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An Experimental Study on the Thermal Performance of Cement Mortar with Granulated PCM

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Abstract

In this study the thermal performance of G-PCM replaced for find aggregate in mortar specimens was evaluated using TG-DTA. As a result, it was found that when solid changed into liquid, it absorbed heat, and when liquid changed into solid, it radiated heat. In addition, the fluidity and the compressive strength of mortar with G-PCM can be applied to the floor mortar and a wall finish material. Also the higher the replacement ratio, the larger the latent heat capacity. It was found that the mortar with G-PCM slowed the increase and decrease of temperature. Thus, the duration of pleasant indoor temperature is extended by the floor and wall mortar with G-PCM. In conclusion, G-PCM is expected to reduce the heating energy consumption.

Keywords : latent heat, thermal conductivity, CO_2, energy saving, granulate PCM

1. Introduction

With recent changes in housing and living environment, demands for the comfortable indoor environment and energy saving are on the rise[1]. In particular, the construction industry uses lots of energy, and accounts for about 42% of the entire CO_2emission of all the industries. There is an urgent need for reduction of energy consumption and CO_2. Moreover, reduction in energy consumption and CO_2 is very important in the construction industry since of the entire life cycle of a structure more than 70% of energy consumption and CO_2 emission takes place in the operation and maintenance phase[2]. And, the operation of the heating and cooling system consumes most of energy during operation and management of a building, and to save more energy more effectively for building operation and management, the heating and cooling system should be used and operated more effectively and efficiently[3]. To save energy consumption, PCM, an innovative thermal control material that can serves thermal storage and thermal control function, has been more actively studied since the 1980s in other fields than in the construction field[4,5]. It is reported that when about 7 tons of phase change material (PCM) are used to keep the room temperature at a comfortable level, the thermal capacity will be equivalent to 200 tons of concrete. Considering the indoor temperature range people feel comfortable, the effect of PCM is expected to be greater.

PCM(Phase Change Material) is called as latent heat material that can absorb and radiate heat when PCM changes from sold to liquid or vice versa. In

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addition, since the heat storage capacity of PCM is excellent, it is also called as low-energy high-efficient material [6]. In particular, the heat of solution of PCM is the characteristics of the material itself. The phase change temperature varies from material to material, and it could be applied in a variety of fields if latent heat is applied appropriately. It is reported that if the optimal melting point of PCM is set in the construction field, the efficiency of PCM can be maximized [7].

Figure 1 illustrates the thermal energy flow of phase change material. At the first phase of movement from solid to liquid, PCM absorbs heat, which is called the endothermic phase or latent heat phase during which heat is stored. Then, when the PCM arrives at the peak of heat capacity, it radiates heat again, which is called the exothermic phase. The types of PCM applicable to the construction field include paraffin wax PCM, microcapsule PCM and granulated PCM. Considering size stability and thermal capacity, G-PCM would be applied widely in the construction field.

