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Thermal and Mechanical Behaviors of Concrete with Incorporation of Strontium-Based Phase Change Material (PCM)

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Abstract

In this study, phase change material (PCM) was used to control the heat of hydration of mass concrete, and the study aimed to evaluate the resulting fundamental and thermal properties of mass concrete with PCM. To evaluate the feasibility of adding PCM to concrete with various binder conditions for mitigating the hydration heat of mass concrete, mechanical and adiabatic temperature rise tests were conducted. The test results showed that the use of PCM did not significantly influence air content, while it slightly reduced flowability. For initial setting properties of concrete, it was found that the initial and final time were delayed when PCM was added. Even though compressive strength was slightly reduced when PCM was added into concrete, the strength development properties of concrete were more closely associated with the strength development properties of the binder. The adiabatic temperature rise test results showed that the addition of PCM resulted in an approximately 15–21% decrease in temperature rise of concrete. From the thermal analysis results, it is noted that thermal cracking probability could be decreased by adding PCM into concrete mix.

Keywords: phase change material, mass concrete, strength development, heat of hydration, adiabatic temperature rise

1 Introduction

As urbanization, economic development, and high-rise buildings have increased due to insufficient land areas or various global demands, large-scale mass concrete construction has also increased, such as mat foundations of skyscrapers, bridge piers, and power plant structures. A critical issue related to mass concrete is that it is difficult to ensure its quality due to cracks caused by the thermal gradient between the center and the surface because concrete is exposed to various environmental effects. Due to the hydration of cement, concrete generates heat and the heat from members with small sections could be dissipated relatively easily, whereas the heat from members with larger sections accumulates inside, which is likely to increase the temperature significantly. This can lead to thermal stress and cracks resulting in a harmful effect on durability.

The reduction methods for the heat of hydration of mass concrete currently used in the field include the material-based method of using a binder that generates less hydration heat, construction-based methods of pre-cooling, in which materials are cooled to reduce placing temperature, and pipe cooling, in which pipes are installed inside mass concrete for cooling. However, construction-based methods are not widely used due to higher costs and limits in the dimensions of members; therefore, the material-based method of reducing the heat of concrete through mix design is primarily used

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(Choi et al. 2006). However, as material-based technology for reduction of hydration heat is not noticeably effective to control the thermal stress and cracks of massive structures, concrete is commonly cast over two or three layers. These layered casting method would cause problems such as requiring additional measures for bonding strength in the cold joints and delays in the construction period (Kim et al. 2008).

Phase change material (PCM) is a material whose phase changes depending on temperature change, keeping latent heat when the phase changes, and can absorb or release more energy than sensible heat (David et al. 2016). In the field of construction, research on PCM was primarily conducted for applying it to slab or the wall to improve energy saving. In the paper, it was reported that the energy required to control the internal temperature of the building could be saved by using PCM for the material of the slab or wall. However, in addition to the application of temperature and energy keeping, PCM can be used for suppressing temperature rise caused by materials (Park 2010). According to the paper, it was reported that the increase of temperature by heat conducted through slab or wall can be suppressed due to the energy storage of the phase change of PCM.

Mass concrete has high cracking probability due to the temperature difference between the inside and the outside of concrete structure by heat of hydration after a large amount of concrete is casted. These thermal cracks can be the main cause of the deterioration of structural performance and mitigation of durability. Therefore, reducing and controlling the heat of hydration are very important technique in mass concrete construction.

The use of thermal energy storage may serve to mitigate the temperature change. Latent heat storage is one of the most efficient methods of storing thermal energy, and offers higher storage density owing to the small temperature difference between storing and releasing heat. PCM is a representative example of a thermal energy storage using a latent heat, and can increase the thermal inertia. A paper published by Dinçer (2002) dealt with thermal energy storage, being PCMs just a part of it, and not focused on the application in buildings. Since then, many researches have been conducted about PCM as thermal energy storage material. In 2004, the research group led by Farid et al. (2004) published two papers on the PCM, and one of them covered the building application of PCM. Lee et al. (2007) evaluated the thermal storage capacity of gypsum wall applied a micro-encapsulating PCM, and reported that thermal storage capacity is increased as the thickness of the PCM film is increased. In addition, many researchers have attempted to apply the PCM in the slab and wall as an energy saving way.

In some countries, researches using an encapsulating PCM has been carried out to reduce the heat of hydration (Lee et al. 2007; Fang et al. 2008; Maruoka and Akiyama 2003). These methods not only require advanced technology to manufacture the microcapsule, but is uncertain about its practical application in mass concrete despite an excellent performance in reducing thermal crack. Likewise, the larger the size of the capsule, dispersibility problem in concrete is raised.

Mihashi et al. (2002) conducted test to apply a retarder containing PCM in a paraffin microcapsule in order to control the heat of hydration. In the study, some hypotheses were formulated; as the paraffin was melted, it derived the hydration heat of mass concrete, and retarder reduces the hydration rate of mixture and releases the heat. This paper reported that the maximum temperatures under the semi-adiabatic curing can be reduced in both small cement paste specimens and large concrete specimens.

Hunger et al. (2009) investigated the fresh and the hardened properties of self-compacting concrete mixes using different amounts of PCM. Microencapsulation of PCM is effectively functional in fresh state concrete, but it detrimentally influences the mechanical strength of the concrete.

Choi et al. (2014) evaluated the applicability of seven types of inorganic PCM under conditions that were similar to those used for concrete materials. In the study, a strontium-based PCM was selected as the most effective PCM for reduction of hydration heat in mass concrete. Based on the previous study test results, it was found to control thermal stress by reducing heat of hydration of mass concrete. To assessment the applicability of the strontium-based PCM for mixture of concrete, the mechanical properties of concrete were investigated.

Eddhahak-Ouni et al. (2014) investigated a Portland cement concrete modified with organic microencapsulated Phase Change Materials (PCMs) by experimental and analytical methods. In the study, a loss of the compressive strength was noticed with the addition of PCMs. And they reported that the thermal conductivity proposed using a multi-scale approach well-predicted the approximation of the equivalent thermal conductivity of the PCM-concrete and the gain in the considerable experimental time.

