Grinding Characteristics and Cementitious Properties of Steel Slag

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Abstract  
The grinding characteristics and cementitious properties of steel slag (SS) were investigated by particle size analysis, specific surface area analysis, field emission electron microscope (FE-SEM), X-ray diffraction, strength test and non-evaporable water content determination. The results show that SS have a slightly better grindabilities than ground granulated blast furnace slag (GGBFS). The specific surface area of SS powder is 690 m²·kg⁻¹ by milling for 100 min. The milled SS product obtained by milling for 100 min contains 81% grain particles smaller than 5 μm which can fill space between cement particles among them, much smaller particles with submicron or nanometer size were also observed. The hydration products of SS are C–S–H gel and Ca(OH)₂. The C–S–H gel produced by SS dose not adhere mutually well, and show a low bonding behavior, thus resulting in a rather low strength of steel slag mortar.

Key words: Steel Slag; Grindability; Specific Surface area; Cement; Hydration Products

1. Introduction  
Currently, ground granulated blast furnace slag (GGBFS) and fly ash are the most widely used mineral admixtures in the production of cement and concrete. Despite the reduction of initial concrete strength due to the partial replacement of cement, the two admixtures can improve the performance of concrete, such as reducing hydration caused temperature rise, increasing the workability of fresh concrete, lowering the risk of cracking, strengthening durability, and so on [1-5]. In actual concrete production, fly ash and GGBFS are often used simultaneously because the combination of fly ash and GGBFS further enhances concrete performance [6-9]. By virtue of the extensive application, both BFS and fly ash have become more scarce and expensive in many Chinese cities. At present, “low carbon” is recognized as the common goal of the concrete industry. With the rise of concrete strength, more and more cementitious materials are consumed during the production of concrete. The massive use of mineral admixtures is crucial to the “low carbon” development of concrete. Therefore, it is
very meaningful to develop and utilize mineral mixtures that can be applied in massive amount and various environments.

Figure 1. Comparison of compositions of SS, BFS and cement [20], %.

As the slag of the steel industry, SS mainly consists of smelting fluxes (e.g. limestone, dolomite and iron oxides) added in the steelmaking process, the slagging materials for adjusting the properties of steel, and the impurities separated from the two liquid phase furnace burdens (not mutually fusible) melted at high temperature. The amount of discharged SS is about 12% to 20% of crude steel production [10, 11]. In China, 80 million tons of SS are produced each year while the stockpiled SS accumulates to 500 million tons, putting the comprehensive utilization rate of SS below 40% [12, 13]. The mineral compositions of steel slag include calcium silicates (C$_2$S, C$_3$S), calcium ferrites (C$_4$AF, C$_2$F), calcium aluminates (C$_3$A, C$_{12}$A$_7$), free CaO, free MgO, RO phase (CaO-MgO-MnO-FeO solid solution), metallic iron, Fe$_3$O$_4$, olivine, manganolite [11, 14-20]. The chemical composition of SS is mainly CaO, SiO$_2$, Fe$_2$O$_3$, MgO, and a small amount of Al$_2$O$_3$, MnO$_2$, P$_2$O$_5$ (Figure 1) [20], and it can be seen that the chemical composition of SS is similar to cement, SS can react with water, producing Ca(OH)$_2$, C-S-A-H gel, C-A-H crystal, C-S-H gel, and so on [19, 21, 22]. For now, SS is mainly used as materials for subgrade engineering, engineering backfills and asphalt concrete aggregates. Less than 10% of the total amount are being applied to cement concrete [23-26]. In recent years, researchers have explored the ways to activate the cementitious property of SS and the feasibility of preparing new materials with SS [27]. In spite of the efforts, the utilization rate of SS still remains at a low level, indicating the lack of sufficient basic research into SS. In particular, systematic and in-depth studies are needed on the activation of cementitious property and hydration hardening mechanism of SS. It is of great necessity to strengthen the theoretical research in these fields. This paper carries out a systematic study of SS from the aspects of the grinding property, cementitious properties, as well as types and morphology of hydration products, thereby laying the theoretical basis for the application of SS in concrete.