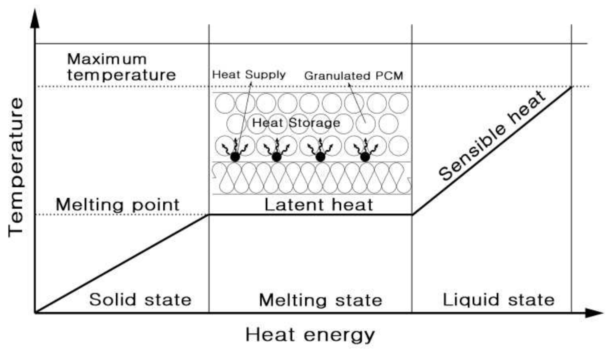

Figure 1. Heating flow of phase change material

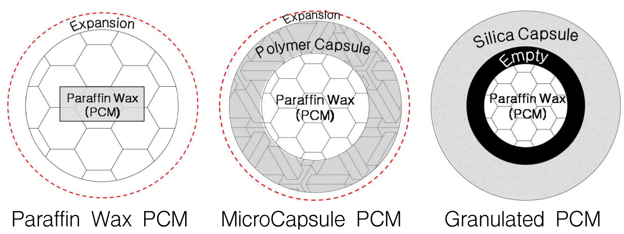

Figure 2. Particulate structure of phase change material

Paraffin wax PCM was reported to have mostly been utilized in the construction field. Paraffin wax is extracted from crude oil, and it is impossible to mix with cement materials due to its phase change. In addition, when the PCM is put in a capsule and used(C-PCM), expansion cracks are reported as a problem[8]. The cracks are caused by expansion of PCM due to phase change. Recently, to resolve the expansion problem by PCM reported, granular PCM made by putting PCM in a hollow capsule (G-PCM) was developed and used as latent heat, but there are few studies conducted on mix of PCM with cement materials.

Therefore, this study aims to provide fundamental data based on which G-PCM can be used as energy-saving cement and concrete structural material and finish material that helps keep the indoor environment comfortable by conducting experimental analysis of latent heat and heat storage capacity of the cement material with G-PCM.

2. Experiment

2.1 Experimental overview

Table 1 indicates the overview thermal performance e of G-PCM. In the Series 1 test, the thermal performance of G-PCM was tested. In the Series 2 test, the physical properties of the cement mortar with G-PCM were evaluated when G-PCM was replaced for fine aggregate for the cement mortar.

2.2 Materials

The properties of G-PCM used in this study are indicated in Table 2. The melting point and heat conductivity of G-PCM are 28℃ and 0.2W/m·K, respectively. In particular, taking into account that the heat storage capacity of the cement material was evaluated by mixing G-PCM, the G-PCM was used according to the temperature recommended by the Korea Energy Management Corporation.

Table 1. Experimental overview of G-PCM

Experiment item	measurement item	Experiment aim
Thermal performance evaluation of G-PCM (Series 1 experiment)	TG-DTA experiment of G-PCM particles	Analysis of absorption heat and radiation heat
Thermal performance evaluation of G-PCM (Series 1 experiment)	The experiment using only the G-PCM thermal performance	Analysis of heat transfer and latent heat
Character and thermal performance of Cement mortar replaced fine aggregate and G-PCM (Series 2 Experiment)	The compressive strength of mortar	Character analysis
Character and thermal performance of Cement mortar replaced for fine aggregate and G-PCM (Series 2 Experiment)	Flow of mortar	Character analysis
Character and thermal performance of Cement mortar replaced fine aggregate and G-PCM (Series 2 Experiment)	Experiment on the thermal performance of cement mortar with Granulated PCM	Thermal performance experiment

Table 2. Characteristics of granulated PCM

PCM(Phase Change Materials)		
Components	Physical performance	
SiO_2, Paraffin 	Bulk density	0.75 kg/l
	Melting point (PCM)	28°C
	Average particle size	1～3mm
	Heat storage capacity	72kJ/kg
	Volume expansion	almost none
	Specific heat capacity	1.5 kJ/(kg*K)
	Flash point (PCM)	approx. 164 °C
	Operating Temperature	max. 90 °C

In addition, OPC was used as cement, and the standard sand stipulated in KS L ISO 679 was used as fine aggregate. On the other hand, to perform a comparative analysis of heat transfer, a 30mm-thick insulation material with 0.029W/m·K of heat conductivity was used in the Series 2 test. In addition, the floor heating system for the Series 1 mock-up specimen was designed and manufactured by incorporating electric heating cables and controller in a system to control heating and stop simultaneously.

2.3 Experimental method and items to be measured

2.3.1 Thermal performance evaluation of G-PCM (Series 1)

To evaluate heat absorption and heat storage capacity of G-PCM, TG-DTA (Model: DTG-60, SHIMADZU CORPORATION) test was implemented for G-PCM particles. As the measurement condition, the heating rate was set at 10℃/min, and taking into account the temperature limit of G-PCM, the maximum temperature was set at 80℃.