This study aims to evaluate the method for reducing the hydration heat using PCM, which can absorb or release a large amount of heat by improving the conventional material-based method for reduction of hydration heat. In this study, PCM was used to control the hydration heat of mass concrete. To evaluate the effect of PCM on the heat of hydration of concrete, adiabatic temperature rise tests and thermal analysis were performed for various types of concrete mix. And mechanical properties of concrete in wet and dry condition were evaluated to find relationship between strength development and hydration heat of concrete.

2 Experimental Program

2.1 Materials

In this study, PCM was mixed into concrete to reduce the hydration heat and several tests were conducted to evaluate air content, slump, compressive strength, setting time, and thermal property. The mix design used in the study is shown in Table 1. Regarding fundamental properties, the targeted air content was set to 4 ± 1%, and changes in slump were examined by applying the same amount of superplasticizer to evaluate the effect of binder conditions and PCM. In mix design, water-binder ratio of all mixes were 0.45. The amount of PCM mixed in concrete is 3% of the weight of binder, and the proportion was chosen as the most effective rate for reducing the hydration heat based on previous study results (Kim et al. 2015). PCM used in this study is strontium-based powder ($Sr(OH)_2$-$8H_2O$) which can absorb a large amount of heat when transitioning from a solid phase to a liquid phase using latent heat. In this study, the PCM was made in the form of gem, and the PCM gem was pulverized into a powder form (grain size range was 108–142 mm) and then was incorporated in concrete when mixing. The strontium-based PCM completely changes to a liquid phase between approximately 89 °C (solid to liquid) and 175 °C (liquid to gas), 83.4 cal/g (349 J/g) of heat is absorbed, based on the analysis results of differential scanning calorimeter tests. The test results were analyzed in the range of 15 to 300 °C to measure the caloric changes of a substance according to temperature change. The amounts of absorbed heat are almost half of the average hydration heat of cement, 200 cal/g, which provides a high heat absorbance effect (Neville 2011).

As supplementary cementitious materials are commonly used in the field these days for environmental and economic reasons, this study attempted to evaluate the feasibility of PCM use in various binder conditions. Three types of binders were used; mixture with Type 1 cement, mixture with Type 4 cement, and ternary blended mixture of Type 1: BFS: FA at 4:4:2 ratio. The physical properties of the used materials are shown in the Table 2.

2.2 Test Methods

This study was carried out several tests to investigate the effects of PCM on the mechanical and thermal properties of mixtures. Tests for the hardened and fresh state properties (ASTM 2010), compressive strength and setting time were respectively performed to verify the physical properties of the concrete with PCM, and adiabatic temperature rise tests for the thermal property were conducted.

The setting of concrete is determined by using the mortar contained in it. A penetrometer is used for determining the initial and final setting times of mortar. Appropriate size needles (cross areas are 645, 323, 161, 65, 32, and 12.5 or 645–12.5 mm^2) by hardening stage of mortar were used. The force required to penetrate one inch in depth is noted. The force divided by the area of the bearing surface of the needle yields the penetration resistance (Ramachandran et al. 2002). The setting time of cement paste was assessed based on penetration resistance in accordance with ASTM C 403 (2008). ASTM C 403 defines the initial time as when the pressure becomes

Table 2 Physical properties of materials.

Materials	Physical properties
Type 1 cement (ordinary portland cement)	Density: 3.15 g/cm^3 Fineness: 3630 cm^2/g
Type 4 cement (low heat portland cement)	Density: 3.20 g/cm^3 Fineness: 3400 cm^2/g
Blast furnace slag	Density: 2.20 g/cm^3 Fineness: 3000 cm^2/g
Fly ash	Density: 2.90 g/cm^3 Fineness: 4000 cm^2/g
Sand	Max. aggregate size: ≤ 5 mm Density: 2.43 g/cm^3 Water absorption ratio: 3.66%
Gravel	Max. aggregate size: ≤ 25 mm Density: 2.64 g/cm^3 Water absorption ratio: 5.24%
Superplasticizer	Naphthalene

Table 1 Mixture design of concrete.

Mix	W/B	PCM (%)	Unit weight (kg/m^3)						
			W	Type 1 cement	FA	BFS	Type 4 cement	S	G
OPC	0.45	0, 3	175	390	–	–	–	806	912
LHC				–	–	–	398	808	914
CBF				156	78	156	–	787	891

W/B water-to-binder ratio, *W* water, *FA* fly ash, *BFS* blast furnace slag, *S* sand, *G* gravel.

500 psi (3.5 MPa) and the final time as when the pressure becomes 4000 psi (28 MPa). Tests were conducted in the thermo-hydrostat room at 20 ± 3 °C and 60 ± 5% humidity, and measurements were taken at 1-h intervals starting from 3.5 h from when the cement came in contact with water.

To evaluate the effect of PCM on the development of concrete, the compressive tests were conducted at 7, 28 and 91 days. Cylindrical specimens of Ø 100 × 200 mm were fabricated and tested as per ASTM C 39 (2015).

To estimate the hydration heat reduction effect of PCM, the adiabatic temperature rise tests were conducted as shown Fig. 1. The degree of temperature rise was measured by keeping a 50-L-capacity specimen in adiabatic conditions. The temperature was measured by a thermocouple embedded in the center of the specimen, which was kept surrounded by air pockets. The air pockets were automatically maintained at the same temperature as that of specimen to ensure the adiabatic state of the concrete. Since the temperature rise of concrete was

