Research Article

Ecological Upgrade of Normal-Strength Mortars by Using High Volume of GGBS

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Normal-strength concrete is widely used in construction sites considering the cost, technology, and structural safety. The ecological upgrade of such materials is more meaningful for the sustainable development in a greener way. To this end, the feasibility of ecological upgrade of normal-strength mortars (NSM) by using high volume of ground granulated blast furnace slag (GGBS) (70%–90%) was evaluated in this paper. Comprehensive experiments were conducted to investigate the influences of experimental variables such as content of cement, curing temperature, and mass ratio of water to binder (w/b) on the fresh properties, compressive strength, hydration products, microstructure, and pore structure of NSM. Ecoefficiency evaluation was conducted based on the energy requirement for the whole production of cement and GGBS. Experimental results showed that ecological upgrade of NSM was viable and feasible. When substituting 70% to 90% cement by GGBS, the energy requirement of 1 t binder can be accordingly saved by 67% to 86%, and the performance energy can be reduced from 25.4 (kWh/t)/MPa to 6 to 8 (kWh/t)/MPa. With proper contents of GGBS (70% or 75%), the 28 d compressive strengths were acceptable with reductions less than 10%. Evaluated curing temperatures and decreased w/b were viable methods to promote the early-age compressive strength of NSM incorporating high volume of GGBS. For instance, raising the curing temperature to 40°C can help achieve higher early-age compressive strength than that of the control group. In addition, the pore sizes within ZII (<100 nm) of GGBS-incorporated NSM were refined by over 20 nm.

1. Introduction

Nowadays, the requirements of low carbon and environmental protection on the construction industry have prompted great motivations to seek alternative materials to cement since the emission of about 7% global CO₂, the consumption of 5% global primary industrial energy, and the release of large amounts of NO_x, SO₂, particulate matter, mercury, and other compounds attributed to the cement production [1–3]. One of the promising strategies is the substitution of cement by low-carbon pozzolanic mineral admixtures, i.e., ground granulated blast furnace slag (GGBS) [4], a by-product from blast furnaces during the production of pig iron [5, 6]. GGBS containing calcium silicoaluminate as its major component is highly vitreous in phases and is reactive to hydroxides released from the

cement self-hydration to yield hydration products, i.e., CSH gel and hydrocalcium aluminate [7, 8].

The employment of GGBS in cementitious materials brings two conspicuous benefits. The first one is the direct environment effect in terms of energy saving, pollutant discharge reduction, natural resources protection, and waste recycling. The manufacture of GGBS mainly involves the processes of cooling of molten slag through high-pressure water jets, drying, and grinding in a rotating ball mill [5, 9]. These operations consume less energy as compared to the clinkering process of cement manufacturing [10]. Shi and Qian [11] estimated that the required energy for grinding GGBS was less than 10% of the total energy requirement for producing cement. Prominently, greenhouse emission and waste or toxic matters release related to the cement production are reduced [12, 13]. It was reported that the

incorporation of 50% GGBS in mortar or concrete can help reduce about 0.5 t CO₂ emission [10].

The second benefit can be classified into the material effect. It is generally agreed that cementitious materials blended with GGBS develop refined pore sizes in their service life [14, 15]. Li et al. [16] confirmed that the pore sizes of paste or mortar moved from RII size range (10 nm–100 nm) to RI size range (<10 nm) when 70% GGBS was incorporated. This finer pore structure of GGBS-containing cementitious composites contributes to barriers for the ingress of harmful substance, i.e., chloride ion and sulfate [5, 15]. Furthermore, GGBS contains no C₃A, making GGBS-incorporating cementitious composites less reactive to sulfates [5]. GGBS itself or its crystalline phases provides additional nucleation sites for the hydration products of cement, contributing to accelerated hydration of cement [17, 18]. Other reported benefits cover the fire resistance, improved workability, increased pumpability, densified ITZ microstructure, and low hydration heat [19–22].

