A Study on Thermal Efficiency of Heat Testing Machine for Heat Transfer of Concrete at High Temperature

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Abstract
The deformation of building frameworks can lead to critical disasters such as building collapse. Loads, thermal expansion and creep are generally known factors, which cause deformation. High temperature due to fire can also be one of the major factors since concrete deterioration can affect the performance of building structures and eventually can weaken the frameworks. It is, however, difficult to estimate the influence of fire on concrete structures and evaluate the performance of fire resistance design. Many researchers have carried out experiments using small-scale specimens to tackle this issue and it was shown that specimens can reflect the real behavior of structures reasonably well. Nonetheless, it is challenging to achieve uniform temperature rise throughout the specimens while heating the structure as concrete has low thermal conductivity. Many different heating methods were used in recent studies to overcome this problem; however, one cannot compare the results directly to other results due to the variation of the experiment conditions. In this study, therefore, a new heating and loading method was suggested which combines the existing heating systems. Several experiments were carried out to show that a new method can maintain uniform temperature while heating so that the experiment can produce more accurate data.

Keywords: properties of concrete at high temperature; heat transfer method; heating and loading machine; fire resistance

1. Introduction
Concrete deterioration at high temperature can cause collapse of buildings or drastic deformation of the internal strength of important members of the structure such as support columns. Therefore, nowadays research considers various factors that deteriorate the compressive strength, Young’s modulus of elasticity, change in thermal strain and creep to estimate the behavior of concrete structures and their design for fire resistance. The results of this research can be used to design special concrete structures that are exposed to high temperature such as safety walls of nuclear power plants, chemical plants, and highways. Meanwhile, it is common that the design of structural members for fire resistance has been evaluated considering the high temperature of concrete and for their fire resistance performance to be optimized to prove its integrity. However, the researchers did not establish standard tests for the evaluation of the mechanical properties of concrete at high temperature; therefore almost every researcher uses his own test methods. Different factors such as heating system, heating method, test period, dimension of specimen, and performance of loading and heating test machine, can manipulate the data.

Hirashima et al. (2003) heated a loading jig with an electric furnace to transfer heat to a 75x150mm concrete cylinder as an indirect heating method (as seen in Fig.1.). The heating was performed at 1ºC/min and it was maintained for 180 minutes at every 100ºC increase. The type and maximum size of aggregate, and W/B were used as variables and Young’s modulus of elasticity, compressive strength and thermal strain of high strength concrete (40~100N/mm²) were evaluated. Abe et al. (1999) used a direct heating method as seen in Fig.1. where the heating rate was 1.25ºC/min and after reaching the target temperature, it was maintained for 1~1.5 hours with a 50x100mm concrete cylinder. Heat tests were performed to analyze the relationship between the compressive strength of high strength concrete of 40, 60, and 80 N/mm² class, deformation in the maximum compressive strength, fracture energy and heating temperature. Khandaker et al. (2004) used an electric furnace. The heating rate was 2.5ºC/min, and after reaching the target temperature, that temperature was maintained for an hour. By using a
100mm cube type concrete specimen, residual strength and durability of volcanic ash concrete exposed to high temperature were tested. Hertz (1992) used concrete mixed with silica fume of 150N/mm² compressive strength. 1°C/min heating rate was applied to 20, 150, 350, 450 and 650°C respectively and then by 1°C/min rate, and the temperature was cooled down to reach normal temperature. After that, unstressed residual strength tests were preformed. Hammer (1995) applied a 100x310mm concrete cylinder to the unstressed test by a heating rate of 2°C/min for high strength concrete of 68~117N/mm² compressive strength. Aggregate types, age and a maximum temperature of 600°C were the main variables. Castillo et al. (1990) tested heat by applying stressed and unstressed methods to a high strength concrete whose specified concrete strength was 62.1N/mm². The specimen used was a 51x102mm concrete cylinder. The heating rate was 7~8°C/min and from 100°C to 800°C, it increased every 100°C. After reaching the target temperature, it was maintained for 5~10 minutes. Sullivan et al. (1992) used a 64x64mm concrete cylinder mixed with lightweight aggregate and crushed gravel, whose compressive strength is 65N/mm². A maximum temperature of 600°C and a heating rate of 1°C/min and 1.5°C/min were applied respectively, and a stressed and unstressed residual strength heat test was performed. Kim et al. (2008) used a mixed heating method as seen in Fig.1. where the heating rate was 0.77°C/min, it was maintained for 30 minutes every 50°C rise and after reaching the target temperature, it was maintained for 1.5 hours. By using a 100x200mm concrete cylinder, the changes of compressive strength, Young's modulus of elasticity and thermal strain according to the heating temperature were evaluated.