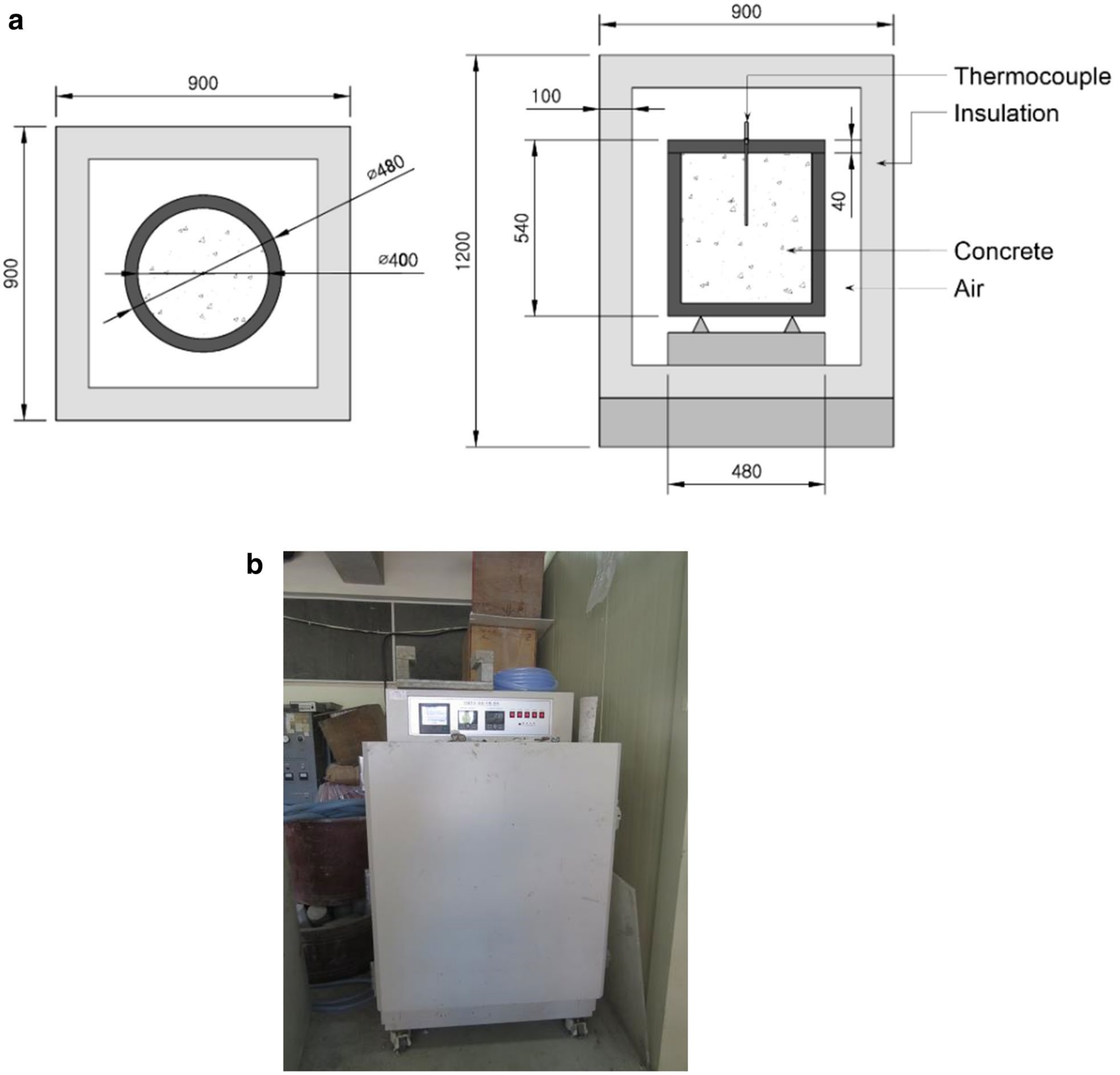

Fig. 1 Device for adiabatic temperature rise test. **a** Dimension [unit: mm], **b** test setup.

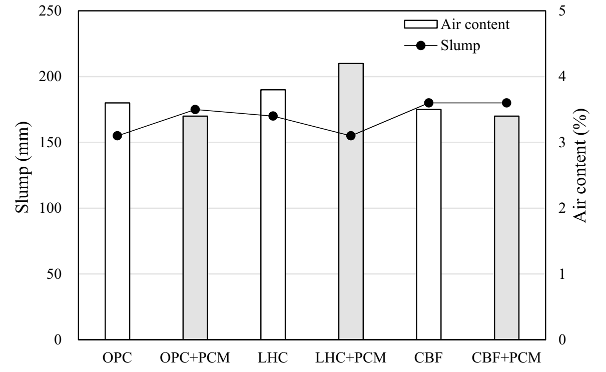

Fig. 2 Slump and air content of fresh state concrete.

influenced by placing temperature, the placing temperature of all mixtures was kept at 20 °C.

3 Test Results

3.1 Property of Fresh Concrete

Figure 2 shows the results on slump test. To evaluate the effect of PCM on the slump, the same amount of superplasticizer was added to all mixtures. The amount of superplasticizer was chosen to make the slump of the OPC mixture, the most basic mixture, 180 mm, which was verified using a preliminary experiment. As shown in Fig. 2, the air content of all mixtures was found to be within the target air content of 4 ± 1%. When mixed with PCM, the air content slightly increased in the OPC mixture, while it decreased in the LHC mixture and showed no significant change in the CBF mixture. These results suggest that in the addition of PCM does not noticeably influence the air content of mixtures. For slump value, a similar level of slump between the OPC mixture and the CBF mixture and higher level in the LHC mixture were shown. This is likely to be due to the characteristics of the content of Type 4 cement and was consistent with the results of previous studies (Min et al. 2007).

3.2 Penetration Resistance

To examine the initial and final time for concrete when PCM was mixed in, a penetration resistance test was conducted, and the results are shown in Fig. 3a. Figure 3b shows the initial and final time for all mixtures, which were estimated by fitting data, as shown in Fig. 3a with Eq. (1) specified in ASTM C403 (2008).

$$\log(PR) = a + b\log(t) \tag{1}$$

where PR is penetration resistance (MPa); t is elapsed time (min); a and b are regression constants.

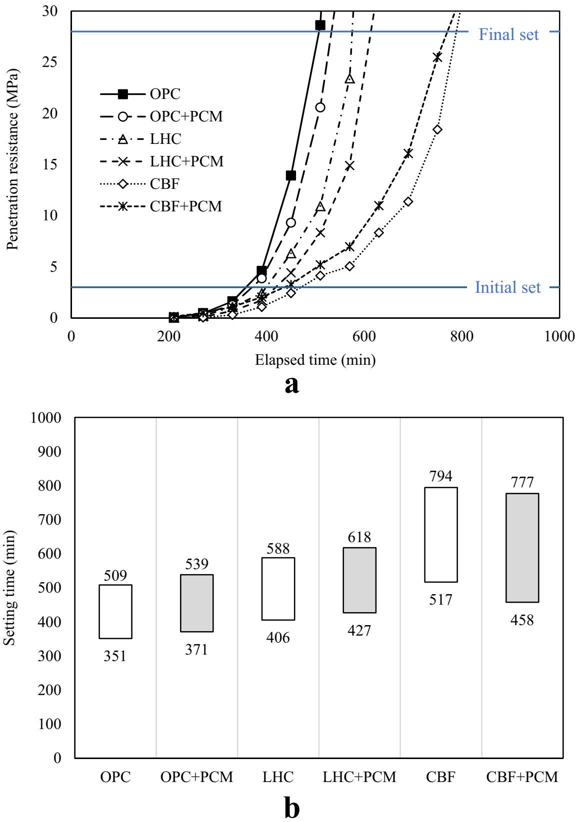

Fig. 3 Setting properties of concrete using PCM; **a** penetration resistance, **b** setting time.