Figure 3 shows the TG-DTA test results. In addition, two specimens were manufactured to evaluate latent heat, storage heat and temperature change: one was the floor heating on which a layer of PCM particles was stacked, and the other was the general mortar floor heating.

Figure 5 is the measuring point of the temperature history, the sectional view of the specimens and mortar mix proportion. The specimen was tested by putting it in a temperature controllable chamber. Similar to the construction method at site, a 30mm-thick insulation material was used on the bottom and tinfoil was covered on the top to prevent the insulation material from being damaged. On top of it, the heating cable was installed and then G-PCM was placed and finished with ceramic tiles on it. At measuring point of the temperature history, the air temperature and the temperature on the floor were measured.

Figure 3. TG-DTA experiments(Series 1)

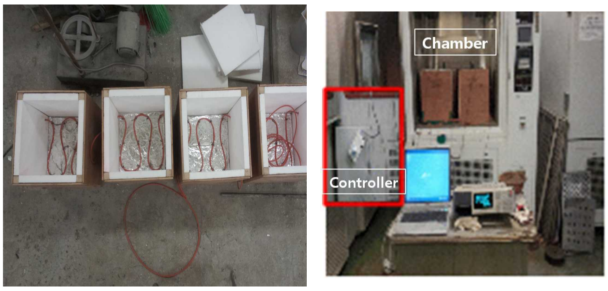

Figure 4. Specimens using the G-PCM thermal performance evaluation(Series 1)

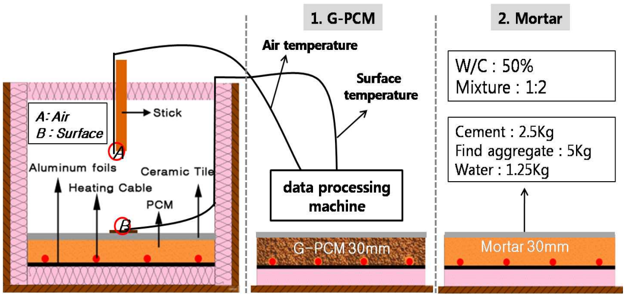

Figure 5. The internal temperature history of specimens extracted position(Series 1)

Table 3 indicates the floor heating method and order. To conduct the test in a condition similar to the outside temperature in winter, the temperature outside of the chamber was set at 0℃ during heating and at −5℃ when it turned off. Considering the characteristic of heater of PCM and 28℃ of the melting point, the maximum temperature was set at 40℃.

Table 3. Heating method and order

Experiment item	Measurement speed	Temperature of chamber inside	Heating	Heating stop	Remark
Heat transfer experiment	1sec	40~ -5℃	Temperature(℃)		Repetition of heating (40 ℃) and the heating stopped (-5 ℃)
Heat transfer experiment	1sec	40~ -5℃	0 →40℃ (20H heating)	40℃ →-5℃ (7H30 stop)	Repetition of heating (40 ℃) and the heating stopped (-5 ℃)
Latent heat experiment	1sec	40~ -5℃	-	Temperature(℃)	Repetition of heating (40 ℃) and the heating stopped (-5 ℃)
Latent heat experiment	1sec	40~ -5℃	-	40 →-5℃	Repetition of heating (40 ℃) and the heating stopped (-5 ℃)

2.3.2 Thermal performance evaluation of mortar with G-PCM (Series 2)

The Series 2 test was performed to evaluate the thermal properties of cement mortar with G-PCM. The mixing design of mortar with G-PCM is shown in Table 4. The order of input and mixing time are indicated in Figure 6. After mixing the mortar, the fluidity was measured before it being hardened, and the compressive strength was measured after it being hardened in compliance with KS L ISO 679.

