Activity of CaO in CaO–SiO₂–Al₂O₃–MgO Slags

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The activity of CaO in CaO–SiO₂–Al₂O₃–MgO slags for blast furnace smelting was determined by a modified slag–metal equilibrium technique with Sn as the solvent metal and a known a_{CaO} slag as the reference slag. Iso-activity contours of CaO in the CaO–SiO₂–Al₂O₃–MgO pseudo-ternary system at $w(\text{Al}_2\text{O}_3)=15\%$ and $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$ were achieved from the measured values. Effects of R (basicity, $R=w(\text{CaO})/w(\text{SiO}_2)$), $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ and $w(\text{Al}_2\text{O}_3)$ on a_{CaO} were discussed. R was significant on a_{CaO} and a_{CaO} increased obviously with the increase of R at 1 873 K. a_{CaO} increased with the increase of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ when R is 1.05 and $w(\text{Al}_2\text{O}_3)$ is 15%. However, the effect of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ on a_{CaO} was not obvious for the slags with $R=1.20$. With the increase of $w(\text{Al}_2\text{O}_3)$, a_{CaO} decreased at fixed $R=1.05$ and $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$. When R is 1.20, a_{CaO} increased with the increase of $w(\text{Al}_2\text{O}_3)$.

KEY WORDS: activity of CaO; CaO–SiO₂–Al₂O₃–MgO system; blast furnace; reference slag; $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$.

1. Introduction

Slag, which is a multicomponent melt with different oxides as the main component in the pyrometallurgy, is a typical by-product during the metal smelting and refining. The blast furnace slag plays an important role in ironmaking, which is directly related to the reduction, desulfurization and other reactions in the blast furnace. Therefore, it is significant to study the thermodynamic properties, such as activity of the components, of blast furnace slag because the activity of CaO is of a direct impact on the desulfurization of the slag.

The activity for each component of silicate systems have been measured by many researchers, especially for the CaO–SiO₂–Al₂O₃–MgO systems, which are the most basic systems for ironmaking and steelmaking. Chipman *et al.*^{1,2)} measured the activities of SiO₂ in CaO–SiO₂–Al₂O₃ and CaO–SiO₂–MgO ternary systems and CaO–SiO₂–Al₂O₃–MgO quaternary systems at 1 873 K. The activities of SiO₂ were obtained by measuring the silicon distribution between slags and Fe–Si–C alloys saturated with either graphite or silicon carbide under $P_{\text{CO}}=101\,325$ Pa. Kay and Taylor^{3,4)} measured the activities of SiO₂ in CaO–SiO₂–Al₂O₃ ternary systems and CaO–SiO₂–Al₂O₃–MgO quaternary systems at 1 823 K. The activities were obtained by measuring the equilibrium partial pressure of CO in the reaction: $\text{SiO}_2+3\text{C}=\text{SiC}+2\text{CO}$. In the abovementioned research, activities of components other than SiO₂ have been calculated by Schuhmann's tangent intercept procedure, which affected the accuracy

in the calculation. For quaternary or more complicated systems, it is difficult to apply this method. In the works of Morita *et al.*,^{5,6)} the silicate slags and silicon alloys were equilibrated at 1 823 K and 1 873 K to determine the activity of CaO by modified Gibbs–Duhem equation for binary and ternary systems. By measuring the distribution of Ca, Al and Mg between slags and Si alloys, the activities of CaO on 10 mass% MgO plane were determined at 1 873 K by employing the activities of SiO₂ reported by Rein *et al.*⁷⁾ for quaternary system. It means that it is difficult to employ the same method as ternary systems considering the accuracy of calculation.

Due to obvious effect of Al₂O₃ content and MgO content on metallurgical performance of slag, many researchers^{8,9)} focused on the influence of Al₂O₃ in blast furnace smelting and proper $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ ratio for ironmaking. Al₂O₃ content and $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ significantly influence the thermodynamic properties of blast furnace slag, especially the activity of CaO. It is necessary to measure the activity of CaO for CaO–SiO₂–Al₂O₃–MgO system in the region of blast furnace slag and discuss the effects of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ and $w(\text{Al}_2\text{O}_3)$ on the activity of CaO.

