rise test.

It shows the tendency for the maximum temperature to be slightly higher in the cases where SO₃ was added compared with the cases where fine limestone powder was added. However, it is difficult to judge whether the addition of fine limestone powder was responsible for the temperature reduction effect due to the different placing dates between the series in which SO₃ was added and the series in which fine limestone powder was added.

To calculate the adiabatic temperature rise formula for each case, a simple heat insulating container was modeled, and verification analysis was carried out by changing the adiabatic temperature rise formula to match the temperature history of each case shown in Fig. 4. The analysis results are shown in Table 5 and the relationship between the adiabatic temperature rise amount and elapsed days is shown in Fig. 5.

As the ultimate value of adiabatic temperature rise and the temperature rise rate coefficients differed for each case, as seen in Table 5 and Fig. 5, we investigated the relationships among the amount of SO₃ and fine limestone powder, the ultimate value of adiabatic temperature rise, the γₐT temperature rise rate coefficient, and the SₐT temperature rise rate coefficient. Figure 5 shows that under the condition of no fine limestone powder, the rate of temperature rise became larger as the amount of SO₃ increased. On the other hand, under the condition of the standard dosage of SO₃, changing the amount of fine limestone powder resulted in almost the exact same

| Case No. | Symbol | W/B (%) | s/a (%) | Water | Cement | Admixture minerals | Fine aggregate | Coarse aggregate | Chemical admixture |
|----------|--------|---------|---------|-------|--------|-------------------|---------------|------------------|--------------------|
| 1-1 | S0C0 | 42.0 | 44.6 | 173 | 124 | BFS Anhydrite LSP | S1 | S2 | G1 | G2 | AE water reducing agent | AE agent |
| 1-2 | S2.5C0 | 288 | 0 | 0 | 20.5 | 38.0 | 1.00 | 1.60 | 0.10 |
| 1-3 | S5C0 | 270 | 19 | 0 | 20.5 | 36.0 | 1.60 | 1.60 | 0.10 |
| 1-4 | S3.5C5 | 252 | 37 | 0 | 20.0 | 35.0 | 1.80 | 1.90 | 0.10 |
| 1-5 | S3.5C2.5 | 264 | 25 | 14 | 19.2 | 32.0 | 2.00 | 1.90 | 1.90 |
| 1-6 | S3.5C0 | 231 | 37 | 21 | 20.0 | 35.0 | 2.00 | 1.80 | 0.20 |
| 1-7 | S5C5 | 252 | 25 | 10 | 19.2 | 34.0 | 2.00 | 1.80 | 0.20 |

Table 4 Mix proportions of concrete.

| Case No. | Symbol | W/B (%) | s/a (%) | Water | Cement | Admixture minerals | Fine aggregate | Coarse aggregate | Chemical admixture |
|----------|--------|---------|---------|-------|--------|-------------------|---------------|------------------|--------------------|
| 1-1 | S0C0 | 288 | 0 | 0 | 20.5 | 38.0 | 1.00 | 1.60 | 0.10 |
| 1-2 | S2.5C0 | 270 | 19 | 0 | 20.5 | 36.0 | 1.60 | 1.60 | 0.10 |
| 1-3 | S5C0 | 252 | 37 | 0 | 20.0 | 35.0 | 1.80 | 1.90 | 0.10 |
| 1-4 | S3.5C5 | 249 | 25 | 14 | 19.2 | 32.0 | 2.00 | 1.90 | 0.20 |
| 1-5 | S3.5C2.5 | 251 | 25 | 10 | 19.2 | 34.0 | 2.00 | 1.90 | 1.90 |
| 1-6 | S3.5C0 | 246 | 25 | 0 | 19.7 | 33.0 | 2.00 | 1.80 | 0.20 |
| 1-7 | S5C5 | 231 | 37 | 21 | 20.0 | 35.0 | 2.00 | 1.80 | 0.20 |

Table 5 Coefficients of adiabatic temperature rise formula of each case.
temperature history in each case. In addition, as shown in Table 5, the ultimate value of adiabatic temperature rise tended to decrease and the temperature rise rate coefficients tended to increase as the dosage of SO3 increased. These trends closely approximate those observed in past research. On the other hand, regarding the influence of adding fine limestone powder, no particular trend concerning the addition of SO3 was observed, and the influence of adding fine limestone powder is thus considered to be small. Nevertheless, given that certain amounts of SO3 are added and that this study is not solely concerned with evaluating the influence of fine limestone powder, multiple regression analysis was performed with ground granulated blast furnace slag amount, SO3 amount and fine limestone powder amount as explanatory variables. The ultimate value of adiabatic temperature rise obtained by multiple regression analysis, the $\gamma_{AT}$ temperature rise rate coefficient, and the $S_{AT}$ temperature rise rate coefficient are shown below, and the relationships between the analysis values and the estimated values are shown in Figs. 6 to 8.