Table 4. Mixing design of mortar with G-PCM

Cement (Kg)	Sand (Kg)	Water (kg)	G-PCM	
			mixing rate	mixing amount (kg)
1.2	2.4	0.6	0%	-
	2.28		5%	0.12
	2.16		10%	0.24
	1.92		20%	0.48

Figure 6. Mortar mixing method and mixing hour

Considering the heat was transferred on the wall, the specimen was manufactured in the plate form with the dimension of 100mm * 120mm * 20mm and the frame that pinned down the specimen was made with the size of 410mm * 450m.

Figure 7 illustrates the installation of test specimens and the measuring point of temperature history.

Figure 8 illustrates the thermal performance experiment of mortar wall with G-PCM[10]. The iron frame was installed in front of the chamber, and that the ceracool material with insulation function was filled and sealed at the joints in prevention of heat flow. Heating and cooling was operated to change the temperature inside the chamber according to a temperature history to evaluate thermal performance with the replacement ratio of G-PCM by measuring the temperature on the external surface of each specimen (Point A) and on the surface of each specimen in the chamber(Point B). In addition, using the insulation material of the specimen, the thermal performance was evaluated. Table 5 is the heating method using temperature change in the chamber and the temperature history. To measure heat storage performance over heating time, the machine was alternately heated and cooled. The heating time was set at 2 hours and 30 minutes first, and then cooling time was set at 1 hour, and the heating time was set at 1 hour and 30 minutes again, and then the machine stopped.

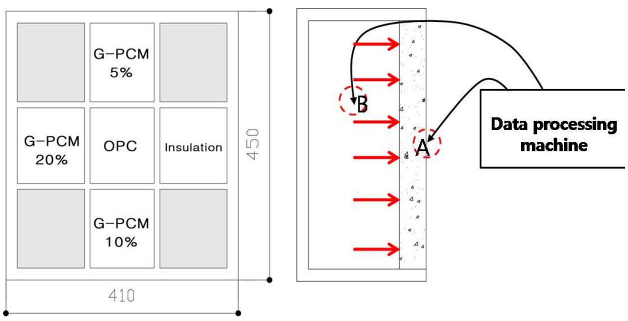

Figure 7. Installation of test specimens and measuring point of temperature history

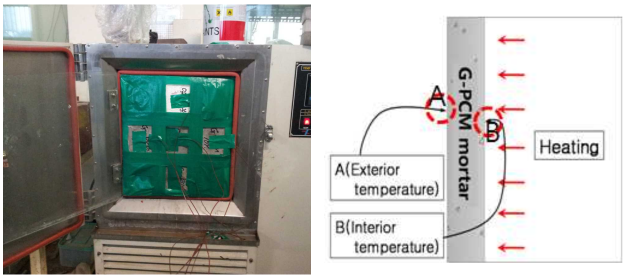

Figure 8. Thermal performance experment of mortar with G-PCM

Table 5. Heating method and order

Experiment item	Measurement speed	Temperature of chamber inside	Heating	Heating stop	Remark
Heat transfer experiment	1sec	Heating	Temperature (℃)		Repetition of heating (50℃) and the heating stopped
Heat transfer experiment	1sec	50℃	0→0℃ (2H30m heating)	50℃→ -1℃ (1H stop)	Repetition of heating (50℃) and the heating stopped
Latent heat experiment	1sec	Stop	-	50 →-1℃	Repetition of heating (50℃) and the heating stopped
Latent heat experiment	1sec	-1℃	-	50 →1℃	Repetition of heating (50℃) and the heating stopped

3. Analysis and considerations

3.1 Thermal performance evaluation of G-PCM particles (Series 1)

Figure 9 is DTA results conducted at the melting point of 28℃ using TG-PCM. The DTA (Differential Thermal analysis) used in the test is the analysis values of thermal change between two different specimens using a time or thermal function when the test specimen and the standard specimen were heated or cooled at a certain rate under an identical condition. The outside temperature change was expressed with a dotted line, while the DTA curve of G-PCM was expressed with a solid line. It was found that the specimen absorbed heat up to about

36.59℃during the movement from solid to liquid while radiated heat at around 28℃ at which the movement from liquid to solid triggered when the temperature decreased. Therefore, if heat storage performance of G-PCM by temperature change is used, it is possible to change the thermal performance of construction materials.