This is attractive in construction sites with dominating requirements of normal-strength concrete (NSC), which receives less attention in the recent years in the concrete studies compared to (ultra) high-strength concrete. Actually, NSC is widely used in construction sites considering the cost, technology, and structural safety. The ecological upgrade of NSC by incorporating high volume of GGBS may provide a better opportunity to develop in a more environmentally friendly manner. To achieve a maximized environmental or material benefit, the substitution rates of GGBS for cement are thus pivotal. By now, the replacement quantity of GGBS to cement has been investigated from 30% to 85% by weight; however, 50% is a common value in most applications [5, 7, 9, 23, 24]. Although abundant studies regarding the properties of concrete or mortar incorporating GGBS up to 60% of the total binder have been carried out, there are still lack of sufficient concerns on higher substitution rates larger than 60% [14]. This may be mainly because incorporating high volume of GGBS into cementitious composites brings about low early-age strength [25, 26]. Nowadays, the defect of low early-age strength can be overcome by means of elevated curing temperatures [27, 28], increasing GGBS fineness [24, 29], and using finer mineral admixtures, i.e., nano-silica [20, 30], nano-CaCO₃ [31], silica fume [32], and metakaolin [33]. In addition, it is also largely agreed that, with proper proportion, GGBS-incorporating cementitious composites can develop comparable or superior compressive strength than that incorporating cement only at late ages.

Therefore, this paper intends to ecologically upgrade normal-strength mortars (NSM) by incorporating high volume of GGBS. The investigated substitution ratios of cement by GGBS range from 70%–90% with an interval of 5%. The feasibility of mechanical compensation methods that higher curing temperatures or lower *w/b* will be examined. Comprehensive experiments were conducted to investigate the content of cement, curing temperature, and *w/b* on the fresh properties, compressive strength, hydration products, microstructure, and pore structure of NSM. TGA-

DTG, SEM, XRD, and MIP were applied to study the underlying mechanisms on multiscales. The ecoefficiency of NSM incorporating various volume of GGBS was evaluated based on the energy requirement for the whole production of cement and GGBS.

2. Materials and Methods

2.1. Materials. P.O. 42.5 ordinary Portland cement was purchased from Anhui Conch Cement Co., Ltd., China. GGBS corresponding to Grade S105 was used according to JC/T2238 [34]. The apparent density and chemical composition of cement and GGBS are listed in Table 1. Their particle size distributions are presented in Figure 1. It can be found that GGBS is finer in particle sizes as the mean particle sizes of cement and GGBS are 28.19 μm and 16.18 μm , respectively. Sand was ordinary river sand with a finesse of 2.6 and an apparent density of 2550 kg/m³. Water used throughout this study was city tap water.

The applied characterization analysis for cement and GGBS was performed by a XRF-1800 sequential X-ray fluorescence spectroscopy (XRF) for the chemical composition investigation and an ASALD-7101 laser particle size analyzer (LPSA) for the particle size analysis.

2.2. Mixing Proportions. Ten mixtures containing one control group were designed, as presented in Table 2. The 28 d compressive strength of the control group was 42.9 MPa, belonging to the context of NSM that normally less than 60 MPa. Three variables were considered encompassing (1) contents of cement in the blend binders (0%, 10%, 15%, 20%, 25%, and 30%), (2) curing temperatures (23°C, 40°C, and 60°C), and (3) *w/b* (0.35, 0.45, and 0.55). All mixtures were prepared following the same procedure. Cement and/or GGBS and sand were mixed firstly and stirred by a harbor mixer in low speeds for 5 min. Then, water was added, and the mixture was stirred for another 3 min. Fresh mixture was casted into 50 mm cubic mortar for the compressive strength testing. Mortars were firstly sealed and cured in specified environments within modules for 24 h, as indicated in Table 2. Afterwards, they were demoulded and continuously cured in previous curing environment. Average value of mortar was reported by quadruplicate specimens. Mixtures were coded in the formula of $C_{xx}T_{yy}W_{zz}$ to directly indicate the content of cement in the blend binder, curing temperature, and *w/b* in sequence.

2.3. Test Methods

2.3.1. Setting Time and Density Tests. The densities of fresh mixtures were simply measured by a container with fixed volume. Setting times of fresh pastes were tested by using a Vicat needle according to ASTM C191 [35].

2.3.2. Hydration Products Analysis. Paste samples were soaked in isopropanol to stop the hydration process. They were vacuum-dried and grounded into particle sizes less

TABLE 1: Apparent density and chemical composition of cement and GGBS.

	Apparent density (kg/m ³)	Chemical composition (wt.%)					
		CaO	SiO ₂	Al ₂ O ₃	MgO	Fe ₂ O ₃	TiO ₂
Cement	3100	71.3	13.7	5.3	0.4	6.0	0.5
GGBS	2800	43.7	26.5	18.2	4.9	1.0	1.0

FIGURE 1: Particle size distributions of cement and GGBS.