In this study, the activities of CaO for CaO–SiO₂–Al₂O₃–MgO system in the region of blast furnace slag have been derived at 1 873 K by using a modified equilibrium technique with Sn as the solvent metal and a 2CaO·SiO₂-saturated CaO–SiO₂ slag as the reference slag. Based on the results of the measurement, the effect of $R=w(\text{CaO})/w(\text{SiO}_2)$, $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ and $w(\text{Al}_2\text{O}_3)$ on activity of CaO was discussed. The results can be applied to improve the metallurgical properties of blast furnace slag.

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2. Experimental

2.1. Experimental Principle

At equilibrium, the principal reactions between molten Sn and reference slag or measured slag may be expressed as reactions (1) and (2) respectively:

where $a_{(\text{CaO})}$ and $a_{(\text{CaO})}^{\theta}$ respectively denote the activities of CaO in the measured slag and the reference slag relative to pure solid, $a_{[\text{Ca}]}$ and $a_{[\text{Ca}]}^{\theta}$ respectively denote the activities of Ca in the metal phase at equilibrium with the measured slag and the reference slag relative to infinite dilute solution, p_{CO} and p^{θ} respectively denote the pressures of CO and standard atmosphere ($p_{\text{CO}} = p^{\theta} = 101\,325\text{ Pa}$). Concentration of Ca in Sn is small enough to make the Henry's law suitable, so $f_{[\text{Ca}]} \approx 1$. When reaction (1) and reaction (2) are at the same conditions, the equation $K_1 = K_2$ can be written as follows:

$$a_{(\text{CaO})} = x_{[\text{Ca}]} a_{[\text{CaO}]}^{\theta} / x_{[\text{Ca}]}^{\theta} \quad \text{..... (3)}$$

where $x_{[\text{Ca}]}$ and $x_{[\text{Ca}]}^{\theta}$ denote the Ca concentration of the metal phase at equilibrium with the measured slag and the reference slag, respectively.

Two parts of the experiment are shown in **Fig. 1**. Figure 1(a) shows the schematic diagram of Part I for determining the activity of CaO for a $2\text{CaO} \cdot \text{SiO}_2$ -saturated $\text{CaO}-\text{SiO}_2$ slag by choosing CaF_2-CaO slag as the reference slag because the activity of CaO is 1, when $w(\text{CaO})$ is higher than 19% for CaF_2-CaO system¹⁰ at 1 873 K as shown in **Fig. 2**. The slag composition at dotted line position in Fig. 2 ($w(\text{CaO})=27.88\%$, $w(\text{CaF}_2)=72.12\%$) was chosen as the ref-

erence slag. As the shaded zone is the $2\text{CaO} \cdot \text{SiO}_2$ -saturated zone,¹⁰ the slag composition at dotted line position ($w(\text{CaO})=60\%$, $w(\text{SiO}_2)=40\%$) was chosen as the measured slag, and point Q ($w(\text{CaO})=55.88\%$, $w(\text{SiO}_2)=44.12\%$) is the liquid composition of this $2\text{CaO} \cdot \text{SiO}_2$ -saturated slag at 1 873 K in **Fig. 3**. Figure 1(b) shows the schematic diagram of Part II for determining the activity of CaO for $\text{CaO}-\text{SiO}_2-\text{Al}_2\text{O}_3-\text{MgO}$ slags by choosing the $2\text{CaO} \cdot \text{SiO}_2$ -saturated slag which activity of CaO has been determined in Part I as the reference slag.