2. Materials and Methods

2.1. Materials

Cement. The cement used was pure type I Portland cement with the strength grade of 42.5 which complies with the Chinese National Standard GB 175–1999. The chemical compositions and the physical properties of the pure Portland cement are shown in Table 1 and Table 2, respectively.

SS. SS used was basic oxygen furnace steel slag without hot closed treatment technology which complies with the Chinese National Standard GB/T 20451-2006, its chemical composition is shown in Table 1. The main chemical composition of SS is CaO (43.73%), followed by the level of residual iron in the steel slag (14.42%). Compared with the Portland cement, SS has higher contents of Fe and Mg and lower contents of Si and Ca. The f-CaO content and f-MgO content in SS are 1.21% and 0.81%, respectively. The activity of SS can be partially reflected by the alkalinity calculated from the chemical composition of SS. In China, SS alkalinity is defined by the method of Mason [28]: CaO/(SiO$_2$+P$_2$O$_5$), and divided into three categories: low alkalinity slag (alkalinity <1.8), medium alkalinity slag (alkalinity = 1.8~2.5) and high alkalinity slag (alkalinity> 2.5). In this paper, the alkalinity of SS is 2.48, which falls in the middle range. The f-CaO content and alkalinity of SS satisfies the requirement in Steel Slag Powder Used for Cement and Concrete (GB/T20491-2006) that f-CaO content should not exceed 3% and the alkalinity should not fall below 1.8. According to the particle size distribution of SS listed in Table 3, the particles within the size range of 0.3~9.5 mm accounts for 95.11% of the total, which indicates that SS need crushing before grinding.
Sand. ISO standard sand will be used as fine aggregate in mortar.

**Table 1. Chemical composition of cement and SS (wt. %)**

<table>
<thead>
<tr>
<th>Materials</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O₂eq</th>
<th>MnO</th>
<th>P₂O₅</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>21.68</td>
<td>4.56</td>
<td>2.63</td>
<td>-</td>
<td>1.83</td>
<td>63.39</td>
<td>0.48</td>
<td>-</td>
<td>0.04</td>
<td>1.86</td>
</tr>
<tr>
<td>SS</td>
<td>14.52</td>
<td>5.64</td>
<td>13.58</td>
<td>6.32</td>
<td>9.66</td>
<td>43.73</td>
<td>0.30</td>
<td>0.74</td>
<td>3.11</td>
<td>1.78</td>
</tr>
</tbody>
</table>

*Note: Na₂O₂eq=Na₂O+0.658K₂O*

**Table 2. Physical properties of cement**

<table>
<thead>
<tr>
<th>Fineness (residue on 80 μm sieve)</th>
<th>Normal consistency</th>
<th>Setting time /min</th>
<th>Flexural strength /MPa</th>
<th>Compressive strength /MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>%</td>
<td>Initial setting</td>
<td>Final setting</td>
<td>3d</td>
</tr>
<tr>
<td>22.13</td>
<td>27.2</td>
<td>160</td>
<td>220</td>
<td>qualified</td>
</tr>
</tbody>
</table>

**Table 3. Particle size distribution of SS and GGBFS %**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Particle size /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+9.50</td>
</tr>
<tr>
<td>SS</td>
<td>4.11</td>
</tr>
<tr>
<td>GGBFS</td>
<td>—</td>
</tr>
</tbody>
</table>

**2.2. Experimental Method**

(1) Specimen Preparation

Before the experiment, SS was crushed to the size of 1~2 mm by EP-150×125 fully sealed jaw crusher, and ground to the desired size with the SM Φ500 mm×500 mm 5 kg small ball grinder at the speed of 48 r·min⁻¹. The grinding media consists of several steel balls and a steel forging. The loading mass of the grinding media should be 100 kg. The steel balls add up to 40 kg, in which the Φ70 mm ball takes up 19.7%, the Φ60 mm ball takes up 33.1%, the Φ50 mm ball takes up 29.6%, and the Φ40 mm ball takes up 17.6%; the Φ25 mm ×30 mm steel forging weighs 40 kg.