$$Q_\infty = 2.02 \cdot BFS + 1.88 \cdot SO_3 + 2.05 \cdot CaCO_3 - 546$$  
(Multiple correlation coefficient: 0.689)

$$\gamma_{AT} = -1.07 \cdot BFS + 0.0813 \cdot SO_3 - 0.104 \cdot CaCO_3 + 32.1$$  
(Multiple correlation coefficient: 0.871)

$$S_{AT} = -0.275 \cdot BFS - 0.259 \cdot SO_3 - 0.280 \cdot CaCO_3 + 80.8$$  
(Multiple correlation coefficient: 0.948)

where $Q_\infty$ = ultimate value of adiabatic temperature rise (°C), $\gamma_{AT}$ = temperature rise rate coefficient (1/days), $S_{AT}$ = temperature rise rate coefficient, BFS = amount of ground granulated blast furnace slag (kg/m³), SO3 = amount of anhydrite (kg/m³), and CaCO3 = amount of...
fine limestone powder (LSP) (kg/m³).

Figures 6 to 8 shows that although the ultimate value of adiabatic temperature rise was relatively weakly correlated, the temperature rise rate coefficients were relatively highly correlated. Further, it was inferred that not only the amount of SO₃, but also the amount of ground granulated blast furnace slag and fine limestone powder also have some influence on exothermic characteristics, and more particularly the hydration rate.

3.2 Relationship between temperature change and strain change

The results of the strain history of each case are shown in Figs. 9 to 10. In Fig. 9, the expansion strain can be seen to increase as the amount of SO₃ increases. In Fig. 11, the maximum strain amount can be seen to be roughly proportional to the amount of SO₃, with the strain amount being about double in the case of SO₃ dosage of 2.5% compared with SO₃ dosage of 0%, and about triple in the case of SO₃ dosage of 5.0%. Further, the rate of strain increase from the inflection point considered to mark the beginning of hardening until maximum strain is reached was 116 ×10⁻⁶/day when the amount of SO₃ was 0.0%, 702 ×10⁻⁶/day when the amount of SO₃ was 2.5%, and 917 ×10⁻⁶/day when the amount of SO₃ was 5.0%, thus a rate of expansion larger by a factor of 7 to 9 times in the case of SO₃ addition compared with no SO₃ addition.

On the other hand, when fine limestone powder was added, the maximum strain amount tended to decrease with increases in dosage. However, as shown in Fig. 12, the change in maximum strain was on the order of 12 ×10⁻⁶ for a 1% change in fine limestone powder amount, which is about 1/7th of the amount of change in maximum strain obtained from a 1% change in the amount of SO₃. In addition, when comparing the case of not adding SO₃ and fine limestone powder with the case of adding 5% of both, the maximum strain amount was about 3 times greater in the latter case. Therefore, the addition of SO₃ is the dominant factor for expansion strain at a very early age, while the addition of fine limestone powder did not significantly affect expansion strain, and if anything, showing a tendency to reduce expansion strain.

Next, the relationship between the temperature change amount and the strain change amount in each case is shown in Figs. 13 and 14. In Fig. 13, we can see that, under the condition of no addition of fine limestone powder, the strain (temperature strain + autogenous shrinkage strain) at the time of temperature rise increases as the amount of SO₃ increases. Compared with the case of no addition of SO₃, the amount of strain change when the temperature change is greatest is about twice as large when the amount of SO₃ is 2.5%, and about 3.3 times as large when the amount of SO₃ is 5.0%, which is almost exactly the same as in the case of the strain history shown in Fig. 9. On the other hand, regardless of the addition or non-addition of SO₃, the amount of strain change remained almost unchanged until the temperature change...
amount reached about 4°C. The temperature change amount of 4°C occurs at about 8 hours after mixing, and coincides almost exactly with the onset of setting (onset of curing). The subsequent strain increase resulted in an increase in the rise gradient depending on the addition or non-addition of SO₃. In the case of the SO₃ dosage of 2.5%, the rise gradient became moderate from when the temperature change amount was about 16°C or so. In the case of the SO₃ dosage of 5.0%, the rise gradient remained large until up to about 23°C, and thereafter the rise gradient becomes gentle in the case of the SO₃ dosage of 2.5%.

In the case where the amount of fine limestone powder was changed under the condition that the SO₃ dosage is the standard value, the maximum strain amount tended to decrease slightly as the dosage of fine limestone powder increased, as shown in Fig. 14.