2.2. Experimental Procedure

The experimental apparatus is shown in **Fig. 4**. The temperature was controlled at 1 873 K within the accuracy of $\pm 2\text{ K}$ by a Pt-6%Rh/Pt-30%Rh thermocouple. A MoSi_2 resistance furnace was used for equilibrium between solvent metal and synthetic oxide solution. Sn, in which the solubility of Ca is very small as infinite dilute solution,^{11,12} was used as a solvent metal. The measured slags were prepared from reagent grade Al_2O_3 , Si_2O , MgO and CaO in the region of blast furnace slag. The compositions of the slags are listed in **Table 1**. 10 grams of $\text{CaO}-\text{SiO}_2-\text{Al}_2\text{O}_3-\text{MgO}$ slags and 5 grams of metallic tin granular (Sn>99.9%) in one hole of a

Fig. 2. CaF_2-CaO binary system phase diagram.

Fig. 1. Two parts of the experiment.

Fig. 3. $\text{CaO}-\text{SiO}_2$ binary system phase diagram.

Fig. 4. Experimental apparatus.

Table 1. Slag compositions.

No.	Slag Composition (mass%)				$R(-)$ $w(\text{CaO})/w(\text{SiO}_2)$	$w(\text{MgO})/w(\text{Al}_2\text{O}_3)$
	CaO	SiO ₂	MgO	Al ₂ O ₃		
401#	40.85	38.9	5.25	15	1.05	0.35
402#	41.77	37.98	5.25	15	1.10	0.35
403#	42.66	37.09	5.25	15	1.15	0.35
404#	43.5	36.25	5.25	15	1.20	0.35
405#	41.62	39.63	3.75	15	1.05	0.25
406#	40.08	38.17	6.75	15	1.05	0.45
407#	44.32	36.93	3.75	15	1.20	0.25
408#	42.68	35.57	6.75	15	1.20	0.45
409#	42.93	40.87	4.2	12	1.05	0.35
410#	38.77	36.93	6.3	18	1.05	0.35
411#	45.71	38.09	4.2	12	1.20	0.35
412#	41.29	34.41	6.3	18	1.20	0.35

two holes graphite crucible reacted under a CO atmosphere ($p_{\text{CO}}=101\,325\text{ Pa}$). Considering the accuracy of experiment, the other hole was filled with a $2\text{CaO}\cdot\text{SiO}_2$ -saturated CaO-SiO_2 slag as the reference slag. After equilibrium, the graphite crucible was quenched by oil-quenching. Thereafter, the metal and the slag were carefully separated for chemical analyses by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES).

3. Results and Discussion

3.1. Equilibrium Time

Due to the equilibrium time was uncertain, in order to ensure equilibrium, 24 h and 36 h was chosen as equilibrium time in preliminary experiments. In order to ensure the reaction equilibrium for the accuracy of experimental result, several preliminary experiments (Nos. 401#, 402#, 403# and 404#) were introduced for equilibrium experiment at 1 873 K. In the case of other conditions were exactly same, experiment times were 24 h or 36 h. The comparisons of $x_{[\text{Ca}]}$ and $w(\text{Ca})$ in metal phase for different experiment times are shown in Fig. 5.

All the Ca content in metal phase equilibrium with the same slag are very close when experiment time was 24 h or 36 h in 4 pairs of experiments with different compo-

 Fig. 5. Comparison of $x_{[\text{Ca}]}$ and $w(\text{Ca})$ in metal phase for different equilibrium times.

nent slags, as shown in Fig. 5. Therefore, 24 h was set as the experiment time for activity determination of CaO in $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-MgO}$ system.

3.2. Part I: Activity of CaO in CaO-SiO_2 System

Three groups of results about the concentrations of Ca in Sn after equilibrium with the binary CaO-SiO_2 and CaO-CaF_2 system slags are listed in Table 2. Si concentration in Sn was too small to consider the effect on the thermodynamic analysis.