As mentioned earlier, these researchers used heating velocity 0.5°C/min~2.5°C/min and specimen size 51x102mm to 100x310mm to evaluate the thermal properties of concrete. These experiments can not be compared with others directly because of the difference in manufacturing conditions such as mixing material and proportions of the specimen and temperature etc. but evaluation of some elements was carried out by researchers such as Tokoyada et al. (2005) and Mohamedbhari et al. (1986). These researchers suggest that change of heating velocity and heating time etc. influence the experimental result while evaluating the thermal properties. In the case of RILEM 129-MHT (1995), the range of heating velocity on specimen size is used as per the RILEM code to evaluate the thermal properties of concrete.

This study aimed to evaluate thermal efficiency on specific temperature according to W/C, heating velocity, heating method with Ø100x200mm cylinder specimen and heating velocity below 1°C/min as per the RILEM code and to demonstrate the transfer of the thermal properties of concrete in order to evaluate them through a homogeneous heating method.

2. Loading and Heating Testing Machine
The direct heating method has a fast heating rate, however, it is likely to damage the surface of the specimen. Due to high heating rate, the inside temperature of the specimen could not reach the target temperature in time. On the other hand, although the indirect heating method does not damage the specimen surface, heating rate is relatively slow in reaching the target temperature. This study can minimize damage to the specimen and maximize the heating rate to reach the target temperature by combining heating transfer systems. It will also contribute to improving the precision of measuring the mechanical properties of concrete at high temperature (Miyamoto et al. 2003)
To evaluate the mechanical properties of concrete at high temperature, the specimen should achieve the target temperature in time, however, as concrete has low thermal conductivity, a temperature difference occurs between the inside and outside of the specimen as shown in Fig.3. Thus, recent research (Miyamoto et al. (2003), Hirashima et al. (2003), Abe et al. (2007)) reduced the size of the specimen and extended the heating time to transmit heat to the specimen evenly. However, this study used Ø100x200mm specimens to suggest the loading and heating method to transmit heat to the entire specimen evenly. A detailed drawing of loading and heating equipment is described in Fig.4.

2.1 Heating machine (Electric furnace)

The heating system is an electric furnace made of a metal heater. It uses the indirect heating method in which the compression jigs are located in the top and bottom part of the heating furnace and at the same time transmit heat into the specimen. The heating system has a dimension of 150mm by 400mm. It was developed to use a Ø100mmx200mm concrete cylinder. By voltage feedback type thyristor regulator, the top and bottom part of the electric heater can independently control the temperature range 100ºC~800ºC. Also, as seen in Fig.4., the electric furnace is divided into two vertical parts. One side of the electric furnace is fixed and the other side can be opened and closed by rail.

Since the compression jig has to apply load and transmit the heat simultaneously, the steel used for it was treated carbon, enabling it to apply force over 2000kN within the range of temperatures used for this study. To prevent heat from being emitted outside, a ceramic fiber blanket was installed as an insulating material.

2.2 Acquisition, record and control of temperature

To evaluate the efficiency of heat transmission in the heating furnace, while making the specimen (as seen in Fig.5.) a thermocouple was installed at the center of the specimen. An automatic control system was used to control the temperature in the heating furnace as shown in Fig.6. Also, before testing the specimen, the thermocouples were fixed on the specimen at distances of 10, 100, and 190mm (①, ②, ③) so the temperature transmitted to the temperature control system was at 5~7mm inside of the surface of the specimen. The data acquisition unit records the temperature every second through thermocouples which were installed at the center of the specimen at distances of 25, 100, and 175mm (④, ⑤, ⑥).
2.3 Loading machine

For loading of the specimen, a material test system of load volume 4,600kN as seen in Fig.7. was used. At the top and bottom of the specimen, a heating and loading jig and a water-cooling type cooler were installed. In the center portion of a material test system and heating furnace system, spherical support was vertically installed to prevent eccentricity of the specimen.

