Experimental study on the pH for activating ground granulated blast-furnace slag activity at different temperatures

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Abstract. In order to explore the initial pH values of activator solution needed for early activation of slag at different temperatures, the effects of curing temperatures (5, 20 and 35°C) and pH (12.10, 12.55, 13.02 and 13.58) on the activation and hydration characteristics of ground granulated blast-furnace slag (GGBFS) were investigated. Sodium hydroxide (NaOH) was used as the alkaline activator. The compressive strength and non-evaporable water content of GGBFS paste cured for 1, 3, 7, 14 days were determined. The hydration characteristics of slag pastes at different temperatures and pH were analyzed by XRD and SEM. The results showed that the pH value required for slag activation decreased with increasing temperature. Based on the 3 days strength of slag paste, the pH values required for activation of slag activity at 5, 20 and 35°C were 13.58, 13.02 and 12.10, respectively. With the high temperature and high pH of solution, a dense calcium-rich product formed on the surface of slag particles, which suppressed the further slag reaction. With the low temperature and high pH of solution, a layer of network product was found on the surface of the slag particles, and the later strength developed rapidly as the further hydration was not prevented. This study provides a reference for the application of alkali-activated slag.

Keywords. Alkali activated slag; pH; temperature; hydration products; microstructure.

1. Introduction

Ground granulated blast furnace slag (GGBFS) is a by-product produced during the iron making process. Because of its potential hydraulic activity, it is widely used as building materials [1–3]. When GGBFS meets water, an impermeable aluminosilicate shell will quickly form on the surface of GGBFS particles to prevent further reaction. The alkaline environment can dissolve the shell and activate the potential activity of slag, which makes the slag shows gelling characteristics [4, 5].

The commonly used ways to activate slag activity include physical excitation, chemical excitation and thermal excitation [6, 7]. The latent activity of slag can be rapidly activated by alkaline chemical activators, such as sodium hydroxide, sodium silicate and lime [8, 9]. According to the literature, the activation of slag activity mainly depends on the initial pH of the activator solution, and the rate of hydration accelerates with the increasing of the initial pH value [10, 11]. Song *et al* [12] reported that when the pH of the activator solution was higher than 11.5, the slag activity began to activate effectively. Yuan *et al*

[13] used the 7-day strength of the alkali-activated slag paste to characterize the activation of slag activity and found that the paste exhibited gelling properties only when the pH of alkaline solutions was over 12.0. The hydration products of alkali-activated slag are mainly hydrated calcium silicate (C-S-H), and the morphology and composition of C-S-H are closely related to the pH of the solution. C-S-H does not form when the solution pH is lower than 9.5 [12–15]. The above literature indicates that there is a minimum requirement for the initial pH value of the activator solution to activate slag activity.

The above studies about the pH needed for activating slag activity are conducted at room temperature. However, the hydration characteristics of alkali-activated slag are susceptible to changes in temperature [16–19]. Increasing the hydration temperature can significantly accelerate the rate of hydration heat evolution and promote early strength development. Low temperature will retard the early age strength development and prolong the setting time of alkali-activated slag [20–23]. Alkali-activated slag often encounters different ambient temperatures during its practical application, such as winter construction. In this condition, a relatively rapid reaction of slag is required. Is the initial pH value of the activator solution required for slag

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activation to be different at different temperatures? How does this affect the hydration characteristics of slag? However, no detailed study of this problem has been found in the literature.

Therefore, considering the influence of the above factors on the activation of slag activity, the main objectives in this paper are as follows:

- The effect of temperature on the initial pH of activator solution for the activation of slag;
- The coupling effect of temperature and pH on early hydration degree of slag;
- The coupling effect of temperature and pH on characteristics of early hydration product of slag.

2. Materials and experimental methods

2.1 Materials

The Blaine surface area of GGBFS used in this experiment was 400 m²/kg, and the chemical composition of GGBFS was shown in table 1. The alkali activator was sodium hydroxide (NaOH), and the deionized water was used. Four solutions with pH values of 12.0, 12.5, 13.0, and 13.5 were designed by adjusting the NaOH concentration. The actual pH values of the prepared solution actually measured by a pH meter were 12.10, 12.55, 13.02 and 13.58, respectively. The type of the pH meter used was PHS-3C produced by Shanghai Leici. The measuring range of the pH meter is 0–14 pH, and the measuring accuracy is 0.01 pH. According to the Chinese standard (GB/T 22592-2008), three standard buffer solutions were prepared for the verification of pH meters. The pH values of the three buffer solutions were 6.86, 9.18 and 12.45, respectively. Before using the pH meter, it was calibrated in the above standard buffer solution. After the measurement, the pH meter was washed with distilled water.