SS paste and mortars were prepared by mixing SS with water at a water-SS ratio of 0.30 (mass ratio of water to slag). The cement pastes were prepared by mixing cement with water at a water cement ratio of 0.42.

Table 4 shows the composition of the cementitious materials used in the experiment. Specifically, the water-cement ratio of the net paste sample is 0.42, the cement-aggregate ratio (mass) is 1:3, and the specimen size is 40 mm×40 mm × 160 mm. After moulding, the specimen was cured for 1d in a standard curing chamber at the temperature of (20±1) °C and relative humidity above 90%, and then cured to the corresponding age water at the same temperature and humidity. The compressive strength of the mortar was tested in reference to *Method of Testing Cements: Determination of Strength* (GB/T 17671-1999).

**Table 4. Composition of cementitious materials (wt. %)**

<table>
<thead>
<tr>
<th>Samples</th>
<th>Cement</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>CS1</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>CS2</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>CS3</td>
<td>55</td>
<td>45</td>
</tr>
</tbody>
</table>

(2) Property Characterization

The f-CaO of SS was determined by EDTA complexometric titration according to *Methods of Chemical Analysis of Steel Slag* (YB/T 140-2009) using ethylene glycol as extractant; the f-MgO was measured by using ammonium nitrate-ethanol as extractant [29].
According to the Chinese National Standard GB/T 19077.1-2008 Particle size analysis - Laser diffraction methods - Part 1: General principles, the particle size distribution of ground steel slag is analyzed using laser particle size analyzer (MASTER SIZER 2000, the analysis range is 0.02~2000.00 μm) with ethanol as the dispersant. The specific surface area is measured using dynamic specific surface area analyzer (SSA-3200). The compressive strength test of samples was based on the Chinese National Standard GB/T 17671-1999 Method of testing cement-determination of strength. The strength was measured using hydraulic pressure testing machine (YES-300) with a maximum load of 300 KN and a loading rate of 2.0±0.5 kN/s. The hydration and exothermic properties of the cementitious material was measured by TONI 7338 isothermal differential calorimeter. The sensitivity of the instrument is 0.2 J/g. The hydration and heat dissipation of the cementitious material was measured at the constant temperature (25±0.3 °C). To prepare the samples for non-evaporable water content measurement, the crushed specimen (smaller than 80μm in diameter) was immersed in ethanol to stop the hydration. The samples were dried at 65 °C for 24 hrs in an oven (DH-101), and then 1~2 g dried samples were burned at 1050 °C for 2 hrs in a furnace (CD-1400X). And the mass loss in the furnace is used to calculate the non-evaporable water content. The XRD spectra were obtained using a D/Max-RC diffractometer (Japan) with Cu-Kα radiation, voltage of 40 kV, current of 150 mA and 2θ scanning ranging between 10 ° and 90 °. And the wavelength is 1.5406 nm. FE-SEM observation was performed to analyze the mineral phase and the hydration products of the paste samples using a Zeiss SUPRATM55 scanning electron microscope coupled with a Be4-U92 energy spectrum.

3. Results

3.1. SS Grinding Characteristics

(1) Particle Size Distribution of SS Powder

Figure 2(a) and 2(b) illustrate the SS particle size distribution after 40 min, 60 min, 80 min and 100 min of powder grinding. The SS particle size after grinding is polarized and does not follow logarithmic normal distribution. When the powder grinding time increases to 80 min, the polarization of the interval distribution of SS particle size gradually weakens owing to the complex composition of SS and the significant grindability difference of the materials contained in SS. With the increase of powder grinding time, the range of SS particle size distribution shrinks, and the average particle size decreases from 13.98 μm, 9.95 μm, and 2.51 μm to 1.81 μm, indicating the falling proportion of the fine-grained particles in SS.