2.4 Compressive strength test method

To calculate deformation of the specimen, in the top and bottom part of the compression jig and in the center of the cooler, a quartz tube was installed through a Ø15mm hole. At the end of the quartz tube, LVDT was installed to protect a displacement meter from high temperature. Due to a hole in the compression jig provided for the quartz tube, an error was seen in the compressive strength test as shown in Table 1. No difference was seen in the compressive strength.

Table 1. Test Results of Compressive Strength to Boring of Jig

| Specimen condition | No. | Normal U.T.M., N/mm² | Loading and heating machine°, N/mm² | Error range (%) |
|--------------------|-----|----------------------|------------------------------------|----------------|
| Specimen with the top, the middle and the bottom bored | 1 | 43.8 | 42.5 | 3.0 |
| Normal specimen | 2 | 42.7 | 43.3 | 2.4 |
| Specimen with the top, the middle and the bottom bored | 1 | 43.3 | 43.1 | 1.0 |
| Normal specimen | 2 | 44.4 | 42.5 | 4.5 |

Note 1) Boring size Φ1mmx5mm: Thermocouple installation
Note 2) Boring Φ15mm: Quartz tube installation

Table 2. Experimental Plan

| ID   | W/C | Target temperature (°C) | Type of heat transmission cover | Heating rate (°C/min) | Heating cycle (°C/cy) | Heat insulator | Experimental factors and level |
|------|-----|-------------------------|---------------------------------|-----------------------|------------------------|----------------|-------------------------------|
| I    | 42  | 700                     | None                            | 1.00                  | 100                    | No             |                               |
| II   | 42  |                         |                                 |                       |                        |                |                               |
| III  | 42  |                         |                                 |                       |                        | Yes            |                               |
| IV   | 42  | 300                     | Single                          | 0.67                  | 50                     |                |                               |
| V    | 42  |                         | Double                          | 50                    |                        | No             |                               |
| VI   | 55  |                         |                                 |                       |                        |                |                               |
| VII  | 42  | 800                     | Single                          | 0.77                  | 50                     |                |                               |
| VIII | 35  |                         |                                 |                       |                        |                |                               |

Note 1) W/C: Water/Cement ratio

3. Experimental Investigation

The experimental plan is listed in Table 2. This study considered the effect of heat transmission covers and heat insulators that can enhance temperature time and heating cycle, and heat transmission efficiency that can affect the testing method of the mechanical properties of concrete at high temperature. Considering the existing results as seen in Fig.8., the heating curve of the target temperature increases from the ambient temperature to 700°C in similar patterns and the mechanical properties of concrete vary within a range of 100~300°C when concrete is exposed to high temperature, and at over 300°C the concrete specimen starts to rapidly deteriorate. (Miyamoto et al. (2003), Hirashima et al. (2003), Abe et al. (1999) and Castillo et al. (1990)). In this study, therefore, the target temperature is fixed at 300°C.

To increase the heat transmission efficiency, a heat transmission cover was designed to transmit heat into the specimen, but for the top and bottom surface of the specimen a cover was not used. As seen in Fig.9., the inseparable mono type and the centrally separable double type heat transmission cover were made for the test. Also, to prevent heat being transmitted to the specimen a heat insulator made of cladding of ceramic fiber was used to evaluate the insulation effect of the test equipment.

Fig.8. Temperature Curve of Specimen I (Without Heat Transmission Cover, 1°C/min, 100°C/cycle, Heat Insulator)

Fig.9. Type of Heat Transmission Cover
Table 3. Physical and Chemical Properties of Materials

| Materials           | Physical and chemical properties                  |
|---------------------|---------------------------------------------------|
| Cement              | Ordinary Portland cement                          |
|                     | Density: 3.15g/cm³                                |
|                     | Specific surface area: 3.770cm²/g                 |
| Fine aggregate      | Sea sand, Max. size: 5mm                          |
|                     | Density: 2.64 g/cm³                               |
|                     | Fineness modulus: 2.85                           |
|                     | Water absorption: 1.03%                          |
| Coarse aggregate    | Granite crushed gravel                            |
|                     | Max. size: 25mm                                   |
|                     | Density: 2.65g/cm³                               |
|                     | Fineness modulus: 6.91                           |
|                     | Water absorption: 0.8%                           |
| High range water reducer | Naphthalene sulfonate acid type                  |