2.2 Experimental methods

2.1a Sample preparation: The slag pastes were prepared by mixing GGBFS and prepared NaOH solutions, the ratios of water-to-slag (*w/s*) were 0.4, 0.5 and 0.6, respectively. 70.7 mm cubic paste specimens were cast for the compressive strength test. Another partial slag pastes were placed in disposable plastic cups for non-evaporable water content test and microscopic analysis. Above prepared

samples were sealed with the plastic wrap to prevent the evaporation of water, then the samples were immediately divided into three parts and placed in a constant temperature curing box with curing temperatures of 5°C, 20°C and 35°C, respectively. After hardening and demoulding, the cubic specimens were sealed again and cured for 1, 3, 7 and 14 days, respectively. Of these three temperatures, 20°C is the standard curing temperature, 5°C is the typical ambient temperature in southern China in winter, and 35°C is the typical ambient temperature in summer.

The hardened pastes in the plastic cup that have been cured to the specified ages were taken out, broken into small pieces of about 2 mm and ground in a mortar to pass through the 0.075 mm square hole sieve. The samples were covered with anhydrous ethanol during the grinding process. After the end of the grinding, the samples were immersed in absolute ethanol for 24 h to terminate the hydration. The samples were then filtered and the filter residue was dried at 105°C for 2 h. The dried samples were ground again in a mortar to disperse the agglomerated sample during the drying process and then were placed in the sealed bag and placed in a desiccator for later use.

2.2b Testing: The compressive strengths of the paste were determined using a hydraulic universal testing machine manufactured. For the specimens were too weak to be demoulded at the desired ages, they were regarded as the non-strength.

The non-evaporable water content was measured by the method of high temperature furnace burning [10], and the dry sample was weighed about 1 g (accurate to 0.0001 g) with an analytical balance, and calcined to constant weight at 950°C, and the non-evaporable water content was calculated according to the following formula:

$$N_{(t)} = [(M_1 - M_2)(100 - L)/M_2] - L[\%] \quad (1)$$

where $N_{(t)}$ is the non-evaporable water content (%) at the hydration age t (day), M_1 and M_2 are the masses of the samples before and after the calcination, respectively (g), and L is the loss on ignition of the initial slag (%).

The hydration product of slag pastes were analyzed by Rigaku SmartLab (3) X-ray diffraction (XRD) analyzer. The samples were scanned in the range of 5 to 80 degrees (2 theta), with a scanning rate of 10 (°)/min. The microstructural and elemental composition of the hydration product on the surface of slag particles were observed by a Hitachi S4800 Scanning Electron Microscope (SEM). The sample magnification is 20,000 times.

Table 1. The chemical composition of GGBFS.

Chemical composition	CaO	SiO ₂	Al ₂ O ₃	MgO	SO ₃	TiO ₂	Na ₂ O	Fe ₂ O ₃	K ₂ O	MnO	LOI
Wt (%)	39.38	32.03	15.46	8.42	1.14	1.02	0.49	0.45	0.36	0.18	0.8

3. Results and discussion

3.1 Compressive strength

Figure 1 shows the variation of slag paste compressive strengths with temperature and pH at different w/s ratios when the curing ages were 1, 3, 7 and 14 days, respectively. It can be seen that the slag paste strength at different temperatures shows significant differences with the change of pH.

At 5°C, the slag paste had strength only in the solution of pH 13.58 throughout the test period, and the paste strength increased with age. At the three w/s ratios, the strength decreased as the w/s ratio increases, but the pH required for the hardening of the slag paste did not change.

At 20°C, the strength of slag paste at different ages increased with the increase of pH. However, the minimum pH of the initial activator solution at which the slag paste hardened varies with age. At 1, 3 and 14 days, the minimum pH of the solution in which the slag paste has strength was 13.58, 13.02 and 12.10, respectively. The minimum pH required for the hardening of the slag paste decreased with the curing age. This indicated that the larger the pH, the quicker the slag activation is and the shorter the setting time is. At the same curing age, the strength increased with the increase of pH. Besides, the change rule of strength under different w/s ratio is consistent.

