Influence of cement type on heat of hydration and temperature rise of the mass concrete

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This paper provides experimental and analytical study results aiming to evaluate the effects of ternary cement types with different binder combinations on the heat of hydration in mass concrete by conducting the adiabatic temperature rise test and finite element thermal analysis of mass concrete mixtures with specified compressive strength of 30 MPa. A finite element thermal analysis for mat foundation with 15 m wide, 30 m long and 3 m thick were conducted based on concrete thermal properties from adiabatic temperature rise test. Test results reveal that concrete mixture mixed with Type IV cement displays the higher rate of heat evolution generated from hydration than those of concrete mixtures with ternary cements. It indicates that the ternary cements, which provide economic and environmental advantages by reducing Portland cement production and CO₂ emission, can be used as an alternative of Type IV cement for massive members.

Keywords: Mass concrete, Low heat concrete, Heat of hydration, Crack index, Ternary cement, Thermal properties, Adiabatic temperature rise test

In recent years, the social demand for bigger and taller concrete infrastructures has led to the increased member size and cement content. These have result in the potential risk for thermal and autogenous shrinkage cracking in these members. Mass concrete is used to build large size structures to resist external loads. A substantial heat in the large size members is emitted by hydration actions. While mass concrete shows a large increase of temperature inside concrete due to the hydration action, the concrete surface shows a temperature drop to keep the thermal balance with the air temperature. This temperature gradients between the core and surface of the concrete member can cause a thermal crack through tensile stress due to the concrete’s expansion and contraction1-5.

These thermal cracks lead to a high possibility of developing cracks which penetrate the structural member as well as micro-scale cracks on the surface of concrete member. They can also affect the structural performance, serviceability, cracking probability, and durability of the concrete structures. The mixture proportions, curing, and construction schedule for mass concrete structures with large cross-sections can be optimized to control temperature variation and improve concrete performance. Commercial software for finite element thermal analysis can be used to quantify and predict internal temperature of concrete members based on the weather, member geometry, insulation, boundary condition, and thermal properties of cast concrete. Mixture proportion and placement schedule of mass concrete can be optimized from results of heat analysis. To reduce mass concrete temperature in field and improve the durability of structures, the use of Type IV low heat cement is common in South Korea. However, replacement of ordinary Portland cement (OPC) with Type IV low heat cement leads to the increase in the cost of hydraulic binder. Therefore, the incorporation of additional cement-based materials, such as fly ash, slags and silica fume, as binder to replace the OPC or low heat cement has been studied.

This paper focuses on the comparison between the influence of two ternary cements and Type IV low heat cement on the heat of hydration and the development of compressive strength of mass concrete with specific compressive strength of 30 MPa. Additionally, the temperature and thermal cracking probability of mat foundation constructed with ternary and low heat cements are analytically investigated and compared by finite element thermal analysis using commercial software MIDAS/GEN
based on thermal properties, such as the maximum adiabatic temperature rise \((K)\) and the reaction rate \((\alpha)\), from adiabatic temperature rise test. Results of this study and the developed analytical technique can allow the optimization of mixture design and placement process of high-rise buildings and large infrastructures\(^6\)\(^7\).

**Finite Element Model for Thermal Analysis of Mass Concrete**

During the early age of concrete, heat is generated from the chemical reactions, i.e., hydration reactions, between cementitious materials and water. The amount of heat generated from cement hydration could vary with the type of cement, water-to-cement \((w/c)\) ratio, initial temperature, and presence of admixtures. Zhang et al.\(^8\) reported that the hydration heat released up to 3 days decreases progressively from 397 kJ/kg at a \(w/c\) ratio of 0.6 to 279 kJ/kg at a \(w/c\) of 0.2. It is evident that at a lower \(w/c\), less heat would be generated. The generated heat per unit volume during the hardening period of cement paste or concrete can be measured by using a conduction calorimeter, by determining the heat of solution, or by adiabatic temperature rise test\(^8\)\(^9\)\(^10\).

After the maximum temperature due to the heat generated from the hydration process of cement is reached inside the concrete mass, the surface of concrete is lower than the temperature at the interior of the concrete. In mass concrete members, the maximum temperature is a function of the adiabatic temperature development and heat transfer with the environment. The temperature gradient between the center and outer of concrete member will create tensile stresses. Thermal cracks will occur if the stress is larger than tensile strength of the concrete. The requirements for control the thermal cracks due to hydration heat difference in the mass concrete vary on a state by state basis.

Therefore, the development of analytical model for mass concrete thermal behavior will allow the establishment of the rational requirements for mass concrete to reduce and control cracking. In this study, the modeling for thermal behavior of mass concrete at early age was conducted with a commercial MIDAS/GEN software package.