Table 4. Mix Proportion of Concrete

| W/C (%) | Air cont. (%) | s/a¹ (%) | Water (kg/m³) | Unit contents (kg/m³) |
|---------|---------------|----------|---------------|-----------------------|
| 55      | 4 ± 1         | 45       | 175           | 318 781 996           |
| 42      | 4 ± 1         | 45       | 170           | 405 756 964           |
| 35      | 2 ± 1         | 45       | 165           | 471 760 969           |

Note 1) s/a: Send/Aggregate ratio

The heating method conformed to the stress test (Potha Raju et al. (2007)). The specimens were subjected to a 25% compressive strength, which was sustained during heating. In terms of the heating method, specimen I, a standard specimen of this study, had a 1°C/min rate, and every 100°C rise was maintained for one hour. For specimens II, III, and IV, the temperature was increased at 0.67°C/min rate, and every 50°C rise was maintained for thirty minutes. For specimens V and VI (VII, VIII) temperature increased at 0.77°C/min rate, and every 50°C was maintained for 30 minutes. For specimen V, heating was performed without constant temperature maintenance time within a range of 100 to 200°C.

Specimens VI, VII and VIII were the final evaluation test of loading and heating equipment and experimental factors selected from results of specimens I–V were applied. This research ultimately studied an evaluation method of loading and heating equipment and the mechanical properties of concrete at high temperature.

3.1 Materials

The materials that were used in this study, as seen in Table 3, were ordinary Portland cement with a fineness modulus of 3,630cm²/g with density of 3.15g/cm³ and the density of fly ash was 2.20g/cm³. As a compound, naphthalene sulfonate acid type high-range water-reducing AE admixture was added. Also, the coarse aggregates used were granitic crushed gravels, whose density was 2.65g/cm³, water absorption 0.8% and size of the maximum particle 25mm. The fine aggregate was desalting sand, as natural fine aggregate, whose density was 2.64g/cm³, with water absorption of 1.03%.

3.2 Specimens

The mixing proportion used for the concrete cylinder was as shown in Table 4. The designed strength of the concrete cylinder was 27, 40 and 60N/mm². According to this, the W/B was set at 55, 42 and 35%, respectively. The compound material was fly ash, and it replaced 10% of the cement weight. The compound material was high-rate water-reducing AE admixture, some of which was added to satisfy target slump and air content. The specimen to measure compressive strength at twenty-eight days was stripped twenty-four hours after it was made and cured for twenty-eight days as per the standard. The specimens used for the loading and heating test were tested at the age of between one hundred and six to one hundred and thirty days, the specimens were water cured for seven days in the thermo-hygrostat room at 20°C and then cured in dry air, 50% R.H. until the test day. However, before testing the specimen, the top and bottom sides were polished using a concrete grinding machine (RILEM 129-MHT (1995)).

4. Test Results and Discussion

4.1 Heat transfer evaluation of loading and heating test machine

Fig.8. shows the temperature heating curves of the specimen without using a heat insulator and a heat transmission cover for the plain test of the loading and heating test equipment and the test method that this study suggested. The temperatures were measured through the thermocouples, which were installed throughout the specimen at six different places. The top and the bottom part of the specimen showed similar temperature heating curves but the middle surface and center of the specimen showed a different curve. However, the temperature curve at the center of the specimen showed differences within the range of 20–100°C from the set temperature heating curve. This result indicates that to heat the entire concrete cylinder evenly, more than 60 minutes is required at a constant temperature.

4.2 Application or non-application of a heat insulator

Fig.10. shows the views of the testing method of the specimen using a heat insulator and without heat insulator. Fig.11. and Fig.12. show temperature curves
for the top, middle, and bottom part of the specimen according to the application and non-application of a heat insulator.

When a heat insulator was used, it was expected that emission of interior heat of the specimen would be prevented. However, the experimental results show that the specimen with a heat insulator reaches the target temperature curve slower than the specimen without a heat insulator at the top and bottom part of the specimen.

