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Mechanical Properties of Eco-friendly and Energy-saving Concrete with Porous Feldspar

Jung-Geun Han¹, Jin-Woo Cho^{2*}, Sung-Wook Kim³, Yun-Suk Park¹ and Jong-Young Lee ^{1*}

¹ School of Civil and Environmental Engineering, Urban Design and Study, Chung-Ang University, Seoul, 06974, Korea; jghan@cau.ac.kr; dbstjr9653@naver.com

² Construction Automation Research Center, Korea Institute of Civil Engineering and Building Technology, Gyeonggi-do, 10223, Korea

³ Geo Information Research Group Co., LTD. 47598, Busan, Korea; suwokim@chol.com

* Correspondence: jinucho@kict.re.kr(J.W.C.); geoljy@cau.ac.kr (J.Y.L.)

Abstract: In this study, to reduce the use of cement and sand, porous feldspar with excellent economic efficiency was used as a substitute in heat storage concrete layer. When cement was replaced with porous feldspar, the compressive strength was approximately 16%–63% higher compared with when cement was replaced with silicate minerals. To compensate for the reduction in strength owing to the decreased cement content, mechanical and chemical activation methods were employed. When the specific surface area of porous feldspar was increased, the unit weight was reduced by approximately 30% and the compressive strength was increased by up to 90%. When chemical activation was applied using a solidifying agent, the strength was increased by approximately 30% even though 70% of the cement content was replaced with porous feldspar. When cement and sand were replaced with porous feldspar, the compressive strength was approximately two times that of ordinary cement mortar. When the heat storage concrete layer material was replaced with porous feldspar in a pilot test, the thermal conductivity and heat storage characteristics were better than those of ordinary cement mortar, and an energy-saving effect of approximately 57% was observed, confirming the excellent applicability of porous feldspar as a building material.

Keywords: Porous feldspar; activation; compressive strength; substitute material; energy saving concrete

1. Introduction

One of the characteristics of South Korea's housing culture is that hot water is circulated through the piping underneath the floor. Fossil fuels, such as LNG, LPG, and coal, are mainly used as the heat source for hot water supply, and cement is mostly used as a flooring material. Cement, which is based on carbonate minerals, has continuously generated debates on human health risks, such as sick house syndrome and atopy, owing to heavy metal releases and high pH. In South Korea, the energy target management system and the emissions trading scheme were introduced based on the 21st United Nations Framework Convention on Climate Change, and efforts are being made to reduce greenhouse gas emissions. Therefore, a method for reducing the use of cement, which emits 700 kg of carbon dioxide per ton, is required. In construction, fly ash, which is the residue of the thermal power generation process, is used as a substitute for cement. The mixture of fly ash and cement has been used as roadbed and fill material [1–2]. For substitute materials to be mixed with cement, compressive strength characteristics vary depending on the mixing ratio. To prevent the reduction in strength owing to the decreased cement content, studies have been conducted on activation methods for increasing the reactivity of substitute materials. Furthermore, studies on eco-friendly materials and the reduction in the use of cement have been conducted of late [3–5].

With the development of nanotechnology, porous materials, for which cavities represent more than 30% of the total volume, have recently been developed. Representative porous materials include

active carbon and zeolite, and studies on their use as construction materials have been reported [6–8]. However, active carbon increases environmental hazards, such as fine dust, owing to logging and heating. In the case of zeolite, only mordenite and clinoptilolite are functional among the entire zeolite mineral groups, but their reserves in South Korea are small.

Feldspar, a representative aluminosilicate mineral, is a commonly found mineral as it accounts for 60% of the earth’s crust. It is used for the manufacture of glass in addition to various potteries and ceramics, and is also used for non-functional purposes, such as land reclamation [9–10]. In South Korea, feldspar is mainly extracted from granite and quartz bedrock, and its reserves are abundant; thus, it is available at low cost.

For feldspar, the mineral composition and surface structure are changed by the weathering process. Cavities are observed on the surface of weathered feldspar porphyry, showing a porous structure. Especially, in feldspar phenocrysts, tens of thousands to hundreds of thousands of cavities are observed. The formation of cavities is related to the specific surface area and the cation exchange capacity. Therefore, feldspar with a porous structure is expected to improve the physical and chemical characteristics, such as adhesion to cement, heat transfer, and preservation capabilities.

In the floor structure of a typical Korean house, cushioning or insulation materials (20–30 mm) and lightweight foamed concrete (more than 40 mm) are placed on the concrete slab and then hot water pipes are installed, as shown in Figure 1. The heat storage layer (more than 50 mm) composed of sand and cement is then constructed at the top [11]. In this study, a certain proportion of cement was replaced with porous feldspar in the heat storage and lightweight foamed concrete layers to increase the thermal efficiency of floor heating. Thermal, mechanical, and chemical methods were used for the activation of natural feldspar, and changes in the density, strength, and surface structure were observed. For the utilization of porous feldspar as a flooring material, it was mixed with cement and the strength characteristics were evaluated according to the mixing ratio. In addition, the thermal conductivity and heat storage characteristics were monitored through the test construction to evaluate porous feldspar as a substitute for cement.

