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RESEARCH ARTICLE

Production of Ground Granulated Blast-furnace Slag Cement: Energy and Carbon Reduction Efficiency of Cement-grinding System

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Abstract

This study used clinker, ground granulated blast-furnace slag (GGBS), and gypsum in a cement-grinding system to produce GGBS cement (GCE). Gypsum was used as the alkaline activator to modify the surface area of GCE and increase its compressive strength. The results revealed that the use of the gypsum activator and the modification of the surface area of GCE effectively increased the formerly inadequate compressive strength of GCE (GGBS >60%) in the early stage. In addition, energy consumption data were obtained during the production of GCE and Portland cement (PCE) by the cement-grinding system. The calculations concerning the production proportions indicated that when GCE was produced in place of PCE, the overall demand for clinker fell by 65%. By comparison, the total energy consumption per ton of production decreased from 1539 to 602 kWh, and CO_2 emissions decreased from 0.78 to 0.31 tons. Furthermore, energy efficiency and carbon-reduction efficiency both reached 60.9%. In summary, the production of GCE through the proposed cement-grinding system appears to be feasible and able to considerably increase the energy efficiency and carbon reduction efficiency of cement production.

Keywords: Admixtures, Cement, Compressive strengths

1. Introduction

To address the threat of ecological imbalance that has come to jeopardize human living environments in the 21st century, in 2015, multiple nations signed the Paris Agreement at the headquarters of the United Nations to formally replace the Kyoto Protocol, which had been signed in 1998. The Paris Agreement stipulates the reduction of greenhouse gas emissions with a view to limiting the increase of the global average temperature to no more than 2 °C above preindustrial levels. Held in Glasgow, Scotland, in late 2021, the United Nations Climate Change Conference (COP26) constituted the first evaluation of climate change after the signing of the Paris Agreement. The concept of "fossil fuel phase-out" was included in the official pact of the COP26 summit. In addition, "Net Zero by 2050" became a global consensus intended to signal the end of the fossil fuel era. Finally, sustainable development became a common goal of nations worldwide.

Construction sustainability has been highlighted in the development policy reports of numerous nations with the aim of reducing environmental damage due to construction activities and resource consumption. The amount of carbon emissions produced by the global cement industry in 2000 was approximately 1 billion tons, and this figure increased considerably to more than 1.5 billion tons by 2010. In construction, 1 ton of cement generates approximately 0.773 tons of CO_2. The International

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Abbreviations: Sa, Surface area; *Ss*, 114p standard cement, $Sa = 377.4\ m^2/kg$; *T*, Time required = 117s; *Ts*, When air was passed through the fixed bed, the time required for the liquid level to drop to the designated scale.

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Energy Agency estimated that the amount of carbon emissions resulting from cement production will continue to increase despite the implementation of reduction measures because of the increasing demand for cement; thus, cement production is projected to account for 9%−10% of the total amount of global carbon emissions by 2050. Khan [1] indicated that to produce environmentally friendly concrete, the amounts of Portland cement (PCE) and admixtures should be reduced and increased, respectively. In addition, Mehta [2−4] advocated the use of industrial waste products (e.g., fly ash, slag) to facilitate cement conservation and reduce the negative environmental impact caused by the production and application of cement concrete. According to the World Steel Association [5], the total global amount of pig iron produced in 2018 was 1.247 billion tons/year, and the total amount of blast-furnace slag (BFS) produced was approximately 500 tons/year. Ground granulated BFS (GGBS) and PCE [6] have similar compositions in the C−S−A system phase diagram. In addition, both undergo cementation and the Portland reaction and are extensively used in engineering projects. According to ASTM [7], maximum GGBS replacement can reach 70% (cement weight ratio). Escalante [8] highlighted that GGBS cement (GCE) has inadequate early-stage strength, and this problem is more pronounced when the proportion of GGBS is greater.

To address the inadequate compressive strength of GCE in the early stage, numerous studies [9−11] have employed alkali activation to stimulate the activity of GGBS and enhance its early-stage strength. In addition, Davidovits [12] used a specific concentration of NaOH solution with minerals rich in Si, Al, and Ca (e.g., kaolinite, limestone, and dolomite) to create “geopolymer,” a new adhesive with a compressive strength of 15 MPa. The results of that study constituted a milestone in research on alkali-activated aluminosilicate materials. Alkali activation [13] can be achieved through two mechanisms. In the first mechanism, Si−Al alloys (most commonly pulverized fuel ash, kaolinite, and metakaolin) rich in Al_2O_3 and SiO_2 are applied. In the second mechanism, Si−Ca alloys (most commonly GGBS) rich in CaO and SiO_2 are employed, and C−(A)−S−H (which is similar to cement) is the main colloid. To enable the $Ca(OH)_2$ generated by GCE in a cement hydration reaction to react with the SiO_2 in GGBS to produce C−S−H colloids, the most common method [14−16,28,29] is to break the bonds of Si, Al, and Ca by using a high-concentration alkaline solution to generate an activation reaction of the dissociated Si, Al, and Ca ions with the silicate and alkali mental ions provided by the alkaline solution. Research [17,18] indicated that the Si, Al, and Ca bonds in GGBS easily break in an alkaline environment with a pH of ≥11.5. Mineral activators (e.g., limestone powder, gypsum) can be used to achieve alkali activation and have a satisfactory effect on construction and durability. In addition to applying alkaline activators, increasing the surface area (*Sa*) of GCE is another primary method for enhancing compressive strength [19,27]. Lin and Yang [20] suggested that using gypsum as an alkaline activator when the GCE *Sa* is $\geq 600\ m^2/kg$ can effectively improve the early-stage compressive strength of GCE. Furthermore, the appropriate addition of slag or fly ash as a cement replacement material can directly reduce the amount of CO_2 generated, improve the durability of cement concrete, and increase the added value and reusability of industrial waste [21−23].

The present study produced GCE by using clinker, GGBS, and gypsum in a cement-grinding system while performing gypsum alkali activation and GCE *Sa* modification. The objective was to improve the inadequate compressive strength of GCE in the early stage. The results indicated that the proposed solution is feasible. Additionally, this study compared GCE and PCE produced by the cement-grinding system in terms of their energy and carbon reduction benefits by examining the amounts of energy consumed and CO_2 generated.