From the relationship between the temperature change amount and the strain change amount of each case, the apparent coefficient of thermal expansion was calculated by dividing the temperature increase region into the sections shown in Fig. 15 based on the addition or non-addition of SO₃. As shown in Fig. 15, the apparent coefficient of thermal expansion during temperature rise when SO₃ was not added is classified into 2 sections, namely the section around the time of the onset of setting (in this study, about 8 hours after mixing, which is hereinafter referred to as the section until the onset of curing), and the section until the maximum temperature was reached. On the other hand, the apparent coefficient of thermal expansion during temperature rise when SO₃ was added is classified into 3 sections, namely the section from the rise in temperature until the time around the onset of curing (section until the onset of curing), the section during which the coefficient of thermal expansion increases (the section during which hydrates such as ettringite or monosulfates that cause expansion strain are considered to be generated; hereafter referred to as the generation activation section), and the section where expansion strain stagnates (the section where SO₃ has been consumed, hereafter referred to as the expansion stagnation section).

The interval when the temperature drops is classified into 2 sections, namely the shrinkage transition section, which marks the transition from the expansion stagnation section to the shrinkage section, regardless of whether or not SO₃ and/or fine limestone powder are added, and the shrinkage section in the temperature drop zone.

Table 6 lists the results of the calculation of the coefficient of thermal expansion from the relationship between the temperature change amount and the strain change amount. In this table, the apparent coefficient of thermal expansion can be seen to be approximately 4 times and 5 times as large for the SO₃ dosages of 2.5% and 5.0%, respectively, in the generation activation section, compared with the case when no SO₃ is added, where the value of the apparent coefficient of thermal expansion is 6.4 \( \times 10^{-6} \) (°C) past the onset of curing when the temperature rises. Further, the generation activation section ended just one day after mixing. Moreover, the transition from the expansion stagnation section to the shrinkage transition section was observed to be faster as the SO₃ dosage rate increased. Compared with 2.1 days when no SO₃ was added, the transition lasted 1.6 days for the 2.5% SO₃ dosage, and 1.4 days for the 5.0% SO₃ dosage, showing a reduction in the duration of the transition of approximately 0.5 days and 0.7 days, respectively for the 2.5% and 5.0% dosages. Although, in the shrinkage transition section, the apparent coefficient of thermal expansion tended to decrease with increasing
SO₃ dosages, in the shrinkage section, its value changed very little among the various cases and remained almost the same.

When the dosage of fine limestone powder was changed under the condition of the dosage of SO₃ being the standard value, the apparent coefficient of thermal expansion remained almost unchanged in the generation activation section in all cases, and given that the SO₃ dosages were the same, the duration of this section was almost the same. In the shrinkage transition section, the apparent coefficient of thermal expansion tended to decrease as the dosage of fine limestone powder increased. Although there was some variation in the shrinkage section, the apparent coefficient of thermal expansion values was almost the same.

Based on the above, the addition of SO₃ is considered to markedly affect the temperature rise characteristics and the expansion characteristics in relation to temperature change, while the addition of fine limestone powder is considered to have only a small effect.

### 3.3 Hydration reaction analysis

The hydration reaction analysis results for each case at the age of 3 days are shown in Table 7. The hydrate products were expressed as the amount produced per unit of mass after ignition loss of each sample. From Table 7, it can be seen that when SO₃ and fine limestone powder were not added, ettringite was hardly produced, whereas hydrogarnet (3CaO·Al₂O₃·6H₂O) and monosulfate were produced. On the other hand, in the case of the SO₃ dosage of 2.5%, monosulfate was the main product, and at the SO₃ dosage of 5.0%, the main product was ettringite. When the dosage of fine limestone powder was changed, zero addition of fine limestone powder resulted in almost no formation of carbonate hydrates, but as the dosage of fine limestone powder increased, so did the amount of generated carbonate hydrates.

The reason why the generation activation section was hardly observed when SO₃ and fine limestone powder were not added is believed to be due to the fact that consumption of SO₃ and formation of ettringite ended approximately 8 hours after mixing (at the onset of setting). On the other hand, ettringite and monosulfate were produced in the case of the SO₃ dosage of 2.5%, and expansion strain is thought to have occurred due to the formation of ettringite in the generation activation section. Further, the fact that the apparent expansion strain grew small in the expansion stagnation section is attributed to the conversion of ettringite to monosulfate. In the case of the SO₃ dosage of 5.0%, ettringite was the main product, and it is inferred that expansion strain was three times or more greater compared with the case without SO₃. However, because there are no analysis results at the age during which generation is activated, analysis in the section where expansion strain increases and hydration reaction analysis in the section where the SO₃ is consumed and the strain increase levels off are considered to be necessary in the future.