The OPC mixture showed the initial set at 351 min and the final set at 509 min. The OPC + PCM showed the initial set at 371 min, 20 min later than that for the OPC mixture, and the final set in 167 min at 539 min.

The LHC mixture showed the initial set at 406 min and the final set in 183 min at 588 min. The LHC + PCM mixture showed the initial set at 427 min, 20 min later than that for the LHC mix, and the final set in 190 min at 618 min. The CBF mixture showed the initial set at 517 min and the final set in 277 min at 794 min. The CBF + PCM mixture showed the initial set at 458 min, about 60 min faster than that for the CBF mixture, and the final set in 319 min at 777 min. To summarize, when PCM was added, the OPC and LHC mixture showed a delay in the initial and final time, while the CBF mixture showed a decrease in the initial and final time. In case of CBF mixture, the effect PCM was not detected because the setting time of concrete with blast furnace slag is slower than that with OPC. When PCM was added, the setting time was delayed for all mixtures; however, the result suggests that the setting time was more influenced by binder conditions than PCM.

3.3 Compressive Strength

Figure 4 shows the results of compressive strength test by age for all mixtures, and each test result in the figure is the average of the three specimens. The test results for compressive strength of concrete is listed in Table 3. As in the results at the age of 7 days, the PCM-added mixtures showed a decrease in compressive strength, but all mixtures reached the target strength of 30 MPa at the age of 28 days. At the age of 91 days, LHC and CBF mixtures showed a significantly higher level than OPC mixture. Moreover, the compressive strength of mixture with PCM showed a similar pattern to the results of earlier ages.

As shown in the Fig. 4, when PCM was added, the compressive strength decreased for the LHC and CBF mixture; however, changes in compressive strength development were likely to be more influenced by the binder conditions than PCM addition. It is thought that the initial hydration rate of the binder is reduced by suppressing the temperature rise due to the hydration heat of the binder due to the phase change of the PCM. The LHC and CBF mixture showed a significant decrease in early-age strength and an increase in 91-day strength. The phenomenon in the LHC mixture is likely to occur because the type 4 cement used in the LHC mixture has low C_3S content associated with early-age strength development and high C_2S content associated with long-term age strength development. The similar strength pattern for the CBF mixture is likely to be due to the pozzolanic reaction of admixtures, as the mixture used slag and fly ash as a replacement for cement.

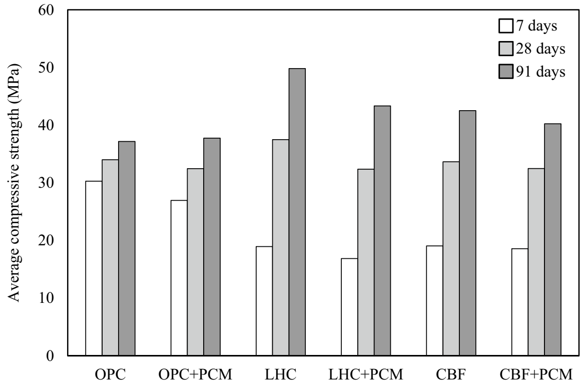

Fig. 4 Average compressive strength with curing age.

3.4 Adiabatic Temperature Rise Test

The results of the adiabatic temperature rise test of the mixtures used in this study are shown in the included Fig. 5. Measurements of the hydration heat showed a temperature rise starting around 12 h from concrete mixing. The maximum temperature rise for the OPC mixture was 46.0 °C, and when PCM was added, the temperature rose to 38.9 °C, showing about a 15% decrease in temperature rise. The LHC showed the maximum temperature rise of 42.6 °C, and when PCM was added, the temperature rose to 30.9 °C, showing about a 28% decrease. The maximum temperature rise of the CBF decreased by about 19% from 32.5 to 26.3 °C when PCM was added. Because Type 4 cement has much higher C_2S content and lower C_3S, C_3A, and C_4AF content compared with Type 1 cement, it has a lower total amount of hydration heat, and the hydration reaction proceeds gradually in the long term. The CBF mixture in particular has less slag and fly ash solution heat and a slower hydration reaction speed, and due to the thermodynamic property of pozzolan, it showed hydration heat properties similar to those of Type 4 cement. The adiabatic test results show that the rate of temperature rise started to decrease around at 10 to 20 °C (real temperature is around 30 to 40 °C, because the initial temperature was 20 °C), which is lower than the phase change temperature (89 to 175 °C) of PCM. It can be referred that the binder and PCM are mixed uniformly as separate solids, and the temperature is increased by the hydration of the cement, and the PCM has melted at about 30 to 40 °C (chemical eutectic point).

Table 3 Test results for compressive strength of concrete.

Mixture	7 day		28 day		91 day	
	f_{cu} (MPa)	S.D. (MPa)	f_{cu} (MPa)	S.D. (MPa)	f_{cu} (MPa)	S.D. (MPa)
OPC	30.3	1.28	34.0	0.89	37.2	1.11
OPC + PCM	26.9	1.46	32.5	1.51	37.8	0.56
LHC	19.0	0.52	37.5	1.59	49.8	1.39
LHC + PCM	16.9	0.47	32.4	1.86	43.3	1.81
CBF	19.1	0.62	33.6	0.55	42.5	1.16
CBF + PCM	18.6	0.56	32.5	0.97	40.2	1.02

S.D. standard deviation.

