CHARACTERISTICS OF SLAG ACTIVATED PHC-PILE WITH REDUCED CEMENT CONTENT

Hongseok Jang,[1] Seungyoung So[2]

ABSTRACT

Ground Granulated Blast-furnace Slag (GGBS) powders, the massive by-products produced in the process of manufacturing cast iron are actively used as a substitute for cement, one of the major causes of greenhouse gas emissions. The purpose of this study was to investigate the proper mixing ratio of the activator, and to reduce the usage of cement in the production of high-strength steam cured concrete using GGBS. The cured products of various ratio were analyzed by XRD and TG/DTA, and the best ratio of the cured product were applied to the Pre-stressed high-strength concrete (PHC) Pile, and the performance was then evaluated. The results showed that the fluidity was improved by mixing with GGBS, and when an appropriate amount of activator was used, it was possible to produce high-strength cured products. In the PHC-Pile test, the replacement rate of 40% GGBS and combined 4% anhydrite gypsum and 2% $Ca(OH)_2$ as an activator was excellent. The compressive strength (2MPa more), shear strength (1.3MPa more), and Axial force strength (2.7Mpa more) were more improved than for the normal Portland cement PHC-Pile, and this GGBS pile can be manufactured more economically (the cost can be saved in the amount of 14.5%). This is caused by the activating agent destroying the glassy film of the GGBS, and actively inducing the pozzolanic reaction, so that the hydrate materials are generated, such as C–S–H. In addition, by positively utilizing the inexpensive industrial by-product, GGBS, it is possible to manufacture environmentally friendly concrete products, while reducing the amount of cement used.

KEYWORDS

Earthen construction material, By-products recycling, PHC-Pile, Substitution cement

INTRODUCTION

It is known that about 8% of CO_2 emissions, which constitute 55% of greenhouse gases, are emitted by the cement manufacturing sector (Robbie 2018). In particular, as Portland cement can only be manufactured by melting it at high temperature (1,450 °C), the manufacturing process for Portland cement requires a large amount of energy (International Energy Agency 2016). Producing a ton of cement requires 4.7 million BTU of energy, equivalent to about 400 pounds of coal, and generates nearly a ton of CO_2 (Panchanan and Susmita 2018). Therefore in

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the future, greenhouse gas reductions will become the biggest issue in the cement industry. When the Rio Climate Convention for the prevention of global warming goes into effect, the cement industry is expected to cut down the amount of cement clinker production by 50% or more.

In general, in order to manufacture high-strength concrete products, such as PHC-pile, precast high-strength concrete member (wall structure, slab, pillar etc.), it is necessary to increase the amount of cement, or to add special admixture, such as silica fume. However, as these materials are very expensive, it is inevitably necessary to develop new materials that can realize high strength at low cost.

In addition to cement, which is widely known as a material that reacts with water at room temperature to form a cured body, materials having alumina silicate composition are known as material that have hydraulic properties by alkali or sulfate stimulation. Continuous research has found that not only alkaline earth metal compounds of group 2 of the periodic table, but also alkali metals of groups 3 and 4 (alumina silicate), of groups 2 and 4 (alkaline earth silicate), and of groups 2 and 3 (alkaline earth aluminate) can produce hydraulic compounds (Krivenko 2017). It has thus been confirmed that the hydraulically-cured product can be obtained, even though it is not a conventional cement.

In particular, from the view of environmental technology, as the GGBS is a typical by-product that is generated in large quantity during the production of pig iron, when the materials used in various construction fields are recycled (Juhasz 1994, Dongxu et al. 2000, Xinghua et al. 2000) as the raw materials for the mixing materials that can replace cement, it is possible to prevent the depletion of minerals, such as limestone, clay and so on, that are necessary for clinker production. And when made with GGBS as the main raw material instead of the high fine powder cements, high-strength mixtures can be developed as high-strength concrete secondary product, the cost can be reduced, and environmental conservation and technology processes for cement concrete material can be made possible.