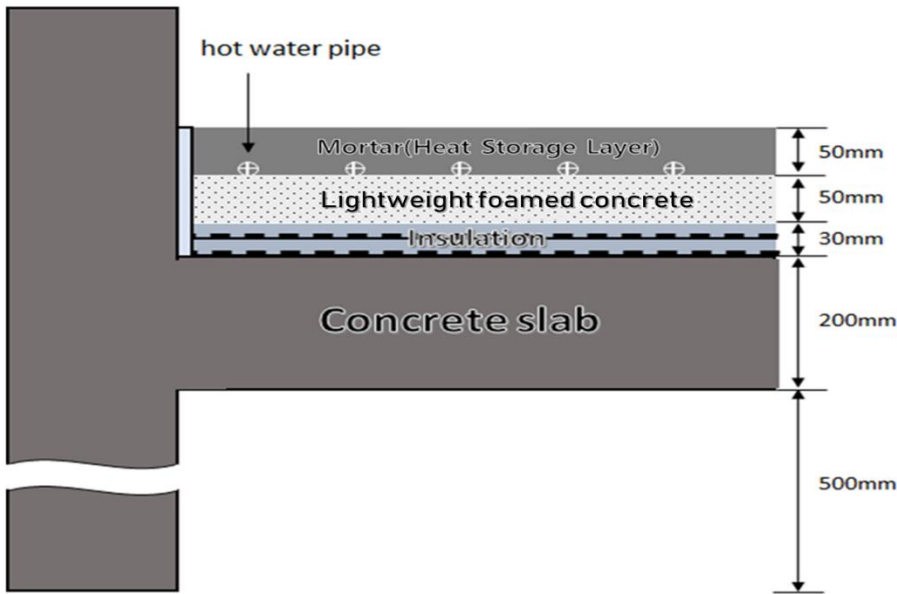


Figure 1. Construction standard of the bottom storage layer

2. Materials and Methods

2.1 Materials

Table 1 shows the mineral and chemical compositions of the porous feldspar used in this study. X-ray fluorescence (XRF) analysis was conducted with samples from three areas in South Korea. The analysis results showed that the content of two components, i.e., SiO₂ and Al₂O₃, accounted for more than 80%. Figure 2 shows the scanning electron microscope (SEM, TESCAN VEGA3 SBH) image of weathered feldspar. It can be observed that irregular cavities are present on the surface and they are connected to each other. When the pore distribution of porous feldspar was measured, a high specific surface area of 334.5 m²/g was obtained. The measurement was performed using Micromeritics Tristar™ as an analyzer and the Brunauer–Emmett–Teller (BET) method. It has been reported that materials with porous structures have excellent physical and chemical characteristics owing to the high specific surface area and the cation exchange capacity [12]. Therefore, it is judged that the pore characteristics of the feldspar used in this study will satisfy the above characteristics. As for the materials used in the experiment, rocks with developed feldspar phenocrysts were collected from the granite and diorite rocks in the Chung-ju area, and were used in their powder form.

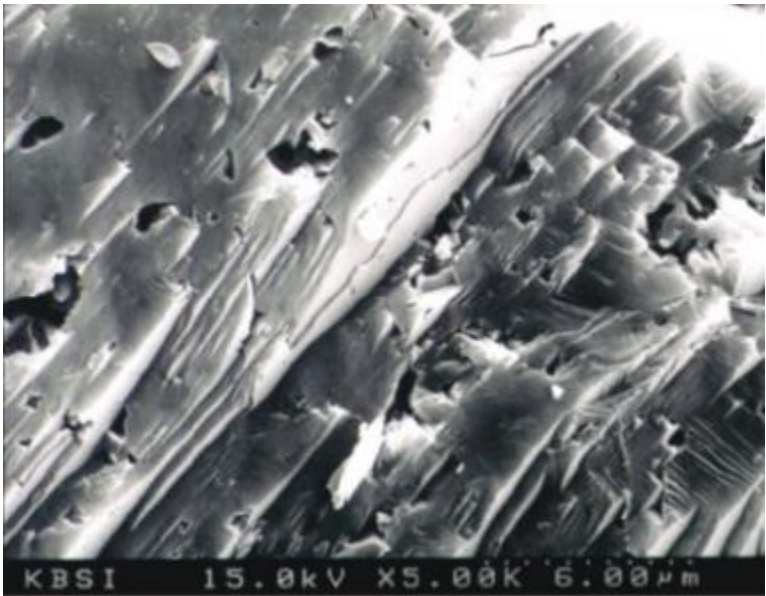


Figure 2. SEM image of weathered feldspa

Table 1. Characteristics of experimental materials

I. Mineral composition of feldspar porphyry										
Albite (NaAlSi ₃ O ₈)		Quartz (SiO ₂)		Orthoclase (KAlSi ₃ O ₈)				Chlorite		
(%)										
38.8		26.5		22.7				8.3		
II. Chemical composition of feldspar										
Location	SiO ₂	Al ₂ O ₃	K ₂ O	Na ₂ O	CaO	Fe ₂ O	MgO	TiO ₂	LOI	Other
	(%)									
Chung-ju	69.59	13.07	2.7	4.53	2.56	2.49	1.61	0.49	2.46	0.50
Muan	67.10	15.26	5.02	3.84	1.88	3.34	0.73	0.40	1.59	0.84
Namwon	68.95	14.59	4.63	3.39	1.29	3.03	0.67	0.37	2.71	0.37

2.2 Experimental Conditions

To examine the reactivity of porous feldspar with cement, the uniaxial compressive strength according to the mixing ratio was measured first and the results were compared with the compressive strengths of other substitute materials. Furthermore, when cement is replaced with porous feldspar, a reduction in strength is expected. To compensate for the reduction, mechanical activation for reducing the particle size of materials and chemical activation for improving chemical reactions by mixing a solidifying agent were employed. In addition, mixing tests were conducted to evaluate the applicability of porous feldspar to the heat storage layer by replacing cement and sand. Table 2 shows the conditions for each test. The purpose and method of each test are as follows.

