Research Article

Ying Xu*, Shan-shan Yang, Qiao-ling Wang, and Chen-guang Hu

Effects of Fluoride and Sulphate Mineralizers on the Properties of Reconstructed Steel Slag

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Abstract: Improving the cementitious activity and volume stability of steel slag by thermal reconstruction is an innovative method for efficient utilization of steel slag. In this study, different amounts of CaF$_2$ and CaSO$_4$ were added to steel slag as a mineralizer based on the determining admixtures needed for the reconstruction reaction, and the effects of CaF$_2$ and CaSO$_4$ on the cementitious activity and volume stability of the reconstructed steel slag were investigated. The results show that when the CaF$_2$ content is increased to 5 wt%, the cementitious activity index of the reconstructed steel slag gradually increases to 92%, which is 12% higher than the first level technical requirement specified by the national standards, and the free CaO ($f$-CaO) and MgO ($f$-MgO) contents gradually decrease to 0.35 and 0.13 wt%, respectively. With increasing CaSO$_4$ content, the cementitious activity index first increases and then decreases, while the contents of $f$-CaO and $f$-MgO show the opposite trend. When the CaSO$_4$ content is 2 wt%, the activity index is 105%, which is 25% higher than the first level technical requirement specified by the national standards, and the $f$-CaO and $f$-MgO contents reach minima of 0.44 and 0.35 wt%, respectively.

Keywords: reconstructed steel slag, calcium fluoride, calcium sulphate, cementitious activity, volume stability

1 Introduction

The amount of steel slag accounts for 15%–20% of total steel production, and the annual output of steel slag in China is close to 100 million tons [1]. However, the comprehensive utilization rate of steel slag in China is only about 20% [2]. Large-scale emissions and accumulation of steel slag occupy land, pollute the environment, and cause waste of resources. By comparison, the utilization rate of steel slag in developed countries is above 95%, in which the in-plant circulation is more than 20% [3]. But steel slag from different countries is mostly used as road building materials, backfill materials, and so on, with low economic benefits. Steel slag is a potential cementitious material because it contains some minerals with cementitious activity, such as C$_3$S, C$_2$S, C$_3$A, and C$_4$AF [4]. However, there is less content of cementitious minerals in steel slag, and the mineral crystals are complete, the grains are coarse and the defects are few, which results in its low cementitious activity. Scholars have developed many kinds of steel slag activation technologies, such as mechanical activation, thermal activation, chemical activation, and so on. But they cannot fundamentally eliminate the effects of component fluctuations. Moreover, steel slag contains free CaO ($f$-CaO) and MgO ($f$-MgO), whose hydration reactions result in volume expansion of the steel slag [5]. Therefore, steel slag can not be widely used as cementing materials.

The temperature of liquid steel slag can reach 1450°C–1650°C, and the enthalpy is up to 2000 MJ/t [6], which is a high quality waste heat resource. At present, the sensible heat recovery technology of steel slag is still in its infancy. Lots of scholars at home and abroad have studied the waste heat recovery of steel slag in various aspects, such as wind quenching [7], continuous casting-continuous rolling dry granulation [8], rotating-drum method, and so on. Although the researches make the waste heat of steel slag be recovered and utilized, the performance problems existing in the tailings are not solved. It is necessary to develop and popularize a technology in order to make steel slag treatment and recycling level reach the scale industrialization. In this paper, an on-line reconstruction technology of steel slag, that is, the composition and structure of
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Table 1: Chemical compositions of the raw materials (wt%)

| Name      | CaO  | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO  | K₂O  | Na₂O | Others |
|-----------|------|------|-------|-------|------|------|------|--------|
| Steel slag| 41.40| 14.96| 0.84  | 7.90  | 5.49 | 0.12 | 0.14 | 29.15  |
| Cement    | 62.60| 21.35| 4.67  | 3.31  | 3.08 | 0.54 | 0.21 | 4.24   |
| Quicklime | 94.45| —    | —     | —     | —    | —    | —    | —      |
| Slag      | 38.20| 28.64| 14.60 | 0.42  | 10.82| 0.44 | 0.32 | 6.56   |