The basis for thermal analysis is heat balance equation or governing heat transfer equation based on the principle of energy conservation. Heat transfer in the global Cartesian can be described by the Fourier equation of flow, relating the temperature \(T\) in each point of cross-section to the time \(t\).

\[
\rho c_p \frac{\partial T}{\partial t} = q + k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad \ldots (1)
\]

which \(\rho\) is the concrete density \((\text{kg/m}^3)\); \(c\) is the specific heat \((\text{J/kg} \cdot \text{°C})\); \(q\) is the rate of heat generated per unit volume \((\text{J/m}^3 \cdot \text{°C})\); and \(k\) is the thermal conductivity \((\text{J/m} \cdot \text{h} \cdot \text{°C})\).

Through Eq. (1), the temperature distribution in concrete produced by the heat of hydration is predicted based on boundary conditions, initial conditions and the internal evolution of heat of hydration. In this study, internal heat of hydration was evaluated by following Eq. (2) that is an exponential function proposed by Tanabe et al.\(^11\) based on experimental research on the adiabatic temperature rise tests.

\[
T(t) = K(1 - e^{-\alpha t}) \quad \ldots (2)
\]

where \(T(t)\) is amount of adiabatic temperature rise at time \(t\) \((\text{°C})\); \(K\) is final amount of adiabatic temperature rise from test \((\text{°C})\); \(\alpha\) is the coefficient of temperature rise; and \(t\) is a time \((\text{day})\).

The assessment of cracking probability in the mass concrete due to the heat of hydration was assessed by using Eq. (3).

\[
I_{cr}(t) = \frac{f_{sp}(t)}{f_{t}(t)} \quad \ldots (3)
\]

where \(I_{cr}(t)\) is thermal crack index; \(f_{t}(t)\) is the maximum thermal stress at day \(t\); and \(f_{sp}(t)\) is the tensile strength of concrete at day \(t\). Korean standard specification for concrete\(^12\) stipulates that the thermal crack index exceeds 1.2 at least to limit thermal cracks of concrete members.

**Experimental and Analytical Investigation**

To investigate the effects of ternary cement types with different binder combinations on the heat of hydration in mass concrete, three different mixtures of concrete with specified compressive strength of 30 MPa were mixed. All of the three concrete mixtures had a water-to-binder \((w/b)\) ratio of 0.45 by weight. Sand-to-aggregate \((s/a)\) ratio was 0.48, and unity quantity of water was 171 kg/m\(^3\). The measurement results of the density were measured as 3.15 g/cm\(^3\) for Portland cement. Type IV low heat cement for 3.22g/cm\(^3\), blast furnace slag for 2.99 g/cm\(^3\), Class C fly ash for 2.12 g/cm\(^3\). Fineness
was measured as $3215 \text{ cm}^2/\text{g}$ for Portland cement, Type IV low heat cement for $3500 \text{ cm}^2/\text{g}$, blast furnace slag for $4729 \text{ cm}^2/\text{g}$, Class C fly ash for $3650 \text{ cm}^2/\text{g}$ the materials.

PSLB–352 mixture consists of ordinary Portland cement (30%), blast furnace slag (50%), and Class C fly ash (20%). PSLB–442 mixture consists of ordinary Portland cement (40%), blast furnace slag (40%), and Class C fly ash (20%). The SP admixture was 2.66% of the total amount of binder, and the hydration heat reducing admixture aiming to increase the reducing effect of hydration heat was 2.72% of binder. The mixture proportions of concretes mixed in this study are shown in Table 1.

A cylindrical form with 1,140 mm diameter and 1,230 mm height for each mixture was created for pouring of the cylindrical specimen to monitor the rate of heat generation. The cylindrical form consists of aluminum insulated container and cover to simulate a fully adiabatic process. A thermocouple was embedded at center of cylindrical specimen for measuring the heat of hydration developed by Japanese company Tokyo Rico. The thermocouple data were recorded in order to validate and calibrate the finite element model’s ability to predict the hydration heat behavior of the concrete cylinders.

Adiabatic temperature rise tests measure the heat of hydration of concrete mixtures in an insulated condition with no heat loss. When the insulated state remained, the process of the temperature increase caused by the heat generation of the concrete sample by itself as well as the maximum temperature rise was recorded. The maximum adiabatic temperature rise ($K$), and the coefficient of temperature rise ($\alpha$) were drawn from adiabatic temperature rise test.

To evaluate the mechanical properties of mass concrete with different types of cements, slump and air content for fresh concrete were tested and compressive strength for hardened concrete was measured at 3, 7, 28 and 56 days of curing age. The compressive strengths were used for assessing the cracking possibility, i.e., crack index.