Regarding the cases where the dosage of fine limestone powder was changed, it is assumed that the change in the coefficient of thermal expansion was almost the same in all cases since the amounts of ettringite and monosulfate produced in each case were almost the same.

### 3.4 TSTM test results

(1) Set temperatures and temperature measurement results

Regarding the set temperature of each case, using the adiabatic temperature rise formula obtained by the simple adiabatic test, temperature analysis was carried out.
with the model of the structure under study (wall-like structure) shown in Fig. 1, and the temperature history at the center of the wall was used. The analysis conditions consisted of the placing temperature of 20°C, outside air temperature of 20°C, specific heat and thermal conductivity equal to the average value of the respective standard value ranges (1.15 J/g°C and 2.7 J/m°C), and density corresponding to the unit volume mass at the time of the simple adiabatic test. The surface heat transfer coefficient used was the constant 14 W/m²°C for both the sides and the top surface. The set temperature history of each case is shown in Fig. 17, and the temperature history of S5C5 is shown in Fig. 18 as an example of the measurement results. In the comparison of the set temperatures and temperature histories of the unrestrained specimen and restrained specimen, as shown in Fig. 18, although the measured values were almost the same as the set temperature at the time of temperature rise and temperature drop, the results were slightly lower than the set temperature around the time the maximum temperature was reached. In each of the other cases, the results closely paralleled the set temperature.

(2) Strain and stress measurement results
The stress histories of the restrained specimens in each case are shown in Fig. 19, and the strain histories of the unrestrained specimens and restrained specimens are shown in Figs. 20 and 21.

Figure 19 shows that, with the exception of case S5C5, cracks occurred at the tensile stress of 2.0 N/mm² or less. Specifically, for S0C0, S2.5C0, S5C0, cracks occurred at the tensile stress of 1.44 N/mm², 1.69 N/mm², and 1.67 N/mm², respectively, and even when SO₃ was added, almost no increase in cracking strength was observed.

In Fig. 20, maximum compressive strain shows a tendency to increase as the SO₃ dosage increases. At the SO₃ dosage of 0%, maximum compressive strain is 220 × 10⁻⁶, whereas at the dosage of 2.5%, it is 369 × 10⁻⁶, which is about 1.7 times larger. In the strain history in the simple adiabatic test shown in Fig. 9, maximum strain was about 400 × 10⁻⁶ when the SO₃ dosage was 2.5%, thus almost the same value. At the SO₃ dosage of 5.0%,
maximum compressive strain was $500 \times 10^{-6}$, thus about $150 \times 10^{-6}$ smaller than the maximum strain value of $650 \times 10^{-6}$ obtained in the simple adiabatic test.

As shown in Fig. 21, regarding the strain history of the restrained specimens, the strain value was on the order of $0 \times 10^{-6}$ in all cases, indicating that the restrained condition was almost perfectly maintained over the test period.

(3) Relationship between temperature change and strain change (TSTM)

Figure 22 shows the relationship between the amount of temperature change and the amount of strain change in each case, and Fig. 23 shows the relationship between the amount of temperature change and the amount of strain change in the simple adiabatic test.

In Fig. 22, strain can be seen to increase during the temperature rises as the amount of SO$_3$ increases, like in the case of the simple adiabatic test. Compared with when no SO$_3$ is added, the amount of strain change at maximum temperature change was approximately 1.7 times at the SO$_3$ dosage of 2.5% (compared with approximately 1.9 times in the case of the simple adiabatic test), and approximately 2.3 times at the SO$_3$ dosage of 5.0% (compared with approximately 3.3 times during the simple adiabatic test). On the other hand, in the case of the simple adiabatic test, whereas the amount of strain change remained almost the same up to the temperature change amount of 4°C regardless of whether or not SO$_3$ was added, in the case of the TSTM test, similar behavior to that during the simple adiabatic test was observed when SO$_3$ was added, but no rise in strain during the earliest stage when no SO$_3$ was added was observed. This is because, in the case of the TSTM test, the start of the test is set as the onset of setting. If the time when the temperature change amount reaches 4°C in the simple adiabatic test is used as the reference (where the temperature change amount and the strain change amount are both 0), the subsequent behavior and that of TSTM are almost the same. Subsequently, like in the simple adiabatic test, strain in relation to temperature went through a generation activation section, expansion stagnation section, shrinkage transition section, and shrinkage section as the result of SO$_3$ addition.