The purpose of this study is to manufacture eco-friendly PHC-Piles of high quality, by utilizing GGBS, an industrial by-product, instead of the conventional cement. Various steam curing formulations using gypsum and alkali stimulants were planned to estimate the compressive strength, flow test, hydration organization analysis, field test, and economic evaluation.

MATERIALS

The cement used was a Type I ordinary Portland cement (OPC) of S company in Korea (KS L 5201), while the GGBS was three kinds of slag that are produced as by-products in the pig iron manufacturing process of K Company in Korea, and classified by the KS F 2563 standard. The standard sands used for the compressive strength test were used as the mortar test aggregate. Also, 20 mm thick aggregate, cleaner, and stone powder were used for the mock-up test for the on site concrete pile. Lignin sulfonate admixture was used as the admixture for cement concrete, and anhydrite gypsum and $Ca(OH)_2$ were used as stimulant to promote the activation of GGBS (Table 1).

EXPERIMENT PLAN

Mix proportion

In this experiment, GGBS, anhydrite gypsum, and $Ca(OH)_2$ were used to obtain the high-strength mixture for the secondary concrete products (Table 2). In the mortar test, the water/binder ratio was 0.5, while the ratio of fine aggregate was 1:3. The test specimen was prepared

TABLE 1. Chemical composition and physical properties of raw materials.

Type	Chemical Composition (%)							Specific surface Area (cm^2/g)	Density (g/cm^3)
	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	LOI		
OPC	21.74	61.06	5.86	3.22	3.99	2.43	0.78	3600	3.15
GGBS	34.76	41.71	15.02	0.48	6.87	0.13	0.23	4200	2.91
Anhydrite Gypsum	0.16	39.07	0.1	0.04	—	53.83	6.71	4600	2.40
$Ca(OH)_2$	1.20	60.50	0.70	0.40	1.40	0.30	24.38	—	2.27

by sufficiently dry mixing the raw materials, followed by mixing for 1 minute and 30 seconds with the mixer (KS L 5109), and then the table flow of the mortar was measured by KS F 2594.

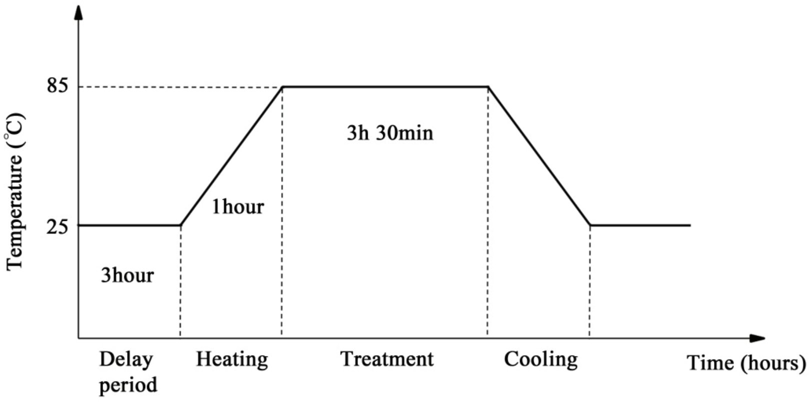
Table flow test

The flow value of the mortar was measured by means of a flow test, in accordance with KS L 5105, using the flow table specified in KS L 5111.

TABLE 2. Mix proportions of the binder (unit: g).

Type	OPC	GGBS	Anhydrite Gypsum	$Ca(OH)_2$	Water
0G	1000	—	—	—	500
20G	800	200	—	—	
40G	600	400	—	—	
60G	400	600	—	—	
40G-1	582	388	30	—	
40G-2	576	384	40	—	
40G-3	570	380	50	—	
40G-4	594	396	—	10	
40G-5	588	392	—	20	
40G-6	582	388	—	30	
40G-7	570	380	40	10	
40G-8	564	372	40	20	
40G-9	558	380	40	30	

FIGURE 1. Heat treating cycle applied.



Curing Method

It is generally known that the optimum temperature for steam curing is (65–85) °C degrees (Turkel and Alabas 2005), considering the appropriate ratio between the strength enhancement rate and maximum strength (Mindess and Young 1981). In this experiment, in order to stabilize the test specimen, after placing the specimen in a 25 °C, 50% RH for 3 hours, steam curing was conducted under the condition shown in Figure 1 (ACI 517.2R-82), the test specimen was demolded from the mold, and the test specimen was then placed in the standard curing chamber.