At equilibrium, the generation reaction of $2\text{CaO}\cdot\text{SiO}_2$ can be written as follows:

$$\Delta G^\theta = -RT \ln \frac{a_{(\text{Ca}_2\text{SiO}_4)(\text{s})}}{a_{(\text{CaO})(\text{s})}^2 a_{(\text{SiO}_2)(\text{s})}} = -118\,800 - 11.3T \text{ J/mol}^{13)} \quad (4)$$

Then $a_{(\text{SiO}_2)} = 0.0281$. Relationships between SiO_2 content of the slag and $a_{(\text{CaO})}$ or $a_{(\text{SiO}_2)}$ are summed and shown in Fig. 6 based on our team's results and other researchers' works.^{3,5,7,14-16)} The activities of CaO and SiO_2 obtained by the present method are within the value range reported by several researchers. Hence, the way of activity measurement is confirmed to be suitable.

3.3. Part II: Activity of CaO in $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-MgO}$ System

Based on the analysis of slag compositions by ICP-AES, the slag compositions did not change obviously during the experiment, and the values of $w(\text{Al}_2\text{O}_3)$, R and $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ for all groups of experiment after equilibrium in Table 3 are approximately equal to the initial values. Concentrations of Ca in Sn after equilibrium with the $\text{CaO-SiO}_2\text{-Al}_2\text{O}_3\text{-MgO}$ slags and the activities of CaO by Eq. (3) are listed in Table 3. The average value of $x_{[\text{Ca}]}$ is 0.00249, which is very close to the value from preliminary experiment, and the relative error is too small to consider. The experimental error was well controlled. Iso-activity contours for CaO were plotted in the pseudo-ternary triangle in the blast furnace slag region as shown in Figs. 7 and 8.

Table 2. Concentrations of Ca in Sn after equilibrium experiment and the activities of CaO.

Slag	201# $x_{[Ca]}$	202# $x_{[Ca]}$	203# $x_{[Ca]}$	Average Value	Activity of CaO
27.88%CaO–72.12%CaF ₂	0.0379	0.0379	0.0387	0.0382	$a_{[CaO]}^{\theta} = 1$
60%CaO–40%SiO ₂	0.00247	0.00248	0.00266	0.00254	$a_{(CaO)} = x_{[Ca]} a_{[CaO]}^{\theta} / x_{[Ca]}^{\theta} = 0.0667$

Fig. 6. Comparison of $a_{(CaO)}$ and $a_{(SiO_2)}$ for the CaO–SiO₂ system at 1873 K.

Figure 7(c) is the shadow of the plane of $w(Al_2O_3)=15\%$ in CaO–SiO₂–Al₂O₃–MgO quaternary phase diagram in Fig. 7(a). As shown in Fig. 7(c), the trend and shape of the iso-activity contours are similar with those of CaO–SiO₂–MgO slag reported by Morita *et al.*⁶⁾ at 1873 K in Fig. 7(b). By the comparison of the activities of CaO in Figs. 7(b) and 7(c), the values of CaO activity increase with the increase of Al₂O₃ content. Figure 8(c) is the plane of $w(MgO)/w(Al_2O_3)=0.35$ in CaO–SiO₂–Al₂O₃–MgO quaternary phase diagram in Fig. 8(a). As shown in Fig. 8(c), the trend and shape of the iso-activity contours are similar with those of CaO–SiO₂–MgO slag reported by Morita *et al.*⁶⁾ at 1823 K in Fig. 8(b). By the comparison of the activities of CaO in Figs. 8(b) and 8(c), the values of CaO activity are close. Since the activity of CaO could hardly be determined due to the difficulty in the experiment error control, no other reliable data are available for comparison in the same slag

Table 3. Concentrations of Ca in Sn and the activities of CaO in CaO–SiO₂–Al₂O₃–MgO slags.