2. Materials and experimental methods

Although according to ASTM C150 [27], the compressive strength of 3, 7, and 28 days only needs to be greater than 12 MPa, 19 MPa and 28 MPa. However, with the improvement of the cement manufacturing level, the compressive strength of each age is significantly higher at the specified value. Therefore, the compressive strength target set as 3 d fc’ ≥ 20 MPa; 7 d fc’ ≥ 30 MPa; 28 d fc’ ≥ 40 MPa.

In the present study, GGBS content (>60%) was used to replace clinker for the production of GCE. The objectives for early-stage compressive strength were achieved by adjusting activated materials and the GCE *Sa*. According to the amount of energy loss during the production process and the market demand for cement, the energy and carbon reduction benefits of the GCE and PCE produced were estimated.

2.1. Materials and preparation of specimens

Laboratory test used cement, GGBS, and gypsum as raw materials to produce GCE (Density 3.15, 2.90, and 2.31, respectively). The chemical compositions of the raw materials are shown in Table 1. In experiments to improve the early-stage compressive strength of GCE, PCE was used as the control group, and T0, composed of 40% cement and 60% GGBS by weight, served as the GCE test group. For T1, which was the T0 sample with added gypsum, the effect of the activator on compressive strength was observed. T2–T4 were the samples where a gypsum activator was added and multiple GGBS *Sa* adjustments were made, resulting in secondary improvement of compressive strength. The PCE and T0–T4 samples were mixed with cement mortar mixture with the proportions listed in Table 2. The gypsum activator was used primarily to limit the SO_3 content to 6.0% ± 1.0% so that the optimal best alkali activation effect could be achieved [20]. The analysis of PCE and the T0–T4 components is detailed in Table 3. In accordance with ASTM code C109 [24], C778 standard Ottawa-graded sand was used, cement mortar was mixed at a water–binder ratio of 0.484, specimens measuring $5 \times 5 \times 5$ cm^3 were casted, and demolding was performed on the subsequent day for conservation for 3, 7, and 28 days before compressive strength tests were conducted.

The specific gravities of the clinker, GGBS, and gypsum used to produce GCE and PCE were 3.20, 2.90, and 2.31, respectively; the basic physical and chemical properties of these materials are listed in Table 4. The composition of PCE per unit was 95% clinker and 5% gypsum. Because considerable amounts of GGBS and the gypsum activator were used to produce GCE, the composition of GCE per unit was 30% clinker, 60% GGBS, and 10% gypsum. The proportions of PCE and GCE in the mixture are listed in Table 5. Continuous grinding was performed for 12 hours for the production of both GCE and PCE. During the production process, samples were taken every 2 hours to analyze the *Sa* properties and chemical composition (Table 6). As shown in Table 6, the SO_3 content in the PCE was 2.5% ± 1%, and gypsum was used as the activator to produce GCE; as a result, the SO_3 content in the GCE substantially increased to 6.0% ± 1%. Furthermore, the *Sa* of the PCE was 370–380 m^2/kg, whereas that of the GCE was 570–670 m^2/kg considerably larger because *Sa* modification had been required for the GCE.

Table 1. Basic physical and chemical properties of materials.

Materials	Chemical Composition (%)							
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O
Cement	63.45	21.00	4.04	3.41	2.30	2.38	0.25	0.62
GGBS	42.69	33.46	13.70	0.42	6.21	1.48	–	0.35
Gypsum	42.03	2.02	1.71	0.55	0.48	52.88	0.06	0.21

2.2. Method of test for fineness (Air permeability apparatus)

In accordance with ASTM C204 [25], Blaine's air permeability tester was used to measure the *Sa* (m^2/kg) of the particles contained within a unit mass of particle sample. The key step was the tight compression of a test sample with a fixed mass of 2.9418 g into a fixed bed. When air was passed through the fixed bed, the tester was used to measure the time required (*Ts*) for the liquid level of the sample to decrease to the designated level. The values obtained from the test sample and reference materials were substituted into Eq. (1), and the *Sa* value of the test sample was obtained.

$$Sa = \frac{S_S\sqrt{T}}{\sqrt{T_S}} \quad (1)$$

Ss: 114p standard cement, *Sa* = 377.4 m^2/kg.
T: Time required = 117s.

3. Results and discussion

3.1. Comparison of PCE and GCE under multiple modification conditions

Multiple studies [15,16,20] have indicated that two conditions must be met to improve the inadequate early-stage compressive strength of GCE. The first condition pertains to activator selection and the amount of activator used; the second condition is a high GCE *Sa*. The compressive strength levels of the GCE produced using the gypsum activator under multiple GCE *Sa* modification conditions were compared with those of the PCE that was produced. The PCE group served as the control group, and the T groups served as the GCE test groups. The material composition data, *Sa* data, and chemical composition data of the mixtures are listed in Tables 2 and 3. The compressive strength levels of the control group and the test groups were examined using the ASTM C109 [24] method; the data are presented in Table 7. First, in the T0 group, a considerable amount of GGBS (>60%) was used to replace PCE, leading to a reduction in the amount of hydration products and further causing the compressive strength levels of the produced GCE to be lower than those of the PCE on the 3rd, 7th, and 28th days. The compressive strength levels of the GCE on the 3rd, 7th, and 28th days were −49%, −39%, and −25%, respectively (Fig. 1). Accordingly, when a considerable amount of GGBS was used in place of PCE and when no activator was employed to increase the activity of GGBS or to modify the *Sa*, the compressive strength of the GCE was considerably lower than that of the PCE. Fig. 1 reveals that using the

Table 2. Cement mortar mixture compositions of PCE and T groups and surface area data.

Group	Unit content (kg/m^3)						Binder materials *Sa* (m^2/kg)			
	Cement	GGBS	Gypsum	Water	Aggregate	Weight	Cement	GGBS	Gypsum	Mix
PCE	170.4	0.0	–	82.5	460.0	1838.1	360	–	–	360
T0	51.1	119.3	–	82.5	460.0	1808.3	360	450	–	428
T1	47.0	109.7	13.6	82.5	460.0	1799.2	360	450	770	438
T2	47.0	109.7	13.6	82.5	460.0	1799.2	360	530	770	508
T3	47.0	109.7	13.6	82.5	460.0	1799.2	360	650	770	604
T4	47.0	109.7	13.6	82.5	460.0	1799.2	360	740	770	668

Table 3. Chemical compositions of PCE and T groups.