TABLE 2: Mixing proportions.

Groups	Curing conditions	w/b	GGBS	Cement	Water	Sand
Con			0	41.40	18.60	40.00
C20T23W45			8.28	33.12	18.60	40.00
C10T23W45	23 ± 2°C		4.14	37.26	18.60	40.00
C15T23W45	>95% RH		6.21	35.19	18.60	40.00
C25T23W45		0.45	10.35	31.05	18.60	40.00
C30T23W45			12.42	28.98	18.60	40.00
C20T40W45	40 ± 2°C		8.28	33.12	18.60	40.00
	>95% RH					
C20T60W45	60 ± 2°C		8.28	33.12	18.60	40.00
	>95% RH					
C20T23W35	23 ± 2°C	0.35	8.89	35.55	15.55	40.00
C20T23W55	>95% RH	0.45	7.74	30.97	21.29	40.00

than 74 μm for further study. A TTR-III h/h rotating anode X-ray diffractometer (XRD) with Cu-Kα radiation at 40 kV and 200 mA was applied to study the crystal compositions. The scan speed and scope of each sample was 8°/min and 2θ = 10°–60°, respectively. A TGA/DSC 1/1600 high-temperature thermogravimetric analyzer was also applied to further study the quantitative composition of the hydration

products of each sample. The grounded pastes were heated from 50°C to 800°C with the speed of 10°C/min.

2.3.3. Microstructure and Pore Structure Analysis. Microstructure analysis of 28 d mortars was performed by a FlexSEM1000 scanning electron microscope (SEM). SEM

samples were collected from the compressive strength testing and were stored in isopropanol to cease the hydration process. Prior to SEM observation, vacuum drying was applied on these samples. A layer of palladium particles was sprayed on the fresh fracture surface for 120 s in the frontage and 30 s in the side direction to achieve well electro-conductibility. The pore structure of 28 d mortars was studied by an AutoPoreIv 9510 mercury intrusion porosimetry (MIP).

2.4. Ecoefficiency Evaluation. Ecoefficiency evaluation was carried out for a full-life cycle environmental assessment of the proposed technology. The ecoefficiency of the blend cement was evaluated by simply calculating the energy required for cement manufacture based on the energy requirement for the whole production of cement and GGBS, as proposed by Hamidi et al. [36, 37]. The required energy is given by the following equation:

$$E = C \times (E_{\text{cement}}^{\text{process}} + E_{\text{cement}}^{\text{grinding}}) + G \times (E_{\text{GGBS}}^{\text{grinding}} + E_{\text{GGBS}}^{\text{process}}), \quad (1)$$

$$E_{\text{performance}} = \frac{E}{f_{\text{cm}}}, \quad (2)$$

where E is the energy consumption for producing 1 t binder (kWh/t); C and G are the mass contents of cement and GGBS, respectively; $E_{\text{cement}}^{\text{process}}$ and $E_{\text{cement}}^{\text{grinding}}$ are the energy consumptions of the production process and the grinding of cement, respectively (kWh/t); $E_{\text{GGBS}}^{\text{grinding}}$ is the energy consumption of the grinding of GGBS (kWh/t); $E_{\text{performance}}$ is the energy consumption for producing 1 t binder, relative to the 28 d compressive strength of mortar s ((kWh/t)/MPa); and f_{cm} is the 28 d compressive strength of mortar. In the case of that, GGBS is a by-product of the steel production, and no energy is specially needed for its production. Therefore, the value of $E_{\text{GGBS}}^{\text{process}}$ is zero.

3. Results and Discussion

3.1. Properties of Fresh Mixtures. Table 3 presents the setting times and densities of fresh mixtures. In general, both the initial and final setting times of pastes are found to be prolonged with increased contents of GGBS. The substitutions of 70% to 90% cement by GGBS resulted in increased initial and final setting times by times of 1.09 to 1.31 and 1.12 to 1.68, respectively. This is more prominent in C20T23W55 but vanishes in C20T23W35, in which the initial and final setting times are 39 min and 6 min less than that of Con. Moreover, elevated curing temperatures accelerated significantly the set of paste. For example, the initial and final setting times of C20T40W45 are about half that of C20T23W45. In addition, the densities of GGBS-incorporating groups are lower than that of Con as a result of the lower density of GGBS than cement, as shown in Table 1.