![Figure 2](image-url)

Figure 2. Particle size distribution curves of SS milled for different time periods

According to Figure 2(a), the particle size decreases after 40 min of powder grinding, leaving over 50% of particles smaller than 10 μm. As the powder grinding persists, fewer and fewer particles remain larger than 10 μm. As shown in the figure, submicron particles are produced, taking up 1.51% of the SS particles, at 40 min of powder grinding; the proportions of submicron particles keep growing and end up at 2.02%, 3.83% and 6.43%, respectively, with the increase of the duration of powder grinding. It is shown that SS particles are gradually refined during the powder grinding process, and the increase of the grinding time promotes the decrease of the SS particle size.
Table 5 lists the analytical results of the characteristic SS particle size analysis at different grinding times. The analysis is targeted at disclosing the variation of $D_{10}$, $D_{50}$ and $D_{90}$. The three parameters stand for the particle size when the volume of cumulative particle size distribution reaches 10%, 50% and 90%, respectively. $D_{10}$ reflects the amount of fine particles, $D_{50}$ reflects the amount of large particles, and $D_{90}$ reflects the average particle size. As can be seen from Table 5, the $D_{10}$, $D_{50}$ and $D_{90}$ of SS particle size distribution declines with the increase of powder grinding time. Specifically, $D_{10}$ drops from 1.64 μm to 0.87 μm, $D_{50}$ drops from 6.98 μm to 2.23 μm, and $D_{90}$ drops from 23.84 μm to 7.55 μm. The results show that with the increase of grinding time, the proportion of large particles decreases, the proportion of fine particles increases, the size range decreases, and the average SSA increases.

<table>
<thead>
<tr>
<th>Grinding time /min</th>
<th>Characteristic particle size /μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_{10}$</td>
</tr>
<tr>
<td>40</td>
<td>1.64</td>
</tr>
<tr>
<td>60</td>
<td>1.43</td>
</tr>
<tr>
<td>80</td>
<td>1.06</td>
</tr>
<tr>
<td>100</td>
<td>0.87</td>
</tr>
</tbody>
</table>

(2) Particle Morphology Characteristics of SS Powder

![FE-SEM images of SS milled for different time periods](image)

**Figure 3.** FE-SEM images of SS milled for different time periods (a) - 40 min, (b) - 60 min, (c) - 80 min, (d) - 100 min.
Figure 3 presents the FE-SEM images of SS powder obtained at different times of powder grinding. Specifically, Figure 3(a) illustrates the situation after 40 min of powder grinding. The SS particles undergo irregular changes. Through powder grinding, the size of some particles decreases drastically to 5 μm. Some large particles are about 15 μm, most of which are in the shape of flakes and irregular polygonal blocks, with sharp edges and corners. After 60 min of powder grinding (Figure 3(b)), the large particles are still clearly visible in the SS, but the particle size is reduced to around 10 μm, indicating that some SS components have poor grindability. With the progress of grinding, the hard-to-grind components in the SS continue to shrink in size. The edges and corners are rounded and the particles are regularized. Figure 3(c) depicts the situation after 80 min of powder grinding. The SS particles are mostly below 10 μm, and the powder particles are very refined. Apart from the emergence of a certain amount of particles smaller than 1 μm, a lot of submicron particles come into being with good sphericity. The situation is an evidence to the growing spherical degree and edge roundness of SS powder particles with the lengthening of grinding time. Figure 3(d) describes the situation after 100 min of powder grinding. Near-spherical and smooth edged nano-particles are clearly observed in the image. Under the action of large surface energy, these nanoscale particles are agglomerated or adsorbed on the surface of the coarser particles. Therefore, ultrafine grinding SS powder captures not only lots of submicron particles, but also spherical nano-particles. The spherical shape is one of the reasons that fly ash is so important in the concrete industry. Adding fly ash into the concrete can boost fluidity of slurry, and, in turn, enhance the workability and mechanical properties of concrete. If the ultra-fine SS powder is applied to the concrete, the ideal spherical shape will fully unlock the filling effect. Moreover, the hydration reactivity of SS powder is enhanced by the lattice distortion and surface energy increase of some submicron and nanoscale particles produced by powder grinding. When the fine-grained SS powder is used as a mineral admixture into the cement concrete system, these submicron and nanoscale particles will further promote the strength and durability of the concrete.