Next, regarding the relationship between the amount of change in temperature and the amount of strain change in the simple adiabatic test and the TSTM test for each case, as compared with the onset of curing for the SO$_3$ dosage of 2.5%, the duration of the generation activation section was almost the same in the simple adiabatic test and the TSTM test, but the gradients (apparent coefficients of thermal expansion) greatly differed, as shown in Fig. 24. Further, in the expansion stagnation section, the gradient tended to be slightly larger in the TSTM test than in the simple adiabatic test. Regarding the shrinkage section of the temperature drop zone, no clear difference was observed in the shrinkage stagnation section and the shrinkage section between the TSTM test and the simple adiabatic test. In the case of the SO$_3$ dosage of 5%, although the duration of the generation activation section was almost the same in the simple adiabatic test and the TSTM test, the apparent coefficient of thermal expansion was about 1.5 times greater in the simple adiabatic test, as shown in Fig. 24. Meanwhile, while the duration of the expansion stagnation section was longer in the TSTM test, the apparent coefficient of thermal expansion showed a tendency to be slightly smaller compared with the simple adiabatic test. As for the shrinkage section, the transition section and the shrinkage section were not conspicuous and exhibited almost the same gradient as in the case of the SO$_3$ dosage of 2.5%.

Next, based on the results of apparent coefficient of thermal expansion calculated at every 1°C change in temperature in the simple adiabatic test and TSTM test, the apparent coefficient of thermal expansion was calculated by using the moving average at approximately 3°C around the time of the target temperature change amount. The calculation results for each case are shown in Fig. 25. In this figure, we can see that with the exception of S0C0, each case showed almost the same behavior, but in simple adiabatic test, the apparent coefficient of thermal expansion at the early age of concrete tended to
be larger than that in the TSTM test. Further, past the age of 2 days (after the maximum temperature was reached), the rate of change in the apparent coefficient of thermal expansion tended to be faster in the simple adiabatic test than in the TSTM test in all cases.

Comparison of the apparent coefficient of thermal expansion by test method showed that the variations in the apparent coefficient of thermal expansion proper were larger in the simple adiabatic test, and that the rate of change in the apparent coefficient of thermal expansion at the time of temperature drop tended to be large.

In light of the above results, if one were to evaluate the influence of the increase in apparent coefficient of thermal expansion due to the addition of SO₃ at a very early age, the TSTM test, which shows the smaller value of apparent stress during shrinkage, would allow evaluation on the safe side. Further, in the case of the TSTM test, given that the temperature history of the target structure is used as the set temperature, it is inferred that the facts that the transition zone from temperature rise to temperature drop is short and that the shrinkage transition section is almost not observable indicate that the results given by the TSTM test closely approximate the change in the coefficient of thermal expansion of the actual structure. Therefore, the TSTM test results were used as the apparent coefficient of thermal expansion used for analysis of the structure under study.

(4) Apparent Young's modulus calculated from the stress-strain relationship

Figure 25 shows the relationship between the restraint strain (elastic strain + creep strain) obtained by subtracting the total strain (autogenous shrinkage strain + thermal strain) of the unrestrained specimen from the total strain of the restrained specimen in the TSTM test, and the stress generated in the restrained specimen. From Fig. 25, we obtained the apparent Young's modulus in relation to the strain including the influence of creep (restraint strain) per 10 × 10⁻⁶. However, since the variation in Young's modulus per 10 × 10⁻⁶ was large, the apparent Young's modulus was calculated by a moving average of 50 × 10⁻⁶ before and after the target strain range. The Young's modulus histories calculated for each case are shown in Fig. 26.

In Fig. 26, we see that the apparent Young's modulus increased until the temperature adjusted age of concrete of 8 days to 10 days, followed by a stagnating or decreasing trend. In the case of S0C0 without addition of SO₃ and fine limestone powder, although the Young's moduli calculated from the TSTM test were slightly lower than the Young's moduli calculated from Equation (2) (Momose et al. 2014) until the temperature adjusted age of concrete of 2 days, as shown in Fig. 26, from the temperature adjusted age of concrete of 2 days, the Young's moduli calculated in the TSTM test became almost the same value. This is thought to be possibly due to the fact that the stress relaxation due to creep at the

---

Fig. 24 Comparison of apparent coefficient of thermal expansion in each section under different test methods.
The young age of the concrete is almost entirely canceled by the autogenous shrinkage stress when no SO₃ and fine limestone powder are added. As a result, it seems that the apparent Young's modulus calculated in the TSTM test is almost the same value as that of the Young's modulus calculated based on the test results of the specimen.