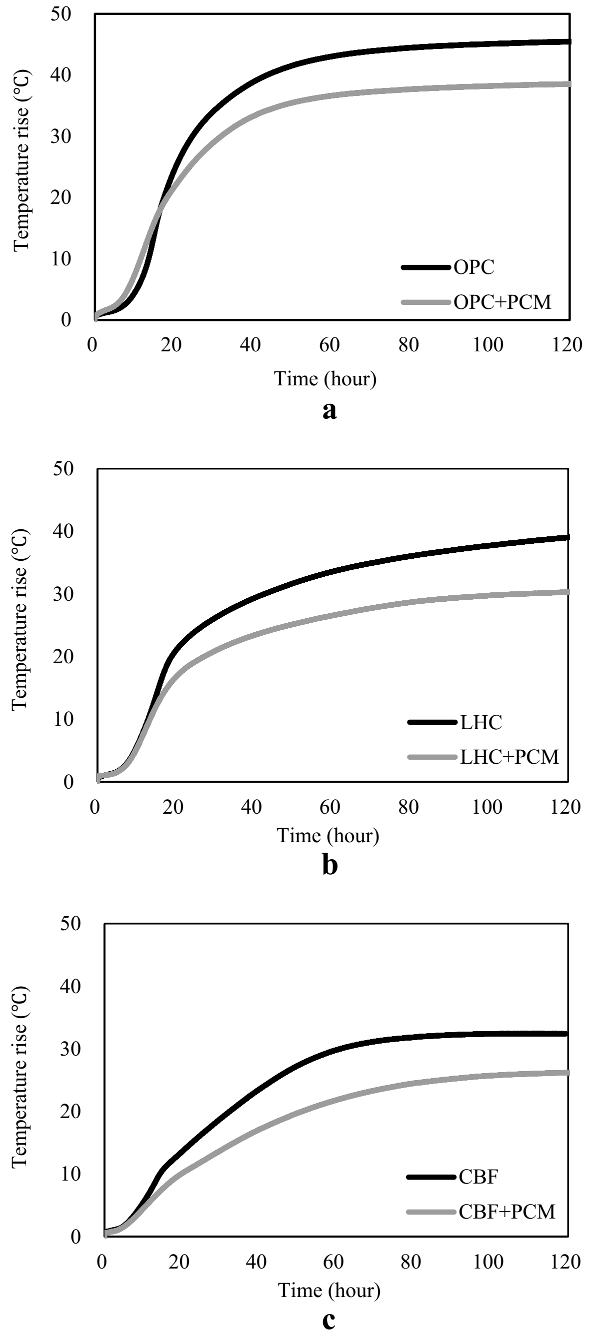

Fig. 5 Results of adiabatic temperature rise test; **a** OPC series, **b** LHC series, **c** CBF series.

4 Thermal Analysis

4.1 Analysis Procedure

Among the methods to predict the thermal stress of mass concrete, measuring stress by installing a measuring device in the actual structure is the most reliable method, but because such a device is significantly affected by the placing condition, it has low consistency and is inconvenient to install. For these reasons, for the estimation of the thermal stress of mass concrete, an analytic method using finite element analysis is commonly used. In this chapter, finite element analysis is performed based on the experimental data, and the effect of applying PCM on the temperature and thermal stress of mass concrete is examined. The software used for the finite element analysis was MIDAS/GEN 2016 (version 1.4).

As shown in Fig. 6, a mat foundation on the ground, which is commonly found in the field, was modeled as a 1/4 symmetric structure for effectiveness of analysis procedure and time.

4.1.1 Thermal Properties of Concrete

To simulate the heat of hydration in mass concrete, the adiabatic temperature rise equation is generally used because the temperature at the center of mass concrete is almost equal to the adiabatic temperature. Since the adiabatic temperature rise curve can vary depending on the type of concrete mixture, the heat generation characteristics of concrete were obtained from the adiabatic temperature rise test results. To obtain the thermal property of the concrete used in this study, the following Eq. (2) was used.

$$\Delta T = K\left(1 - e^{-rt}\right) \tag{2}$$

where ΔT is adiabatic temperature rise (°C) at t days; K is maximum adiabatic temperature rise (°C); r is reactive rate coefficient; t is time (day).

The thermal characteristic values of the concrete used in this study are shown in Table 4. As shown in Table 4, when the PCM was applied to the OPC, the maximum temperature K decreased to 38.91 °C by about 15%, which was lower than 42.61 °C in the case of low heat Portland cement. The hydration heat reduction effect of PCM was found to be most effective in LHC mixture. In the case of the CBF mixture, the hydration heat reduction effect of PCM was about 19%. As for the reaction rate r, the mixtures with PCM showed a reduction of about 3–10%.

4.1.2 Material Property

Thermal and physical properties for the concrete and ground are shown in Table 5. For compressive strength development coefficient of concrete, data from the tests were used depending on the mixtures.

4.2 Thermal Analysis Results

4.2.1 Temperature Distribution

Figure 7 shows the temperature history at the central point of the concrete block having 14.4 m (width) × 9.6 m (length) × 2.4 m (thickness) for all mixes. For the OPC mix, the highest temperature is

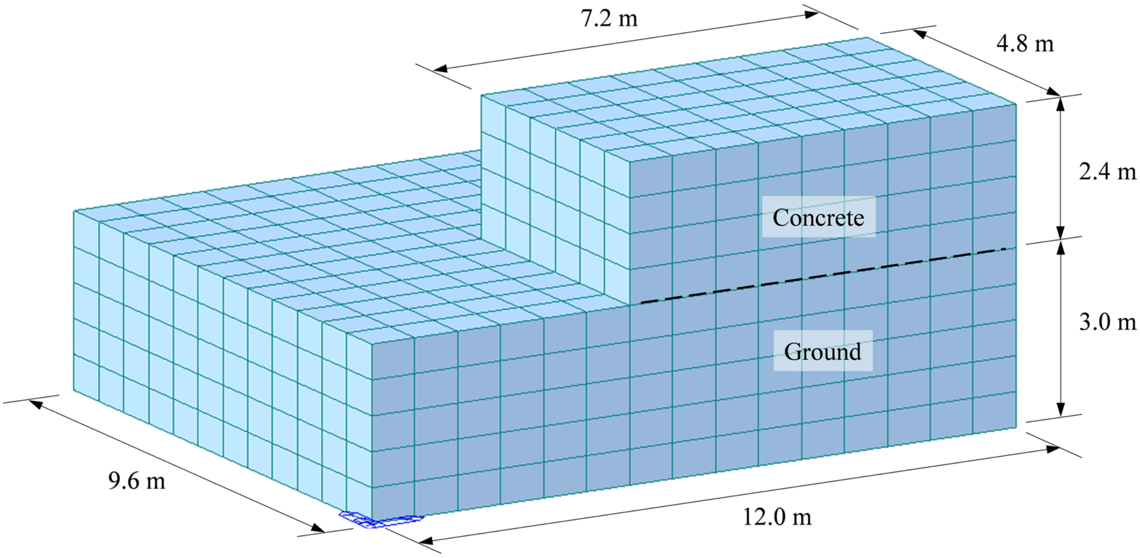

Fig. 6 Finite element mesh of the mat foundation.