(3) Grindability of SS

The energy consumption of GGBFS powder grinding is a well-known parameter in the field of building materials. In order to grind GGBFS into GGBFS powder above 400 m²·kg⁻¹ in Blaine specific surface area), 80 kW·h·t¹ of energy should be consumed by using a large-scale industrial ball grinder, and 50–60 kW·h·t¹ by using an advanced vertical powder grinder [30]. Therefore, this paper attempts to study to grindability of iron tailings in reference to the grindability of GGBFS. In the experiment, different batches of SS and GGBFS are ground by the same SM Φ500 mm×500 mm experimental ball grinder. SSA difference between the two materials treated with the same powder grinding time are compared after the experiment. The granularities of SS and GGBFS are contrasted in Figure 3, while the relationship between the SSA and powder grinding time of the two materials are compared in Figure 4.

According to Figure 4, the SSA of SS is 450 m²·kg⁻¹ and that of GGBFS is 430 m²·kg⁻¹ after 40 min of powder grinding; At the 100 min of powder grinding, the SSAs of SS and GGBFS increase to 690 m²·kg⁻¹ and 620 m²·kg⁻¹, respectively. Throughout the powder grinding process, SS always stay ahead of GGBFS in terms of SSA. This shows that only a few particles of SS are difficult to grind, while most components are easily grindable. Beside, the SSA of SS powder grows faster than that of GGBFS powder, i.e. the newly added SSA of SS powder is greater than that of GGBFS powder. The difference is demonstrated by the grater slope of the curve corresponding to SS powder. This further confirms that SS has better grindability than GGBFS. Combined with the findings of Hou et al. [31], it is unscientific to follow the traditional view that SS is poorly grindable.

Mechanical activation is the first step in the preparation of cementitious materials from SS. In view of the different grindability between SS components, the best option is to adopt the two-stage powder grinding process. In this process, the hard-to-grind components are identified, such as MgO·2FeO and Ca₂(Al, Fe)₂O₃ in SS. The removal of such components overcomes the hydration and expansion of MgO in the late stage of concrete curing, and improves the economic value thanks to the high content of oxides in the two minerals (e.g. the mass content of Fe is 61% in MgO·2FeO). The high economic value is extremely important for the use and high added value of SS [31]. Through the above analysis and in light of Figure 4, it is concluded that 40–60 min grinding with the experimental ball grinder is needed so that the GGBFS and SS meet the common SSA (400–500 m²·kg⁻¹) in the field of building materials; 80–100 min powder grinding is required to achieve the goal that over 50% of the SS are particles smaller than 5 μm. At the same time, it can be predicted that the powder grinding energy consumption of large-scale industrial grinder is basically unchanged whether the object is SS powder or commonly used GGBFS powder. As a result, it is technically and energetically feasible to grind SS into lots of ultrafine particles and apply the particles to concrete.
3.2. Effect of Content on Strength