In the case of S2.5C0, as shown in Fig. 26, the Young's moduli were lower than those calculated from the concrete specimen within the TSTM measurement period, and the apparent Young's moduli from the temperature adjusted age of concrete of 2 days were 20% to 40% lower than those calculated from Equation (2). In the case of the SO₃ dosage of 5% (S5C0), as shown in Fig. 26, in the section from the temperature adjusted age of concrete of 2 days up to the temperature adjusted age of concrete of 10 days, during which the apparent Young's moduli reach their maximum value, are approximately 10% to 30% lower in value, but from the temperature adjusted age of concrete of 10 days onward, they are 10% to 30% lower. In the case with SO₃ dosage of 5% and fine limestone powder dosage of 5% (S5C5), the behavior was almost the same as that of S5C0 until the temperature adjusted age of concrete of 8 days.

(5) Calculation of reduction coefficient for creep

Based on the Young's modulus from the TSTM test in each case and the Young's modulus calculated from Equation (2), the reduction coefficient for creep was calculated. Calculation of the reduction coefficient was done from the section where the apparent Young's modulus in the TSTM test is assumed to be linear owing to the stress-strain relationship. The calculation results are shown in Fig. 27.

Figure 27 shows that in the case of no addition of SO₃ and fine limestone powder, the apparent Young's modulus obtained by the TSTM test is a larger value than the Young's modulus calculated from the concrete specimen as described above, and the apparent coefficient of reduction of Young's modulus is about 1.0 from the temperature adjusted age of concrete of 2 days to 12 days. The value then gradually declines and from the temperature adjusted age of concrete of 14 days, it remains almost constant at approximately 0.8. Even during the subsequent thermal stress analysis, the coefficient of reduction remained a constant value of 0.8 from the temperature adjusted age of concrete of 14 days. In the case of the SO₃ dosage of 2.5%, the coefficient of reduction gradually increased from 0.6 to 0.8 from the temperature adjusted age of concrete of 2 days, a range that is narrow enough for the value to be considered as almost constant. Even in the subsequent thermal stress analysis, the coefficient of reduction was considered to remain a constant value of 0.8 from the temperature adjusted age of concrete of 18 days. In the case of the SO₃ dosage of 5.0%, the coefficient of reduction was approximately 0.7 during the temperature adjusted age of concrete of 2 to 8 days, and from the temperature adjusted age of concrete of 8 days, it gradually decreased, becoming almost constant at 0.6 from the temperature adjusted age of concrete of 14 days. In the case of the 5% dosage of both SO₃ and fine limestone powder, the coefficient of reduction showed almost exactly the same behavior as in the case of the SO₃ dosage of 5%, and after that it gradually increased, becoming almost constant at 0.8 from the temperature adjusted age of concrete of 18 days.

In light of the above results, in this study, 0.8 was
adopted as the coefficient of reduction for creep regardless of whether SO3 is added from the temperature adjusted age of concrete of 14 days, taking into consideration the fact that although the coefficient of reduction of the apparent Young’s modulus varies depending on the amount of SO3 added, the temperature adjusted age of concrete of 14 days, taking into consideration the fact that although the coefficient of reduction of the apparent Young’s modulus varies depending on the amount of SO3 added between the temperature adjusted age of concrete of 2 and 10 days, it is basically constant (fluctuating in the range between 0.6 and 0.8) from the temperature adjusted age of concrete of 14 days.

3.5 Thermal stress analysis based on results of simple adiabatic test and TSTM test

Thermal stress analysis of the structure under study shown in Fig. 1 was carried out using the thermal characteristics obtained by the simple thermal insulation test and the thermal characteristics and mechanical properties obtained by the TSTM test as design values. As shown in Table 8, in addition to the S0C0, S2.5C0, S5C0 and S5C5 cases subjected to the TSTM test, concrete using ordinary Portland cement with almost the same conditions, and concrete made with blast furnace slag cement type B, were used.

The analysis conditions for the temperature analysis were the use of existing concrete for the slab member, and initial temperature of the ground and base plate of 20°C. Further, the placing temperature of the concrete for the side walls was 20°C, and the outside air temperature was set to 20°C. The average value of the range indicated in the Guidelines for Control of Cracking of Mass Concrete 2016 of the Japan Concrete Institute (JCI 2016) was adopted as the thermal constant, and 2.7 W/m°C and 1.15 kJ/kg°C were adopted as the thermal conductivity value and the specific heat value, respectively. The density value of 2320 kg/m³, was calculated from the table of mix proportions, was adopted for S0C0, S2.5C0, S5C0 and S5C5, and the density value of 2300 kg/m³ was used for ordinary Portland cement and blast furnace slag cement type B.

As the adiabatic temperature rise formula of concrete, the adiabatic temperature rise formula obtained from the simple adiabatic test was used, and for ordinary Portland cement and blast furnace slag cement type B, the adiabatic temperature rise formula indicated in Cracking Control Guidelines (JCI 2016) was used. The surface heat transfer coefficient used was the constant 14 W/m²°C for both the sides and the top surface.