3.2. Hydration Products of Pastes Analyzed by XRD. XRD analysis was conducted to investigate the crystalline

compositions of 3 d and 28 d pastes, as presented in Figures 2 and 3, respectively. A total of ten substance, i.e., CH ($\text{Ca}(\text{OH})_2$), calcite, C_4AH_{13} , C_3S , C_2S , CSH (I), gehlenite, quartz, hydrotalcite, and Aft (ettringite), were identified out as marked in the figures according to their JCDP files.

Figure 2(a) shows the XRD patterns of 3 d pastes incorporating 0% or 70% to 90% GGBS cured at 23°C with the fixed $w/b = 0.45$. Among the ten identified substance, hydrocalumite with the characteristic peak at $2\theta = 10.8^\circ$ and gehlenite with the characteristic peak at $2\theta = 30.9^\circ$ were only found in the GGBS-incorporating pastes other than Con. These new crystals are thus speculated as a result of the activation reaction of GGBS by the free CH released from cement hydration. In fact, the hydration of cement-GGBS cementitious system primarily involves two associated hydration processes, which are the self-hydration of cement and the activation of GGBS by alkalis, i.e., CH [7, 11]. The activation reaction of GGBS is highly depended on the released CH by the self-hydration of cement in both the content and the formation rate [19]. The quantity of CH within paste is a critical indicator to understand the underlying hydration mechanism. Figure 2(a) reveals that the characteristic peak heights of CH at $2\theta = 18^\circ$ and 33° increase in a saltatory tendency with the increasing contents of cement from 10% to 30%. Tiny peaks of CH were detected in C15T23W45 rather than in C10T23W45. This may indicate that the released CH was consumed almost completely by the activation reaction of GGBS. This, on the one hand, confirms the dilution effect of cement by GGBS leading to less CH production and, on the other hand, suggests an initial equilibrium between the demand of GGBS for the activation reaction and the supply of CH by the cement hydration at early age. 15% cement is sufficient to provide the required CH for 85% GGBS at 3 d.

Figure 2(b) presents the XRD patterns of 3 d pastes considering the variables curing temperature and w/b . As for curing temperature, the characteristic peak heights of CH within pastes located at $2\theta = 18^\circ$ and 33° firstly increase from 23°C to 40°C but then decrease or even tend to disappear from 40°C to 60°C. This may be the competitive result of both the enhanced self-hydration of cement and activation of GGBS by elevated curing temperatures. From 40°C to 60°C, the activation reaction of GGBS seems to be far accelerated than that of the self-hydration of cement, leading to most CH consumption. In addition, the XRD patterns of C20T23W55, C20T23W45, and C20T23W35 display no distinct difference in this figure.

Figure 3(a) presents the XRD patterns of 28 d pastes with the content of cement as the variable. A similar tendency that the characteristic peak heights of CH increase gradually with the content of cement is found in Figure 2(a). The equilibrium proportion of the blend cement for sufficient activation of GGBS has shifted from 85% GGBS–15% cement at 3 d to 90% GGBS–10% cement at 28 d since C10T23W45 has the lowest peak heights of CH at $2\theta = 18^\circ$ and 33° . Figure 3(b) shows the XRD patterns of 28 d pastes prepared by different curing temperatures and w/b . It can be seen from this figure that the characteristic peaks of CH of C20T40W45 and C20T60W45 are lower than that of C20T23W45. This

TABLE 3: Setting times and densities of fresh mixtures.

	Initial setting (min)	Final setting (min)	Density of fresh paste (g/ml)
Con	323	414	2.138
C10T23W45	424	696	2.082
C15T23W45	405	650	2.133
C20T23W45	383	575	2.114
C25T23W45	400	608	2.111
C30T23W45	353	465	2.127
C20T40W45	242	313	2.114
C20T60W45	125	163	2.114
C20T23W55	611	>720	2.006
C20T23W35	284	408	2.175

FIGURE 2: XRD patterns of 3 d pastes ((1) CH, (2) calcite, (3) hydrocalumite, (4) C₃S, (5) C₂S, (6) CSH (I), (7) gehlenite, (8) quartz, (9) hydrotalcite, and (10) AFt). FIGURE 3: XRD patterns of 28 d pastes ((1) CH, (2) calcite, (3) hydrocalumite, (4) C₃S, (5) C₂S, (6) CSH (I), (7) gehlenite, (8) quartz, (9) hydrotalcite, and (10) AFt).