Table 2: Experimental proportions of the reconstructed steel slag with CaF₂ samples

| Sample | Steel slag /wt% | Quicklime /wt% | Slag /wt% | CaF₂ /wt% |
|--------|-----------------|----------------|-----------|-----------|
| K0     | 50              | 17             | 33        | 0         |
| F1     | 49              | 17             | 33        | 1         |
| F3     | 49              | 16             | 32        | 3         |
| F5     | 48              | 16             | 31        | 5         |

Table 3: Experimental proportions of the reconstructed steel slag with CaSO₄ samples

| Sample | Steel slag /wt% | Quicklime /wt% | Slag /wt% | CaSO₄ /wt% |
|--------|-----------------|----------------|-----------|------------|
| K0     | 50              | 17             | 33        | 0          |
| L1     | 50              | 17             | 33        | 1          |
| L2     | 50              | 17             | 32        | 2          |
| L3     | 49              | 16             | 32        | 3          |
| L4     | 48              | 16             | 32        | 4          |

the steel slag are modified by the residual heat is proposed. That is, suitable conditioning components are added to the molten steel slag and high-temperature phase reactions between the steel slag and conditioning components occur by the waste heat of the steel slag and the composition and structure of the steel slag are regulated. This is performed to improve the cementitious activity and volume stability of steel slag.

In this process, it is important to improve the kinetic conditions of the reconstruction reaction at high temperature. Addition of a mineralizer, such as CaF₂ or CaSO₄, can effectively solve this problem. Mineralizers are widely used in cement industry, and some trace elements from industrial waste can be used as mineralizers for the purpose of solid waste utilization. Scholars [9–11] found that CaF₂ can decrease the temperature of phase transition and promote the formation of C₃S in clinker. Kacimi, et al. [12] found that CaF₂ can, in some cases, improve the hydraulic properties of Portland clinker. Horkoss et al. [13, 14] found that [SO₄]²⁻ can replace [SiO₄]⁴⁻ in belite, and activation of the C₂S lattice can be promoted. Uda, et al. [15] suggested that SO₃ can promote the absorption of f-CaO and improve the burnability of raw materials.

In summary, many experiments have proven that CaF₂ and CaSO₄ contribute to formation of cementitious minerals to some extent. However, there is the lack of a quantitative study of their effects on the reconstructed steel slag cementitious activity and stability, and there is no systematic study of the mechanisms of action of fluoride and sulphate mineralizers. Therefore, in this study, different amounts of CaF₂ and CaSO₄ were added as mineralizers to reconstructed steel slag and the effects of CaF₂ and CaSO₄ on the cementitious activity and volume stability of the reconstructed steel slag were investigated.

2 Experimental

2.1 Raw materials

The steel slag comes from Tangshan Iron and Steel Company, the cement is Portland cement from a cement plant in Hubei Province, the conditioning components are quicklime and slag, and the mineralizers are CaF₂ and CaSO₄. The chemical compositions of the raw materials are given shown in Table 1.

2.2 Experimental methods

The lime saturation coefficient (KH) of the reconstructed steel slag was adjusted according to the cement clinker. The KH value of cement clinker is generally between 0.88 and 0.96. The KH value of the reconstructed steel slag was determined to be 0.9, and the specific proportions are given in Tables 2 and 3. The steel slag, quicklime, slag, and mineralizer were mixed in different proportions. The mixed raw materials were then placed in a mold for molding and forming, and the reconstructed steel slag samples were obtained. Finally, the reconstructed steel slag samples were
calcined at 1400°C in a high-temperature box furnace and then cooled to about 1000°C for water quenching after holding at 1000°C for 30 min.

The reconstructed steel slag was ground into a fine powder with a specific surface area of 400 ± 10 m²/kg. The reconstituted steel slag was then mixed with cement at a mass ratio of 3:7 to prepare a steel slag–cement slurry. The compressive strength of the slurry was measured after curing in a standard maintenance room for 7 or 28 days. The cementitious activity index of the steel slag was calculated according to the relevant regulation in “Steel Slag Powder Used for Cement and Concrete” (GB/T 20491-2017) [16]:

$$A = \frac{R_t}{R_0} \times 100$$  \(1\)

where \(A\) is the activity index of the steel slag (%), \(R_t\) is the strength of the tested mortar at the corresponding age (MPa), and \(R_0\) is the strength of the cement mortar at the corresponding age (MPa).