Materials	Surface area (m^2/kg)	Chemical Composition (%)							
		CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O
PCE	360	63.45	21.00	4.04	3.41	2.30	2.38	0.25	0.62
T0	428	50.08	23.59	16.55	2.31	4.41	2.17	0.24	0.53
T1	438	50.07	21.56	14.41	1.68	4.80	6.00	0.29	0.39
T2	508	50.20	21.70	14.52	1.60	4.40	6.12	0.20	0.45
T3	604	50.33	21.89	14.31	1.56	4.46	6.00	0.21	0.44
T4	668	49.72	21.27	14.67	2.01	4.84	6.09	0.20	0.36

Table 4. Basic physical and chemical properties of production materials.

Materials	Density (g/cm^3)	Chemical Composition (%)							
		CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O
GGBS	2.90	42.69	33.46	13.70	0.42	6.21	1.48	–	0.35
Gypsum	2.31	42.03	2.02	1.71	0.55	0.48	52.88	0.06	0.21
Clinker	3.20	64.83	21.14	5.07	3.65	2.23	0.64	0.35	0.48

Table 5. Mixture proportions for producing PCE and GCE.

Group	Unit content (kg/m^3)					
	Clinker	GGBS	Gypsum	Water	Aggregate	Weight
PCE-1	161.9	0.0	8.5	82.5	460.0	1862.1
PCE-2	161.9	0.0	8.5	82.5	460.0	1862.1
PCE-3	161.9	0.0	8.5	82.5	460.0	1862.1
PCE-4	161.9	0.0	8.5	82.5	460.0	1862.1
PCE-5	161.9	0.0	8.5	82.5	460.0	1862.1
PCE-6	161.9	0.0	8.5	82.5	460.0	1862.1
GCE-1	51.1	102.2	17.0	82.5	460.0	1823.8
GCE-2	51.1	102.2	17.0	82.5	460.0	1820.0
GCE-3	51.1	102.2	17.0	82.5	460.0	1820.0
GCE-4	51.1	102.2	17.0	82.5	460.0	1820.0
GCE-5	51.1	102.2	17.0	82.5	460.0	1820.0
GCE-6	51.1	102.2	17.0	82.5	460.0	1820.0

gypsum activator while employing the method applied to the T0 group increased the SO_3 content in the T1 group from 2.17% to 6.0%. Although the compressive strength levels of the produced GCE on the 3rd (−43%), 7th (−35%), and 28th (−20%) days were still lower than those of the produced PCE, they were higher than those of the T0 group; this finding indicated that the use of the gypsum activator increased the compressive strength of GCE. In brief, the gypsum activator was used to increase GGBS activity, and the GGBS *Sa* was modified to increase the GCE *Sa* in groups T2—T4. Although the compressive strength levels of the GCE produced in multiple stages were still lower than the corresponding strength levels of the produced PCE (T2: −32% to −3%; T3: −26% to −5%; T4: −14%—8%), the increase of the GCE *Sa* through *Sa* modification effectively increased the compressive strength levels of the produced GCE in all stages. Furthermore, an increase in the compressive strength level was revealed to be positively correlated with an increase in the GCE *Sa*.

In summary, the compressive strength of the GCE was considerably lower than that of the PCE when no improvement measures were applied. The use of an activator to increase GGBS activity alongside the implementation of *Sa* modification substantially and effectively increased compressive strength. By contrast, the use of a single method produced limited effects the designated compressive strength standard could be achieved only when both methods were applied in combination.

3.2. Comparison of produced GCE and PCE

The results of this study revealed that the use of the gypsum activator in GCE production effectively increased the SO_3 content, promoted GCE *Sa*

Table 6. Surface area and chemical compositions of produced PCE and GCE.

Group	*Sa* (m^2/kg)	Chemical Composition (%)							
		CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O
PCE-1	372	62.68	21.38	4.24	3.60	2.55	2.29	0.32	0.48
PCE-2	373	62.60	21.41	4.31	3.52	2.57	2.27	0.36	0.50
PCE-3	376	62.57	21.45	4.34	3.45	2.62	2.24	0.36	0.51
PCE-4	372	62.59	21.48	4.38	3.33	2.66	2.22	0.37	0.48
PCE-5	374	62.59	21.48	4.39	3.33	2.67	2.20	0.37	0.47
PCE-6	379	62.64	21.29	4.58	3.27	2.55	2.24	0.38	0.54
GCE-1	625	50.21	24.18	9.58	1.09	3.80	6.43	0.51	0.35
GCE-2	599	50.47	24.65	10.03	1.33	4.40	6.31	0.53	0.37
GCE-3	649	50.21	24.69	10.12	1.89	4.46	6.25	0.48	0.34
GCE-4	650	50.38	23.42	10.00	1.73	3.84	5.86	0.51	0.35
GCE-5	625	49.66	23.56	9.40	1.64	3.97	5.99	0.51	0.33
GCE-6	584	49.95	23.46	9.18	1.69	4.58	6.22	0.49	0.32

Table 7. Compressive strength of Portland cement group and T groups.

Group	Compressive strength (MPa)											
	3 day				7 day				28 day			
	Data 1	Data 2	Data 3	average	Data 1	Data 2	Data 3	average	Data 1	Data 2	Data 3	average
PCE	24.4	24.6	24.3	24.4	33.1	34.2	34.1	33.8	41.0	41.5	40.8	41.1
T0	12.9	12.5	11.9	12.4	21.8	20.5	19.9	20.7	30.2	31.3	31.5	31.0
T1	14.0	13.9	14.0	14.0	22.0	22.0	22.1	22.0	33.0	32.7	33.0	32.9
T2	16.5	16.6	16.6	16.6	24.8	25.3	24.8	25.0	35.5	35.1	35.3	35.3
T3	21.3	21.5	21.6	21.5	28.0	28.3	29.0	28.4	37.8	38.2	38.1	38.0
T4	23.9	23.9	23.7	23.8	33.0	31.5	31.6	32.0	44.4	44.9	44.5	44.6