Table 4 Thermal characteristics of concrete mixtures.

Mixture	*K*	*r*
OPC	45.99	1.423
OPC + PCM	38.91	1.284
LHC	42.61	1.215
LHC + PCM	30.86	1.180
CBF	32.45	0.842
CBF + PCM	26.32	0.804

Table 5 Thermal and mechanical properties of concrete and ground.

Properties	Concrete	Ground
Specific heat (kcal/N·°C)	0.025	0.02
Density (N/m^3)	23,500	17,000
Thermal conductivity (kcal/m h °C)	2.3	1.7
Convection coefficient (kcal/m^2 h °C)	12	12
Ambient temperature (°C)	20	–
Prescribed temperature (°C)	20	–
Compressive strength (MPa)	Variable	–
Modulus of elasticity (MPa)	Variable	980
Coefficient of expansion	1.0×10^{-5}	1.0×10^{-5}
Poisson's ratio	0.167	0.2

61.9 °C and the lowest temperature at the surface is 20.6 °C at 60 h after concrete casting. The temperature difference between center and surface is 41.3 °C. For the LHC mix, the highest temperature is 58.2 °C and the lowest temperature at the surface is 20.6 °C at 65 h after casting, with a temperature difference of 37.6 °C. The maximum temperature as compared with the OPC mix was reduced by 6 percent. For the CBF mix, the highest temperature is 47.7 °C, approximately 23% lower than that of the OPC mix, and the lowest temperature is 20.6 °C at 80 h after casting, with a temperature difference of 26.8 °C.

For the OPC + PCM mix, the highest temperature is 55.1 °C and the lowest temperature at the surface is 20.5 °C at 65 h after casting, with a temperature difference of 34.6 °C. The maximum temperature was reduced by 11% compared to the OPC mix. This result indicated that the PCM has a temperature reducing effect of superior to the LHC mix. The LHC + PCM mix showed the highest temperature of 47.6 °C at 65 h after casting, approximately 23% lower than that of the OPC mix and reduced by 11% than that of the LHC mix. The lowest temperature at the surface is 20.5 °C and the temperature difference is 27.1 °C. It can be seen that a temperature reducing effect of the LHC + PCM mix is comparable to the CBF mix. when using CBF + PCM mix, the highest temperature is 42.3 °C, 32% lowered than that of the OPC mix and decreased by 11% compared to the CBF mix, at 85 h after casting and the lowest temperature at surface is 20.4 °C. This result shows the highest temperature reduction of mixture used in this study. The results of the thermal analysis show that the hydration heat decreased by over 10% when PCM was used. It is referred that the temperature reduction effect is likely to be higher when PCM is used with the low heat mixture. Figure 8 illustrates the contours of the temperature distributions at the time when the maximum temperature is shown.

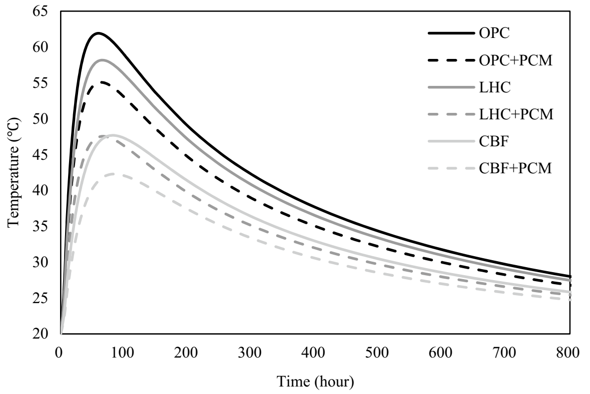

Fig. 7 Temperature evolution.

4.2.2 Thermal Crack Index

The evaluation of cracks generated by the hydration heat at an early age in mass concrete is generally conducted using temperature in a variety of ways. In the Korea Standard Specification for concrete, temperature-induced cracking is examined using a crack index in principle, and the index can be calculated using the following Eq. (3).

$$I_{cr}(t) = \frac{f_{sp}(t)}{f_t(t)} \tag{3}$$

where $f_{sp}(t)$ is the tensile strength of concrete at t day (MPa); $f_t(t)$ is the maximum thermal stress at t day (MPa).

The probability of cracking can be examined using crack index based on previous experience. The relationship between the probability of cracking and crack index is shown in Fig. 9 and crack criteria are listed in Table 6. From the table, the crack index should exceeds 0.7 at least to limit harmful cracks. This index should be determined by depending on the structure important, economy, construction environment, etc.

Figure 10 present the results of the minimum crack index and cracking probability of each mixture. In the early age, the minimum crack index occurs at the surface, over time, generated inside and bottom of concrete. In the OPC mixture, the thermal crack index was 0.65 at 60 h after casting. In the LHC mixture, the thermal crack index was also 0.68 at 55 h after casting, suggesting an approximately 87% probability of cracking. It is considered that the thermal crack index is decreased due to the strength development of the concrete was lower at early age although the maximum tensile stress is lower than that of OPC mixture. In the CBF mixture, the thermal crack index is 0.93 at 70 h after casting, suggesting an approximately 61% probability.

In the OPC + PCM mixture, the thermal crack index is 0.75, implying an approximately 82% probability. The thermal crack index for the LHC + PCM mixture is 0.88 and the maximum tensile stress is decreased 20% than that of the LHC mixture. In the CBF + PCM mixture, the thermal crack index is 1.16 with an approximately 27% probability of cracks. To summarize, the occurrence probability of heat-induced cracking decreased in the all mixture because the use of PCM reduced the tensile stress at the surface without a strength reduction in early age.