The \(f\)-CaO and \(f\)-MgO contents in the reconstructed steel slag samples were measured by ethylenediaminetetraacetic acid (EDTA) chemical titration.

The stability of the reconstructed steel slag samples was tested according to the relevant regulation in the “Cement Standard Consistency, Setting Time and Stability Test Method” (GB/T 1346-2011) [17].

The microstructure, composition, and morphology of the reconstructed steel slag were analyzed by scanning electron microscopy (SEM), X-ray diffraction (XRD), and the lithofacies test.

3 Results and Discussion

3.1 Effects of fluoride and sulphate mineralizers on the cementitious activity of the reconstructed steel slag

The reconstructed steel slag samples with different CaF₂ and CaSO₄ contents were aged at room temperature for curing times of 7 and 28 days, respectively. The compressive strengths of the reconstructed steel slag samples aged for different times were determined and the cementitious activity index values were calculated. The results are shown in Figures 1 and 2.

From Figures 1 and 2, the early activity index of the reconstructed steel slag without mineralizer (K₀) is 40% and the late activity index is 54%. With increasing CaF₂ content, the early activity index of the reconstructed steel slag first increases and then decreases (Figure 1). When 3 wt% CaF₂ is added, the early activity index reaches the highest value of 70%, which is 16% higher than that of the K₀ sample and 5% higher than the first level technical requirement stipulated in “Steel Slag Powder Used for Cement and Concrete” (GB/T 20491-2017). When the CaF₂ content exceeds 3 wt%, the early activity index gradually decreases. Because an increase in the total fluorine content in the C₃S solid solution leads to a decrease in the C₃S early hydration activity. The late activity index of the reconstructed steel slag gradually increases with increasing CaF₂ content. When 5 wt% CaF₂ is added, the late activity index reaches 92%, which is 22% higher than that of the K₀ sample and 12% higher than the first level technical requirement specified in GB/T 20491-2017. However, the CaF₂ content should not be too high, because when the concentra-
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3.2 Effects of fluoride and sulphate mineralizers on the volume stability of the reconstructed steel slag

To test the effects of CaF$_2$ and CaSO$_4$ on the volume stability of the reconstructed steel slag, EDTA chemical titrations and stability tests were performed. The $f$-CaO and $f$-MgO contents are given in Tables 4 and 5, and the trends are shown in Figures 3 and 4.

From Tables 4 and 5, the $f$-CaO and $f$-MgO contents are all less than 2 wt%, which is within the standard range of good stability.

### Table 4: Effect of CaF$_2$ on the $f$-CaO and $f$-MgO contents in the reconstructed steel slag

| Sample | CaF$_2$ content/wt% | $f$-CaO/wt% | $f$-MgO/wt% |
|--------|---------------------|-------------|-------------|
| K0     | 0                   | 0.51        | 0.36        |
| F1     | 1                   | 0.48        | 0.30        |
| F3     | 3                   | 0.44        | 0.22        |
| F5     | 5                   | 0.35        | 0.13        |

### Table 5: Effect of CaSO$_4$ on the $f$-CaO and $f$-MgO contents in the reconstructed steel slag

| Sample | CaSO$_4$ content/wt% | $f$-CaO/wt% | $f$-MgO/wt% |
|--------|----------------------|-------------|-------------|
| K0     | 0                    | 0.51        | 0.36        |
| L1     | 1                    | 0.47        | 0.34        |
| L2     | 2                    | 0.36        | 0.30        |
| L3     | 3                    | 0.43        | 0.33        |
| L4     | 4                    | 0.44        | 0.35        |

Figure 3: Effect of CaF$_2$ on the $f$-CaO and $f$-MgO contents in the reconstructed steel slag.
Figure 4: Effect of CaSO\textsubscript{4} on the f-CaO and f-MgO contents in the reconstructed steel slag.