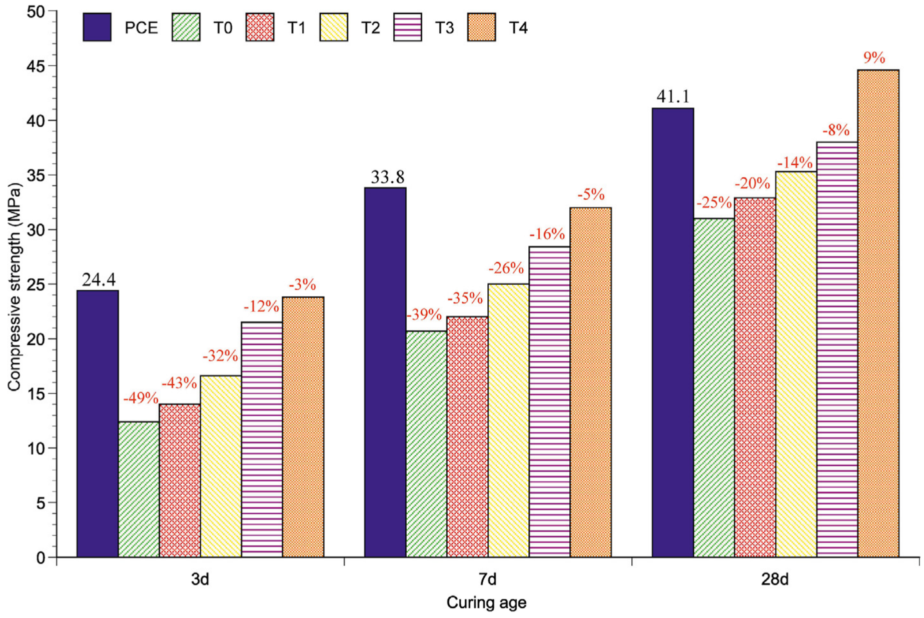

Fig. 1. Comparison of compressive strength of T group and Portland cement.

modification, and increased the compressive strength of the produced GCE. Therefore, this study used the cement-grinding system for 12 hours consecutively for the production of both GCE and PCE. The basic physical and chemical properties of the materials used to produce GCE and PCE, the proportions of each material, and the *Sa* of the finished product are listed in Tables 4 and 5. The grinding speed of the powder concentrator used to produce GCE and PCE was set to 1350–1400 rpm. Because the compositions of GCE and PCE were slightly different and because the *Sa* of the produced GCE had to be modified (GCE *Sa* > 600 m^2/kg), the capacity per unit time of the produced GCE (11–12 tons/h) was lower than that of the produced PCE (28–30 tons/h) by 55%–65% (Table 8). The *Sa* of the produced PCE and GCE were 370–380 and 584–650 m2/kg, respectively (Fig. 2). Fig. 2 shows that the fluctuation of the *Sa* of the produced GCE was greater than that of the produced PCE. This difference was related to the proportions of the raw materials used, the ease of grinding, the air volume of the system, and the number of spinning cycles that the powders were subjected to in the powder concentrator.

3.3. Compressive strength of produced PCE and GCE

Six samples of the produced PCE and GCE were obtained to compare their compressive strengths. The *Sa* of the PCE was 370–380 m^2/kg, and the SO_3 content in the produced PCE ranged from 2.0% to 2.5%. The produced GCE underwent physical and chemical modification, and thus, its *Sa* was 570–670 m^2/kg. The SO_3 content in the produced PCE ranged from 5.5% to 6.5% (Table 6). The compressive strength levels of the produced PCE on the 3rd, 7th, and 28th days were 25.1–26.1, 31.9–33.0, and 42.3–43.2 MPa, respectively, whereas those of the produced GCE were 19.3–24.3, 28.9–32.0, and 39.8–43.9 MPa, respectively (Table 9). Although the compressive strength levels of the produced GCE on the 3rd, 7th, and 28th days were lower than those of the produced PCE by 13.4%, 5.6%, and 1.6%, respectively, they met the standards for compressive strength (Fig. 3). The relationship between the compressive strength and *Sa* of the produced GCE is illustrated in Fig. 4, which reveals that the compressive strength of the produced GCE increased with the *Sa* and that this increasing trend was identical in each stage. In addition, the correlation was satisfactory (R^2 > 0.84). Notably, the compressive strength of the produced GCE was likely to be lower than the set target value when the GCE *Sa* was lower than 600 m^2/kg. These results indicated that the use of the gypsum activator and the control of the GCE *Sa* during the production of GCE effectively improved the compressive strength of the GCE, particularly during the early stage, when the compressive strength of the GCE was inadequate. Accordingly, the use of the proposed cement-grinding system to produce GCE through cogrinding appears to be feasible.

3.4. Energy consumption and carbon emissions of PCE and GCE produced by the cement-grinding system

The use of the proposed cement-grinding system for GCE production enabled the produced GCE with modifications to reach a level of compressive strength meeting the design requirements. In this study, the energy consumption levels of the produced PCE and GCE were compared. According to the Guidelines for Energy Conservation and the Energy Efficiency Indicators followed by the Cement Manufacturing Industry, both of which were published in 2015, cement is produced using a cement-rotary-kiln system, a cement-raw-meal-and-clinker system, and a cement-grinding system. The upper limits for energy consumption in the cement-rotary-kiln system, cement-raw-meal-and-clinker system, and cement-grinding production system are 893 Mcal/t-clinker, 74 kWh/t-clinker, and 46 kWh/t-cement, respectively. The energy efficiency data of these three systems during the production of PCE and GCE are presented in Table 10. In the present study, a cement-grinding system was used to produce PCE and GCE; therefore, the energy consumption levels of the cement-rotary-kiln and cement-raw-meal-and-clinker systems remained unchanged (828 Mcal/t-clinker and 69 kWh/t-clinker, respectively). When PCE was produced by the cement-grinding system, its *Sa* was controlled to 360–380 m^2/kg, output was maintained

Table 8. Mixture proportions, system parameters, capacity, and Sa of PCE and GCE.

