

# Effect of curing temperature on the properties of ground granulated blast furnace slag-cement bentonite slurry

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**Abstract.** To investigate the curing temperature effect on the engineering properties of ground granulated blast furnace slag-cement bentonite (GGBS-CB) slurry for cutoff walls, the laboratory experiments including the setting time, unconfined compressive strength, and permeability tests were carried out. The mixing procedure for GGBS-CB slurry was as follows: (1) montmorillonite-based bentonite slurry was first fabricated and hydrated for four hours, and (2) cement or GGBS with cement was added to the bentonite slurry. The dosage range of GGBS was from 0 to 90 % of cement by mass fraction. The GGBS-CB slurry specimens were cured and stored in environmental chamber at temperature of 14±1, 21±1, 28±1°C and humidity of 95±2% until target days. The highest average temperature of three seasons in South Korea was selected and used for the tests. The experimental results indicated that in early age (less than 28 days) of curing the engineering properties of GGBS-CB slurry were primarily affected by the curing temperature, whereas the replacement ratio of GGBS became a main factor to determine the properties of the slurry as the curing time increased.

**Keywords:** curing temperature; cutoff walls; ground granulated blast furnace slag; permeability; slag-cement bentonite; strength

## 1. Introduction

A slurry wall is vertical barrier with low hydraulic conductivity and has been used to prevent infiltration of groundwater from dams, levees, and reservoirs. Recently, growth of urbanization and industrialization have caused a large amount of household garbage and industrial waste, which requires sanitary landfills in or near urban region. In these sites, one of the biggest problems is leaching of contaminated liquid and water from the waste resulting in significant environmental issues including ecological destruction and harmful effects of human health and life. Implementing a slurry wall with low permeability in these zones has been considered as one of effective solutions not to spread the contamination (Institute of Civil Engineers (ICE), 1999). Soil-bentonite (SB), cement-bentonite (CB), slag-cement-bentonite (SCB) (or called ground granulated blast furnace slag-cement-bentonite (GGBS-CB)), fly ash-cement-bentonite (FCB), plastic concrete, high-density polyethylene geomembrane, and curtain grouting are primary construction materials of slurry walls (Bennert *et al.* 2005, Li *et al.* 2013, Kim and park 2019, Kim and Moon 2020, Huang *et al.* 2021). SB and SCB are the primary

composites to construct cut-off slurry walls in the United States and the United Kingdom, respectively (Opdyke and Evans 2005).

In 1938, Christian Vender was a pioneer who proposed the concept of a continuous structural wall based on supporting muds when it was excavated with bentonite (Xanthakos 1979). In 1945, Major General M.C. Tyler in US Army used a puddle clay cutoff wall (called slurry trench cutoff) to protect levees on the Mississippi river from erosion (Jefferis 1997). From 1970s to 1980s, SB slurry cutoff wall was mainly employed to manage groundwater and contamination in urban area (Millet and Perez 1981). In general, two-step procedure has been chosen in construction site: (1) the first phase was to pour the bentonite-water slurry in the excavated trenches and (2) the second one was to inject SB backfill slurry into the bottom of trenches and the bentonite slurry was displaced to the top of trenches (ICE 1999). The pros of SB slurry walls were low hydraulic conductivity (less than 10<sup>-7</sup> cm/sec), low price, and environmental-friendly (Sharma 1994, Du 2011). The SB slurry had no capability to carry a large amount of loads due to low strength, and a vast amount of working space was necessary in the field (Ryan 2008, Yiduo 2017). In addition to these weaknesses, due to low chemical resistance, it had been challenging to use it in contaminated zones (Jo *et al.* 2001, Kolstad *et al.* 2004, Fernandez and Quigley 2011, Scalia *et al.* 2014). According to the literature reviews by Caron (1972, 1973) and Canizo (1975), Caron constructed the bentonite cutoff walls using CB slurry in 1960s and 1970s in Europe. In 1978 and 1981, Guner and Card

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investigated the properties of CB slurry for cutoff wall and eventually developed the design method for CB slurry walls, respectively. Since CB slurry walls contained a large amount of cement, it was uneconomical and had high coefficient of permeability (approximately  $10^{-6}$  cm/sec). Guner (1978) and Card (1981) also proposed SCB (or GGBS-CB) slurry for cutoff walls by adding slag or ground granulated blast furnace slag (GGBS) to the CB slurry. The SCB slurry had lower hydraulic conductivity and higher strength than CB slurry. Due to these properties, the SCB (or GGBS-CB) slurry has been mainly employed for cutoff walls in the world. In 1999, Garvin and Hayles studied the cement-bentonite mixtures for cutoff walls containing the GGBS and pulverized fuel ash to investigate chemical resistance to contamination. Opdyke and Evans (2005) conducted the permeability and unconfined compressive tests on the SCB slurry and found that the coefficient of permeability decreased with under the conditions of 70 to 80% slag replacement. In 2010, Joshi *et al.* performed various tests to estimate the hydraulic conductive and performance of an 11-year-old SCB slurry wall at a contaminated region. It was measured that the permeability decreased with time by the three years and then converged to the certain point and its performance was dependent on aging, wall depth and location, and type and duration of contaminant. Snoeck *et al.* (2015) studied the autogenous shrinkage of mixture with GGBS and superabsorbent polymers. Royal *et al.* (2018) carried out the unconfined compressive strength, triaxial, and oedometer tests to evaluate the deformation and mechanical behaviors of SCB slurry walls exposed to various environmental conditions. In 2021, Huang *et al.* reviewed and summarized the four different types of self-hardening slurry CB, SCB, FCB, and Impermix slurry. In spite of a lot of articles, studies, and research on the investigation of GGBS-CB slurry cutoff walls in terms of engineering features, to the authors' knowledge, there are few works on the effect of curing temperature on the properties of GGBS-CB slurry. To bridge this gap, engineering characteristics of GGBS-CB slurry cured in different temperature conditions are first obtained through the laboratory tests, and the experimental results can be employed to update how curing temperature affects the engineering properties of the slurry.