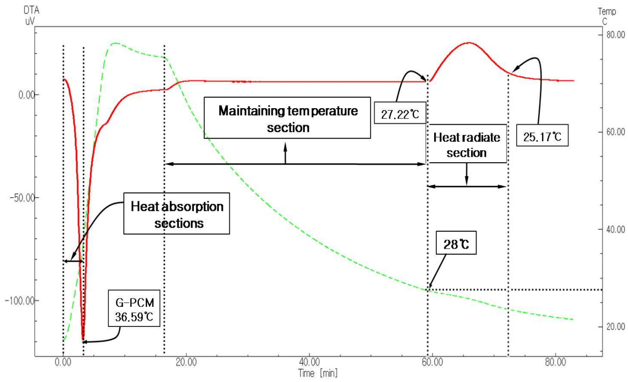

Figure 9. DTA(Differential Thermal Analysis) curves of the G-PCM

3.2 Latent heat and temperature keeping of G-PCM (Series 1)

To perform a comparative analysis of thermal transfer performance, the floor was manufactured with mortar with G-PCM and mortar only. The air temperature (Point A) and the floor temperature (Point B) were measured to analyze the temperature change affected by the thermocouple.

Figure 10 shows the air temperature change of the specimen(A). PCM is reported to show a gradual increase and decrease in temperature by heat absorption and radiation. The G-PCM charged floor showed a relatively sharp increase in temperature compared to the mortar floor. It is likely that the floor held G-PCM particles, and the floor heat was directly conducted through the vacant space between particles, which led in turn to the temperature rise. On the other hand, when the heating was stopped after the phase change of PCM, the temperature of the G-PCM specimen fell more slowly to about 18℃ compared to the mortar specimen. This is believed that the heat stored in the G-PCM specimen helped to keep the temperature from decreasing rapidly, and the latent heat section is illustrated in Figure 10.

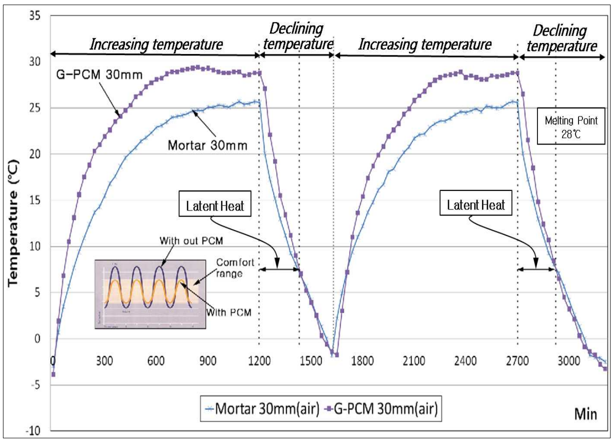

Figure 10. Air temperature change of the internal specimen(A)

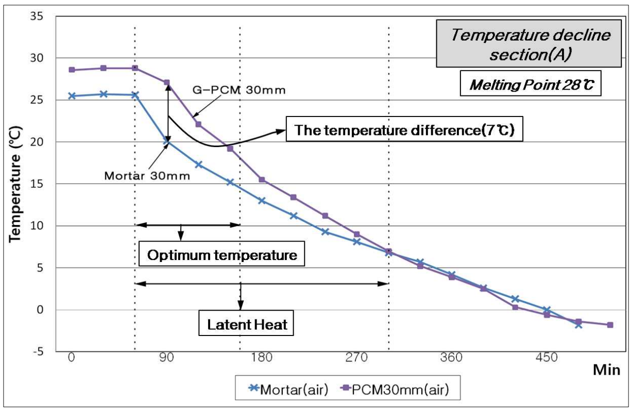

Figure 11. Latent section of the internal specimens(A)