When a heating insulator was used, the average temperature difference between the center of the specimen and center of the top and bottom portion of the specimen was 10.06°C. On the other hand, when a heat insulator was not used, the average temperature was 5.62°C, and the heat transmission efficiency was 18 to 30 minutes faster, as seen in Fig.13., interior heat circulation diagram and in Fig.14., surface temperature curve of the middle of the specimen according to the application and non-application of a heat insulator. When the heat insulator is not applied, heat that is emitted in the furnace directly heats part of the top and bottom surface of the heat transmission cover, which increases the heat transmission efficiency at the center of the specimen. This is because the convective heat of the high temperature generated in the top and bottom is circulated to the central space, and factors generated by interior heat insulation affect the heat transmission to the center of the specimen. Thus, it showed higher heat transmission efficiency than when a heat insulator was applied.

4.3 Type of heat transmission jig

Fig.12. and Fig.15. show the core temperature curve of the top, middle, and bottom of the specimen according to the types of heat transmission cover. In the heat transmission cover, a spring at the top and center of the single heat transmission cover and double heat transmission cover respectively match up with the length of the specimen, while it is being compressed (Fig.9.). So, initially it was expected that a double heat transmission cover would show higher heat transmission efficiency than a single transmission cover. However, the specimen that used the double heat transmission cover has a similar temperature
control curve to that of the single heat transmission cover, but only the middle portion of the specimen's temperature differs from the specimen that uses a single heat transmission cover. The spring, which is installed in the middle of the specimen as shown in (b) of Fig.9, does not transmit heat as efficiently as the heat transmission cover, thus, the temperature rise at the middle takes 40–80 minutes longer than the rest of the specimen. It can be said that the double heat transmission cover does not transmit heat evenly to the center of the specimen. Finally the specimen with a single heat transmission cover shows higher thermal efficiency than one with a double heat transmission cover.

4.4 The difference of heating methods

Fig.16. shows the specimen temperature rising curve for the single heat transmission cover according to heating methods. The rate of temperature used for this heating method was 0.77°C/min. within the range of 20–100°C. After increasing every 50°C the temperature was maintained for the next thirty minutes. After further increase in temperature the same cycle of temperature increase was used as that used for 20–100°C.

In a range from 20–100°C and 200–300°C, the temperature of the center of the specimen increased about 10 to 20 minutes later than that of the top or
bottom of the specimen. This means that under the same conditions, it transmits heat to the center of the specimen faster than Fig.12., which shows the set-heating rate of 0.67ºC/min (about 18–30 minutes).

Therefore, the heating rate of 0.77ºC/min is much more effective.

Compared with rising temperature per one cycle according to the range of temperature, the case in which the temperature was raised to the range of 100ºC per one cycle showed a greater temperature difference between the top and bottom of the specimen and the center than the case in which the temperature was raised to the range of 50ºC per one cycle. As a result, the best heating method is to set 0.77ºC/min as the temperature rising rate, and to maintain the regular temperature for thirty minutes every 50ºC.

4.5 Decision regarding the test method and the final test

Table 5 is the summary of the decided test method of this study and Fig.17. shows the final central temperature curve of the top, the middle and the bottom of the specimen. As seen in the figures, the center temperature at the top, middle and bottom of the specimen is similar to the proposed heating temperature curve. Also, when each center temperature at the top, middle and bottom were compared, they showed a similar temperature and increased to the target temperature. This trend shows in all specimens irrespective of W/C ratio. This means that the loading and heating test method that this study suggests for the mechanical properties of concrete at high temperature is very efficient and effective.

6. Conclusions

Experiments using different heating methods were carried out in order to examine the uniformity of temperature rises in concrete specimens. A new heat transmission cover was developed, which can provide better performance of uniform temperature rise and less chance of having deterioration on the concrete surface. First, a set of experiments were carried out to evaluate the influence of heating methods and heating rate. It was shown that the specimens were heated most effectively when the heating rate was 0.77ºC/min and when it was maintained for 30 minutes every 50ºC temperature rise. Then, another set of experiments were carried out to examine whether Water/Cement ratio (35%–55%) affects the temperature difference and it was found that W/C ratio does not have a significant influence on the performance of generating uniform temperature.

Finally, the new transmission cover performed reasonably well and it is expected to provide more precise experimental data in a more effective and safer way than the traditional heating methods. It is, however, necessary to continue further quantitative analysis on the mechanical characteristics of concrete in high temperature. It is also required to investigate and compare the actual results obtained by various heating methods in detail.

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