Table 2. Test conditions

I. Characteristics of strength with mixed cement										W/C ratio	
Mixed ratio (cement : feldspar)											
EXP-R1	EXP-R2	EXP-R3	EXP-R4	EXP-R5	EXP-R6	EXP-R7	EXP-R8	EXP-R9	EXP-R10		
10:0	9:1	8:2	7:3	6:4	5:5	4:6	3:7	2:8	1:9		
Mixed Ratio (Cement : Clay mineral)			Metakaolin	Silica fume	Illite	Dolomite	Feldspar	1:0.5			
7:3			EXP-RM	EXP-RS	EXP-RL	EXP-RD	EXP-RF				
II. Mechanical activation											
Feldspar size (μm)								Mixed ratio (cement : feldspar)	W/C ratio		
Unit weight test		20	38	48	80	100	500			1:0.5	
Compressive strength test		30	50	80	100	150	200	7:3			
III. Chemical activation											
Mixed ratio (cement : feldspar : solidifying agent*1)											
EXP-A1			EXP-A2				EXP-A3				
100:0:0			100:0:0.5				30:70:0.5				
IV. Feldspar mixed test											
		Mixed ratio*1							Curing time(day)		
		EXP-FM1			EXP-FM2						
Compressive strength test		PC 25% : AG 75%			PC 20% : AGF 40%, PF:40%, S:0.1%					3, 7, 14, 28	

^{*1} PC : Portland cement, AG : Aggregate (sand), AGF : Aggregate (Feldspar), PF : Powder (Feldspar), S : solidifying agent

2.2.1 Characteristics of Strength

The purpose of this test is to investigate the strength characteristics according to the weight ratio of porous feldspar powder. The mixing ratio of cement and porous feldspar was varied and three specimens were fabricated for each mixing ratio in accordance with KS L ISO 679. The specimens were cured at room temperature(20°C~24°C) for seven days. The average compressive strength of the three specimens was used as the compressive strength under each condition (EXP-R1 to EXP-R10).

Industrial minerals that can be widely utilized as construction materials are clay minerals generated from weathered silicate minerals [13]. Among silicate minerals, silica fume, metakaolin,

illite, and dolomite, which are representative pozzolanic materials containing a large amount of silica and alumina, which are highly reactive with cement, were selected as substitutes for cement. When cement was replaced with porous feldspar, the compressive strength was compared with those of these materials (EXP-RM to EXP-RF). Five specimens were fabricated under each condition in accordance with KS L ISO 679, and the average compressive strength was used. After the fabricated specimens were cured at room temperature for seven days, the uniaxial compressive strength was measured. Section 1 in Table 2 shows the mixing ratios of the materials under the above experimental conditions.

2.2.2 Method of Activation and Experimental

To compensate for the strength reduction when porous feldspar was used as a substitute for cement, mechanical and chemical activation methods were used.

The particle size of the material causes changes in the physical characteristics, such as the unit weight and compressive strength. In this study, the unit weight and compressive strength according to the particle size of porous feldspar were analyzed. The specimens used in the experiment were fabricated and the compressive strength test was conducted in accordance with KS L ISO 679.

When feldspar was used as a material to replace cement, a chemical activation method involving mixing a solidifying agent was used for preserving strength. A developed liquid-type inorganic product was used as a solidifying agent in the test. Table 3 shows the components of the solidifying agent obtained via the SEM/energy-dispersive X-ray spectroscopy (EDS) measurement results. The fabrication of specimens and the compressive strength test were conducted in accordance with KS L ISO 679, and changes in the surface structure were observed using SEM imaging (EXP-A1 to EXP-A3). The particle size of the feldspar used for specimen fabrication was 80 μm , which was selected based on the strength change results obtained via mechanical activation.

Table 3. Chemical compositions of EXP-A1–EXP-A3

	Si	Al	Ca	Na	Cl	Mg	K	S	Fe
	(%)								
EXP-A1	12.3	2.9	73.8	N.D	N.D-	1.9	1.2	3.5	2.6
EXP-A2	11.2	3.1	73.6	0.8	0.9	1.7	3.2	2.7	2.8
EXP-A3	29.6	7.2	43.9	1.6	1.3	3.1	4.7	2.5	6.1

* N.D : Non-detection

2.2.3 Feldspar Mixed Test

This test was conducted to investigate the strength characteristics when cement and sand were replaced with porous feldspar. Specimens in which the ratio of ordinary cement to sand was 1:3 (EXP-FM1) and other specimen in which sand was replaced with feldspar smaller than 1 mm and feldspar powder smaller than 40 μm (EXP-FM2) were fabricated in a cubic form (side length: 50 mm). Three specimens were fabricated under each condition. After they were cured in water for 3–28 days, the compressive strength was measured in accordance with the ASTM C109 (KS L 5105) method.