Analysis for the Hydration Structure

The strengths at (1, 3, and 7) days were measured for the cured product obtained by the atmospheric steam curing process (KS L 5105), and the product was immersed in acetone solution, followed by the drying treatment. After that, thermo gravimetric and differential thermal analysis (TG/DTA) and X-ray Diffraction (XRD) analyses were performed using TA Q20 to evaluate the degree of hydration of the specimen.

On-site Experiment for the Final Mixture

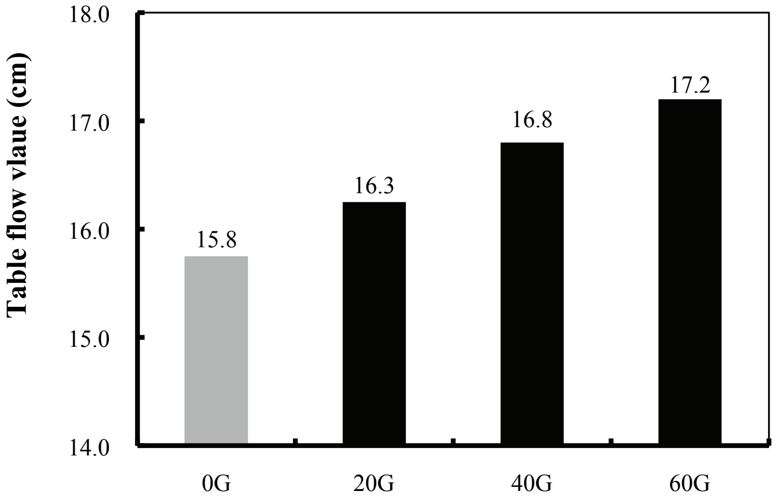
Applying the finally acquired ratio to the secondary products of high-strength concrete, the economic feasibility and physical properties of products were compared with normal Portland cement concrete piles. After molding the PHC-pile of 6 mm thickness, 400 mm diameter, and 10 m length, the strength was evaluated according to KS F 4306 standard.

RESULTS AND DISCUSSION

Flow Test

Figure 2 shows the flow table value of the mortar according to the substitution rate of GGBS. As the substitution rate of the GGBS increases, the fluidity of the mortar is remarkably increased. When the GGBS was replaced by (20–60)% of the weight of the OPC, the fluidity was increased by about (0.2 to 1.6) cm. This increase is due to the pozzolanic characteristics in which the GGBS has a relatively slow hydration rate at the initial state. It is known that the effect of GGBS on the material cohesion can improve mortar performance (such as improvement of the

FIGURE 2. Flow of mortar with variation in GGBS proportion.



workability, suppression of hydration heat, and improvement of the finish) (Tokyay 2003). For this reason, its usage has increased over the years.

However, Figure 3 shows that the fluidity of the 40G mortar mixed with the various activators was lower than that of 40G mortar. In particular, the fluidity of the test specimen containing anhydrite gypsum as the activator dropped sharply. This can be explained by the compactness and elasticity being decreased with the expansion of pores as the exothermic reaction is increased, due to the chemical reaction according to the contents of the alkali stimulant (Sébaïbi et al. 2006) and its high reactivity with water and strong interaction between powder particles.

Compressive Strength

As shown in Figure 4, in general, as the ratio of GGBS is increased, the initial strength is decreased. However, when GGBS was mixed, it was confirmed that the long-age compressive strength was remarkably increased and the microstructure and the durability were improved. Specifically, for the cases of 20G and 40G, the compressive strength is higher than the general OPC mortar after 182 days. This is because GGBS makes $Ca(OH)_2$ of the cement that induces the pozzolanic reactivity, and forms C–S–H as the hydration constituent, resulting in a denser microstructure (Chidiac et al. 2008, Bentz 2006, Mazloom et al. 2004).