No.	$w(Al_2O_3)/\%$	R $w(CaO)/w(SiO_2)$	$w(MgO)/$ $w(Al_2O_3)$	$x_{[Ca]}$ in Sn	$a_{(CaO)}$
401#	15	1.05	0.35	0.00098	0.0262
402#	15	1.10	0.35	0.00107	0.0286
403#	15	1.15	0.35	0.00130	0.0349
404#	15	1.20	0.35	0.00154	0.0413
405#	15	1.05	0.25	0.00086	0.0230
406#	15	1.05	0.45	0.00148	0.0397
407#	15	1.20	0.25	0.00160	0.0429
408#	15	1.20	0.45	0.00169	0.0453
409#	12	1.05	0.35	0.00095	0.0254
410#	18	1.05	0.35	0.00059	0.0159
411#	12	1.20	0.35	0.00125	0.0334
412#	18	1.20	0.35	0.00181	0.0484

systems.

Accordingly, the activity of CaO in CaO–SiO₂–Al₂O₃–MgO slags for blast furnace smelting has been determined by the technique developed in the present study, and it is practical significant for the ironmaking process.

3.4. Effect of R on Activity of CaO

Slag of CaO–SiO₂–Al₂O₃–MgO system consists of different structural units containing simple ions (Ca^{2+} , Mg^{2+} , O^{2-}) and molecules (SiO_2 , Al_2O_3 , $CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, $CaO \cdot Al_2O_3$, $MgO \cdot SiO_2$ etc.) at 1873 K based on the ion and molecule coexistence theory.^{17–20)} In the theory, $a_{(CaO)} = a_{(Ca^{2+})} + a_{(O^{2-})}$, and simple ions continuous coexist with molecules in the dynamic equilibrium reactions. The main reactions that affect the $a_{(CaO)}$ are shown as follows:

Fig. 7. Iso-activity contours for CaO in the CaO-SiO₂-Al₂O₃-MgO system on the plane of $w(\text{Al}_2\text{O}_3)=15\%$. (a) CaO-SiO₂-Al₂O₃-MgO diagram on the plane of $w(\text{Al}_2\text{O}_3)=15\%$, (b) Iso-activity contours for CaO in the CaO-SiO₂-MgO system at 1 873 K (Morita *et al.*⁶⁾, (c) Iso-activity contours for CaO in the CaO-SiO₂-MgO pseudo-ternary system on the plane of $w(\text{Al}_2\text{O}_3)=15\%$ at 1 873 K (present work).

Fig. 8. Iso-activity contours for CaO in the CaO-SiO₂-Al₂O₃-MgO system on the plane of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$. (a) CaO-SiO₂-Al₂O₃-MgO diagram on the plane of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$, (b) Iso-activity contours for CaO in the CaO-SiO₂-Al₂O_{1.5} system at 1 823 K (Morita *et al.*⁶⁾, (c) Iso-activity contours for CaO in the CaO-SiO₂-Al₂O₃-MgO system on the plane of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$ at 1 873 K (present work).

The effect of R on $a_{(\text{CaO})}$ in slags is shown in **Fig. 9**. When $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$, $w(\text{Al}_2\text{O}_3)=15\%$ and $R=1.05, 1.10, 1.15$ and 1.20 in slags for experiments Nos. 401#, 402#, 403# and 404# as shown in Table 1, the activity value of CaO increased with the increase of R . With the increase of R , CaO content increased, MgO and Al_2O_3 contents remained unchanged, SiO_2 content decreased. In silicate melt, O^{2-} from alkaline oxide was reacted with SiO_2

Fig. 9. Effect of basicity on $a_{(\text{CaO})}$ in slags.

Fig. 10. Effect of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ on $a_{(\text{CaO})}$ in slags.

as shown in the reactions (5)–(7) and (11), (12), therefore, the activity of CaO increased with increase of CaO content and decrease of SiO_2 content.