With increasing CaF\textsubscript{2} content, the f-CaO and f-MgO contents in the reconstructed steel slag linearly decrease (Figure 3). The f-CaO content decreases from 0.51 to 0.35 wt\% and the f-MgO content decreases from 0.36 to 0.13 wt\%. The f-CaO and f-MgO contents first decrease and then increase with increasing CaSO\textsubscript{4} content (Figure 4). When the content of CaSO\textsubscript{4} is 2 wt\%, the f-CaO content decreases from 0.51 (without CaSO\textsubscript{4}) to 0.36 wt\% and the f-MgO content decreases from 0.36 (without CaSO\textsubscript{4}) to 0.30 wt\%. The f-CaO and f-MgO contents in the reconstructed slag samples with mineralizer are all lower than those of the K0 sample.

Addition of CaF\textsubscript{2} and CaSO\textsubscript{4} reduces the viscosity of the steel slag, which results in more f-CaO participating in the reactions to form C\textsubscript{2}S and C\textsubscript{3}S. In addition, CaF\textsubscript{2} and CaSO\textsubscript{4} promote the dissolution of f-MgO in gelling minerals, and the reasons are as follows. When S and F are dissolved into C\textsubscript{3}S crystal respectively, S\textsuperscript{6+} displaces Si\textsuperscript{4+} and F\textsuperscript{−} displaces O\textsuperscript{2−}. In order to balance the electricity price, the vacancy reaction in C\textsubscript{3}S is likely to occur in the form of co-substitution of different price ions [22].

\[
\text{SO}_3 + \text{Al}_2\text{O}_3 \xrightarrow{\text{C}_3\text{S}} \text{Si}^{2−} + 2\text{AlSi}^{3+} + 6\text{O}_3
\]

\[
\text{CaF}_2 + \text{Al}_2\text{O}_3 \xrightarrow{\text{C}_3\text{S}} 2\text{AlSi}^{3+} + 2\text{F}^{−} + \text{Ca}^{2+} + 3\text{O}_3
\]

As shown above, Al\textsuperscript{3+} participates in the substitution reaction together with S\textsuperscript{6+} or F\textsuperscript{−}. Thus, the Al\textsuperscript{3+} content in the C\textsubscript{3}S solid solution increases, which leads to the change of crystal structure of C\textsubscript{3}S. The ionic radius of Si\textsuperscript{4+} is 0.26 nm and that of Al\textsuperscript{3+} is 0.39 nm. When Al\textsuperscript{3+} replaces Si\textsuperscript{4+} and enters Si-O tetrahedron, the space of Si-O tetrahedron will be enlarged, which may indirectly cause the deformation of adjacent Ca-O octahedron. MgO and CaO have the same configuration, and the ionic radius of Mg\textsuperscript{2+} is 0.72 nm and that of Ca\textsuperscript{2+} is 1.0 nm. Therefore, Mg\textsuperscript{2+} with a smaller ion radius is more likely to replace the Ca\textsuperscript{2+} ions in C\textsubscript{3}S lattice to form solid solution in order to keep the balance of the structure [23].

CaF\textsubscript{2} and CaSO\textsubscript{4} have similar effects on the f-CaO content in the reconstructed steel slag, but the f-MgO content in the reconstructed steel slag with CaF\textsubscript{2} is lower than that with CaSO\textsubscript{4}. The f-CaO and f-MgO contents in the reconstructed slag with CaF\textsubscript{2} are lower than those with CaSO\textsubscript{4} at the optimal amount of mineralizer, which indicates that addition of CaF\textsubscript{2} as a mineralizer to improve the stability of steel slag is better than addition of CaSO\textsubscript{4}.

Considering the effects of CaF\textsubscript{2} and CaSO\textsubscript{4} on the cementitious activity and volume stability of the reconstructed steel slag, the optimum contents of CaF\textsubscript{2} and CaSO\textsubscript{4} in the reconstructed steel slag are 5 and 2 wt\%, respectively.