2.3 Pilot Test

To evaluate the thermal conductivity, heat storage characteristics, and energy efficiency of porous feldspar, a large-scale single-story experimental building composed of temporary structures was installed. The outer wall of the experimental building was insulated to reduce the influence of the external temperature. Inside this experimental building, two temporary houses each of dimensions 3,000 (L) \times 4,000 (W) \times 3,000 (H) mm were constructed. Based on the floor layer

construction standard in Figure 1, a heat storage layer composed of typical concrete mortar (PT-2) was constructed in a temporary house and a heat storage layer in which sand was replaced with feldspar (PT-1) was installed in the other temporary house. EXP-FM1 and EXP-FM2 were applied as the concrete mixing ratios of the heat storage layers. In addition, the temporary houses were separated from the ground by 50 cm to minimize the influence of the ground temperature. Construction and measurement for the two conditions were simultaneously performed to minimize the influence of external environmental factors. After installing a 2 kW electric boiler in each temporary house for hot water supply, a watt-hour meter was installed to determine the power consumption according to the experimental conditions. The temperature of the heat storage layer was measured using an infrared thermal-imaging camera (FLIR A615, temperature range: 20–150 °C, measurement error: 1 °C). Temperature sensors were installed at intervals of 80 cm in the heat storage layer to measure the temperature change and power consumption owing to the boiler operation. The measured data were transmitted to the Internet via a wireless router and stored in a cloud service to apply a remote measurement method [14]. The power consumption during the boiler operation was calculated from the images obtained by the CCTVs installed in the watt-hour meters [15].

3. Results and Discussion

3.1 Response Characteristics

In the development of substitute materials for cement, the cement replacement rate is generally determined by the uniaxial compressive strength. The strength decreases if the mixing proportions of substitute materials are excessive, and the cement content increases if they are too low. In other words, appropriate mixing of cement and substitute materials is important because increasing the cement content is beneficial for strength but not for the environment.

Figure 3 shows the uniaxial compressive strength according to the mixing ratio of cement and porous feldspar powder. The compressive strength of the specimen with only cement was 11.43 MPa, and the compressive strength decreased as the cement content decreased. The compressive strength linearly decreased for EXP-R10 to EXP-R4 in which the cement content was reduced to 40%, and it rapidly changed for EXP-R3 to EXP-R1 in which the cement content was less than 30%. This indicates that the proper mixing proportion of porous feldspar powder is less than 70% for a modest reduction in strength.

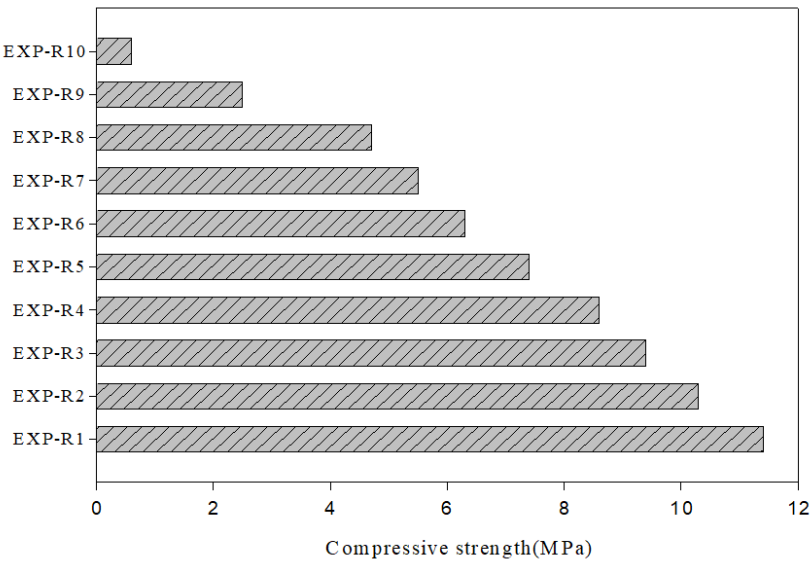


Figure 3. Compressive strength according to the ratio of cement and porous feldspar

Figure 4 shows the uniaxial compressive strength according to the silicate mineral type. When feldspar powder was used, the strength was approximately 16%–63% higher compared with when other silicate minerals were used, indicating that porous feldspar can be used as a substitute for cement. As for the characteristics of aluminosilicate minerals, SiO₂ and Al₂O₃ are representative pozzolanic components. It appears that porous feldspar increased the strength through the reaction with Ca(OH)₂ in the cement hydration process because approximately 80% of its content is accounted for by these two components.