5 Conclusion

This study aimed to investigate the effect of adding PCM on the fundamental properties of concrete and reducing the hydration heat in three binder conditions. The study conducted an evaluation of the fresh state properties, setting time, compressive strength, and the adiabatic temperature rise test and performed finite element analysis using experimental data. Based on the test and analysis results, the following conclusions were drawn.

1. The results of fresh state properties suggest that adding PCM does not change the air content of fresh state concrete. It is confirmed that the slump is dependent on the binder conditions than use of PCM, and the highest slump value was for the LHC mixture due to the characteristic of Type 4 cement. When PCM was used, it was found that the slump slightly decreased overall. However mix design and the use of superplasticizer are likely to compensate for the change.
2. For the setting property of concrete, it was identified that the setting time depends on the binder conditions and was particularly high for the CBF mixture. When PCM was used, it was found that the setting time increased. However the setting time was likely to be more influenced by binder conditions than the use of PCM. Moreover, the initial and final time of the OPC and LHC mixtures were delayed when adding PCM.
3. For compressive strength development properties, the LHC and CBF mixtures showed lower strength development at an early age, while the OPC mixture showed higher strength development at a long-term age. When PCM was added, all mixtures showed a slight decrease in strength. However strength development properties are most likely to be more influenced by binder conditions rather than use of PCM.
4. The adiabatic temperature rise test results showed the greatest temperature rise for the OPC mixture and the lowest temperature rise for the CBF + PCM mix. The OPC + PCM mixture showed a tempera-

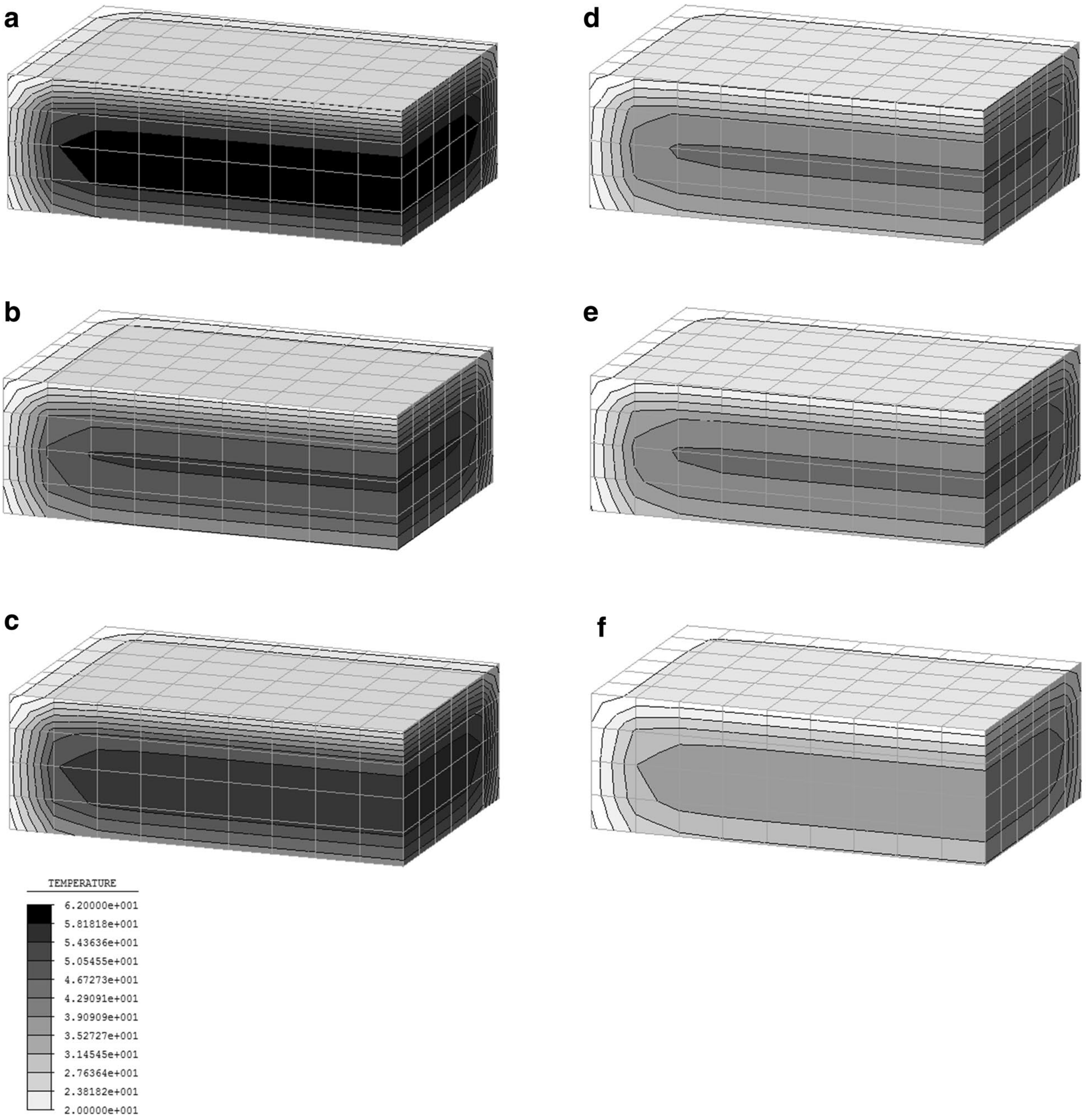

Fig. 8 Temperature distributions at the time of reaching the maximum temperature of each mixture; **a** OPC, **b** OPC + PCM, **c** LHC, **d** LHC + PCM, **e** CBF, **f** CBF + PCM.

ture rise level similar to that for the LHC mixture, and the LHC + PCM mixture showed a temperature rise equivalent to that for the CBF mixture. The temperature rise decreased in all mixtures when PCM was added, showing 11–18% reduction.

5. The thermal analysis results showed the maximum temperature decrease of over 10% in all mixtures when PCM was used, and the effect was larger in the low heat mixtures (LHC and CBF). The crack probability was also found to decrease when PCM was added, and the effect was greatest for the CBF mixture. The CBF + PCM mixture showed an index of about 1.16, suggesting the mixture is very stable against heat-induced cracking.