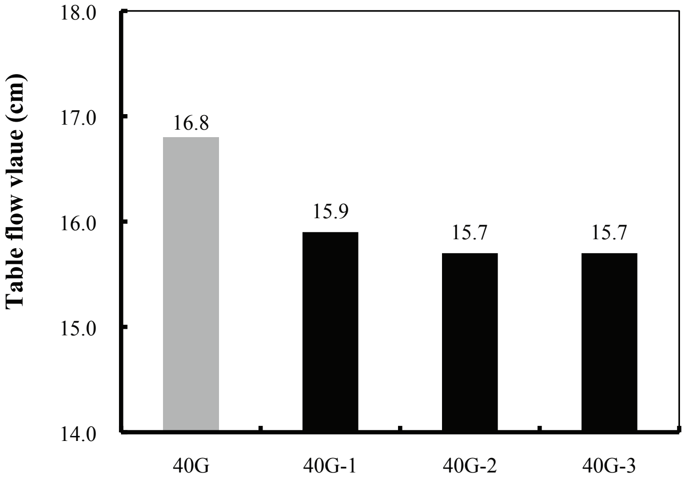
Figure 5 shows the properties of compressive strength by age of the test specimen cured as the OPC is simply replaced by GGBS. The GGBS 40% specimen by steam curing and 7-day aging was 1.6% higher than the 182-days compressive strength of the conventional cured mortar, and the compressive strength of the GGBS 60% specimen was 10.8% higher. This is because the pozzolanic reaction is accelerated to promote gel formation, as both the hydration proportion of the cement and the diffusion proportion of the hydration product increase at high temperature.

Effect of addition rate and type of activator

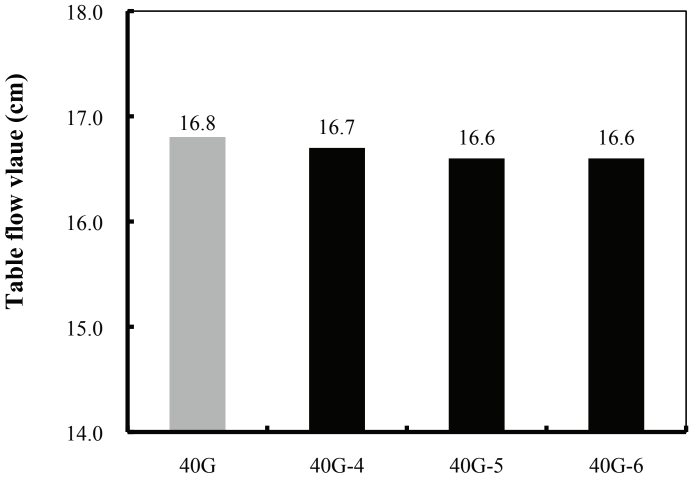
While GGBS does not become hydrated upon contact with water, when added with alkali or sulfate, it tends to hydrate and harden (Mun et al. 2003, Peiyu and Wenyan 2000).

$$\text{Pozzolan} + \text{CH} + \text{H} = \text{C-S-H} \qquad (1)$$

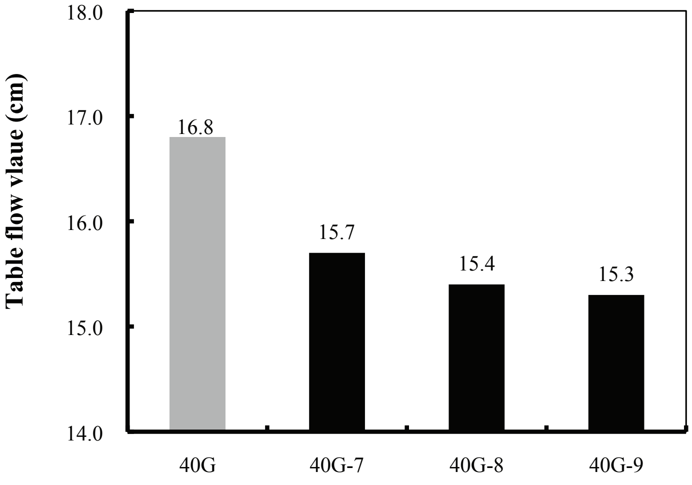
FIGURE 3. Flow of mortar containing GGBS and activator.



a) Anhydrous gypsum



b) $Ca(OH)_2$



c) Anhydrous gypsum and $Ca(OH)_2$

FIGURE 4. Compressive strengths of mortar according to GGBS replacement ratio at moisture curing.