Figure 11 is the latent heat section. Based on the range of comfortable indoor temperature between 18 and 20℃, when using a 30mm-thick layer of G-PCM on the floor, the temperature was 7℃ higher than when using a 30mm-thick layer of mortar on the floor. Moreover, the duration to be cooled below the range of comfortable indoor temperature was shown to be longer. It was found that G-PCM could help extend the duration to be cooled below the range of comfortable indoor temperature up to 40~50 minutes compared to using the mortar only. Hence, it is believed possible to reduce heating energy by extending the time range of comfortable indoor temperature using the characteristics of absorption and radiation of G–PCM and its latent heat.

Figure 12 is the temperature change of the floor surface in the Series 1 specimen(B). Figure 13 shows the latent heat section. The temperature change of the floor surface was shown to be similar to that of the air temperature. During the temperature decline from 39℃ to 15℃, the latent heat section was found, based on which it is expected to reduce not only the heating time for floor warming but also the energy consumption required for floor warming.

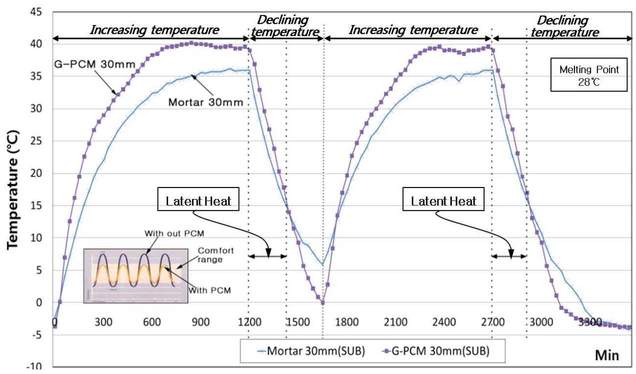

Figure 12. Surface temperature change of the internal specimen(B)

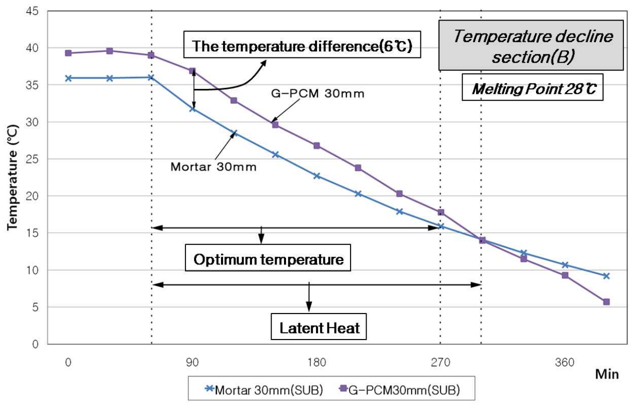

Figure 13. Latent section of the internal specimens(B)

3.3 Physical properties of the cement mortar with G–PCM (Series 2)

Figure 14 shows the fluidity change by replacement ratio of G–PCM when G–PCM was replaced for some of aggregate in the mortar. The change in fluidity was shown about 1.5cm up to 20% of replacement ratio, which is interpreted that little change took place. This might be because the size of G–PCM particles was between 1 and 3mm, and the coating prevented water from being absorbed. Thus, the flow can be controlled by using admixture as can in general mortar.

Figure 15 shows the average of compressive strength of the three mortars at 28 days. It was found that the higher the replacement ratio, the lower the compressive strength. It can be interpreted that the surface of PCM was coated with silica which is weaker than fine aggregate, and G–PCM was destructed when reaching the maximum strength, which can be found on the factures. However, about 21MPa of compressive strength was measured at 20% of replacement ratio, exceeding 18MPa, the compressive strength criterion for the floor mortar. The test was performed in compliance with KS L ISO 697 Mortar Test, and there were no great differences in mix proportion used at a construction site. For this reason, PCM is believed to have enough usability.