The remainder of this study is organized as follows. First of all, the ordinary Portland cement (OPC), bentonite, and GGBS used in the research were first analyzed in terms of physical and chemical properties and the mixture proportions of GGBS-CB slurry were explained in detail. Second, the lab tests were carried out to identify the curing temperature effect on the engineering properties, and meaningful findings were finally reached through the data from the tests.

## 2. Experimental program

### 2.1 Materials

OPC (Type I KS L 5201) was employed in this experiment. Tables 1 and 2 present physical and chemical properties of OPC, respectively.

Table 1 Physical properties of OPC

Specific gravity	3.14	Density (g/cm <sup>3</sup> )	3.15	
Specific surface area (cm <sup>2</sup> /g)	3780	Curing time	Compressive Strength (MPa)	
Hydration heat (cal/g)	39	3 Day	32.1	
Setting time (min.)	Initial	280	7 Day	44.9
	Final	350	28 Day	55.1

Note: OPC is ordinary Portland cement

Table 2 Chemical properties of OPC

SiO <sub>2</sub> (%)	22.23	CaO (%)	64.58
Al <sub>2</sub> O <sub>3</sub> (%)	5.21	MgO (%)	2.3
Fe <sub>2</sub> O <sub>3</sub> (%)	3.38		

Table 3 Physical properties of bentonite

Specific gravity	2.46
Moisture content (%)	11.8
Particle size (% of passed by 200 mesh)	82.2
Swelling volume (ml/2 g)	25
pH	10.3

Table 4 Chemical properties of bentonite

SiO <sub>2</sub> (%)	53.8	MgO (%)	2.62
Al <sub>2</sub> O <sub>3</sub> (%)	18.4	K <sub>2</sub> O (%)	1.37
CaO (%)	3.37	Na <sub>2</sub> O (%)	3.74

Table 5 Physical properties of GGBS

Specific gravity	2.90	Curing time	Activity index (%)
Specific surface area (cm <sup>2</sup> /g)	4530	7 Day	65
Loss ignition (%)	1.03	28 Day	83
Chloride ion (%)	0.01	91 Day	99
MgO (%)	2.33		
SO <sub>2</sub> (%)	1.90		

Note: GGBS: ground granulated blast furnace slag

Bentonite is a clay composed of montmorillonite, which has the capability to absorb a large amount of water. In general, it is classified into three types, calcium bentonite, sodium bentonite, and activated calcium (sodium-calcium) bentonite, depending on the type of exchangeable sodium and calcium cations existing in the interlayers of bentonite particles (Sarvaiya *et al.* 2017). Calcium bentonite swells to approximately 20 Å in contact with water, while sodium bentonite swells to more than 150 Å, so it is mainly used as a liner and cover material (Fukushima 1984, Yun, *et al.* 2019). Swelling amount of activated calcium is between 20 and 150 Å. In this research, sodium bentonite, which has high swelling and ion-adsorption capacity, was used to ensure excellent water-repellent properties of the slurry. Tables 3 and 4 demonstrates the physical and chemical properties of bentonite, respectively.

Table 6 Mixture proportion of GGBS-CB cut-off walls

Sample	Materials (kg/m <sup>3</sup> )			Curing Temperature (°C)	
	B	C	GGBS		
S-0	200	0		14, 21, 28	
S-1	180	20			
S-2	160	40			
S-3	140	60			
S-4	60	120	80		to total volume of 1 m <sup>3</sup>
S-5		100	100		
S-6		80	120		
S-7		60	140		
S-8		40	160		
S-9	20	180			

Note: B is bentonite; C is cement; GGBS: ground granulated blast furnace slag

GGBS is an industrial by-product obtained from iron manufacturing and has a latent hydraulic property. The GGBS has been mainly used as an admixture due to several advantages that improve the physical properties of the composites including water tightness, fluidity, long-term strength, and chemical resistance. However, quality standards of GGBS are different from country to country because its properties vary depending on the place it is produced. In the experiment, commercial GGBS produced in South Korea was used and its physical properties are summarized in Table 5.

## 2.2 Mixture proportions

To investigate the effect of curing temperature on the physical properties of GGBS-CB slurry walls, the samples were initially produced by mixing 60 kg/m<sup>3</sup> of bentonite and 200 kg/m<sup>3</sup> of cement, and the cement was then replaced with GGBS with different replacement ratios. In general, the procedure of GGBS-CB slurry was as follows: (1) stirring bentonite and water for two minutes (called bentonite slurry), (2) hydrating it for four hours, and (3) adding slag and cement to the bentonite slurry and stirring them again for 3 minutes. Generally, hydraulic conductivity of fully hydrated bentonite was the range of  $1 \times 10^{-8} \sim 10^{-9}$  cm/sec, which was 10~100 times lower coefficient of permeability and higher strength of non-hydrated bentonite (Xiao *et al.* 2021). Because the proposed GGBS-CB cutoff walls in this study were mainly used to repair and reinforce reservoir dam bodies, hydration process was not required to achieve the best performance of cutoff walls with less than  $1 \times 10^{-5}$  of the coefficient of permeability.

Table 6 shows the mixture proportions of ground granulated blast furnace slag-cement bentonite (GGBS-CB) cutoff walls. Two-step procedure of GGBS-CB slurry is shown in Fig. 1. First step is that bentonite in the form of powder was mixed with water to make a bentonite slurry and stirring period was about 2 minutes. Second step is that cement or GGBS with cement was added into the bentonite slurry and mixing period was approximately 3 minutes.



(a) Placement of bentonite with water



(b) Mixing process of bentonite slurry for 2 min.



(c) Addition process of cement or cement with GGBS



(d) Stirring process of GGBS-CB slurry for 3 min.

Fig. 1 Preparation of GGBS-CB slurry with S-0 sample

The mixing speed for all samples was set at 550 RPM. All samples were cured in an environmental chamber (TEM1100, SAM HUNG MACHINERY CORP., KOREA) under three different temperatures (14, 21, and 28°C) and humidity of 95±2%. These temperatures were selected based on the highest average temperature of the three seasons (spring, summer, and fall) in 62 cities in South Korea. The seasonal temperature data were collected from the National Climate Data Center of the Korea meteorological administration.