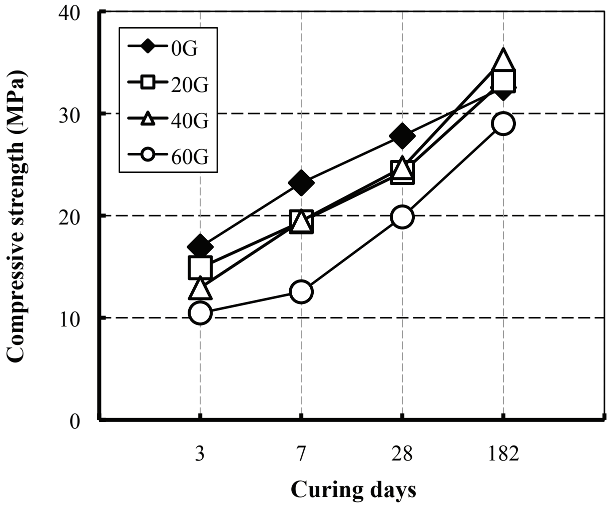
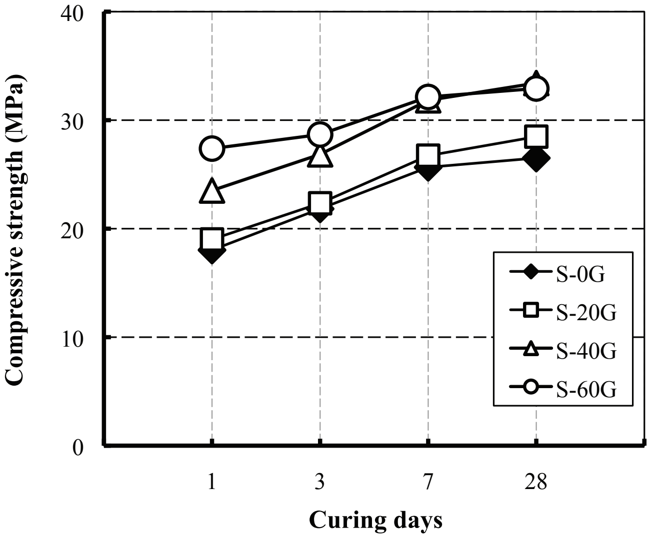


FIGURE 5. Compressive strengths of mortar according to GGBS replacement ratio at steam curing.



Eq. (1) is the chemical reactions of the cement and of the GGBS and its significance.

Gypsum played an important role in increasing the mechanical strength. As the stimulation of alkali and sulfate destroys the glassy film of GGBS, various ions eluted from GGBS react with gypsum to produce ettringite and gradually form C–S–H (Mun 2002). This means that the gypsum not only acts as a stimulant to destroy the film, but also reacts with GGBS to act as a binder (Mun et al. 2003, Mun 2002). In contrast, mixing a large amount of gypsum either creates cracks due to the volume expansion pressure resulting from the conversion of residual anhydrite into dehydrate gypsum (Erdem and Ölmez 1993).

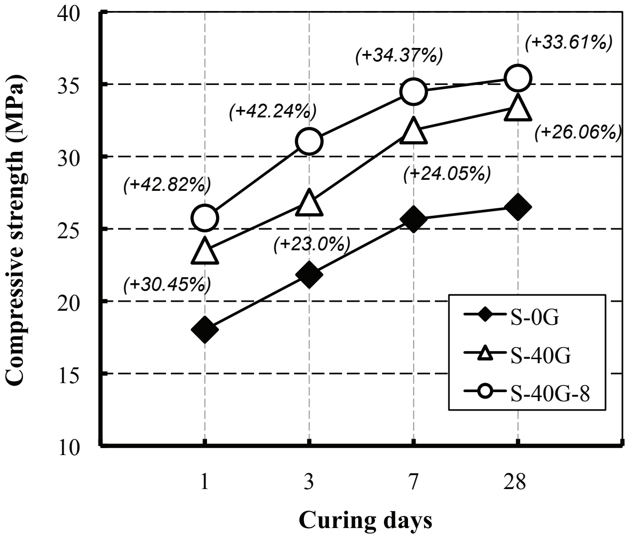
TABLE 3. Compressive strength of the mortars containing activators (MPa).