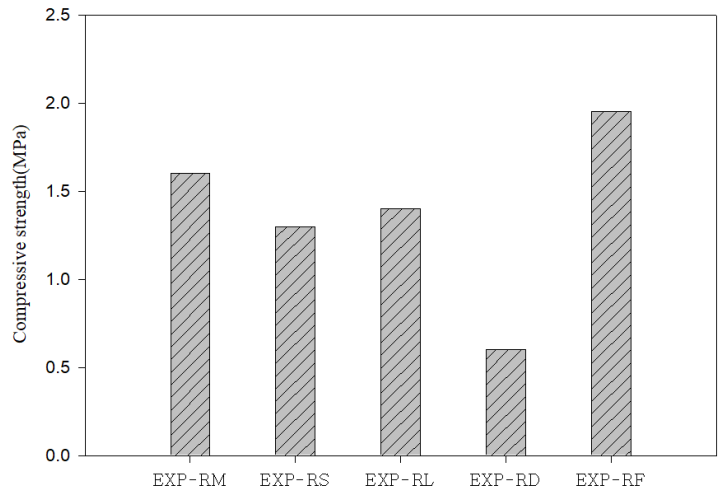


Figure 4. Compressive strength according to the type of silicate minerals

3.2 Mechanical Activation

Figure 5 shows the unit weight and compressive strength according to the particle size of porous feldspar. The unit weight decreased as the particle size of feldspar decreased. The unit weight for the particle size of 20 μm was 1.06 g/cm³, which was approximately 31% lower than that for 500 μm. As for the compressive strength according to the particle size, the lowest strength was observed for the largest particle size of 200 μm. As the particle size decreased, the strength slowly increased up to approximately 90%, confirming that the physical characteristics were improved by reducing the particle size through mechanical activation.

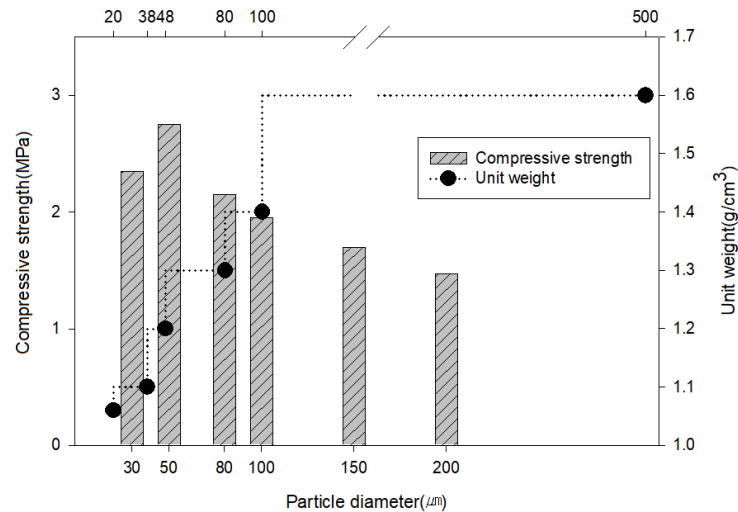


Figure 5. Relationship between the unit weight and compressive strength of feldspar according to the particle size

3.3 Chemical Activation

Figure 6 shows the compressive strength according to the mixing condition of porous feldspar. The compressive strength of EXP-A2 in which 100% cement was mixed with 0.5% solidifying agent ranged from 15 to 19 MPa, showing that the compressive strength was improved by approximately 33% compared with that of EXP-A1 in which only 100% cement was used. The compressive strength of EXP-A3 in which 70% of the cement weight was replaced with porous feldspar and solidifying agent corresponding to 0.5% of the cement weight was added ranged from 15 to 18 MPa, which was approximately 30% higher than that of EXP-A1 in which only cement was used. Figure 7 shows the surface structures of the specimens analyzed using SEM-EDS. For EXP-A3 in which cement was replaced with porous feldspar, reaction products of the chemical reactions of the inorganic solidifying agent and porous feldspar were observed. Table 3 shows the results of analyzing the chemical compositions of the specimens used in the tests. Na and Cl, which are the major components of the solidifying agent, were detected in EXP-A2 and EXP-A3 in which the solidifying agent and porous feldspar were added. In EXP-A3, the Si and Al contents were 20.6% and 7.2%, respectively, which were two to three times higher than the other results. They appear to have increased the strength through the reaction with $\text{Ca}(\text{OH})_2$ generated from the cement hydration process.