When cured at 35°C, slag paste exhibited hardening characteristics in the solution of pH 13.02 at the age of 1 day. At 3 days, the minimum pH required to harden the

Figure 1. Compressive strength of slag paste cured at different temperatures and w/s for (a) 1 day, (b) 3 days, (c) 7 days and (d) 14 days.

slag paste was less, only 12.02. It is apparent that elevated temperature has an evident effect on the pH value needed to activate slag activity. However, at the same age, the strength varies with pH differences. The strength of slag paste increased with the increase of pH within 3 days (figures 1(a-b)). But at the age of 7 days and 14 days (figures 1(c-d)), the strength of slag paste first decreased and then increased with the increase of pH. Even the strength of slag pastes for some w/s in the solution pH 12.10 exceeded than in the solution pH 13.58. The reason for this phenomenon may be that the coupling effect of temperature and pH has a different effect on the hydration process of slag. As shown in table 2, the strength growth rate of slag paste with w/s 0.6 at different curing temperatures from 3 days to 7 days were different, it can be seen that the strength growth rate of slag paste decreased with the increase of temperature when the initial activator solution pH was 13.58. At this time, the increase of temperature inhibited the hydration of slag. When the curing temperature was 35°C, the strength growth rate of slag paste decreased with the rise of pH. Under these circumstances, the increase of pH is unfavorable to the strength growth of slag paste. In section 3.2, the effect of temperature and pH on the hydration degree of slag will be further studied by non-evaporable water content.

In figure 1, there is a phenomenon that under the hydration conditions of pH 13.58, the strength of the slag paste cured at 20°C was more significant than that cured at 35°C during the whole age. Besides, the slag paste compressive strength at 5°C exceeded than at 35°C at the age of 7 days and 14 days. This may be related to the “shelling” characteristics of alkali-activated slag hydration [24, 25]. Under the condition of 35°C, the slag activity in high pH solution (pH = 13.58) was quickly activated, and a dense hydration product was rapidly formed on the surface of the slag particles, which prevented further hydration of the slag so that the late strength developed slowly. However, in the low temperature and high pH or high temperature and low pH conditions, although the slag hydration was slow and the initial porosity of the paste was large at early period, the late hydration product was more densely packed between the slag particles so that the strength increased rapidly, which was verified in the later SEM testing.

Table 2. Growth rate of 3-7 days strength of slag paste with w/s 0.6 at different temperatures.

Growth rate	pH			
	12.10	12.55	13.02	13.58
5°C	—	—	—	207%
20°C	—	—	855%	141%
35°C	774%	296%	37%	11%

3.2 Non-evaporable water content

The content of non-evaporable water reflects the amount of chemical combined water formed by hydration reaction, which can represent the degree of hydration of the slag [10, 21]. Figure 2 presents the variation non-evaporable water contents of slag paste with pH cured at different temperatures and w/s ratios for 1, 3, 7 and 14 days, respectively. It can be seen that the non-evaporable water content of the slag paste at each curing age increased as the pH of the activator solution increases. But there is a pH that the non-evaporable water content sudden increase. At 5°C, in the solution with pH ≤ 13.02 , the non-evaporable water content increased very slowly as the pH increases. But at the solution of pH 13.58, the non-evaporable water content suddenly increased. This indicated that there is a particular value between the pH of 13.02 and 13.58, so that the slag activity is rapidly excited. Similarly, at 20°C, when the non-evaporable water content of the slag paste suddenly increased at 1 day, 3 days and 14 days, the pH values of the solution were 13.58, 13.02 and 12.10, respectively. While at 35°C, these pH values were smaller. The pH values at which the non-evaporable water content appears mutation point at 1 day and 3 days were 13.02 and 12.10, respectively. This rule was consistent under different w/s ratios and the change of w/s ratio did not affect the activation of slag. Also, the non-evaporable water content of slag pastes increased with the increase of w/s [26]. However, in figure 2, some non-evaporable water content at low w/s was higher than that at high w/s. This anomaly may be caused by errors in sample preparation and testing, and does not affect the overall analysis of the test.