FIGURE 4: Hydration products of pastes with different contents of cement: (a) TGA-DTG results of 3 d pastes; (b) TGA-DTG results of 28 d pastes; (c) calculated contents of CH or CC (—) or total CH.

further confirms that the consumption rates of CH by the activation reaction with GGBS surpassed the formation rates of CH by the self-hydration of cement at elevated curing temperatures.

3.3. Quantitative Analysis of Hydration Products by TGA-DTG. Figures 4(a) and 5(b) present the TGA-DTG results of 3 d and 28 d pastes with cement content as the variable, respectively. Four major endothermic peaks were distinctly identified in these DTG curves as marked, which correspond to the dehydration of CSH as well as decomposition of ettringite and gehlenite ranging from 80°C to 200°C, dehydroxylation of CH around 450°C, and decarbonation of CaCO_3 (CC (—)) crystals in amorphous or crystalline phases around 700°C [38–41]. In general, the endothermic peak

heights or their enveloping areas are observed visually to increase when more cement was incorporated.

The amounts of CH and CC (—) were calculated based on the mass losses ranging from 400°C to 500°C for CH and 600°C to 800°C for CC (—), as presented in Figure 4(c). The formation of CC (—) was attributed to the carbonation of CH during the moisture curing. Therefore, the total CH encompasses the content of CH and the carbonated CH with the same stoichiometric mole to that of CC (—). For 3 d pastes, the amounts of CH or CC (—) or the total CH of these pastes are less than half of that of Con (i.e., 30%–50% for the total CH). This is due to the dilution effect of cement by GGBS at early ages in particular. For 28 d pastes, the contents of CH and total CH of GGBS-incorporating groups are far lower than that of Con. For instance, the contents of total CH of these GGBS-containing groups are just

FIGURE 5: Hydration products of pastes prepared by different curing temperatures and w/b : (a) TGA-DTG results of 3 d pastes; (b) TGA-DTG results of 28 d pastes; (c) calculated contents of CH or CC(—) or total CH.

15%–25% of that of Con. This decreased CH and total CH from 3 d to 28 d reveals the consumption of CH by GGBS.

Figures 5(a) and 5(b) show the TGA-DTG curves of 3 d and 28 d pastes prepared by different curing temperatures and w/b . The endothermic peaks of DTG curves are similar to that in Figure 4. In general, the contents of CH and total CH of pastes increase, and the content of CC(—) decreases with increasing curing temperatures, as further studied in Figure 5(c). This confirms that elevated curing temperatures were beneficial for the improvement of cement hydration, contributing to the generation of more hydration products. The amounts of CH or total CH of pastes with different w/b values decrease with the decreasing w/b at 3 d and 28 d. Since the contents of cement in pastes with lower w/b were actually higher as less water was used, it is indicated that lower w/b promoted the consumption rates of CH.

3.4. Compressive Strength. Figure 6(a) presents the compressive strength of mortars with different contents of cement. In general, the compressive strength of these mortars increases with increasing contents of cement at three ages. The early-age compressive strengths of GGBS-incorporating mortars are markedly lower than that of Con and are 30%–50% at 3 d and 40%–79% at 7 d of Con, respectively. Nevertheless, the 28 d compressive strengths of those GGBS-incorporating mortars developed much quickly, and the values of C25T23W45 and C30T23W45 are 90.7% and 95.3% of that of Con. The subsequent increments of the compressive strengths of GGBS-incorporating mortars are primarily attributed to the activation reaction of GGBS with the free CH. Through this activation reaction, supplementary stress-bearing C-S-H can be generated [7, 10]. This also implies important achievement that one can replace 75% or

FIGURE 6: Compressive strength of mortars: (a) mortars with different contents of cement; (b) mortars prepared by different curing temperatures and w/b .

70% cement by GGBS to prepare NSM with comparable longer compressive strength to that of mixtures prepared by cement only. Thanks to this, great benefits can be gained in terms of environment protection, cost reduction, waste utilization, as well as energy saving.