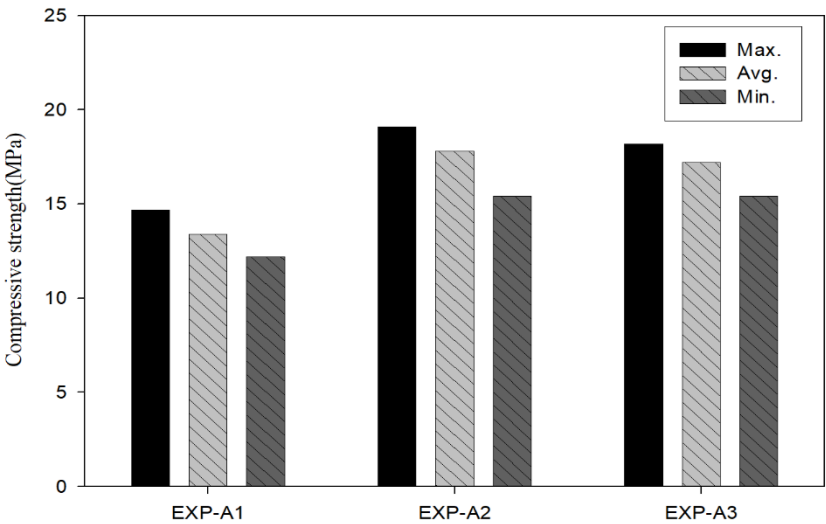
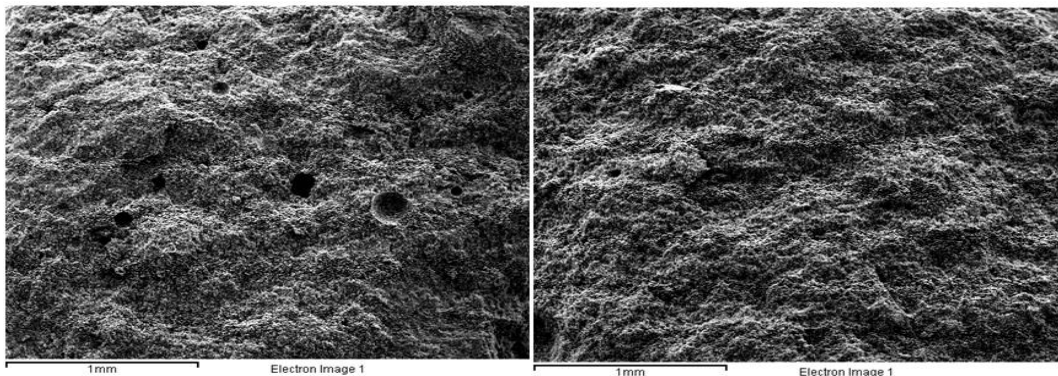
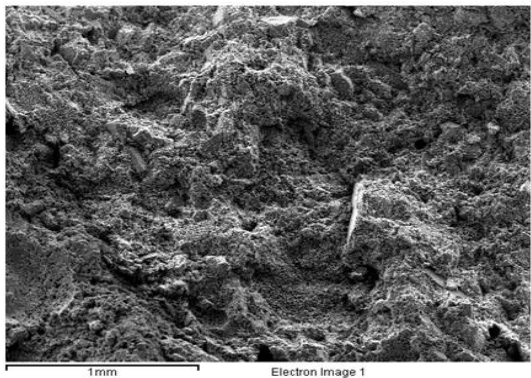


Figure 6. Compressive strength of cement and feldspar mixture



(a) EXP-A1

(b) EXP-A2



(c) EXP-A3

Figure 7. SEM image of specimens. (a) EXP-A1, (b) EXP-A2, and (c) EXP-A3

3.4 Evaluation of Substitute Materials

The compressive strength test was conducted to evaluate the applicability of porous feldspar to the heat storage layer in the heating floor layer. For a relative comparison, a specimen was fabricated in the same manner by mixing cement mortar and sand in a ratio of 1:3. The mixing proportion of porous feldspar less than 70% was proposed in Section 3.1, and the inorganic solidifying agent corresponding to 0.5% of the cement weight was added based on the experiment results in Section 3.3 to prevent the rapid reduction in strength and to increase the addition of porous feldspar.

Figure 8 shows the results of the compressive strength test. As for the strength characteristics according to the curing time, the strength showed a tendency to increase over time for both materials. Especially, for EXP-FM2 with porous feldspar, the compressive strength at 3 days was 10.53 MPa even though the cement content was reduced by 5%. This result indicates that the strength was improved by approximately 43% compared with that of EXP-FM1. The compressive strengths of EXP-FM1 and EXP-FM2 at seven days were 7.3 and 14.94 MPa, respectively, showing that the strength of EXP-FM2 was two times higher. Both compressive strengths satisfied the quality criterion of South Korea (strength at seven days: 7 MPa) [16]. The compressive strengths of EXP-FM1 and EXP-FM2 at 28 days were 14.14 and 18.97 MPa, respectively, confirming that the strength of EXP-FM2 with porous feldspar was approximately 35% higher than that of EXP-FM1 even though its strength increment slightly decreased.