The stability of the reconstructed steel slag with CaF\textsubscript{2} and CaSO\textsubscript{4} was tested by boiling experiments, and the results are shown in Figure 5. The reconstructed steel slag test cakes are smooth with no cracks, and the test cakes can be completely removed from the glass sheets. This shows that the volume stability of the reconstructed steel slag is up to standard.

3.3 Effects of fluoride and sulphate mineralizers on the composition and morphology of the reconstructed steel slag

The XRD patterns of the reconstructed steel slag with different CaF\textsubscript{2} and CaSO\textsubscript{4} contents are shown in Figures 6 and 7, respectively. The diffraction peaks of the three cementing minerals C\textsubscript{2}S, C\textsubscript{3}S, and C\textsubscript{3}A are present for the reconstructed steel slag samples (Figure 6). However, the diffrac-
tion peaks of these three minerals are weaker for the reconstructed steel slag without CaF₂ than for the other steel slag samples, and the peaks of the RO phase are present. For the reconstructed steel slag with CaF₂, the diffraction peaks of the RO phase are absent but the diffraction peaks of C₃AF and C₂F are present, which indicates that CaF₂ is helpful to decompose the RO phase. FeOₓ from decomposition of the RO phase reacts with calcium and aluminum oxide to form C₄AF and C₂F. The diffraction peaks of C₂S gradually decreases and the diffraction peaks of C₃S and C₃A gradually increases when the CaF₂ content exceeds 1 wt%, indicating that CaF₂ promotes the reactions of C₂S and Al₂O₃ with CaO to form C₃S and C₃A, respectively. As shown in Figure 7, the main cementitious minerals of the reconstructed steel slag with CaSO₄ are C₁S, C₂S, C₁A, and C₂F. The diffraction peaks of the RO phase are absent. FeOₓ from decomposition the RO phase mainly reacts with CaO to produce C₂F. As the amount of CaSO₄ increases, the C₁A content gradually increases, and the C₂S and C₃S contents first increase and then decrease. When 2 wt% CaSO₄ is added, the diffraction peaks of the main cementitious minerals, such as C₂S and C₃S, are the most acute. This is because of the excessive amount of SO₄ generated from CaSO₄ under high temperature stabilizes C₂S and prevents absorption of f-CaO by C₂S, which are not conducive to formation of C₃S [24].

SEM images of the reconstructed steel slag with different CaF₂ and CaSO₄ contents are shown in Figures 8 and 9, respectively. The minerals in the reconstructed steel slag without CaF₂ are in the form of loose short rods. With increasing CaF₂ content, the minerals are gradually refined, and some minerals begin to exist in a melting state. When the CaF₂ content is 5 wt%, the minerals are in the melting state. Some of them have fish scale or droplet shapes, which are determined to be mainly C₁S, C₁A and C₂F according to energy spectrum analysis. The mineral structure is dense and uniform, and there are fewer pores and more liquid phase in the steel slag sample. When the CaSO₄ content is 2 wt%, the reconstructed steel slag has a better melting state and more liquid phase (Figure 9). Moreover, there is more C₂S and C₃S, whose grain shapes tend to be complete and the grain boundaries are clear. The reason why CaF₂ or CaSO₄ increases the amount of liquid phase is that the addition of them increases the composition of the system, and greatly reduces the minimum eutectic temperature and the liquid phase appearance temperature.

The lithofacies test images of the reconstructed steel slag with different CaF₂ and CaSO₄ contents are shown in Figures 10 and 11, respectively. The minerals in the steel slag without CaF₂ are coarse, varied in shape, and loose in arrangement (Figure 10). After addition of CaF₂, the main minerals in the reconstructed steel slag include cross bicrystalline, round-grained, or elliptical β-C₂S, hexagonal or long-flake C₁S, and gray acicular or dendritic C₂F and C₁AF. With increasing CaF₂ content, the particles of C₂S and C₃S increase and are significantly refined. When the CaF₂ content is 5 wt%, club-shaped C₁S and round-grained C₂S show a uniform agglomeration distribution. When the content of CaSO₄ is 2 wt%, a large number of round or elliptical C₂S and hexagonal C₃S particles appear with a uniform distribution and high degree of crystallization (Figure 11b). In addition, scattered white sheet minerals are observed in the reconstructed steel slag doped with CaF₂ and CaSO₄. An energy dispersive spectroscopy (EDS) test of this substance was performed (Figure 12). From EDS
Figure 8: SEM images of reconstructed steel slag with different CaF$_2$ contents. (a) 0, (b) 1, (c) 3, and (d) 5 wt% CaF$_2$.