## 2.3 Experimental methods

In order to obtain basic material properties of bentonite, swelling volume, pH, and chemical analysis test were conducted in accordance with KS K 0767, KS F 2103, KS L 4007, respectively. To investigate effects of curing temperature on properties of GGBS-CB slurry, the setting



time, unconfined compressive, falling head permeability test were performed as per KS L ISO 9597, KS F 2314, and KS F 2322, respectively. To measure the initial and final setting times of the GGBS-CB slurry, an Automatic Vicat apparatus (VICATMATIC-2 65-L2700, CONTROLS Group, Italy) was used and demonstrated in Fig. 2(a). The procedure of the setting time was carried out according to KS F 2322. However, as the GGBS-CB slurry was directly poured into the mold, the slurry flowed out of the bottom of the mold due to the high fluidity (high slump flow value). Therefore, aluminum container was employed, as presented in Fig. 2(b). The model was placed inside the aluminum container, the slurry was poured (see Fig. 2(c)). After completion of pouring, the slurry was cured in the environmental chamber at temperature of  $14\pm 1$ ,  $21\pm 1$ ,  $28\pm 1^\circ\text{C}$  and humidity of  $95\pm 2\%$  for about 20 hours, as display in Figs. 2(d) and 2(e). The bleeding was also observed. Measurement of the setting time was performed every 30 minutes after placing the samples in the apparatus. When the setting was not properly measured, the specimen was stored in the chamber again for 30 minutes. The measurement intervals were shortened from 30 minutes to 1 minute as the expected setting time approached.

Unconfined compressive strength tests were conducted according to KS F 2314. Fig. 3 shows procedures of specimen production for unconfined compression test. The compressive strength test specimens were fabricated using a mold with a diameter of 50 mm and a height of 100 mm. Because of the high fluidity of GGBS-CB slurry, the molds were placed in container box and the mixing slurry was



Fig. 3 Procedures of specimen production for unconfined compression test

poured (see Figs. 3(a) and 3(b)). After 20 hours of curing in the environmental chamber with target temperature and humidity, bleeding occurred as shown in Fig. 3(b). The specimens were extracted from the box and trimmed (see Figs. 3(c) and 3(d)). The specimens were cured in the environmental chamber with temperature of  $14\pm 1$ ,  $21\pm 1$ ,  $28\pm 1^\circ\text{C}$  and humidity of  $95\pm 2\%$  for the maximum 90 days. During the compressive strength test, the loading rate was maintained at 1 mm/min, which was 1% of the specimen's height for 1 minute.

The falling head permeability test was performed as per KS F 2322. Due to the high fluidity of GGBS-CB slurry resulting in leaks between the sides of the specimen and the mold and gap space between the specimen and the mold after curing, the following specimen production method was developed. Cylindrical mold with a diameter of 110 mm and a height of 120 mm was prepared as shown in Fig. 4(a).

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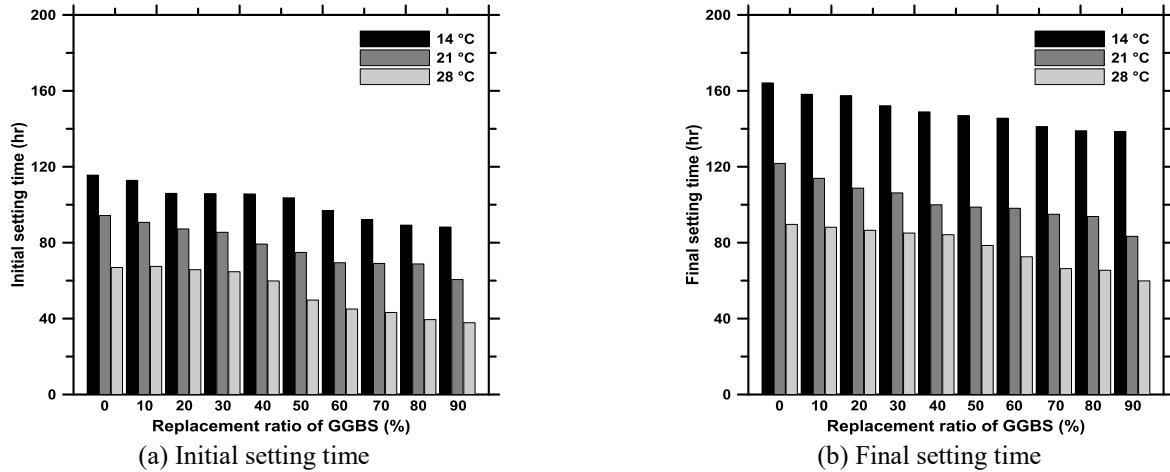