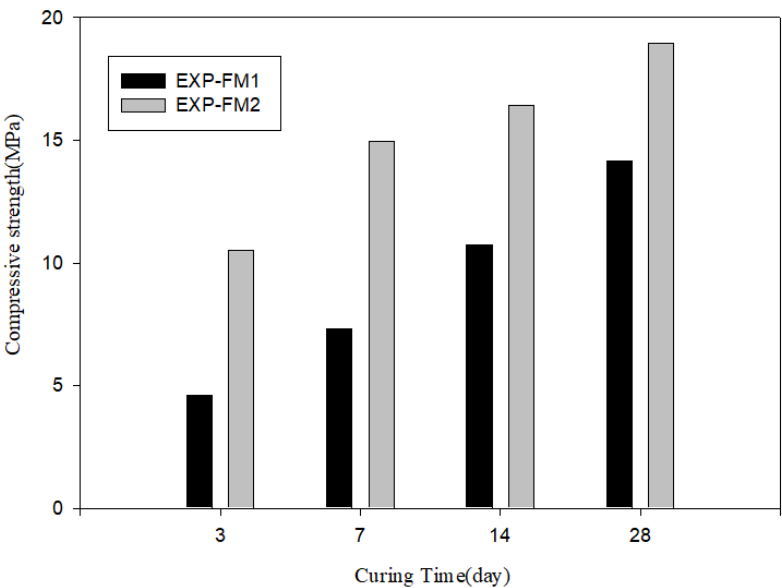


Figure 8. Compressive strength for different mixing ratios and curing times

3.6 Pilot Test

3.6.1 Characteristics of Thermal Conductivity and Heat Storage

Figure 9 shows the temperature distribution of the heat storage layer measured using the thermal-imaging camera during the heating time after hot water was supplied to the floor. The temperature of the supplied hot water was 55 °C. At 10 min after the boiler operation, the heat storage layer mixed with porous feldspar (PT-1) exhibited a temperature approximately 2 °C higher than that of the heat storage layer composed of ordinary concrete (PT-2). The temperature difference increased to approximately 3 °C at 2 h after the boiler operation, indicating that PT-1 had better heat transfer than PT-2. Figure 10 shows the temperature variation during the cooling period after the boiler operation was stopped. PT-2 exhibited a fast cooling speed and no thermal image could be obtained after 90 min. The average temperature was 21 °C after 120 min and 18 °C after 180 min, which was identical to the temperature before the boiler operation. In contrast, PT-1 with porous feldspar exhibited temperatures approximately 2 °C higher than those of PT-2. The temperature remained at over 23 °C even after 180 min of cooling, confirming the excellent heat storage characteristics.

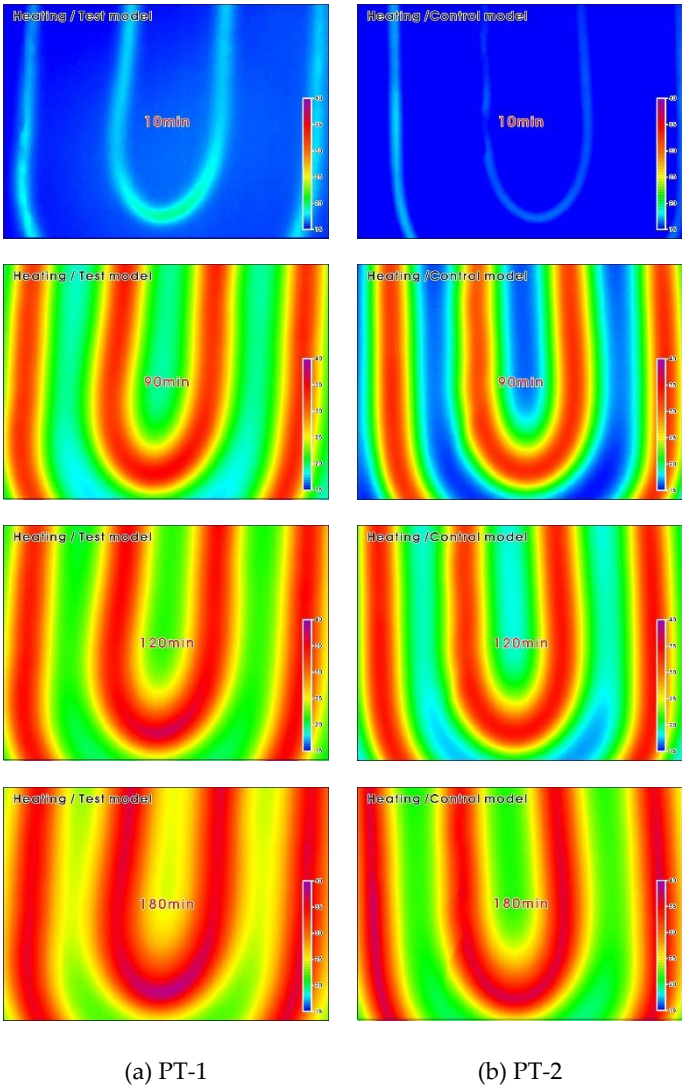


Figure 9. Temperature change of heat storage layer (heating cycles)