Compared with the paste strength, in the solution of pH 13.58, the non-evaporable water content also showed different changes with the hydration temperature and age. During the whole hydration age, the non-evaporable water content cured at 20°C was always higher than that cured at 35°C. While after 3 days, the non-evaporable water content cured at 5°C exceeded that cured at 35°C for 7 days and 14 days. This is consistent with the change of slag paste strength with temperature and pH. It is mentioned in section 3.1 that the coupling effect of temperature and pH may have different effects on the process of slag hydration. It is crucial to determine the degree of slag hydration for evaluating the process of slag hydration. Powers [27] found that the non-evaporable water content of ordinary Portland cement after complete hydration was about 22%. Therefore, in this study, the degree of slag hydration under different hydration conditions is calculated by measuring the non-evaporable water content of slag fully hydrated samples. The calculation formulas are as follows.

$$\alpha_{(t)} = \frac{N_{(t)}}{N_u} \quad (2)$$

where $N_{(t)}$ is the non-evaporable water content (%) of slag paste at the hydration age t (day), N_u is ultimate non-

Figure 2. Non-evaporable water content of slag paste at (a) 1 day, (b) 3 days, (c) 7 days, (d) 14 days.

evaporable water content (%), and $\alpha_{(t)}$ is the degree of hydration at the hydration age t . The complete hydration sample of slag paste was prepared by placing the slag in the 1 mol/L NaOH solution at curing temperature of 35°C for three months. During the period, the hardened slag paste was crushed and ground several times. The NaOH solution was added continuously so that the slag was always immersed in the solution. By measuring the non-evaporable water content of the complete hydrated sample, the ultimate non-evaporable water content ($N_{(u)}$) was obtained, which was stable at 19.97%.

According to equation (2), the hydration degree of slag pastes with w/s of 0.6 was calculated, and the hydration degree changes with the curing age at different

temperatures and pH were shown in figure 3. It can be observed that when the pH of the activator solution was less than 13.02 (figures 3(a–c)), the degree of hydration of slag was positively correlated with temperature. Taking figure 3(a) as an example, the hydration degree of slag at 5, 20 and 35°C for 14 days reached 2.1%, 15.8% and 23.2%, respectively. This indicated that the higher the curing temperature is, the higher the hydration degree is. But when the slag was in high pH ($pH = 13.58$) solution (figure 3(d)), the degree of slag hydration was not positively correlated with temperature. For example, the degree of slag hydration was the highest at 20°C for 1 day. But when the slag was hydrated for 7 days, the hydration degree of slag was the highest at 5°C, which reached 41.6%. It can be seen that

Figure 3. Early hydration degree of slag in different pH solutions.

increasing curing temperature during this period will inhibit the hydration reaction degree of slag. Actually, the reaction degree of slag reflects the breaking rate of Si-O and Ca-O bonds in slag particles to some extent, and the dissolution rate of Si and Ca ions in solution is greatly influenced by the concentration of OH^- and temperature in solution. In the solution with $\text{pH} \leq 13.02$, low temperature will slow down the OH^- movement rate and weaken the collision ability with slag particles, which was not enough to destroy enough Ca-O and Si-O bonds, so the degree of hydration was low. Because the activation energy of the chemical reaction decreased with the increase of temperature, so more Ca-O and Si-O bonds were broken, and the degree of slag reaction was significantly increased. However, in the solution with high pH ($\text{pH} = 13.58$), because of the high

initial OH^- concentration, the hydration degree of slag will be very high for 1 day at three curing temperatures. However, different curing temperatures may lead to the difference of the structure of slag hydration products, which in turn affects the later dissolution of Si and Ca ions, leading to the highest degree of slag hydration at low temperature. The conjecture is further validated by the analysis below.

3.3 XRD analysis

Figure 4 shows the X-ray diffraction patterns of slag paste hydrated for 1 day at different temperatures and pH with the w/s of 0.4. Seen from the XRD pattern of the raw slag, the raw slag was mainly an amorphous vitreous structure,

Figure 4. X-ray diffraction pattern of slag paste at different pH and temperatures for 1 day.

containing a small number of aluminosilicate minerals, such as pyroxene and melilite crystals (approximately 31°). At 5°C (figure 4(a)), it can be observed that the hydrated slag samples in the solution with pH 13.02 appeared a peak near $29.3^\circ 2\theta$, which may be C-S-H with poor crystallinity or calcium carbonate produced by carbonization [28, 29]. In the solution with pH 13.58, in addition to the formation of C-S-H, aluminosilicate (C-A-S-H) and hydrotalcite were also formed in the slag hydration products. Similarly, when the slag was in an environment of 20°C (figure 4(b)), the types of slag hydration products and the formation conditions were consistent with those at 5°C . However, different results were observed at 35°C (figure 4(c)). The hydration product C-S-H appeared in the solution with pH 12.55, and the peak value of C-S-H increased in the solution with pH 13.02, indicating that the number of C-S-H increased. Besides, the formation of silicate aluminate (C-A-S-H) and the diffraction peak of hydrotalcite appeared near the diffraction angle of 32.5° . When the pH reached 13.58, a more prominent hydrotalcite diffraction peak appeared at the 11.5° .