Group	Unit content (ton)			Powder concentrator engine speed (rpm)	Capacity (ton/hr)	Binder materials *Sa* (m^2/kg)
	Clinker	GGBS	Gypsum			
PCE	95%	–	5%	1350–1400	28–30	370~380
GCE	30%	60%	10%	1350–1400	11–12	584~650

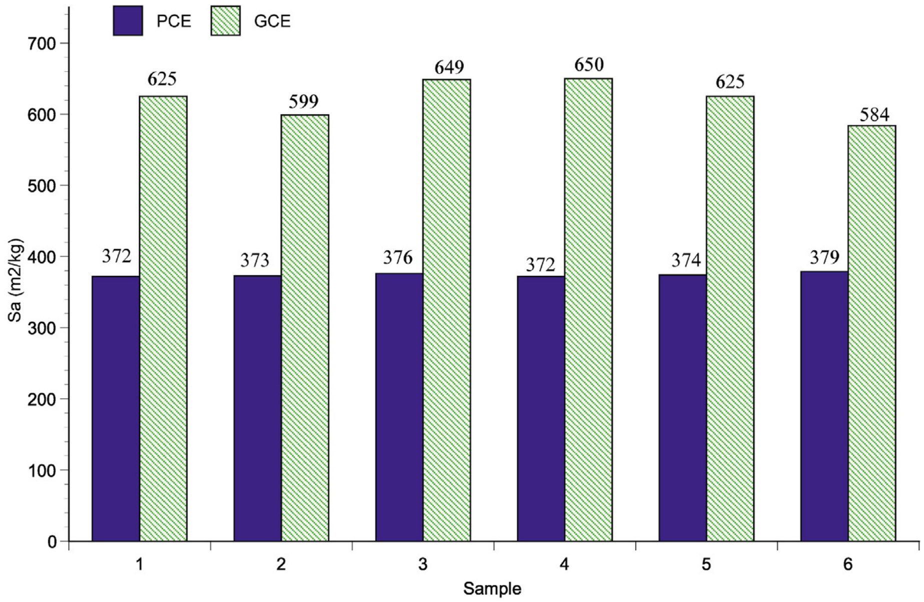

Fig. 2. Comparison of Sa of PCE and GCE produced by cement-grinding system.

at 28–30 tons/h, and the energy consumption of the cement-grinding system was estimated to be 45 kWh/t. During GCE production, output was reduced to 11–12 tons/h because the *Sa* of the produced GCE was set to ≥600 m^2/kg. The energy consumption of the cement-grinding system was estimated to be 130 kWh/t. The *Sa* of the produced GCE needed to be ≥ 600 m^2/kg to adequately increase the early-stage compressive strength. Therefore, the output of the GCE decreased as the *Sa* increased, and the energy consumption during production increased from 45 to 130 kWh/t. Accordingly, when this study compared only the energy consumption levels per unit time and the average energy consumption levels of the GCE and PCE produced by the cement-grinding system, the production of GCE was more energy intensive than was that of PCE (Fig. 5).

Based on the 2019 annual carbon emission coefficient data (0.509 kg CO_2/kWh) released by the Bureau of Energy in Taiwan, the CO_2 emissions generated by the cement-grinding system in this study during the production of PCE and GCE were estimated to be 0.023 and 0.066 tons, respectively. According to an energy efficiency seminar [26], every ton of GGBS produces approximately 0.05 tons of CO_2, which is equivalent to an energy consumption level of 100 kWh/t. This study compiled data regarding the energy consumption levels and CO_2 emissions of the PCE, GCE, and GGBS produced by the cement-grinding system. The total energy consumption and CO_2 emissions generated

Table 9. Compressive strength for producing PCE and GCE.

Group	*Sa* (m^2/kg)	Compressive strength (MPa)											
		3 day				7 day				28 day			
		Data 1	Data 2	Data 3	average	Data 1	Data 2	Data 3	average	Data 1	Data 2	Data 3	average
PCE-1	372	25.6	24.7	25.1	25.1	31.9	31.6	32.2	31.9	42.6	42.3	42.1	42.3
PCE-2	373	25.2	25.9	25.6	25.6	32.0	32.4	32.0	32.1	42.3	42.8	42.4	42.5
PCE-3	376	25.9	25.4	24.9	25.4	32.7	32.6	32.4	32.6	42.8	42.6	42.4	42.6
PCE-4	372	25.9	25.2	25.3	25.5	33.2	31.8	32.3	32.4	43.2	42.3	42.6	42.7
PCE-5	374	25.5	25.3	25.8	25.5	32.8	33.0	32.9	32.9	42.8	43.3	42.7	43.0
PCE-6	379	26.1	26.4	25.9	26.1	33.2	33.1	32.7	33.0	43.5	42.9	43.1	43.2
GCE-1	625	22.1	22.9	23.1	22.7	31.1	32.0	30.3	31.2	42.7	42.4	43.0	42.7
GCE-2	599	20.6	20.7	21.2	20.8	30.0	30.3	30.3	30.2	41.4	41.7	40.9	41.3
GCE-3	649	23.3	24.3	25.3	24.3	30.9	31.3	31.1	31.1	43.6	43.8	44.2	43.9
GCE-4	650	22.9	23.7	24.0	23.5	32.2	31.8	32.0	32.0	43.2	42.5	42.9	42.9
GCE-5	625	22.5	22.0	21.7	22.0	30.7	30.3	30.8	30.6	42.2	41.1	41.8	41.7
GCE-6	584	19.0	19.6	19.4	19.3	29.4	28.6	28.9	28.9	40.2	39.8	39.3	39.8

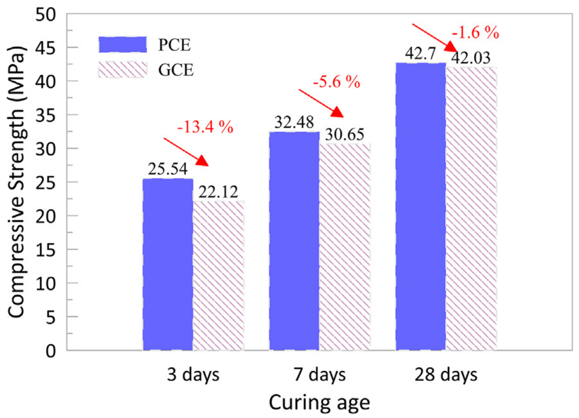

Fig. 3. Comparison of compressive strength of PCE and GCE.