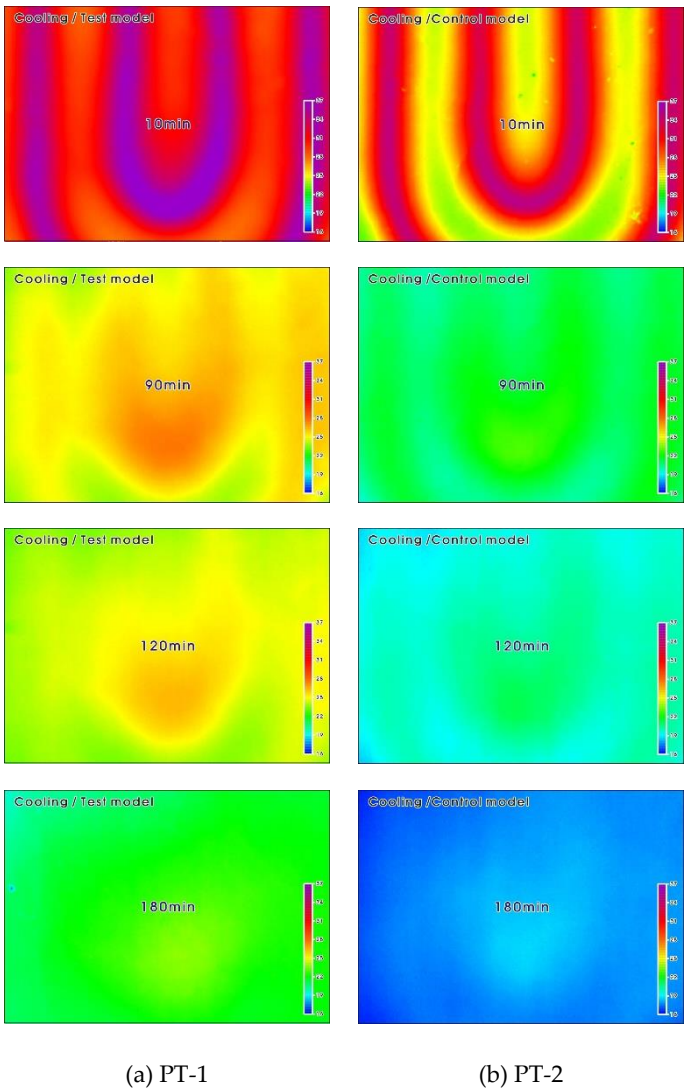


Figure 10. Temperature change of heat storage layer (cooling cycles)

3.6.2 Energy Efficiency

Figure 11 shows the heat storage layer temperature and power consumption during the experiment period under the two conditions. PT-1 exhibited a higher temperature increase rate than PT-2 until 100 min after heating, and the increase rate decreased after 30 °C. PT-2 showed a temperature increase rate similar to that of PT-1 until 20 °C, but its temperature increase rate became lower than that of PT-1. During 180 min of heating, the maximum temperature was 34.4 °C for PT-1 and 31.6 °C for PT-2, showing that the value for PT-1, which used porous feldspar, was 2.7 °C higher. When the target temperature of the heat storage layer was set to 25 °C, the boiler operation was stopped after approximately 40 min and the power consumption was 1.84 kWh for PT-1. For PT-2, the boiler operation was stopped after approximately 70 min and the power consumption was 3.22 kWh. In other words, the boiler was operated 30 min longer for PT-2 than for PT-1, and PT-2 required the additional power of 1.38 kWh, confirming that PT-1 could save approximately 57% power. If the boiler restart temperature is set to 20 °C after the cooling process, it is expected that the boiler will restart after 380 min for PT-1 and after 310 min for PT-2; thus, PT-1 will delay the boiler operation by approximately 70 min. Through the experiment, the rapid temperature increase effect in the heating process owing to the high thermal conductivity caused by the specific surface area characteristics of

porous feldspar and the energy-saving effect in the cooling process owing to the delay effect caused by the heat storage characteristics of porous feldspar could be confirmed.

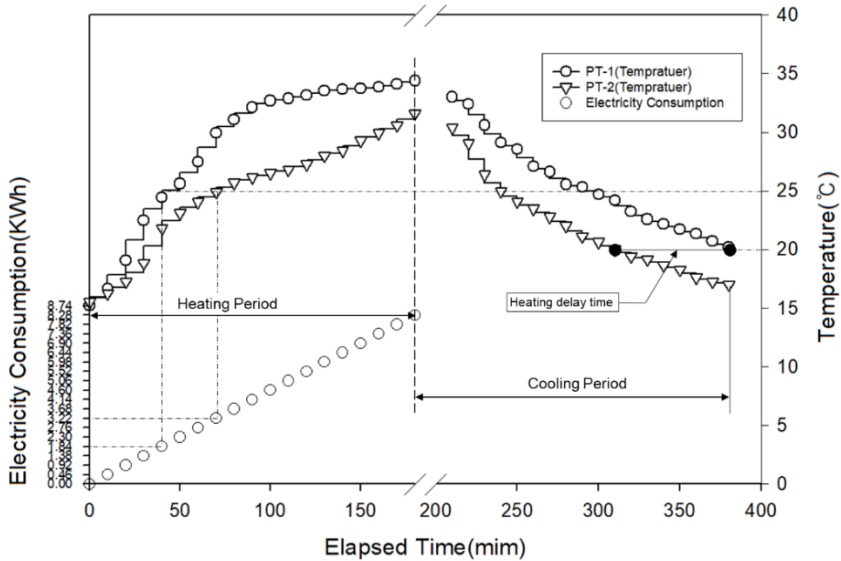


Figure 11. Change of temperature and electric consumption

4. Conclusions

In this study, feldspar, which is found in South Korea in large quantities and has a porous structure owing to weathering, was used as a substitute for cement. When porous feldspar was used as a substitute for cement, the compressive strength was approximately 16%–63% higher compared with when four representative silicate minerals were used as substitute materials for cement, confirming the applicability of porous feldspar as a substitute for cement.

When the particle size was reduced via mechanical activation to increase the specific surface area of porous feldspar, the unit weight decreased by approximately 30%, but the uniaxial compressive strength increased by up to 90%, confirming that the physical characteristics were improved.

A solidifying agent was mixed to compensate for the strength reduction caused by the addition of porous feldspar. When 70% of the cement weight was replaced with porous feldspar and the solidifying agent was mixed, the compressive strength was improved by approximately 30% compared with when only cement was used.

In the compressive strength test in which cement and sand were replaced with porous feldspar, the 3-day compressive strength was improved by approximately 43% and the 7-day compressive strength was twice as high as that of the specimen in which cement and sand were mixed at a ratio of 1:3.

When the heat storage layer material was replaced with porous feldspar in the pilot-test, the thermal conductivity and heat storage characteristics were better than those of ordinary cement mortar, and an energy-saving effect of approximately 57% was observed, confirming that porous feldspar can be used as a building material.

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