Li [32] and Zhang et al. [33] studied the relationship between SS particle properties and cementitious capability, and argued that the SSA should be controlled within 500 m²·kg⁻¹; larger SSA does not result in greatly improved activity but makes SS preparation costlier. Thus, the effect of SS content on mortar strength is tested with SS (SSA: 540 m²·kg⁻¹) after 60 min of powder grinding and cement (SSA: 320 m²·kg⁻¹). The mass ratio between water and cementitious material (water-cement ratio) is an important influencing factor on strength. The higher the water-cement ratio, the more the mortar porosity, the lower the mortar strength. Figure 5 shows how SS dosage affects the compressive strength of mortar. It can be seen that the compressive strength of the mortar decreases with the increase of the SS dosage at the same age. The changing pattern is attributable to the low activity of SS. When some cement is replaced by SS, the water-cement ratio actually increases, leading to reduced mortar strength.
Table 6 lists the compressive strength of composite cementitious mortar as a percentage of the compressive strength of pure cement mortar (denoted as M). Suppose the percentage of cement mass to the total mass of the composite cementitious material is N in each group. The N value of CS1, CS2 and CS3 are 85%, 70% and 55%, respectively. As can be seen from Table 6, within 7 d, the M value is smaller than the N value in CS1, CS2 and CS3; after 7 d, the M value is greater than the N value in any group. The comparison reveals that SS contributes little to the initial strength of the mortar due to the low hydration activity in the early phase; the contribution of SS to strength gradually increases with the increase of age. At 28 d, the M value in each group far exceeds the N value. However, the M value of any group at 90 d is lower than that at 28 d, indicating that the strength of “composite binder” grows slowly than that of “pure cement” binder. The possible reasons are as follows: because the amount of Ca(OH)$_2$ produced by hydration in the later stage of strength development of mortar blocks decreases, it can be seen from Table 1 that the content of CaO in the chemical composition of cement is 63.39%, while that in the chemical composition of steel slag is 43.73%, the difference is 19.66%. The content of cement in CS1, CS2 and CS3 cementitious materials is 85%, 70% and 55%, respectively. The corresponding amount of Ca(OH)$_2$ produced by hydration decreases [34]. So the hydration reaction rate of steel slag is lower than that of cement after 90 d, and the strength growth rate of CS1, CS2 and CS3 samples after 90 d is lower than that of pure cement binder.

<table>
<thead>
<tr>
<th>Time/d</th>
<th>CS1</th>
<th>CS2</th>
<th>CS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81.72</td>
<td>68.66</td>
<td>38.43</td>
</tr>
<tr>
<td>3</td>
<td>76.21</td>
<td>52.61</td>
<td>39.07</td>
</tr>
<tr>
<td>7</td>
<td>83.69</td>
<td>80.82</td>
<td>63.44</td>
</tr>
<tr>
<td>28</td>
<td>96.40</td>
<td>78.68</td>
<td>73.12</td>
</tr>
<tr>
<td>90</td>
<td>85.01</td>
<td>74.81</td>
<td>63.85</td>
</tr>
<tr>
<td>180</td>
<td>83.29</td>
<td>74.94</td>
<td>62.11</td>
</tr>
</tbody>
</table>

3.3. Hydration Characteristics of SS

(1) Hydration Process of SS

The non-evaporable water content is a common indicator of the degree of hydration for the cementitious materials. In the hardened cementitious materials, the water inside can be separated into two portions. One portion of water exists as free water in the pores of the materials, while the other portion is considered to non-evaporable water as a component of hydration products in a form of OH. The amount of non-evaporable water increases as the amount of hydration products increases. Figure 6 shows the non-evaporable water amounts of SS paste and cement paste at varying ages. The non-evaporable water content of cement paste is much higher than that of SS paste at the early age, while its increase at the later ages is smaller than that of SS paste. During the curing age from 90 d to 180 d, the non-evaporable water content increase by 0.42% and 1.91% in the cement paste and SS paste, respectively. The non-evaporable water content of the cement paste at the age of 180 d is 17.02%. At the same age, the amount of SS only account for 57.64% of that in the cement paste. There is a maximum difference of the non-evaporable water content with a value of 9.10% between the two pastes at the age of 7 d. As the age increases, the difference becomes smaller, and there is a minimal difference with a value of 7.21% at the age of 180 d. This indicates that the hydration rate of SS exceeds that of cement after 7 d.

When cement hydration enters a stable stage, the hydration reaction is controlled by diffusion process. The thickness of diffusion barrier (C-S-H layer) determines the speed of hydration reaction. The early hydration rate of cement is fast, and the thickness of hydrated product layer on the surface of particles increases rapidly, which makes it more difficult for water to reach the surface of unhydrated particles. However, the early hydration rate of SS is slow, and the thickness of hydrated product layer on the surface of particles increases very slowly, which makes it relatively easy for water to reach the surface of unhydrated particles in the later hydration process. At the same time, because the active ingredient in SS is much lower than that in cement, some of the hydration products of steel slag encapsulate unhydrated particles, which weakens the thickness of the hydration layer on the surface of active ingredient particles to a certain extent, and is conducive to the further hydration of active ingredients [35].