Fig. 5 Initial and final setting time

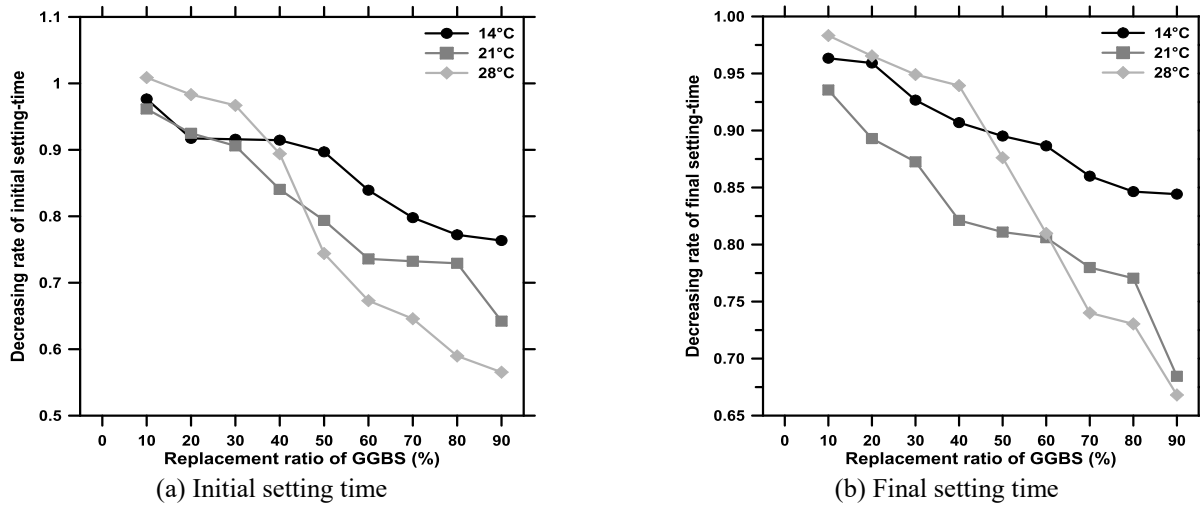


Fig. 6 Decreasing rate of setting time

after curing, the following specimen production method was developed. Cylindrical mold with a diameter of 110 mm and a height of 120 mm was prepared as shown in Fig. 4(a).

### 3. Experimental results and discussion

#### 3.1 Setting time

Fig. 5 provides the results of the initial and final setting times for GGBS-CB slurry under different curing temperatures. Based on the initial setting time of curing temperature of 14°C, the initial setting time of curing temperatures 21°C and 28°C decreased by about 0.69~0.82 times and 0.43~0.62 times, respectively. It was observed that the final setting time of the curing temperature of 14°C was approximately 0.60~0.74 times and 0.43~0.57 times shorter than that of the curing temperature of 21°C and 28°C, respectively. It signifies that setting time of GGBS-CB slurry was obviously influenced by curing temperature. In particular, the setting time of the GGBS-CB slurry for cutoff walls decreased with increasing the curing temperature, and the difference was greater at the final

setting time than at the initial setting. In addition, the difference in setting time between curing temperatures 14°C and 21°C was larger than that between curing temperatures 21°C and 28°C denoting that the lower the curing temperature, the greater the effect on the setting characteristics of GGBS-CB cutoff walls.

Fig. 6 shows the decreasing rate of setting time according to the replacement ratio of the GGBS. The decreasing rate is defined as ratio of the setting time of S-0 sample (0% of GGBS) to the setting time of each sample (from S-1 to S-9). When the curing temperature was 14°C, it was measured that the decreasing rate of initial setting time was 0.76~0.98, which was approximately -0.0027 of the slope (ratio of decreasing rate to replacement ratio of GGBS) with an R-squared ( $R^2$ ) of 94%. It signifies that the change in initial setting time according to the replacement ratio of GGBS was the smallest among the curing temperatures. In addition, for less than 40% of the GGBS replacement ratio, there was a little change in the decreasing rate of the initial setting time. However, the initial setting time tended to decrease significantly starting from the GGBS replacement ratio of 50%. It means that the GGBS replacement ratio of 40% or less had less influence on the

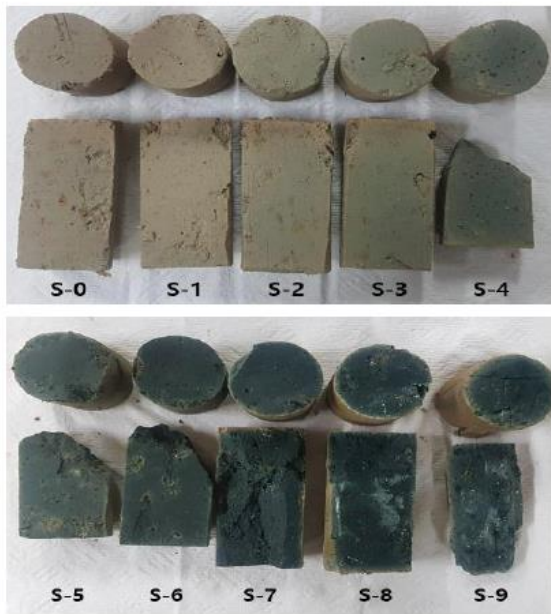


Fig. 7 Cross-section of specimens after 90 days of curing

determination of the initial setting time, while the GGBS replacement ratio of 40% or greater had the effect on the initial setting time of the slurry. In case of the curing temperature of 21°C, the decreasing rate of the initial setting time was between 0.64 and 0.96. Its slope was about -0.0039 with  $R^2$  of 96%, which was 144% less than that of the curing temperature of 14°C. Furthermore, there was a relatively constant decrease in the initial setting time as the replacement ratio of the GGBS increased among three different temperature conditions. For 28°C of the curing temperature, the decreasing rate of the setting time was 0.57~1.00, which was about -0.0064 of the slope with an  $R$ -squared ( $R^2$ ) of 95%. This was 237% less than that of the curing temperature of 14°C. It was obviously measured that as the curing temperature and replacement ratio of the GGBS increased, the slope of the decreasing rate of initial setting decreased. Moreover, the decrease pattern in initial setting time was similar to other curing temperatures until the GGBS replacement rate of 30%, whereas the initial setting time decreased significantly from the GGBS replacement ratio of 40%. It was clearly concluded that the initial setting time decreased as the GGBS replacement rate increased at all curing temperatures.

In addition, in case of GGBS replacement ratio of more than 50%, high curing temperature significantly reduced the initial setting time.