Figure 6(b) presents the compressive strength of mortars prepared by different curing temperatures and w/b . It can be found that 40°C is the optimal curing temperature to achieve desired compressive strength. Compared to Con, the compressive strengths of C20T40W45 are higher by 7.8% at 3 d and 5.9% at 7 d than that of Con. The 28 d compressive strength of C20T40W45 is lower but still gained 91% of that of Con at 39.0 MPa. From the point of chemical reaction, curing temperature is one of the methods to facilitate the dissolution of GGBS and cement and crystallization of hydration products. However, too high temperatures may cause degraded properties of the hydration products as well as the mechanical strength, i.e., 60°C. Another method to gain desired compressive strength is well adopted reducing the w/b . As can be seen from this figure, the compressive strength normally increases with decreased w/b mainly due to formation of a denser microstructure. The compressive strengths of C20T23W35 are 74.2% at 3 d, 95.2% at 7 d, and 93.2% at 28 d of that of Con.

3.5. Microstructure Observation by SEM. The microstructure evolution of GGBS-incorporating mortars was examined by SEM, as shown in Figure 7. Figure 7(a) presents the SEM image of 3 d C10T23W45 mortar. It displays a much porous microstructure constituted by adhesive particles and tiny schistose crystals that most possibly are CH. In the case of that 90% of the binder is GGBS, the particles are GGBS that have reacted with the released CH, nevertheless with low reaction degree. When incorporating 20% cement into the mortar (Figure 7(c)), a larger porous matrix formed instead

of part of the adhesive particles, as observed in Figure 7(a). More prominently, as shown in Figure 7(e), the morphology of the 3 d C30T23W45 mortar is much denser as irregular particles are bonded compactly by porous binders as further observed from the inset in this figure. The differences in the 3 d morphology among these mortars vanished at 28 d as they display a similar microstructure. As presented in Figures 7(b), 7(d), and 7(f), a dense matrix formed in the three samples despite the contents of GGBS varying from 70% to 90%. This confirms that a longer curing duration has transformed GGBS into the binder that structured the dense stress-bearing matrix.

Figure 7(g) shows the SEM images of 3 d C20T40W45 mortar. Large dense matrix and fine particles are found, and ribbon-like CSH formed. This figure is much different from that of C20T23W45 with the same proportion but lower curing temperature at 23°C. This confirms the role of a higher curing temperature in enhancing both the self-hydration of cement and activation reaction of GGBS by CH. Figure 7(h) presents the SEM image of 28 d C20T40W45 mortar. The noteworthy feature of this figure is the existence of fibrous CSH intertwining together. Figure 7(i) presents the SEM images of 3 d C20T23W35. It displays a porous morphology and nevertheless is still denser than that of C20T23W45, as proved in Figure 7(j). This is one of the reasons for the higher compressive strength of mortars with a lower w/b .

3.6. Microstructure Analysis by MIP. The pore structures of representative mortars were studied by MIP, as presented in Figure 8. The pore sizes of all mortars primarily distribute within two zones: ZI ($>50\mu\text{m}$) and ZII ($<100\text{nm}$). The former commonly suggests the existence of voids or gas inclusion. Within ZI, the pore volume of Con is the lowest while that of GGBS-incorporating mortars cured under 23°C

FIGURE 7: SEM images of partial GGBS-incorporating 3 d and 28 d mortars: (a) 3 d C10T23W45; (b) 28 d C10T23W45; (c) 3 d C20T23W45; (d) 28 d C20T23W45; (e) 3 d C30T23W45; (f) 28 d C30T23W45; (g) 3 d C20T40W45; (h) 28 d C20T40W45; (i) 3 d C20T23W35; (j) 28 d C20T23W35.

are much higher. Within ZII, the pore sizes of GGBS-incorporating groups are finer than that of Con. It can be seen that the pore sizes of Con mainly concentrate around 50 nm as a peak. When 90% GGBS and 10% cement were blended, two peaks of pore sizes appear in C10T23W45. The first one is higher but shifts left to the sole peak of Con. The second intense peak of pore sizes formed around 10 nm, as further expounded by the inset. When blending more cement in mortars, the first peak of pore sizes observed in C10T23W45 disappears in C20T23W45 and C30T23W45, and consequently, broader peaks of pore sizes formed. This suggests that the incorporation of GGBS into NSM results in

promoted porosity but refined pore sizes. The formation of the binding system in these mortars incorporating GGBS as the major cementing material highly depended on the activation reaction of GGBS with the free CH. The activation reaction generated hydration products which filled the voids or pores within the microstructure of mortars. Nevertheless, the produced hydration products among these GGBS-incorporating mortars are less than that of Con, as calculated in Figures 4 and 5, leading to less pores being occupied or filled.