The coefficient of thermal expansion in the thermal analysis gave the volume strain rate with temperature change calculated based on the strain history of the unconstrained specimen in each case in the TSTM test including the autogenous strain and the temperature strain. Therefore, in this study, analysis for S0C0, S2.5C0, S5C0 and S5C5 was done without taking autogenous shrinkage strain into consideration. The values calculated from the results of the TSTM test were used as the coefficient of reduction for Young’s modulus and creep. For ordinary Portland cement and blast furnace slag cement type B, calculation was performed using the adiabatic temperature rise formula indicated in Cracking Control Guidelines (JCI 2016).

3.5.1 Analysis results

The temperature history of each case is shown in Fig. 28, and the stress history is shown in Fig. 29. In Fig. 28, whereas the maximum temperature was 68.5°C for concrete using ordinary Portland cement and 68.7°C for concrete using blast furnace slag cement type B, it was 56.2°C for S0C0, 53.7°C for S2.5C0, 54.5°C for S5C0, and 53.0°C for S5C5, thus 12°C to 15°C lower compared with concrete using ordinary Portland cement and concrete using blast furnace slag cement type B.

Regarding the stress history, as shown in Fig. 29, maximum compressive stress of the concrete using ECM was low compared with concrete using ordinary Portland cement and concrete using blast furnace slag cement type B, and while maximum tensile stress was 4N/mm² for S0C0 and S2.5C0, lower compared with concrete using blast furnace slag cement type B, it was almost the same.

Table 8 Case studies (thermal stress analysis).

| Case   | Water-cement ratio (%) | Unit water content (kg/m³) | Remarks                                      |
|--------|------------------------|---------------------------|----------------------------------------------|
| S0C0   | 42.0                   | 173                       | Value calculated from each test result was used |
| S2.5C0 | 42.0                   |                           | Conforms to crack control guidelines          |
| S5C0   | 42.0                   |                           |                                              |
| S5C5   | 42.0                   |                           |                                              |
| OPC    | 51.6                   |                           |                                              |

![Fig. 28 Temperature history of each case.](image1)

![Fig. 29 Stress history of each case.](image2)
value as that of concrete using ordinary Portland cement. On the other hand, in the case of S5C0, maximum compressive stress was almost the same value as in the case of concrete using ordinary Portland cement, and maximum tensile stress was 2.4 N/mm², thus only about 60% of the maximum tensile stress of concrete using ordinary Portland cement. This is assumed to be due to the fact that the coefficient of reduction of Young's modulus in the tensile zone was less than two thirds that in the other cases. For S5C5, maximum compressive stress was approximately -2N/mm², which was lower than that of concrete using ordinary Portland cement. Maximum tensile stress was approximately 2.4 N/mm², thus about 40% lower compared with concrete using ordinary Portland cement.

4. Conclusions

This study conducted a simple adiabatic temperature rise test and examination by TSTM to clarify to what extent the small amount of SO₃ and calcium carbonate contained in ECM influences thermal and mechanical properties of concrete and also to clarify the optimum mixing ratio most effective to control thermal cracking. The findings of this study are summarized as follows.

1. The influence of addition of anhydrite and fine limestone powder (LSP) depresses the adiabatic temperature rise characteristics and the tendency is consistent with past research. However, not only the amount of anhydrite, but also the amounts of ground granulated blast furnace slag and fine limestone powder are believed to have some influence on exothermic characteristics, and more particularly the hydration rate.

2. Regarding the amount of strain change in relation to the temperature change amount, the addition of anhydrite is considered to have a marked influence, whereas the addition of fine limestone powder (LSP) is considered to have only a small effect. Thus, if one were to evaluate the influence of the increase in apparent coefficient of thermal expansion due to the addition of anhydrite at a very early age, the TSTM test, which shows the smaller value of apparent stress during shrinkage, would allow evaluation on the safe side. Therefore, as the apparent coefficient of thermal expansion used for analysis of the structure, use of the TSTM results seems more appropriate.

3. Regarding the apparent coefficient of reduction of Young's modulus, although the coefficient of reduction of the apparent Young's modulus varies depending on the amount of anhydrite added between the temperature adjusted age of concretes of 2 and 10 days, it is basically constant (fluctuating in the range between 0.6 and 0.8) from the temperature adjusted age of concrete of 14 days. Thus, in this study, the coefficient of reduction in the tensile zone was set to 0.8 regardless of anhydrite addition.