The decreasing rate of the final setting time was 0.84~0.96, 0.68~0.94, and 0.67~0.98 for the curing temperature of 14, 21, and 28 °C, respectively. Its slopes of curing temperature of 14, 21, and 28 °C were approximately -0.0016 with  $R^2$  of 97%, -0.0026 with  $R^2$  of 93%, and -0.0042 with  $R^2$  of 95%, respectively. Particularly, the slopes of curing temperature of 21 and 28 °C was 163% and 263% less than that of the curing temperature of 14°C, respectively. Decreasing trends of the final setting time were similar to the pattern of the initial setting time

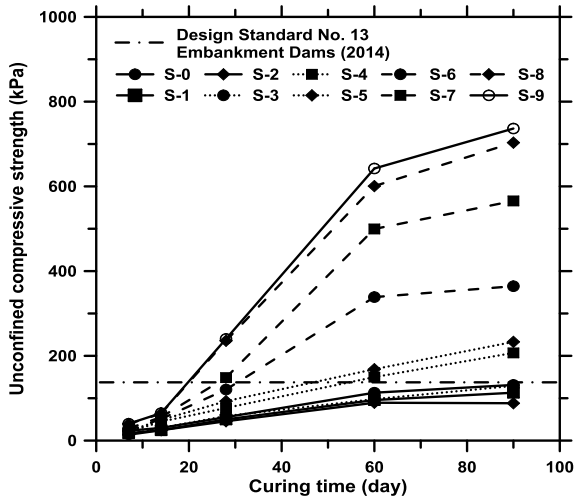
(compared Figs. 6(a) with 6(b)). In other words, the final setting time decreased as the GGBS replacement ratio increased. When the curing temperature was 14°C and 21°C, the final setting time consistently decreased with increasing as the GGBS replacement ratio, whereas for 28°C of the curing temperature, the final setting time tended to decrease significantly from a GGBS replacement rate of 40%. Therefore, it was confirmed that curing temperature and replacement ratio of GGBS obviously affected the determination of the setting time. It stands for that the setting time was influenced by the curing temperature.

### 3.2 Unconfined compressive test

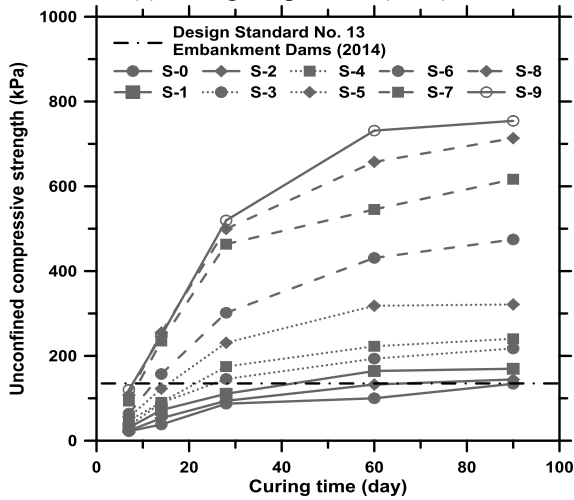
Fig. 7 depicts the cross-section of GGBS-CB specimens after 90 days of curing. The darker the color, the more GGBS was added. In addition to the color, it was clearly observed that the space of the mold was almost perfectly filled with the mixing slurry implying that the proposed GGBS-CB slurry can be used for cutoff walls in the field.

The unconfined compressive strength results of GGBS-CB slurry are shown in Fig. 8. The results marked in Fig. 8 was the average value of three specimens and there was no coefficient of variation due to ignorable standard deviation. It was clearly measured that the unconfined compressive strength increased as both the GGBS replacement ratio and curing period increased at three different curing temperatures. At the curing temperature of 14°C (see Fig. 8(a)), a dramatical increase in the strength was observed by 60 days of curing and its increasing rate significantly decreased. Moreover, when the replacement ratio and curing time were less than 30% and more than 90 days, respectively, the compressive strength was less than that of the Reclamation Design Standard (2014), which is 137.88 kPa (or 20 lb/in<sup>2</sup>). Although four compressive strengths with replacement ratio of 30% or less were less than the maximum value of the Standard, there was the minimum value of 68.95 kPa (or 10 lb/in<sup>2</sup>) so that the four strengths can satisfy that of the Standard. When the curing temperature was 21°C or 28°C (see Figs. 8(b) and 8(c)), a relatively sudden increase in unconfined compressive was obviously measured until 28 days of controlled curing, its slope began to decrease and it was then converged to a certain point. All compressive strength values were located within that of the Standard.

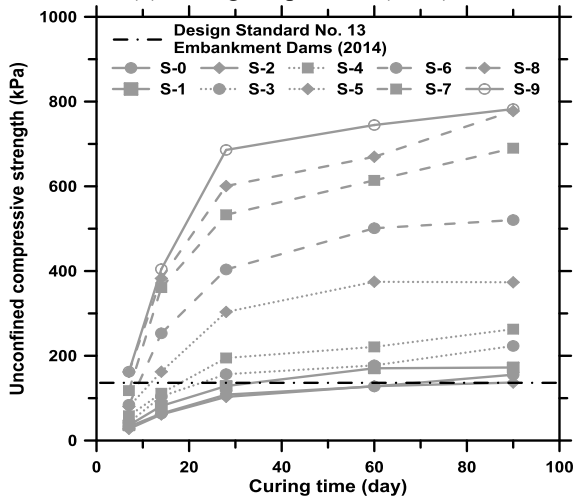
Fig. 9 shows the strength development ratio (SDR) of GGBS-CB slurry according to the replacement ratio of GGBS where the SDR is defined as a ratio of the unconfined compressive strength at 28 days to the compressive strength at 90 days. According to the Institute of Civil Engineers (ICE, 1999), there were the minimum value of hydraulic conductivity at 90 days and unconfined compressive strength at 28 days. This is the reason why the strength values at 28 days and 90 days were used for analyzing the SDR. The range of the SDR at 14, 21, and 28 °C was 0.26~0.52, 0.64~0.75, and 0.70~0.88, respectively. It was obviously observed that for the curing temperature of 14°C, the SDR decreased with increasing GGBS replacement ratio, while the SDR slightly increased as the replacement ratio increased when the curing temperature



(a) Curing temperature (14°C)



(b) Curing temperature (21°C)



(c) Curing temperature (28°C)

Fig. 8 Unconfined compressive strength of GGBS-CB slurry

was 21 and 28°C. It implied that at 28 days the compressive strength under the curing temperature at 14°C was lower than that under the curing temperature at 21 and 28°C and this was due to the delay of hydration reaction (Zhang *et al.* 2014, 2018, Teltayev and Suppes 2017, Zhu *et al.* 2019,