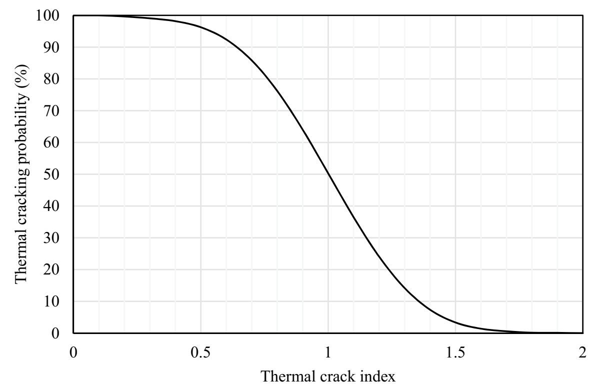

Fig. 9 Relationship probability of crack growth and crack index.

Table 6 Thermal crack criteria.

Criteria	Thermal crack index (I_{cr})
To prevent cracks	$I_{cr} \geq 1.5$
To limit cracks	$1.2 \leq I_{cr} < 1.5$
To limit harmful cracks	$0.7 \leq I_{cr} < 1.2$

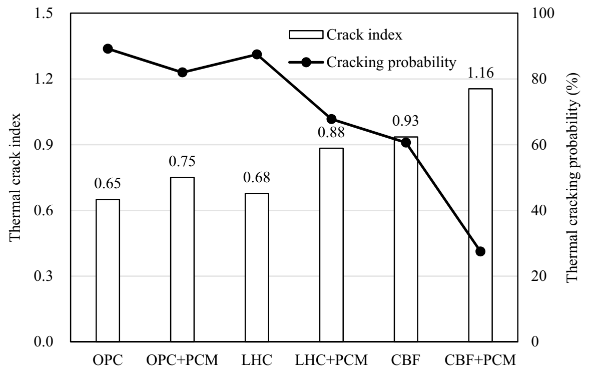

Fig. 10 Thermal crack index and probability of different mixtures.

Authors' contributions

KLA, SJJ, BSK, and WSP made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data. SWK and HDY analyzed the data and were involved in drafting the manuscript or revising it critically for important intellectual content. All authors read and approved the final manuscript.

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References

ASTM. (2008). *Standard test method for time of setting of concrete mixtures by penetration resistance*. West Conshohocken: ASTM International.

ASTM. (2010). *Standard test method for slump of hydraulic-cement concrete*. ASTM C, 143, C143M-2010.

ASTM. (2015). *Standard test method for compressive strength of cylindrical concrete specimens*. West Conshohocken: ASTM international.

Choi, S. W., Jo, H. T., & Ryu, D. H. (2006). The experimental study on the heat hydration properties of concrete according to binder conditions. *Journal of the Korea Concrete Institute, 18*(6), 769–776.

Choi, W. C., Khil, B. S., Chae, Y. S., Liang, Q. B., & Yun, H. D. (2014). Feasibility of using phase change materials to control the heat of hydration in massive concrete structures. *The Scientific World Journal, 2014,* 781393.

David, D., Kuznik, F., & Roux, J. J. (2016). Experimental investigation of natural convection near a wall containing phase change material. *International Journal of Thermal Sciences, 104,* 281–291.

Dincer, I. (2002). On thermal energy storage systems and applications in buildings. *Energy and buildings, 34*(4), 377–388.

Eddhahak-Ouni, A., Drissi, S., Colin, J., Neji, J., & Care, S. (2014). Experimental and multi-scale analysis of the thermal properties of Portland cement concretes embedded with microencapsulated Phase Change Materials (PCMs). *Applied Thermal Engineering, 64*(1), 32–39.

Fang, Y., Kuang, S., Gao, X., & Zhang, Z. (2008). Preparation and characterization of novel nanoencapsulated phase change materials. *Energy Conversion and Management, 49*(12), 3704–3707.

Farid, M. M., Khudhair, A. M., Razack, S. A. K., & Al-Hallaj, S. (2004). A review on phase change energy storage: materials and applications. *Energy Conversion and Management, 45*(9), 1597–1615.

Hunger, M., Entrop, A. G., Mandilaras, I., Brouwers, H. J. H., & Founti, M. (2009). The behavior of self-compacting concrete containing micro-encapsulated phase change materials. *Cement and Concrete Composites, 31*(10), 731–743.

Kim, Y. R., Khil, B. S., Jang, S. J., Choi, W. C., & Yun, H. D. (2015). Effect of barium-based phase change material (PCM) to control the heat of hydration on the mechanical properties of mass concrete. *Thermochimica Acta, 613,* 100–107.

Kim, Y. R., Kim, D. S., Khil, B. S., Kim, O. J., & Lee, D. B. (2008). An experimental study on properties of concrete using latent heat binder. *Journal of the Korea Concrete Institute, 20*(5), 661–668.

Lee, S. H., Yoon, S. J., Kim, Y. G., Choi, Y. C., Kim, J. H., & Lee, J. G. (2007). Development of building materials by using micro-encapsulated phase change material. *Korean Journal of Chemical Engineering, 24*(2), 332–335.

Maruoka, N., & Akiyama, T. (2003). Thermal stress analysis of PCM encapsulation for heat recovery of high temperature waste heat. *Journal of Chemical Engineering of Japan, 36*(7), 794–798.

Mihashi, H., Nishiyama, N., Kobayashi, T., & Hanada, M. (2002). Development of a smart material to mitigate thermal stress in early age concrete. *Control of Cracking in Early Age Concrete*, 385–392.

Min, H. J., Kim, W. J., Gong, M. H., An, M. Y., Lim, N. G., & Jung, S. J. (2007). An experimental study for basic property of ultra high strength concrete using belite cement. *Journal of the Architectural Institute of Korea Structure & Construction, 23*(7), 103–110.

Neville, A. M. (2011). *Properties of concrete* (5th ed.). Upper Saddle River: Prentice Hall.

Park, S. L. (2010). *A study on alternate air-conditioning method using PCM (phase change material)*. Kumi: Kumoh National Institute of Technology.

Ramachandran, V. S., Paroli, R. M., Beaudoin, J. J., & Delgado, A. H. (2002). *Handbook of thermal analysis of construction materials* (1st ed.). Norwich: William Andrew.