Through the above analysis, it is found that C-S-H was first formed in NaOH solution, which was the main product of alkali-activated slag hydration. Aluminosilicate (C-A-S-

H) and hydrotalcite were then present in the product as the reaction progressed, but the formation of these two hydration products was affected by the curing temperature and pH. Compared with figures 4(a) and (b), in the solution of pH 13.02, no aluminosilicate product was observed in the slag at 5°C , but it was observed at 35°C . This is related to the hydration mechanism of slag. When the slag is in alkaline solution, the Si-O bond, Al-O bond and Ca-O bond on the surface of slag particles will break under the polarization of OH^- . Because the Ca-O bond is much weaker than the Si-O bond and Al-O bond, so the C-S-H will be first formed. Increasing the temperature or the pH of the activator solution will increase the polarization of OH^- and make more Si-O bonds, Al-O bonds and Mg-O bonds break, and the hydration products of silicate-aluminate (C-A-S-H) and hydrotalcite begin to appear, which is beneficial to the development of strength [30].

3.4 SEM and energy dispersive spectrum analysis

According to the analysis as mentioned above of compressive strength of slag paste, in the high alkali solution of pH 13.58, the compressive strength of the slag paste at

20°C was higher than the compressive strength at 35°C in each age. After 7 days, the compressive strength at 5°C was the largest. The same rule applies to non-evaporated water content. This macroscopic phenomenon can be more clearly understood by scanning electron microscopy of the hydration state of the slag particles surface.

Figure 5 shows the surface reaction conditions of the slag particles cured at 5°C and 35°C for 1 day and 14 days with the solution pH 13.58. The energy spectrum of the hydration products on the surface of these slag particles were analyzed, as shown in figure 6. As can be seen from figure 5, when the slag was cured for 1 day, a large number of intricately connected network products appeared on the surface of the slag particles at 5°C, while the bulk product covered the surface of the slag particles was observed except for the network product when cured at 35°C. When the hydration age reached 14 days, the surface of the slag particles at 5°C was still similar to that at 1 day, but the pores of the product were finer and denser. While the surface of the slag particle cured at 35°C was completely surrounded by massive hydration products, which formed a hard reaction shell.

The energy dispersive spectrum analysis of figure 6 indicated that the elemental composition of the slag hydration products in different hydration environment was the same. The main product components were calcium (Ca), silicon (Si) and aluminum (Al) with lesser amounts of magnesium (Mg) and sodium (Na). The peak intensity of Ca and Si were very close at 5°C for 1 day and 14 days. But it can be seen that the peak intensity of Ca in slag hydration products of 14 days at 35°C was obviously higher than that of Si, which indicated that a denser calcium-rich product layer will be formed on the surface of slag particles [31].

The above analysis illuminated that in the solution of pH 13.58, the slag particles hydrated slowly at 5°C, forming a network of products on the surface of the particles. This structure allowed OH^- to pass through the network pores and further penetrate into the inside of the slag particles. The product gel filled the particle gap more densely, so the late strength developed rapidly. At 35°C, the slag particles were quickly hydrated, forming a reaction shell of the dense calcium-rich product on the surface. Although the initial porosity of the paste was reduced, the further slag reaction

Figure 5. SEM images of slag particles with $w/s = 0.4$ in the solution pH 13.58 (a) 5°C – 1 day, (b) 35°C – 1 day, (c) 5°C – 14 days and (d) 35°C – 14 days.

(a) 5 °C -1 day

(b) 35 °C -1 day

(c) 5 °C -14 days

(d) 35 °C -14 days

Figure 6. Energy spectrum of the hydration products on the surface of slag particles with $w/s = 0.4$ in the solution pH 13.58 (a) 5°C – 1 day, (b) 35°C – 1 day, (c) 5°C – 14 days and (d) 35°C – 14 days.

of slag particles was suppressed, so that the growth rate of long-term strength was slower than that of early stage.