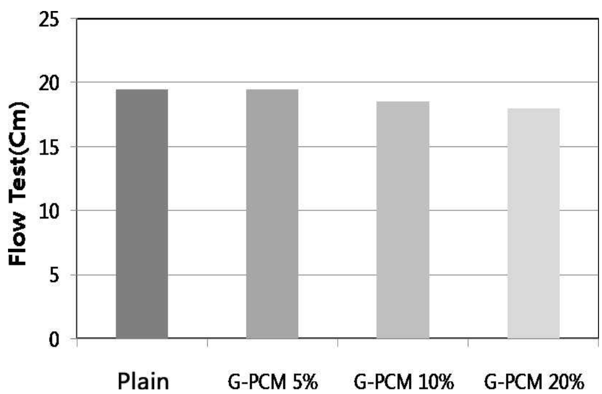

Figure 14. Flow test of the mortar with G–PCM

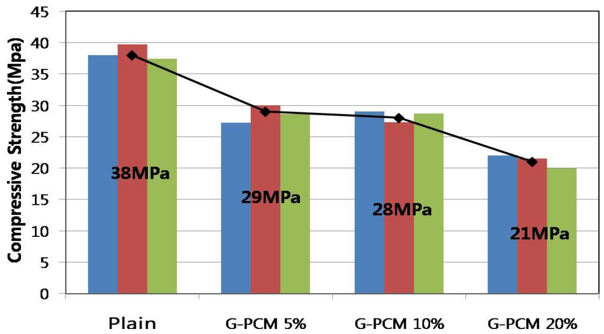

Figure 15. Compressive strength of mortar with G-PCM (28days)

G-PCM 5% G-PCM 10% G-PCM 20%

Figure 16. The particles distribution of G-PCM

3.4 Thermal performance of the mortar with G-PCM

Figure 17 is the temperature change at the surface (Point A) of the mortar with G-PCM used as a wall. During the temperature rise, the surface temperature was increasing over time in all specimens. However, compared to the mortar specimen with not G-PCM, the surface temperature was shown to be lower in the mortar specimen with G-PCM when heated for a certain time. In addition, it was found that the higher the replacement ratio of G-PCM, the lower the surface temperature. After the heating in the chamber was stopped, the temperature change was measured. The mortar specimen with no G-PCM showed a sharp decline in temperature, while the mortar specimen with G-PCM showed gradual decline in temperature, and slower in the mortar specimen with a higher replacement ratio of G-PCM. That is, the higher the replacement ratio, the more slowly the temperature increased and decreased, which is believed that the phase change of PCM took place at the temperature of 28℃, and PCM absorbed and radiated heat. And, when the heating and cooling process was repeated, the phase change was repeatedly found. Based on the test results of PCM durability conducted by German Company B[11], G-PCM is believed to be used repeatedly.

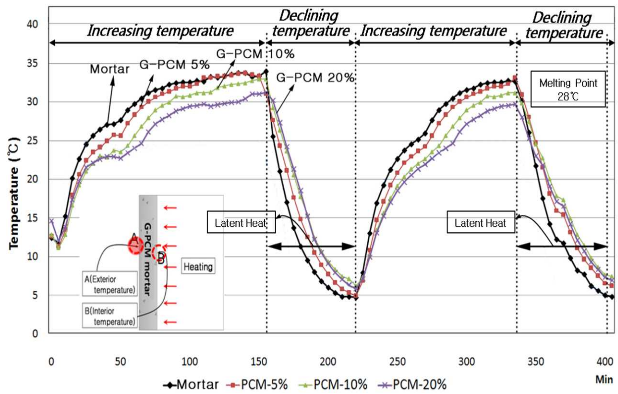

Figure 17. Temperature change of the mortar with G-PCM

Figure 18 shows the surface temperature chance by specimen in the temperature rising section. In comparison with the mortar with no G-PCM, the mortar with G-PCM showed relatively slow increase in temperature, which is believed that the PCM in the chamber changed its phase, and PCM absorbed some of the transferred heat. In addition, the higher the replacement ratio, the slower the temperature rise on the surface, which is likely that the mortar held more G-PCM particles as the replacement ratio of G-PCM increased, and the heat capacity of the specimen itself had improved.