3.5. Effect of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ on Activity of CaO

The effect of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ on $a_{(\text{CaO})}$ in slags is shown in **Fig. 10**. When $R=1.05$, $w(\text{Al}_2\text{O}_3)=15\%$ and $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.25, 0.35, 0.45$ in slags (Nos. 405#, 401#, 406#), the activity of CaO increased with the increase of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$. With the increase of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$, the increasing of MgO content might offer more O^{2-} to join the reactions (11), (12) and (13), which greatly consumed acid oxides needed in the reactions (5)–(10) at the same time. Therefore the enough absolute content of CaO ensured the activity of CaO kept increasing, especially when $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ increased from 0.35 to 0.45. However for the slags of $R=1.20$ (Nos. 407#, 404#, 408#), the effect of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ on $a_{(\text{CaO})}$ is not obvious. On the basis of the ΔG^θ of reactions (5)–(13), SiO_2 and Al_2O_3 were easier to react with CaO than MgO. For the slags of $R=1.20$, the content of CaO in slag was high enough to offer O^{2-} to join the reactions (5)–(10) with SiO_2 and Al_2O_3 . With the increase of the MgO content, some CaO was liberated from the reactions (5)–(10) for the slags of $R=1.05$, but not for the slags of $R=1.20$.

3.6. Effect of $w(\text{Al}_2\text{O}_3)$ on Activity of CaO

The effect of $w(\text{Al}_2\text{O}_3)$ on $a_{(\text{CaO})}$ in slags is shown in **Fig. 11**. When $R=1.05$, $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$ and $w(\text{Al}_2\text{O}_3)=12\%, 15\%, 18\%$ in slags (Nos. 409#, 401#, 410#), the activity value of CaO decreased with the increase of $w(\text{Al}_2\text{O}_3)$. With the increasing of the content of Al_2O_3 , more CaO was consumed by the reactions (8)–(10). It led to the reduction of $a_{(\text{CaO})}$ in slag. When $R=1.20$, the activity value of CaO increased with the increase of $w(\text{Al}_2\text{O}_3)$. Al_2O_3 For the slags of the $R=1.20$ (Nos. 411#, 404#, 412#), with the increase of Al_2O_3 content and $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ unchanged, MgO was easier to join the reaction (13) with Al_2O_3 at the high level of basicity and more CaO joined the reactions (8) and (9), which led CaO prefer to join the reaction (5) rather than reactions (6) and (7). This led to the transition from high valence silicate ion to SiO_3^{2-} and

Fig. 11. Effect of $w(\text{Al}_2\text{O}_3)$ on $a_{(\text{CaO})}$ in slags.

the increase of the activity of CaO.

4. Summary

For determining activity of CaO in the silicate system, a modified slag-metal equilibrium technique was applied to CaO–SiO₂–Al₂O₃–MgO system at 1 873 K for 24 h with Sn as solvent metal and a known $a_{(\text{CaO})}$ slag as the reference slag. The activities of CaO for CaO–SiO₂–Al₂O₃–MgO system in the region of blast furnace slag were determined by calculating equilibrium distribution data in the solvent metal Sn. Iso-activity contours for CaO were plotted from the measured values in the CaO–SiO₂–Al₂O₃–MgO pseudo-ternary triangle at $w(\text{Al}_2\text{O}_3)=15\%$ and $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$ in the blast furnace slag region. Based on the result of the CaO activity measurement, the effects of R , $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ and $w(\text{Al}_2\text{O}_3)$ on $a_{(\text{CaO})}$ were discussed. R was significant on $a_{(\text{CaO})}$ and $a_{(\text{CaO})}$ increased obviously with the increase of R at 1 873 K. With the increase of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$, $a_{(\text{CaO})}$ increased when R is 1.05 and $w(\text{Al}_2\text{O}_3)$ is 15%. However, the effect of $w(\text{MgO})/w(\text{Al}_2\text{O}_3)$ on $a_{(\text{CaO})}$ was not obvious for the slags with $R=1.20$. With the increase of $w(\text{Al}_2\text{O}_3)$, $a_{(\text{CaO})}$ decreased at fixed $R=1.05$ and $w(\text{MgO})/w(\text{Al}_2\text{O}_3)=0.35$. When R is 1.20, $a_{(\text{CaO})}$ increased with the increase of $w(\text{Al}_2\text{O}_3)$. The results were significant in improving the metallurgical properties of blast furnace slag.

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