4. Thermal stress analysis of the structure under study was carried out using as design values the thermal characteristics obtained by the simple adiabatic test and the thermal and mechanical properties obtained by the TSTM test. Maximum tensile stress of S0C0 and S2.5C0 was nearly equal to that of concrete using ordinary Portland cement and in the case of S5C0 and S5C5, maximum tensile stress was about 40% lower than that of concrete using ordinary Portland cement. Therefore, the addition of about 5% anhydrite, a minor constituent, to ECM is thought to yield a higher crack control effect against thermal crack than in the case of ordinary Portland cement and blast furnace slag cement type B.

References

Arai, J., Ishizeki, K., Kanda, T., Kojima, M. and Mizobuchi, T., (2016). “Study on resistant properties for cracking caused by shrinkage with volume change of concrete using high volume blast furnace slag cement.” In: Fourth International Conference on Sustainable Construction Materials and Technologies SCMT4.

Inaba, Y., Kanda, T. Yoda, K., Momose, H., Ishizeki, H., Tsuji, D., Kojima, M. and Kuroda, M., (2013). “Resistance performance against cracking of concrete containing high amount blast furnace slag for massive concrete.” In: Summaries of technical papers of annual meeting (Hokkaido), Architectural Institute of Japan, A1, 9. (in Japanese)

JCA, (2001). “Report of committee on limestone filler.” Japan Cement Association. (in Japanese)

JCI, (2016). “Guidelines for control of cracking of mass concrete 2016.” Japan Concrete Institute.

Kanda, T., Inaba, Y., Ishizeki, K. and Kojima, M., (2014). “Basic study on thermal crack resistance of concrete using cement with high amount of blast furnace slag”, Proceedings of the Japan Concrete Institute, 36(1), 1720-1725, (in Japanese)

Kanda, T., Inaba, Y., Ishizeki, K. and Kojima, M., (2015). “Thermal cracking resistance investigation for a new high-volume blast-furnace slag cement concrete.” In: Proceeding of the fifth international conference on construction materials.

Kanda, T., Yoda, K., Yonezawa, T. and Kuroda, M., (2013). “Experimental study on structural strength of concrete using cement with high amount of blast furnace slag.” Proceedings of the Japan Concrete Institute, 35(1), 229-234. (in Japanese)

Kim, J., Na, S., Zhang, W., Sagawa, T. and Hama, Y., (2017). “Effect of limestone powder and gypsum on the compressive strength mixture design of blast furnace slag blended cement mortar.” Journal of Advanced Concrete Technology, 15(2), 67-80.

Lokhorst, S. and van Breugel, K., (1995). “Experimental and numerical analysis of stress development in hardening concrete, Progress in concrete research.” Delft University of Technology, faculty of Civil Engineering, 11-20.
Mizobuchi, T., Ishizeki, K., Kanda, T. and Arai, J., (2016). “Study on crack resistance of concrete using cement with high amount of blast furnace slag.” Proceedings of the Japan Concrete Institute, 38(1), 531-536. (in Japanese)

Mizobuchi, T., Yokozeki, K. and Nobuta, Y., (2000). “Experimental estimation on thermal cracking using the constraint testing method.” Control of Cracking in Early-Age Concrete, 297-306. (in Japanese)

Momose, H., Kanda, T., Imamoto, K., Kiyohara, C. and Ishizeki, K., (2014). “Study on quantitative evaluation of shrinkage crack resistance of blast furnace slag cement type B concrete.” Journal of Structural and Construction Engineering (Transactions of AIJ), 79(7906), 1717-1727. (in Japanese)

Nito, N., Hanehara, S., Koibuchi, K. and Sakai, E., (2010). “Influence of temperature dependence of hydration reaction of blast furnace slag cement on adiabatic temperature rise.” Proceedings of the Japan Concrete Institute, 32(1), 59-64. (in Japanese)

Sagawa, T. and Nawa T., (2014). “Hydration analysis and phase composition of cement-based materials by X-ray diffraction/Rietveld method using an external standard.” Cement Science and Concrete Technology, 68, 46-52. (in Japanese)

Schoppel, K. and Plannerer, M., (1994). “Determination of restraint stress and of material properties during hydration of concrete with the temperature-stress testing machine.” In: Proceedings of the International RILEM Symposium, 153-160.

Senba, R., Arai, J., Hasegawa, T. and Mizobuchi, T., (2015). “Study on cracking limit of concretes using various types of cement.” Proceedings of the Japan Concrete Institute, 37(1), 1171-1176. (in Japanese)

Springenschmid, R. and Breitenbucher, R., (1994). “Development of the cracking frame and the temperature-stress testing machine.” In: Proceeding of the International RILEM Symposium, 137-144.

Yonezawa, T., Sakai, E., Koibuchi, K. and Kinoshita, M., (2012). “Energy CO₂ minimum (ECM) cement concrete system.” In: Proceeding of fib Symposium Stockholm 2012, Concrete Structures for Sustainable Community, 463-466.