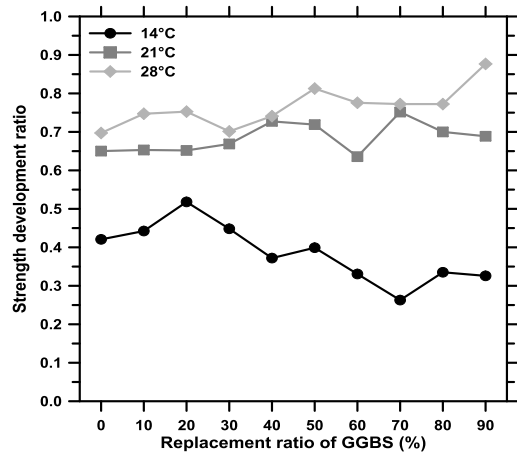


Fig. 9 Strength development ratio of GGBS-CB slurry

Kim *et al.* 2021). In addition, under the same mixing conditions and curing time, the higher the curing temperature, the greater the strength development of GGBS-CB slurry, and the strength was influenced by the curing temperature.

The unconfined compressive strength of GGBS-CB slurry according to the curing period is demonstrated in Fig. 10. In a relatively short curing period such as 14 and 28 days, it was measured that the difference in the unconfined compressive strength of the GGBS-CB slurry according to the curing temperature increased as the GGBS replacement ratio increased. In particular, when the replacement ratio of GGBS and curing days were 90% and 14 days (or 28 days), respectively, the difference between the strengths at 14 and 21°C and 14 and 28°C was 382 (or 216) and 624% (or 286%), respectively. It meant that the strength at a curing temperature of 14°C at 14 and 28 days of curing was significantly lower than that at a curing temperature of 28°C. In a relatively long curing period including 60 and 90 days, the difference in the strength of the mixture according to the curing temperature was significantly smaller than 14 and 28 days of curing, which indicates that the difference in the strength of the GGBS-CB slurry for cutoff walls according to the curing temperature decreased with increasing curing days because lower curing temperatures required longer curing period to develop strength (Zhang *et al.* 2014, 2018, Teltayev and Suppes 2017, Zhu *et al.* 2019, Kim *et al.* 2021).

### 3.3 Permeability test

Fig. 11 describes the hydraulic conductive of the GGBS-CB slurry at 28 and 90 days of curing with three different temperature conditions (14, 21, 28°C). At 28 days of curing, the range of the hydraulic conductivity was between  $2.38 \times 10^{-6}$  and  $9.68 \times 10^{-6}$  cm/sec, which satisfied the permeability value (less than  $10^{-6}$  cm/sec) in Reclamation Design Standard (2014). As the GGBS replacement rate was less than 40%, the coefficients of permeability under curing temperatures of 21 and 28°C were similar to each other, while in case of more than 50% of the GGBS replacement rate, the hydraulic conductivity at 21°C was slightly higher than that of 28°C (see Fig. 11(a)). In addition,

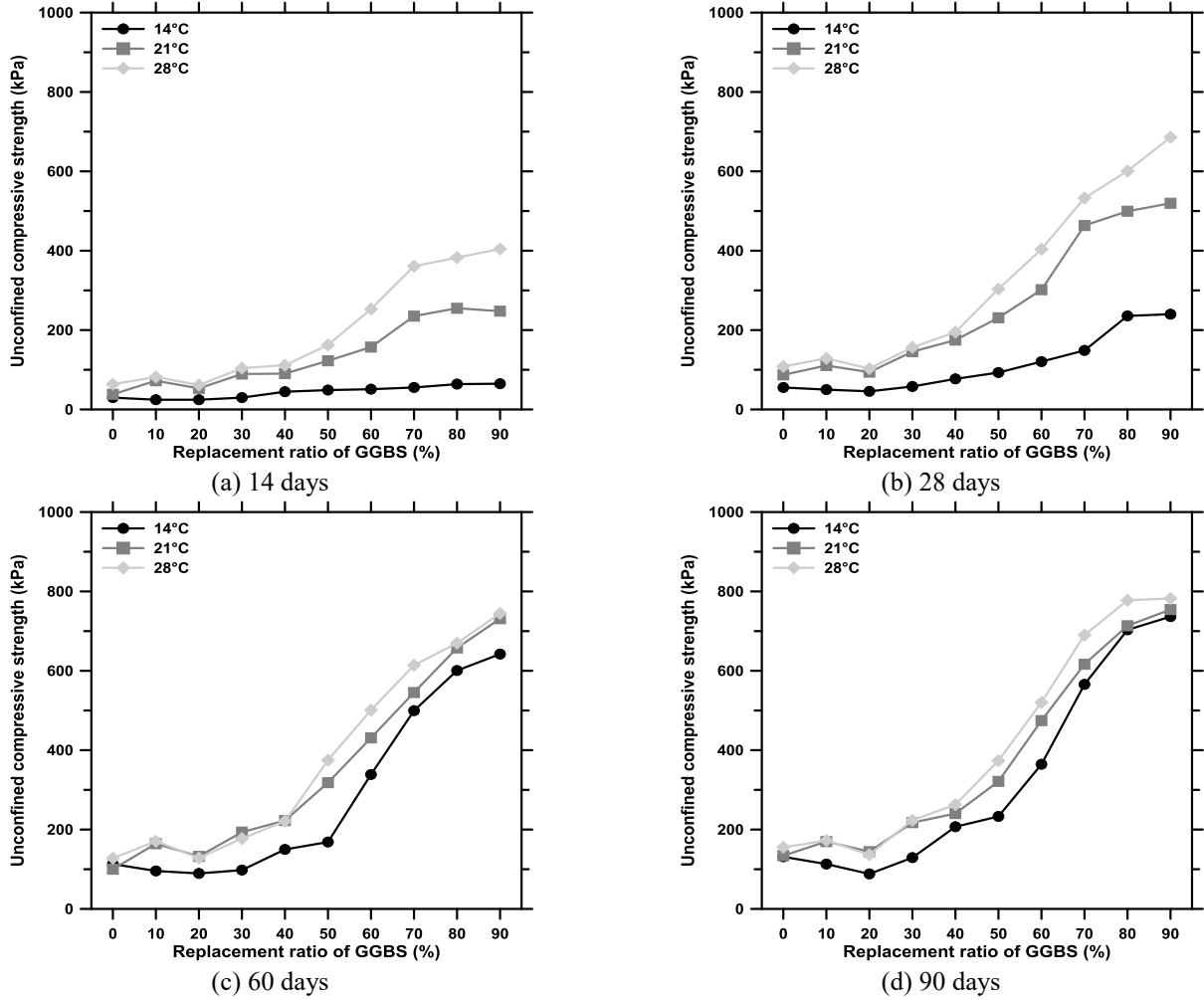


Fig. 10 Unconfined compressive strength of GGBS-CB slurry according to the curing period