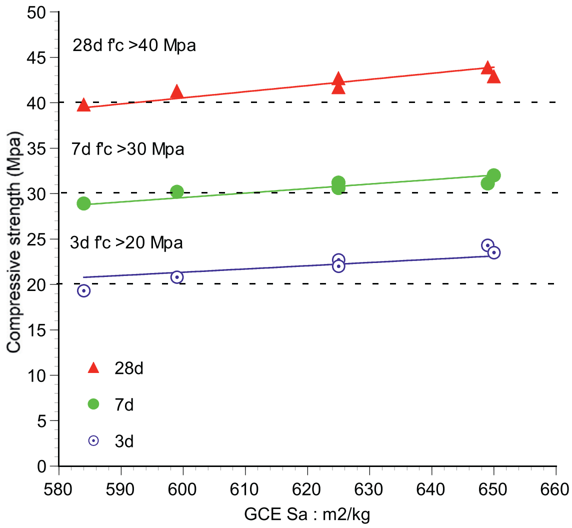

Fig. 4. Sa of GCE as function of compressive strength.

Table 10. Energy Efficiency Indicators production record value for PCE and GCE.

Energy Efficiency Indicators	Rotary kiln system (Mcal/t-clinker)	Raw and clinker system (kWh/t-clinker)	Cement Mill System (kWh/t-Cement)
	≦893	≦74	≦46
PCE	828	69	45
GCE	828	69	130

by the cement-grinding system were estimated on the basis of the total energy consumption and CO_2 emissions generated by the 11.769 million tons of cement produced in 2020 in Taiwan (Table 11). In this study, the CO_2 emissions generated during the production of PCE, GCE, and GGBS decreased in the order of PCE, GGBS, and then GCE. This finding relates to the findings for output per unit time and energy consumption. The differences between the levels of CO_2 emissions produced resulted from the different *Sa* requirements of the products. Therefore, the change in the amount of CO_2 emissions that occurred when the *Sa* changed should be considered further. This study divided CO_2 emissions on the basis of the *Sa* results and measured the CO_2 generated per unit increase in *Sa*. The CO_2 generated per unit increase in the *Sa* of each of the produced PCE, GCE, and GGBS was 0.060–0.064, 0.102–0.110, and 0.100–0.125 kg, respectively (Fig. 6). Fig. 6 reveals that the production of PCE generated the lowest amount of carbon emissions and exhibited the highest stability in terms of carbon emissions, followed by the production of GCE and then GGBS. This result differs from that obtained solely on the basis of the CO_2 generated by the cement-grinding system. The main factor behind this difference was that although the production of GCE caused lower CO_2 emissions than did the production of GGBS, the *Sa* requirement for the production of GCE (i.e., ≥ 600 m^2/kg) resulted in the final amount of CO_2 emissions generated on a unit basis being higher for the production of GCE than for the production of GGBS.

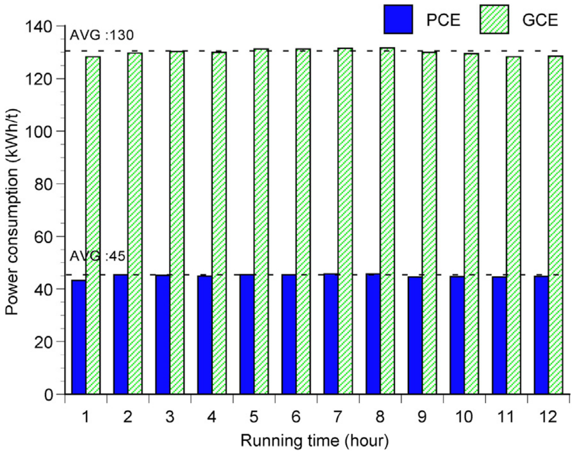

Fig. 5. Power consumption of cement-grinding system for PCE and GCE production.

If PCE, GCE, and GGBS were produced using the cement-grinding system and if the output required by Taiwan in 2020 (11.79 million tons) were used as a basis, the total annual energy consumption levels of PCE, GCE, and GGBS would be 53.05 million, 153.27 million, and 117.9 million kWh, respectively, and the total CO_2 emissions would be 27,005, 78,014, and 58,950 tons, respectively. The purpose of this study was to replace PCE with a large amount of GGBS to substantially reduce the energy consumption and CO_2 emissions generated during the production of GCE and to increase the compressive strength of GCE to the level required for PCE through

Table 11. Comparison of energy consumption for production of PCE, GGBS, and GCE through cement-grinding system.

Output	*Sa* (m^2/kg)	Power consumption (kWh/t)	CO^2 (ton)	Total power consumption (kWh)	Total CO^2 (ton)	Compare with Portland cement
PCE	360~380	45	0.023	53,055,000	27,005	–
GCE	600~650	130	0.066	153,270,000	78,014	289%
GGBS	400~500	100	0.050	117,900,000	58,950	218%

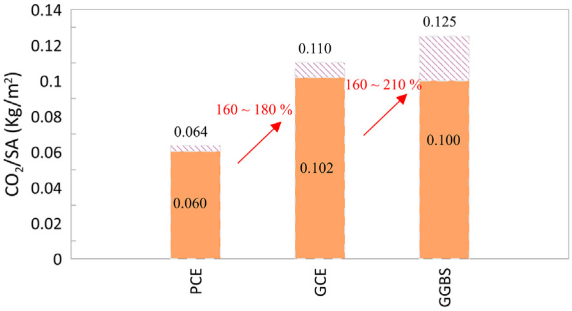

Fig. 6. The CO_2 produced per unit Sa of PCE, GCE and GGBS.

modification. However, for cement-grinding production, the aforementioned approach resulted not in increased energy or increased carbon reduction efficiency but rather increased energy consumption and carbon emissions by a factor of 2.89.

3.5. Comparison of total energy consumption levels generated by produced PCE and GCE

The results detailed in Subsection 3.4 indicated that the production of GCE through the cement-grinding system and cogrinding was energy intensive. However, during the production process in which GCE was used in place of PCE, the 95% clinker proportion that was originally used to produce a ton of PCE was lowered to 30% during the production of GCE. Thus, the clinker output decreased accordingly. Therefore, the total energy consumption levels of the cement-rotary-kiln and cement-raw-meal-and-clinker systems both decreased with demand. Owing to the decrease in the demand for clinker during GCE production, the energy efficiency levels of the cement-rotary-kiln, cement-raw-meal-and-clinker, and cement-grinding systems should be corrected to 282 Mcal/t-clinker, 23 kWh/t-clinker, and 130 kWh/t-cement, respectively (Table 12). Although the production of GCE through the cement-grinding system increased by 289% because of the considerable increase in the GCE *Sa*, the overall demand for clinker decreased by 65% such that the energy consumption levels of the rotary-kiln and cement-raw-meal-and-clinker systems both decreased by 316%. The total energy consumption per ton of GCE produced decreased from 1539 to 602 kWh (Fig. 7). From the perspective of overall PCE and GCE production, the energy consumption required to produce GCE was approximately 31.5% of that required to produce PCE, and the CO_2 emissions generated during GCE production decreased from 0.78 to 0.31 tons. Accordingly, the production of GCE through the cement-grinding system increased energy efficiency and carbon reduction efficiency.