A commercial software MIDAS/Gen was used to analyze the hydration heat of mass concrete. To verify the proposed model reliability, the temperatures at center of specimens obtained from finite element thermal analysis were compared with the measured temperature from the center of cylindrical specimen. First, the same conditions and an idealized model with the same volume as cylindrical specimen for the adiabatic temperature rise test were utilized to verify the maximum adiabatic temperature rise and the reaction rate. The model used a three-dimensional solid factor, and the shape of the model was a polyhedral column that is nearly a circular column, yet not a fully circular column. Because the adiabatic temperature analysis results and test results showed a little difference, the data of the adiabatic temperature analysis results were calibrated to derive the maximum adiabatic temperature rise ($K$) and the reaction rate ($\alpha$).

To evaluate the effect of cement types on the heat evolution and thermal stress of a massive structure, a mat foundation was analyzed by proposed finite element model. A thermal analysis for mat foundation based on the thermal properties of mass concrete mixtures drawn from adiabatic temperature rise tests was conducted by proposed finite analysis model. The mat foundation has the dimension of 15 m length, 20 m width and 3 m depth. For thermal analysis of the mat foundation, soil supporting the mat foundation also was idealized as the dimension of 24 m length, 30 m width and 1 m depth. To improve the efficiency of the analysis, advantage was taken of the double symmetry of the mat foundation can be idealized as one-quarter of the mat foundation as shown in Fig. 1(a). Three types of concrete mixtures for thermal analysis of the mat foundation were used. The mixtures were the same as the three concrete mixtures that were used for the adiabatic temperature rise test.

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>$f_c$ (MPa)</th>
<th>w/b (%)</th>
<th>s/a (%)</th>
<th>Water (kg/m³)</th>
<th>Thermal properties</th>
<th>Unit weight (kg/m³)</th>
<th>OPC</th>
<th>Blast-furnace Slag</th>
<th>Fly ash</th>
<th>Fly ash</th>
<th>S</th>
<th>G</th>
<th>SP (%)</th>
<th>HR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSLB–352</td>
<td>40</td>
<td>45.0</td>
<td>47.4</td>
<td>171</td>
<td>K : 25.8 α : 0.577</td>
<td>114</td>
<td>190</td>
<td>76</td>
<td>823</td>
<td>928</td>
<td></td>
<td></td>
<td>2.66</td>
<td>2.72</td>
</tr>
<tr>
<td>PSLB–442</td>
<td>40</td>
<td>45.0</td>
<td>47.4</td>
<td>171</td>
<td>K : 30.2 α : 0.579</td>
<td>152</td>
<td>152</td>
<td>76</td>
<td>823</td>
<td>928</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type IV</td>
<td>40</td>
<td>45.0</td>
<td>47.4</td>
<td>171</td>
<td>K : 36.3 α : 0.559</td>
<td>380</td>
<td>-</td>
<td>-</td>
<td>842</td>
<td>949</td>
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</tr>
</tbody>
</table>
Results and Discussion

Mechanical properties

Slump was measured as 210 mm for PSLB–352 mixture, 220 mm for PSLB–442 mixture, and 250 mm for Type IV cement. Air quantity was approximately 5% in all three concrete mixtures.

The evolution of the compressive strength for different types of cements between 3 and 56 days is shown in Fig. 1(b). It is shown from the figure that early compressive strengths of concretes with ternary cements were higher than those of the control concrete incorporating Type IV cement but after 7 days of curing age, control concrete showed higher strength. The development curves of compressive strength were used for the assessment of tensile strength and cracking possibility.

Adiabatic temperature rise

Black lines in Fig. 1(c) present the adiabatic temperature rise with respect to time, which is output obtained from adiabatic temperature rise tests, of cylindrical concrete specimens mixed with different types of cements; Type IV low heat cement and ternary cements (PSLB–352 and PSLB–442). It appears that the heat released by the reference concrete (Type IV concrete) mixed with Type IV low heat cement increased initially faster than those of the PSLB–352 and PSLB–441 concretes made with blended ternary cements. For Type IV concrete mixed with Type IV low heat cement, the highest temperature, 37.5°C at 264 h after pouring, was measured at the center of the cylindrical specimen. For PSLB–352 and PSLB–442 concretes mixed with two types of ternary cements, the maximum temperatures of 24.5°C and 30.0°C at 195 and 204 h after being poured was measured at the center, respectively. The temperature increase trend in cylindrical specimens mixed with blended ternary cements shows a lower heat of hydration as compared with the control concrete mixed Type IV cement. Similar results were reported by existing researches\textsuperscript{2,5}. 

For the heat characteristics data of the used materials and concrete required for the analysis of the hydration heat, compression strength was calculated through the previous material tests. The maximum adiabatic temperature rise value and reaction rate derived through the adiabatic temperature rise test modeling were also applied. These are shown in Table 2.