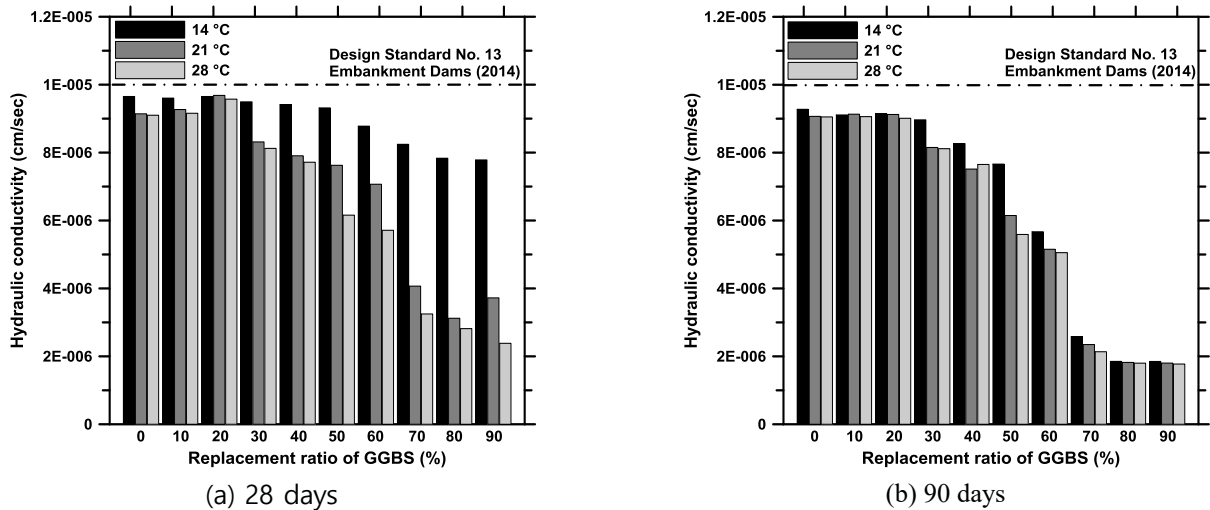
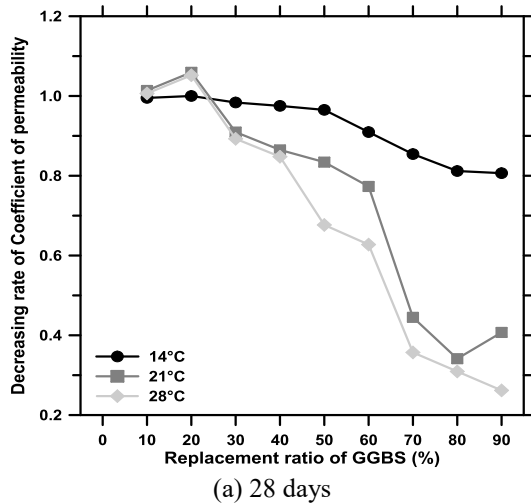


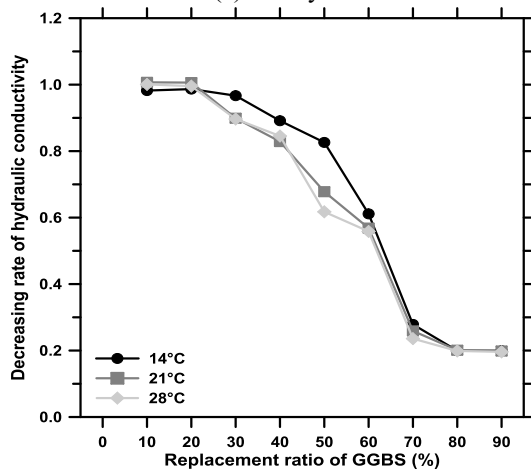
Fig. 11 Hydraulic conductivity of GGBS-CB slurry

when the curing temperature was 14°C, the coefficient of permeability was higher than that of the curing temperatures of 21 and 28°C at all GGBS replacement ratio. Particularly, difference in hydraulic conductivity increased with the GGBS replacement ratio. It was concluded that low curing

temperature resulted in a relative higher hydraulic conductivity regardless of the replacement ratio of GGBS at 28 days of curing. At 90 days of curing, the range of the coefficient of permeability was from  $1.77 \times 10^{-6}$  to  $9.28 \times 10^{-6}$  cm/sec, which was also less  $10^{-6}$  cm/sec (Reclamation



(a) 28 days



(b) 90 days

Fig. 12 Decreasing rate of hydraulic conductivity of GGBS-CB slurry according to replacement ratio of GGBS

2014). It was observed that the hydraulic conductivity of the GGBS-CB slurry under the same condition of the GGBS replacement ratio was similar to each other except for 50% of replacement ratio. This was considered as human error. It denoted that the difference in the coefficient of permeability of the mixing slurry according to the curing temperature decreased as the curing period increased.