Type	1d	3d	7d	28d
S-0G	18.03	21.83	25.66	26.51
S-40G-1	20.03	24.25	27.81	28.15
S-40G-2	22.44	24.19	30.97	31.57
S-40G-3	24.83	27.83	28.58	29.03
S-40G-4	22.00	25.20	33.20	33.71
S-40G-5	21.80	24.20	32.20	32.84
S-40G-6	20.70	21.60	27.80	28.22
S-40G-7	22.81	24.30	28.81	29.58
S-40G-8	25.75	31.05	34.48	35.42
S-40G-9	24.19	28.50	30.22	30.96

S : Steam cured

As shown in Table 3, the compressive strength of the GGBS replacement mortar depends on the type and ratio of the activators. The test specimens mixing the GGBS with the activator showed that they all have a higher compressive strength than the comparative specimen of S-0G. In the cases of S-40G-1, 2, 3 specimens, in which the activator was mixed alone, the compressive strength was increased by increasing the anhydrite gypsum ratio; however, in the cases of S-40G-4, 5, 6 specimens, the compressive strength was proportionally decreased by increasing the $Ca(OH)_2$ mixing ratio. In contrast, for the specimens with simultaneous mixing of anhydrite

FIGURE 6. Comparison of compressive strength with added activators (S-40G8), without activator (S-40G) and with OPC (S-0G).



gypsum and $Ca(OH)_2$, the compressive strength of the mortars showed different trends. The compressive strength of S-40G-8 mortars with 40% GGBS-added anhydrite gypsum (4%) and $Ca(OH)_2$ (2%) increased to 34.48 MPa for 7-day.

Figure 6 shows the compressive strength of S-40G-8 compared to S-0G and S-40G. The strength of S-40G-8 increased about 42.8% for 1-day and 33.61% for 28-day over that of S-0G, and even increased about 12.4% for 1-day and 7.5% for 28-day over that of S-40G. The results indicate that the $Ca(OH)_2$ is consumed and C–S–H is formed. The anhydrite gypsum played a crucial role in revealing the early compressive strength of mortar under the same mixing condition (Mun et al. 2007). When substituting 40% GGBS, the best mixture ratio was 4% of anhydrite gypsum, and 2% of $CaOH_2$.

Figure 7 shows the result of DTA analysis. The determination of $Ca(OH)_2$ content is based upon the mass loss in the range of calcium hydroxide decomposition at about 450–550°C in the TG and DTG curves (Ei-Jazairi and Illston 1980). Meanwhile, the content of $Ca(OH)_2$ of S-40G-2 mortar with 40% GGBS and 4% anhydrite gypsum was about 0.6549% lower than that of the S-40G mortar. However, the S-40G-8 mortar with 40% GGBS and activator was about 0.5774% lower than that of the S-40G-2. Sobolev et al. (2007) suggested that the main difference between glass-containing mortar and normal cement is related to the decrease in the content of $Ca(OH)_2$, caused by consumption of $Ca(OH)_2$ as a result of the pozzolanic reaction. The S-40G-8 mortar showed a low peak value for $CaSO_4$ and $Ca(OH)_2$. This means that anhydrite gypsum and $Ca(OH)_2$ were partially used to destroy the hyaline films of GGBS, so that the ions are eluted in the GGBS to produce the ettringite and C–S–H.

Figure 8 shows the result of the XRD analysis of S-40G, S-40G-2, and S-40G-8. In S-40G-8, the peak of C–S–H and ettringite increased, compared to S-40G. The pozzolanic reaction produce a denser microstructure because C-S-H is formed (Jang et al. 2014).