The energy efficiency of the production of PCE and GCE in this study was based on the 11.79 million tons required by Taiwan in 2020. Relative to the production of PCE, the production of GCE resulted in a decrease in total energy consumption from 18.14 billion to 7.09 billion kWh/year; this finding constitutes an annual reduction of 11.05 billion kWh (Table 13). Regarding energy efficiency, the production of PCE requires the burning of 11.43 million tons of coal per year, whereas the production of GCE requires the burning of just 4.47 million tons of coal per year. Therefore, GCE production could reduce annual coal consumption by 6.96 million tons. Next, regarding carbon reduction efficiency, the amount of CO_2 emissions per year decreased from 9.234 million to 3.611 million tons, constituting an annual reduction of 5.624 million tons, a carbon-reduction efficiency of 60.9%, and an increase in afforestation of 365,000 ha/year. In contrast to the conventional method of grinding PCE and GGBS separately before mixing, the cogrinding method that was applied in this study

Table 12. Comparison of energy consumption between PCE and GCE in actual production of cement system.

Output	Clinker	Gypsum	GGBS	Rotary kiln system (Mcal/t-clinker)	Raw and clinker system (kWh/t-clinker)	Cement Mill System (kWh/t-Cement)	Power consumption (kWh/t)	CO^2 (ton)
PCE	95%	5%	0%	893	74	45	1539	0.78
GCE	30%	10%	60%	282	23	130	602	0.31

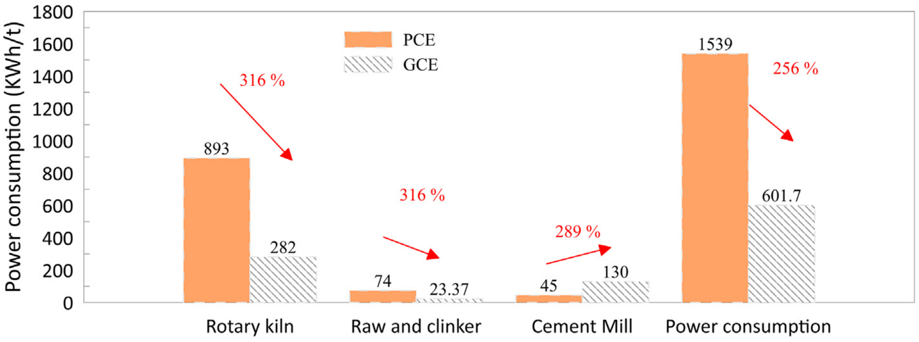

Fig. 7. Comparison of energy consumption of various systems during production of PCE and GCE.

Table 13. Overall energy and carbon-reduction efficiency for production of PCE and GCE.

Output	Power consumption (kWh)	Energy saving			Carbon reduction	
		Oil fuel (kL)	Fire coal (ton)	Natural gas (ton)	CO^2 (ton)	Afforestation benefits (hm^2)
PCE	18,143,277,300	13,607,458	11,430,265	15,149,637	9,234,928	–
GCE	7,094,613,884	5,320,960	4,469,607	5,924,003	3,611,158	364,763

Notes: 1 kWh = 0.75 Oil fuel (kL) = 0.63 Fire coal (ton) = 0.835 Natural gas (ton) = 0.509 CO_2.
1 Afforestation benefits(hm^2) = 9.9 CO_2 (ton).

Table 14. Difference between this study the traditional practice.

GGBS Cement Comparison		
Method	Traditional practice	This study
Material composition	Cement、GGBS、admixtures	Clinker、GGBS、admixtures
GGBS unit content	Due to early strength requirements, the dosage is ≦40% more [8]	Can be used up to 70% [20].
Admixtures type	NaOH、Na2O and alkaline metal activators	Gypsum
Admixtures unit content	0.5%–5% [17,18]	10% [20]
Production process used	Mixing production in ready-mixing plants	Cement system cogrinding production

through the cement-grinding system can prevent uneven mixing, maximize GGBS use, and promote the energy efficiency and carbon reduction efficiency of cement production. The difference between this study and the traditional practice is shown in Table 14.

4. Conclusions

In this study, producing GCE by using a gypsum activator and by modifying the *Sa* of GCE improved the compressive strength of GCE in the early stage. Because of the reduced demand for clinker during the production of GCE, this method can indirectly promote the energy efficiency and carbon reduction efficiency of cement production. The conclusions of this study are summarized as follows:

1. During GCE production, the blaine (*Sa*) was controlled, and the SO_3. The 3-, 7-, and 28-day compressive strength levels of GCE were 19.3–24.3, 28.9–32.0, and 39.8–43.9 MPa, respectively. The compressive strength increased with the GCE *Sa*, and the trends in each stage were identical. Furthermore, the correlation between the two variables was favorable ($R^2 > 0.84$).
2. The use of the gypsum activator and the increase of the GCE *Sa* effectively improved the formerly inadequate compressive strength of the GCE in the early stage. The compressive strength of the produced GCE was likely to be lower than the set target value when the *Sa* of the GCE was slightly larger than 600 m^2/kg.
3. Regarding the energy consumption and average energy consumption per unit time during cement grinding, the increased GCE *Sa* (≥600 m^2/kg) reduced the output of GCE and increased the energy consumption of GCE production by 289% relative to PCE production.
4. Regarding overall cement production, clinker use decreased by 65% during GCE production. Therefore, the energy consumption required for GCE production was approximately 31.5% of that required for PCE production. In addition,

the amount of CO_2 emissions observed for GCE production decreased from 0.78 to 0.31 tons. Accordingly, the production of PCE through the cement-grinding system promoted energy efficiency and carbon reduction efficiency.

5. Producing cement by using GCE in place of PCE can reduce energy consumption by 11.86 billion kWh/year. Regarding energy efficiency and carbon reduction efficiency, this method can reduce coal consumption by 6.96 million tons/year and reduce CO_2 emissions by 562.4 tons/year and achieve a carbon reduction efficiency level of 60.9%. Accordingly, the production of GCE through the proposed cement-grinding system can considerably increase energy efficiency and carbon-reduction efficiency.