Therefore, from the point of view of the whole hydration process, the hydration of SS is a slow process, and the contribution of hydration during the hydration stabilization period to its hydration degree is much greater than that of cement hydration during the hydration stabilization period.
(2) Hydration Products of SS

Figure 7 shows the mineralogical phases of SS and hardened SS paste for 3, 90 and 180 d, which are determined by X-ray diffraction (XRD) analysis.

The intensity of the diffraction peaks of RO phase, FeO₄ and C₂F varies little with age in Figure 7, which indicates that these components do not participate in chemical reactions and are inert components in steel slag. The intensity of the diffraction peaks of C₃S, C₂S, C₁₂A₇ and Ca₂Al₂Si₃O₁₂ decrease obviously with age, which indicates that these substances undergo hydration reaction and have a higher degree of later reaction. These components can be collectively referred to as cementitious components in SS [36]. C-S-H gel and Ca(OH)₂ are the main hydration product of cementitious components in SS, because C-S-H gel is amorphous, it can not show its diffraction peak in Figure 7. It is difficult to confirm the characteristic peak of Ca(OH)₂ from the Figure 7 of SS hydration for 3 d, which indicates that the amount of Ca(OH)₂ produced is very small at 3 d, indicating that the hydration rate of SS is slow and the degree of hydration is low in the early stage.

Therefore, the hydration products of SS are mainly hydration products (C-S-H gel and Ca(OH)₂), unhydrated cementitious components (C₃S, C₂S and Ca₂Al₂Si₃O₁₂) and inert components (C₂F, FeO₄ and RO phase) [36].
Figure 8 shows the compressive strength and flexural strength of SS mortar at various ages. The strength of SS mortar increased evidently with ages, especially from 90 to 180 d. The growth trend of the strength was consistent with that of the non-evaporable water content. As mentioned above, massive products of SS could be produced at the age of 180 d due to the high hydration degree of cement clinker phase. However, as shown in Figure 8, the strength of SS mortar was rather low.

Figure 8 Strength of SS mortar at various ages

Figure 9 shows the microstructure of SS paste at the age of 180 d. Massive C–S–H gel was produced. However, it seems that the C–S–H gel was scattered and did not adhere together. Figure 10 shows the microstructure of cement paste at the age of 28 d. It is apparent that the microstructure of cement paste was more solid than that of SS paste (Figure 9 and Figure 10). Because the bond behavior of the C–S–H gel produced by SS is not fairly good, the interface between the gel and sands is so weak, so the strength of SS mortar is rather low.

Figure 9. Microstructure of SS paste at the age of 180 d
Figure 10. Microstructure of cement paste at the age of 28 d

4. Conclusions

(1) SS has slightly better grindability than GGBFS. After 100 min of powder grinding, the SSA of SS powder is 690 m²·kg⁻¹. Further powder grinding after 80 min only leads to slow increase in the SSA of SS. After 100 min of powder grinding of the SS with the experimental ball grinder, the particles smaller than 5 μm that can fill in the gaps in the cement powder stacking structure take up 81% (mass) of SS, and a lot of submicron and nanoscale particles appear in the SS.

(2) The hydration products of SS are mainly hydration products (C₃S-H gel and Ca(OH)₂), unhydrated cementitious components (C₃S, C₂S and Ca₂Al₂Si₃O₁₂) and inert components (C₂F, Fe₂O₃, and RO phase)

(3) SS has weak cementitious properties, and the slowly hardened mortar made from SS can obtain low strength. The morphology of hydration products of pure SS are similar to those of cement clinker. However the amount of C₃S-H gel is less, the bond behavior of the gel is not good, so the strength of the SS mortar is rather low.

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