Elevated curing temperatures or low w/b are also helpful to refine the pore sizes of GGBS-incorporating mortars. The

FIGURE 8: Pore sizes of representative 28 d mortars.

major difference between the two compressive strength compensation methods on the pore sizes is that elevated curing temperatures increase the refined pore sizes from 10 nm to 20 nm within ZII and nevertheless decrease the pore volumes within ZI, as found in Figure 8 and the inset. Figure 9 presents the calculated cumulative pore volume based on Figure 8. This figure clearly confirms that the incorporation of GGBS promoted the pore volumes of NSM as the ultimate cumulative pore volume of Con is the lowest. Nevertheless, the pore sizes of GGBS-incorporating groups are finer than that of Con since most ascending curves of GGBS-incorporating groups shift left to that of Con. This refinement in pore sizes is beneficial to improve the durability performance of NSM with respect to external environmental actions, i.e., chloride migration and sulfate attack [16].

FIGURE 9: Cumulative pore sizes of representative 28 d mortars.

3.7. Ecoefficiency Evaluation of the Binary Cement. The energy consumption for producing and grinding 1 t cement has been reported as $E_{\text{cement}}^{\text{process}} = 1039 \text{ kWh/t}$ [42] and $E_{\text{cement}}^{\text{grinding}} = 50 \text{ kWh/t}$ [37]. According to DB31 581 [43], a comprehensive electricity consumption of GGBS encompasses the whole production process of GGBS, i.e., raw material conveying, drying, grinding, powder separating, product storage and delivering, and the supporting processes, i.e., electricity consumption for illumination and temperature control. It has been specified that the norm of comprehensive electricity consumption of GGBS should be less than 50 kWh/t. Therefore, the energy consumption for grinding 1 t GGBS is determined as $E_{\text{GGBS}}^{\text{grinding}} = 50 \text{ kWh/t}$ in this paper.

Figure 10 presents the calculated energy requirements of 1 t binder E and performance energy $E_{\text{performance}}$. The

ecoefficiency of NSM incorporating high volume of GGBS is obvious. In general, incorporating 70% to 90% GGBS into binders contributes to decreased E by 67% to 86% as well as lessened $E_{\text{performance}}$ by 65% to 75%. Among the ten mixtures, the three lowest values of $E_{\text{performance}}$ are 6.28 (kWh/t)/MPa (C15T23W45), 6.44 (kWh/t)/MPa (C20T23W35), and 6.61 (kWh/t)/MPa (C20T40W45). From the point of performance energy, it is thus suggested to replace 80% to 85% cement by GGBS to gain optimal ecoefficiency. Low w/b and high curing temperature at 40°C are effective methods to gain a lower $E_{\text{performance}}$. Therefore, the ecological upgrade of

FIGURE 10: Ecoefficiency evaluation of mortars with and without GGBS.

NSM by using high volume of GGBS provides a better choice for the sustainable development in a greener way. It should be noted that the calculation of $E_{\text{performance}}$ of C20T40W45 and C20T60W45 did not involve the extra energy for high temperature curing; thus, the ecoefficiency was underestimated from a practical point.

4. Conclusions

This paper has evaluated the feasibility of ecological upgrade of NSM by using high volume of GGBS (70%–90%). The following conclusions can be drawn based on the experimental results:

- (i) Ecological upgrade of NSM is viable and obvious by substituting 70% to 90% cement by GGBS. Accordingly, the energy requirements of 1 t binder can be saved by 67% to 86%, and the performance energy can be reduced from 25.4 (kWh/t)/MPa to 6 to 8 (kWh/t)/MPa.
- (ii) The setting times of pastes were prolonged with increased GGBS. The substitution of 70% to 90% cement by GGBS resulted in increased initial and final setting times by times of 1.09 to 1.31 and 1.12 to 1.68, respectively.
- (iii) NSM with proper contents of GGBS can develop acceptable 28 d compressive strengths than that of the control group. The early-age compressive strengths of GGBS-incorporating NSM were far lower but can be mitigated by methods of evaluated temperature curing or decreasing w/b .
- (iv) The incorporation of high volume of GGBS increased the porosities but refined the pore structures of mortars. Mortars with GGBS displayed very porous

microstructures at 3 d with visible bonded GGBS particles. Nevertheless, raising the curing temperature to 40°C or decreasing w/b at 0.35 helped dense the microstructures. At 28 d, all mortars displayed a similar morphology consisted by a dense matrix. Moreover, the pore sizes of mortars were significantly refined by incorporating GGBS.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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