In figures 1(c) and (d), after slag pastes were cured at 35°C for 7 days, the slag paste strength showed a decreasing trend with the increase of pH in the solution of $pH \leq 13.02$, and paste strength in the solution pH 12.10 even exceeded the paste strength in the solution pH 13.58. Similarly, figure 7 illustrated this phenomenon by microscopic analysis of the slag particles cured at 35°C for 1 day and 14 days with the solution pH 12.10. There was a small amount of hydration product on the surface of the slag particles at 1 day, but the amount was not sufficient to form a bond between the particles. On the 14th day, a large

number of network products developed on the surface of the particles, and the gel product adhered to it. However, compared with figure 5(d), the surface of the slag particles did not form a hydrated hard shell, so the slag can continue to hydrate and the strength developed rapidly in the later stage.

4. Discussion

Whether the latent slag activity is activated or not can be judged by the content of dissolved silicon iron [12] and the slag paste strength [13]. Therefore, in this paper, the lowest

Figure 7. SEM images of slag particles with $w/s = 0.4$ in the solution pH 12.10 (a) 35°C – 1 day, (b) 35°C – 14 days.

pH of the activator solution at which the slag paste hardens at the age of 3 days is used as the judgement basis, to explore the effect of temperature on the pH required for activation of slag activity.

As shown in figure 1(b), at the age of 3 days, the pH values required for activation of slag activity at 5, 20 and 35°C are 13.58, 13.02 and 12.10, respectively. This indicates that the initial pH required to activate slag activity gradually decreased as the temperature increases. This pattern is related to the influencing factors of slag activity [32]. The main factors affecting the activity of slag are the type of activator, the amount of activator and the temperature. The slag is mainly an amorphous vitreous structure. When the slag contacts with water, because of the Ca-O bond on the surface of the slag particles is much weaker than the Si-O bond and the Al-O bond, Ca-O bond will first break under the polarization of OH^- , and the rich Si-Al layers are quickly formed on the surface of the slag particles. However, the OH^- concentration is still insufficient to break the Si-O bond and the Al-O bond to form a considerable amount of C-S-H [33]. In the high pH solution, OH^- in the solution not only destroys the Ca-O bond, but also breaks a considerable amount of Si-O bonds and Al-O bonds, and a thin layer of hydration product is rapidly formed on the surface of the slag particles. The higher the pH value, the more the amount of Ca and Si ions eluted, and the faster the formation of C-S-H, the quicker the slag activity is motivated. Conversely, in a solution with a lower pH, the longer it takes to form a significant amount of C-S-H. The temperature will affect the diffusion rate and dissolution rate of the ions [34]. Moreover, the low temperature will slow down the OH^- diffusion rate in the solution, the collision ability with the slag particles will be weakened, the dissolution rate of Si and Al ions will be slowed down, so that the hydration product content will also decrease. To activate the slag activity in the same age period, the pH required at low temperatures is higher. The

variation of the pH required for the slag activity activation with temperature provides a reference for the application of alkali-activated slag. For example, when NaOH is used as an activator, to make the alkali-activated slag exhibit hardening characteristics at 5°C, the pH of the activator solution should be increased to above 13.5.

5. Conclusion

By studying the compressive strength, non-evaporable water content and the characteristics of hydrated products of alkali-activated slag paste at different temperatures and pH, the following conclusions are obtained.

- a. By using NaOH as an alkali activator, based on the 3 days strength of slag paste, the pH values required for activation of slag activity at 5, 20 and 35°C were 13.58, 13.02 and 12.10, respectively. The pH of the solution needed for slag activation decreased with increasing temperature.
- b. The degree of slag hydration was analyzed by non-evaporable water content. It was found that when the pH of the activator solution was less than 13.02, the degree of slag hydration was positively correlated with temperature. When the slag was in high pH (pH = 13.58) solution, the degree of slag hydration was negatively correlated with temperature.
- c. The XRD analysis of the products after hydration of slag at different temperatures for 1 day showed that C-S-H is first formed in slag hydration products. Aluminosilicate and hydrotalcite were then present in the product as the reaction progressed, which were affected by the curing temperature and pH.
- d. From the SEM images of the surface of hydrated slag particles, in the high temperature and high pH solution, the slag particles were rapidly hydrated, forming a dense

and calcium-rich product shell, which inhibited the hydration reaction in the later stage. In the low-temperature and high pH solution, the network structure formed on the surface of the particles allowed the slag to continue to react, which contributed to the development of strength.

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