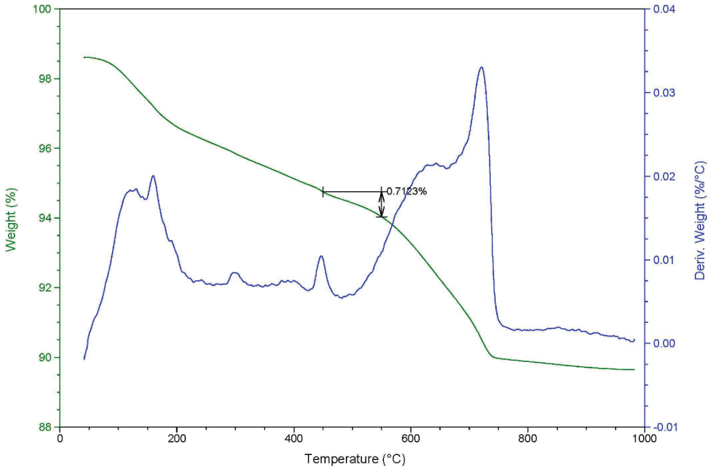
Field Test

Figure 9 shows PHC-piles using GGBS and activator. From the results of laboratory tests, the replacement rate of 40% GGBS and combined 4% anhydrite gypsum and 2% $Ca(OH)_2$ as an activator in mortar was excellent from the point of view of the mechanical characteristics. The compressive strength of PHC-pile with GGBS increased about 2 MPa over that of normal PHC-pile (Table 4).

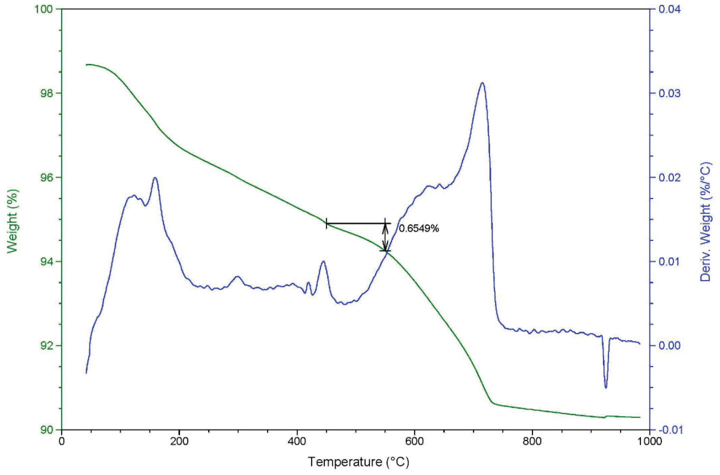
TABLE 4. Concrete pile product of physical characteristic.

Test item		Size (mm)			Bending strength (kN·m)		Axial force strength (kN·m)		Shear strength (kN)	Compressive strength (MPa = N/mm²)
		Outer diameter	Thickness	Length	Cracking flexural moment	Fracture flexural moment	Cracking flexural moment	Fracture flexural moment		
PHC Pile (OPC)	Ø400-10	402	67	10003	55.7 (Nomal)	87.8	184.7 (Nomal)	278.4	164.1	82.7
PHC Pile (40G-8)	Ø400-10	401	66	10003	54.5 (Nomal)	86.5	186.8 (Nomal)	281.1	165.4	84.6

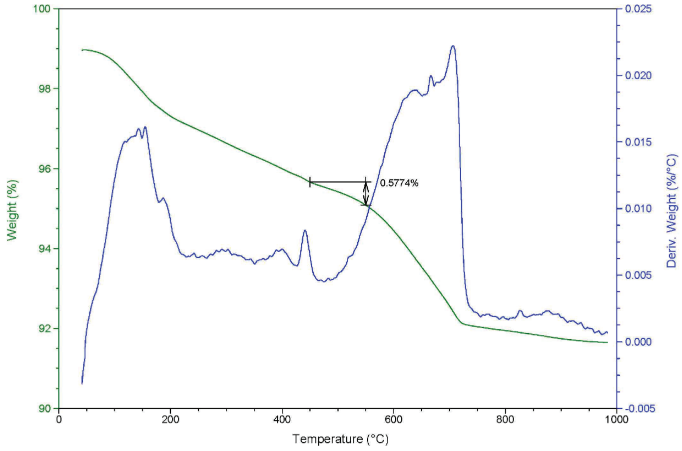
FIGURE 7. Schematic diagram of weight loss measurements of specimens using TG-DTA.