Figure 19 is the surface temperature change by specimen. Compared with the mortar with no G-PCM, the surface temperature decline was relatively smaller in the mortar with G-PCM. The slow phase change of PCM took place below around 30℃, and PCM changing from liquid to solid radiated heat, which slowed the temperature decline on the surface of the specimen. In the phenomena, it was found that when the mortar contained more PCM particles, the temperature decline took place more slowly.

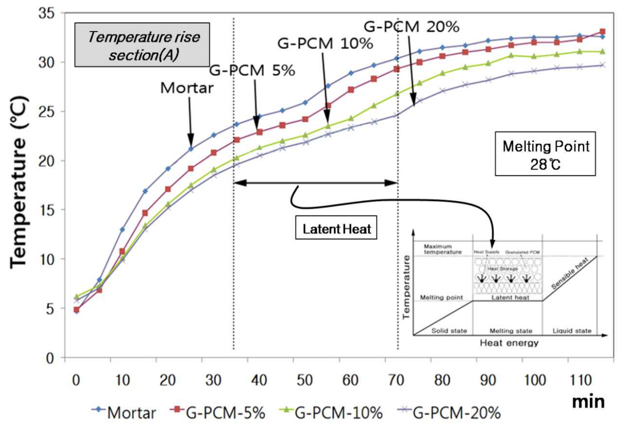

Figure 18. Increasing temperature change of the mortar with G-PCM

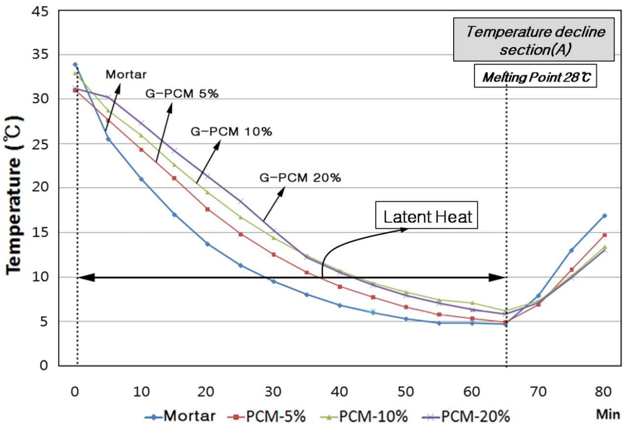

Figure 19. Latent section of the mortar with G-PCM

4. Conclusion

The research findings of this study are as follows:

1) The latent heat was found in the DTA test result of G-PCM (melting point 28℃) in that the specimen with G-PCM absorbed heat by 36.59℃ during temperature rise while radiated heat at around 28℃ during temperature decline
2) In the Series 1 test using G-PCM particles for the floor warming, the G-PCM floor helped extend the time range of comfortable indoor temperature, and delayed the reheating, based on which it is expected to reduce heating energy.
3) In the Series 2 test using the mortar with G-PCM, the fluidity hardly declined up to 20% of replacement ratio of G-PCM. On the other hand, in the test condition, the compressive strength decreased as more G-PCM was replaced. But the compressive strength was measured at 21MPa that exceeded 18MPa, the compressive strength criterion for the floor mortar, and PCM is believed to be applicable to a wall structure up to 20% of replacement ratio.
4) In the heat transfer test of the mortar wall with G-PCM (Series 2), the higher the replacement ratio, the more slowly the temperature increased and decreased both during temperature rise and during temperature decline. It is believed that at the boundary temperature (28℃), the phase change of PCM took place, and PCM absorbed and radiated heat.

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