Figure 9: SEM images of reconstructed steel slag with different CaSO$_4$ contents. (a) 1, (b) 2, (c) 3, and (d) 4 wt% CaSO$_4$. 
Figure 10: Lithofacies test images of reconstructed steel slag with different CaF$_2$ contents. (a) 0, (b) 1, (c) 3, and (d) 5 wt% CaF$_2$.

Figure 11: Lithofacies test images of reconstructed steel slag with different CaSO$_4$ contents. (a) 0, (b) 2, (c) 3, and (d) 4 wt% CaSO$_4$. 
and XRD analysis, it is concluded that the white sheet mineral is MgFe$_2$O$_4$ formed by the reaction of FeO$_x$ and MgO from decomposition of the RO phase solid solution. This is also a reason for reduction of f-MgO.

Figure 12: EDS energy spectrum of the reconstructed steel slag.

3.4 Mechanisms of the effects of fluoride and sulphate mineralizers on the hydration activity of the reconstructed steel slag

Strength development and the volume stability of steel slag are strongly affected by the hydration mechanisms of the cementitious minerals and the microstructures of the hydration products. The hydration reactions of the cementitious minerals at room temperature are

C$_3$S:

C$_3$S + nH → C–S–H + (3-x)CH

C$_2$S:

C$_2$S + mH → C–S–H + (2-x)CH

C$_3$A:

C$_3$A + CH + 12H → C$_4$AH$_{13}$

When CaSO$_4$ exists:

C$_4$AH$_{13}$ + 3CSH$_2$ + 14H → C$_3$A·3CS·H$_{12}$

C$_4$AF:

C$_4$AF + 4CH + 22H → 2C$_6$(A,F)H$_{13}$

When CaSO$_4$ exists:

C$_4$AF + 2CH + 6CSH$_2$ + 50H → 2C$_3$(A,F)·3CS·H$_{32}$

When steel slag–cement is mixed with water, C$_3$A is hydrated first and the hydration reaction is severe. Hydration of C$_4$AF and C$_3$S then occurs, and hydration of C$_2$S finally occurs because it has the slowest hydration rate. Hydrated calcium silicate (C–S–H), the hydration product of C$_2$S and C$_3$S, is the most abundant mineral in hardened steel slag–cement slurry and it plays a major role in its strength. Ca(OH)$_2$, another hydration product of C$_3$S and C$_3$S, affects the strength by closely intertwining with C–S–H gel. The high hydration rate and high early strength of C$_3$S make it the main material that determines the early strength of steel slag. In the presence of CaSO$_4$, hydrated calcium sulfoaluminate (also known as AFt), the hydration product of C$_3$A, also plays a role in the early strength. C$_3$S not only has high early strength, but it also has good late strength development. The effect of C$_2$S on the strength is not great until the late stage. Thus, the late strength is mainly affected by C$_2$S and C$_3$S. C$_4$AF has a favorable effect on the sulfate resistance properties, but it has little effect on the strength.

The hydration process is the comprehensive action of mineral hydration, which is different from the general chemical reaction in solution or liquid. In particular, migration of ions is difficult and they cannot completely participate in the reaction in a short time. Instead, ions start from the surface and slowly migrate into the center by diffusion under the condition of constantly changing concentration. In this process, the change in the mineral composition of the reconstructed steel slag caused by participation of the mineralizer has a different effect on the hydration process and strength of the steel slag in different periods.