a) S-40G



b) S-40G-2



c) S-40G-8

FIGURE 8. X-ray diffraction patterns.

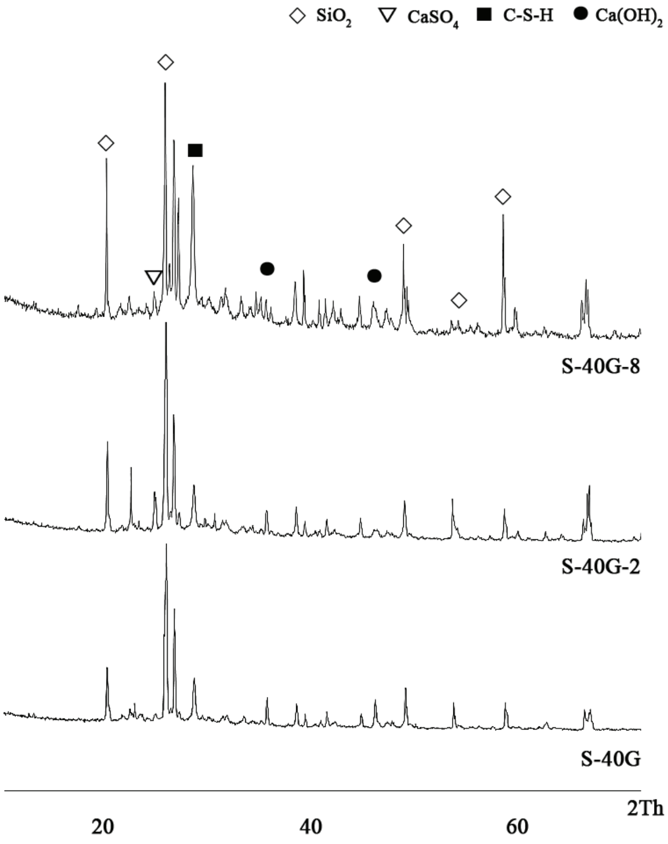


FIGURE 9. PHC-pile using GGBS and activator.

TABLE 5. Cost formula of PHC-pile type.

Type	PHC-pile (OPC only)	PHC-pile with GGBS (with 40% GGBS, Gypsum 4%, 1% $Ca(OH)_2$)
OPC	0.9 × \$54 = \$48.6	0.55 × \$54 = \$29.7
GGBS	—	0.38 × \$37 = \$14.06
Anhydrite Gypsum	0.1 × \$75 = \$7.5	0.04 × \$75 = \$3
$Ca(OH)_2$	—	0.02× \$108 = \$2.16
Total	\$56/ton	\$48.9/ton

* OPC: \$54/ton, GGBS: \$37/ton, Anhydrite Gypsum: \$75/ton, $Ca(OH)_2$: \$108/ton

Economic evaluation

Table 5 shows the results of the economic evaluation when the PHC-pile was manufactured using the final ratio of this study. As the result of substituting GGBS with 40% and using anhydrite gypsum and $Ca(OH)_2$, cost can be saved in the amount of 14.5%, compared with the conventional OPC-only piles.

CONCLUSION

- The workability of the mortar increased with GGBS due to the slower rate of the pozzolanic hydration process. But the addition of gypsum decreased their workability.
- The compressive strength of PHC-pile with 40% GGBS with activator was increased compared with that of the normal PHC-pile.
- GGBS is a very attractive mineral admixture to use in concrete, but proper curing and activating of GGBS concrete is important to ensure they meet their performance and durability to provide both economic and environmental benefits.

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