Conflict of interest

No conflict of interest.

Acknowledgments

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References

[1] Khan MS. Environment-Friendly Concrete (EFC) for Green Highways. from. 2007. http://www.greenhighways.org/Template.cfm?FrontID=5060.

[2] Mehta PK. Making Concrete Greener with Fly Ash. Concr Int 1999;121(5):61–6.

[3] Mehta PK. Concrete Technology for Sustainable Development. Concr Int 1999;21(11):47–53.

[4] Mehta PK. Reducing the Environmental Impact of Concrete. Concr Int 2001;23(10):61–6.

[5] World Steel Association. World steel in figures. https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/.

[6] Mindess S, Young JF. Concrete. Englewood Cliffs, N.J, USA: Prentice-Hall, Inc.; 1981.

[7] ASTM C989/C989-18a : Standard specification for slag cement for use in concrete and mortars. West Conshohocken, PA, USA: ASTM International; 2018. https://doi.org/10.1520/C0989_C0989M-18A.

[8] Escalante-Garcia JI, Espinoza-Perez LJ, Gorokhovsky A, Gomez-Zamorano LY. Coarse blast furnace slag as a cementitious material, comparative study as a partial replacement of Portland cement and as an alkali activated cement. Construct Build Mater 2009;23(7):2511–7. https://doi.org/10.1016/j.conbuildmat.2009.02.002.

[9] Borchert W, Keidel J. Beiträge zur Reaktionsfähigkeit der Silikate bei niedrigen Temperaturen. Heidelb Beiträge Mineral Petrogr 1947;1(1):2–16. https://doi.org/10.1007/BF01112365.

[10] Purdon AO. The action of alkalis on blast furnace slag. J Soc Chem Indus 1940;59(9):191–202.

[11] Glukhovsky VD. Soil silicates: their properties, technology and manufacturing and fields of application. Doct Tech Sc. Degree thesis. Civil Engineering Institute; Kiev, Ukraine: 67–71.

[12] Davidovits J. Chemistry of Geopolymeric Systems Terminology. In: Proceeding of geopolymer. France: International Conference; 1999. p. 9–37.

[13] Li C, Sun H, Li L. A review: The comparison between alkali-activated slag (Si+Ca) and metakaolin (Si+Al) cements. Cement Concr Res 2010;40(9):1341–9. https://doi.org/10.1016/j.cemconres.2010.03.020.

[14] Glukivski VD, Visheka Shkola K. Alkali-earth binder and concrete produced with them. Kiev, USSR: Visheka Shkola; 1979.

[15] Talling B, Brandstetr J. Present state and future of alkali-activated slag concretes. In: Malhotra, V.M., (ed.) 3rd International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete. American Concrete Institute; Trondheim, Norway: 1989. p. 1519–46.

[16] Roy DM. Alkali-activated cements: Opportunities and challenges. Cement Concr Res 1999;29(2):249–54. https://doi.org/10.1016/S0008-8846(98)00093-3.

[17] Matschei T, Bellmann F, Stark J. Hydration behaviour of sulphate-activated slag cements. Adv Cement Res 2005;17(4):167–78. https://doi.org/10.1680/adcr.2005.17.4.167.

[18] Esping O. Effect of limestone filler BET (H_2O)-area on the fresh and hardened properties of self-compacting concrete. Cement Concr Res 2008;38(7):938–44. https://doi.org/10.1016/j.cemconres.2008.03.010.

[19] Mohammad S, Kiachehr B, Hamid S. The effect of the blaine fineness on the mechanical properties of the alkali-activated slag cemen. J Build Eng 2019;26:100897. https://doi.org/10.1016/j.jobe.2019.100897.

[20] Lin KH, Yang CC. Effects of types and surface areas of activated materials on compressive strength of GGBS cement. Mag Concr Res 2021;36(1):48–55. https://doi.org/10.1680/jmacr.21.00110.

[21] Li D, Shen J, Chen Y, Cheng L, Wu X. Study of properties on fly ash-slag complex cement. Cement Concr Res 2000;30(9):1381–7. https://doi.org/10.1016/S0008-8846(00)00360-4.

[22] USGS. Natural Aggregates – Foundation of America's Future. 2010. http://minerals.usgs.gov/minerals/pubs/commodity/aggregates/fs14497.

[23] Yazici H, Yigiter H, Karabulut AS, Baradan B. Utilization of fly ash and ground granulated blast furnace slag as an alternative silica source in reactive powder concrete. Fuel 2008;87(12):2401–7. https://doi.org/10.1016/j.fuel.2008.03.005.

[24] ASTM C109/C109M-20b: Standard Test Method for Compressive Strength of Hydraulic cement mortars (using 2-in. Or [50 mm] cube specimens). West Conshohocken, PA, USA: ASTM International; 2020. https://doi.org/10.1520/C0109_C0109M-20B.

[25] ASTM C204-18e1. Standard test methods for fineness of hydraulic cement by air-permeability apparatus. West Conshohocken, PA, USA: ASTM International; 2018. https://doi.org/10.1520/C0204-18E01.

[26] Huang Q. Analysis of Cement Industry Energy Efficiency. Cement Industry Energy Efficiency Improvement Seminar. Industrial Technology Research Institute (in Taiwan). from: https://emis.itri.org.tw/Content/Upload/Manage/Files/8fedae06-a3e7-45d4-8cfc-2167f953acbd.pdf. (2021.08.06.

[27] ASTM C150/C150M-22 : standard specification for Portland cement. West Conshohocken, PA, USA: ASTM International; 2022. https://doi.org/10.1520/C0150_C0150M-22.

[28] Hsieh Shao-Heng, Yeih Wei-Chung, Huang Ran. The Impact of Variable Curing Conditions on the Properties and Microstructures of Mixtures of Ground Granulated Blast Furnace Slag and Circulating Q1 Fluidized Bed Combustion Ash. J Mar Sci Technol 2021;29(5):609–18. https://doi.org/10.51400/2709-6998.2463.

[29] Chi Mao-Chieh. Mechanical strength and durability of alkali-activated fly ash/slag concrete. J Mar Sci Technol 2016;24(5):958–67. https://doi.org/10.6119/JMST-016-0603-1.