In terms of the thermal properties data such as thermal conductivity and thermal expansion coefficient, representative values were applied based on the Korean standard specification for concrete. Both environmental and concrete casting temperatures of 20°C were used for all analyses. MIDAS/Gen was used to analyze the hydration heat of the basic structural members, and the maximum temperature of the center, maximum tensile strength of the end, and crack index were investigated.

Fig. 1 – Analytical modeling for mat foundation and mechanical properties of mass concrete used in this study
Blue lines in Fig. 1(c) show analytical temperature and time histories of cylindrical specimens made with three types of concretes for adiabatic temperature rise tests. Finite element analysis results are in good agreement with temperature measured from the center of specimen. It is shown that this analytical model can be applied for thermal analysis of practical massive structures.

**Finite element thermal analysis of mat foundation**

Figure 1(a) shows the model depicting the mat foundation exposed to ambient condition at top surface and four sides with plywood and polystyrene insulation. The bottom of mat foundation was supported to soil.

Figure 2(a) presents the comparison of temperature profiles of mat foundation with different types of cements at the center, 1.5 m away from the ground surface of foundation. The maximum temperature of three mat foundations with different types of cements is shown at about 120 h after the concrete placement. The maximum temperature rise is observed at the central area of mass concrete, which is 1.5 m away from the ground surface. Tensile reaches the maximum value at the central area of mass concrete, which is 0.5 m away from the ground surface. As shown in Fig. 2(a), the maximum temperature of the central area of the case of low heat cement was 58.0°C. PSLB–442 was 46.4°C and PSLB–352 was 42.6°C, which was the lowest among the three, resulting in about a 15°C temperature difference.

Figure 2(b) provides the calculated tensile stresses and the allowable tensile stresses versus curing age curves of mat foundations with different types of cements. As shown in Fig. 2(b), the maximum tensile stress of 3.78 MPa was generated from temperature gradient of mat foundation concrete mixed with Type IV cement, exceeding the allowable tensile force between 50 and 220 h after concrete placement. For PSLB–442, however, the value was 2.4 MPa; for PSLB–352, the value was 2.1 MPa. These maximum temperatures of mat foundation concretes mixed with ternary cements were less than the allowable tensile stresses of the concretes.

Figure 2(c) presents the crack indices versus curing age at the centers of mat foundation constructed with three types of concretes. As shown in Fig. 2(c), the thermal crack index with the maximum tensile force turned out as 0.72 when using low heat cement. The crack index of concrete with Type IV cement was the lowest among concretes mixed with three types of cements and mean about 85% of the probability of thermal cracking in the mat foundation. Thermal crack index of mat foundation made with PSLB–442 mixture was observed as 1.01 with about 50% of the probability of crack initiation. The PSLB–352 mixture showed a thermal crack index of 1.18 with 30% of probability of crack initiation. From these results, use of ternary cement for massive structures were considered to be safer against potential cracks than using low heat cement.

It appears that the use of ternary cement is effective to mitigate the cracking risk in massive concrete members and probability of thermal cracking depends on the ratio of cementitious binders in the ternary cement.
Conclusions

The influence of cement types, such as ternary cements and Type IV cement, on the heat of hydration of concrete during hydration was investigated in this study. To examine the thermal properties of three mass concrete mixtures mixed with three types of cements, adiabatic temperature rise tests for three concrete mixtures were conducted. Based on thermal and mechanical properties of these concretes, finite element thermal analysis for mat foundation with dimension of 15 m length, 20 m width and 3 m depth was performed. From the results of experimental and analytical studies, following conclusions can be drawn.

From results of adiabatic temperature rise tests, concrete mixture mixed with Type IV cement displays the higher rate of heat evolution generated from hydration than those of concrete mixtures with ternary cements; PSLB–352 [ordinary Portland cement (30%), blast furnace slag (50%), and Class C fly ash (20%)] and PSLB–442 [ordinary Portland cement (40%), blast furnace slag (40%), and Class C fly ash (20%)]. It indicates that the ternary cements can be used as an alternative of Type IV cement for massive members.

From results of finite element thermal analyses for mat foundation, it is noted that the highest temperatures and tensile stresses were located at the center and the top edge exposed to ambient atmosphere, respectively.

Concrete mixed with Type IV cement experienced tensile stresses high enough to cause thermal cracks on all surfaces. In the case of PSLB–352 and PSLB–442 mixture concretes made with ternary cements, the rate of temperature increase was slower and the maximum temperature at the center of mat foundation was less.

The tensile stresses at all the surfaces of mat foundation made with ternary cement were less than allowable tensile strength. The probability of thermal cracking in the mat foundation concrete with ternary cements was less than that of concrete with Type IV cement.

The finite element thermal analytical models developed for this study is feasible and effective to simulate the thermal behavior of massive members mixed with different types of cement.

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