Fig. 12 presents the decreasing rate of hydraulic conductivity according to the replacement ratio of the GGBS where the decreasing rate is defined as ratio of hydraulic conductivity of S-0 sample (0% of GGBS) to that of each specimen (from S-1 to S-9). At 28 days of curing, as the GGBS replacement ratio under curing temperature of 14, 21, and 28 °C increased, the coefficient of permeability decreased, as shown in Fig. 12(a). The range of decreasing rate was 0.81~1.00 at 14°C, 0.34~1.06 at 21°C, and 0.26~1.05 at 28°C. When the replacement ratio of GGBS was 20%, the decreasing rate was greater than 1.0 for 21 and 28 °C. It implied that hydraulic conductivity increased under the conditions of high temperature curing and 20% of GGBS replacement ratio. A slight increase in the hydraulic conductivity was considered as human error. Moreover, when the curing temperature was 14°C, it was clearly

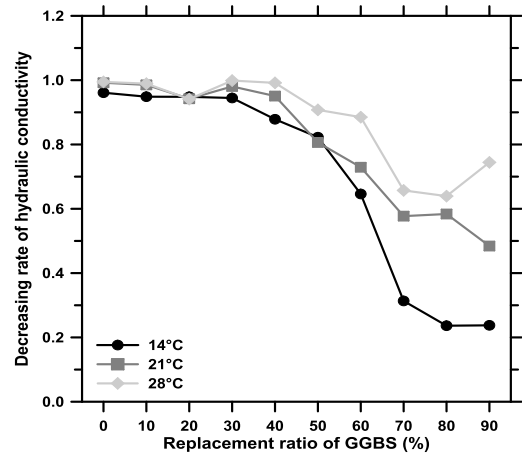


Fig. 13 Decreasing rate of hydraulic conductivity of GGBS-CB slurry according to curing time

calculated that the decrease in hydraulic conductivity was less than that under 21 and 28°C of curing temperature. After 90 days of controlled curing, the range of the coefficient of permeability at 14, 21, and 28°C was 0.20~0.99, 0.20~1.01, and 0.20~1.00, respectively, as exhibited in Fig. 12(b). The decreasing trend was similar to each other. It signified that effect of curing temperature decreased with curing time.

Decreasing rate of hydraulic conductivity of GGBS-CB slurry according to curing time is displayed in Fig. 13 where the decreasing rate of hydraulic conductivity is defined as a ratio of a hydraulic conductivity at 28 days to that at 90 days under the same mixing condition. At 14°C of the curing temperature, it was measured that the range of the decreasing rate was 0.24~0.96 and the slope ratio of a decreasing rate to a replacement ratio of GGBS) was approximately -0.0095 with  $R^2$  of 84%. The range of the decreasing rate at curing temperature of 21 and 28°C were 0.48~0.99 and 0.63~0.99, respectively, and their slopes were approximately -0.0061 with  $R^2$  of 88% and -0.004 with  $R^2$  of 71%, respectively. To sum up, the slopes of curing temperature of 21 and 28 °C were 65% and 42% of the slope at 14°C, respectively. In addition, when the GGBS replacement ratio was less than 30% at all curing temperatures, there was almost no change in the coefficient of permeability, whereas the coefficient of permeability started to decrease as the curing period increased at replacement ratio of 40%. In particular, the sharp decrease in the hydraulic conductivity was observed when the replacement ratio of exceeded 70%. It denoted that the effect of curing temperature was dominant based on short period (28 days) of curing time, while the replacement ratio of GGBS was a critical factor to determine the hydraulic conductivity when curing time was 90 days or more.

#### 4. Conclusions

To identify the effect of curing temperature on engineering properties of GGBS-CB slurry, a laboratory tests such as setting time, unconfined compressive strength, and permeability tests were conducted with samples

fabricated with ten different replacement ratios of GGBS and three different curing temperatures. The following conclusions can be drawn;

- Based on the experimental results of setting time tests, it was measured that the setting time was shortened as the curing temperature and GGBS replacement ratios increased. In addition, the greater the curing temperature, the greater the decrease in setting time according to the GGBS substitution rate.
- As a result of the unconfined compressive strength tests, it was analyzed that the higher the curing temperature, the higher strength. In particular, at 28 days of curing the SDR slightly increased with GGBS replacement ratio when the curing temperature was 21 or 28°C, while the SDR decreased as the replacement ratio increased under the curing temperature condition of 14°C. It signified that under the same mixture proportion and curing period, the strength of GGBS-CB slurry for cutoff walls increased with higher curing temperatures.
- In a short curing time including 14 and 28 days in this study, the difference in the unconfined compressive strength of the GGBS-CB slurry according to the curing temperature increased with the GGBS replacement ratio. It denoted that under the condition of short curing time the strength at a curing temperature of 14°C of curing was significantly lower than that at 28°C. On the contrary to this, in a relatively long curing time such as 60 and 90 days, the difference in the strength of the mixture according to the curing temperature was smaller than the short curing time, which indicates that the difference in the strength of the GGBS-CB slurry for cutoff walls according to the curing temperature decreased with increasing curing days because lower curing temperatures required longer curing time for the required strength of the slurry.
- It was found that high curing temperature resulted in decrease in the hydraulic conductivity of GGBS-CB slurry and at all three different temperatures the hydraulic conductivity decreased as the GGBS replacement ratio increased. Moreover, the decrease in the coefficient of permeability according to the increase in the GGBS replacement ratio was more observed with increasing the curing temperature.
- As the curing period increased, the hydraulic conductivity of the GGBS-CB slurry for cutoff walls decreased. In particular, it was obviously measured that when the curing temperature and the replacement ratio of GGBS were 14°C and greater than 70%, respectively, the coefficient of permeability rapidly decreased with the curing time. When the curing temperature was 14°C, the hydraulic conductivity at 28 days of curing was very high compared to the case where the curing temperature was 21 and 28°C. This difference in the hydraulic conductivity became larger as the GGBS replacement ratio increased, but after 90 days of curing, the coefficients of permeability of the GGBS-CB slurry according to the curing temperature were similar to each other. Therefore, it was concluded that the effect of the curing temperature on the hydraulic conductivity of the slurry decreased with the curing time.

- The engineering properties such as the setting time, compressive strength, and hydraulic conductivity of GGBS-CB slurry in early age of curing were greatly influenced by the curing temperature. However, as the curing time increased, the replacement ratio of GGBS became dominant to determine the properties of the slurry.

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