Mineralizer improves the early strength of the C$_2$S slurry. This is because the C–S–H gel produced by early C$_2$S hydration has a large specific surface area, which make F$^-$ or SO$_4^{2-}$ adsorb on the gel surface and precipitation of the gel on unhydrated particles surface is reduced, and C–S–H is immediately isolated once formed. The hydration reaction of C$_2$S is then accelerated and the amount of C–S–H gel increases. The mineralizer can also decrease the distortion degree of the C$_3$S crystal, and the symmetry of the C$_3$S crystal structure increases. Moreover, with increasing F$^-$ or SO$_3$ content in C$_3$S solution, Ca(OH)$_2$ supersaturation becomes slow, and crystallization and nucleation growth of Ca(OH)$_2$ is delayed. Therefore, mineralizer can reduce the early hydration rate of C$_3$S. In the latter stages of hydration, the mineralizer also enables C–S–H to grow to elongated fibers, which cross and overlap, resulting in a denser and harder hydration product structure. The strength of C$_3$A especially increases when CaSO$_4$ is added. This is because AFt can form a diffusion barrier on the surface of C$_3$A particles to slow down the hydration reaction, smooth heat release, and greatly reduce the probability of crack generation.
3.5 Potential applications and prospects

It is found that the interior of the slag block is still red-hot when turning over slag and cracking the large slag block. It can be seen that the steel slag has a large thermal capacity, and the steel slag in the middle can maintain a high temperature state for a long time. However, the aim of steelmaking is to control the quality of steel, thus, the composition, the viscosity and the temperature range of liquid phase of steel slag in each furnace sometimes vary [25]. If the viscosity is large and the temperature range of the liquid phase is narrow, it is not conducive to the reconstruction reaction of steel slag. Addition of mineralizers based on the determining admixtures needed for the reconstruction reaction can reduce viscosity and increase the temperature range of liquid phase and make the reconstitution reaction more thorough.

The on-line reconstruction of steel slag makes use of residual heat of steel slag and improves its cementitious and stable properties at the same time. This study provides a theoretical basis for the high efficiency application of low activity metallurgical slag in building materials industry. It is beneficial to promote energy saving and emission reduction, and to reduce environmental pollution.

4 Conclusion

With increasing CaF2 content, the early activity index of the reconstructed steel slag first increases and then decreases. When 3 wt% CaF2 is added, the early activity index reaches the highest value of 70%, which is 5% higher than the first level technical requirement stipulated by the national standards. The late activity index gradually increases with increasing CaF2 content, and it reaches the highest value of 92% with addition of 5 wt% CaF2. This value is 12% higher than the first level technical requirement. The f-CaO and f-MgO contents gradually decrease with addition of CaF2. When the CaF2 content is 5 wt%, the f-CaO and f-MgO contents reach the lowest values of 0.35 and 0.13 wt%, respectively. After adding CaF2 to the reconstructed steel slag, the RO phase decomposes and C2F is generated. The optimum dosage of CaF2 is 5 wt%.

With increasing CaSO4 content, the early activity index of the reconstructed steel slag gradually increases. When 4 wt% CaSO4 is added, the early activity index reaches the highest value of 84%, which is 19% higher than the first level technical requirement. The late activity index of the reconstructed steel slag first increases and then decrease. When 2 wt% CaSO4 is added, the late activity index reaches the highest value of 105%, which is 25% higher than the first level technical requirement. The f-CaO and f-MgO contents first increase and then decrease with increasing addition of CaSO4. When the CaSO4 content is 2 wt%, the f-CaO and f-MgO contents reach the lowest values of 0.44 and 0.35 wt%, respectively. After adding CaSO4 to the reconstructed steel slag, the RO phase decomposes and C2F is generated. The optimum dosage of CaSO4 is 2 wt%.

The effect of CaSO4 as a mineralizer to improve the cementitious activity of steel slag is better than that of CaF2. In contrast, the effect of CaF2 as a mineralizer to improve the stability of steel slag is better than that of CaSO4.

The on-line reconstruction of steel slag is an efficient way to utilize steel slag by making full use of the residual heat of molten steel slag and modifying the steel slag. And the gelling activity and volum stability of steel slag is improved. This paper provides a theoretical basis for the high efficiency application of steel slag. It is beneficial to reduce environmental pollution and waste of resources.

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