Effects of Basicity and Al$_2$O$_3$ Content on Viscosity and Crystallization Behavior of Super-High-Alumina Slag

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Abstract: The CaO-SiO$_2$-MgO-Al$_2$O$_3$ slags with high alumina content are widely applied in various pyrometallurgical processes. However, for super-high-alumina slags, especially for those with alumina content of more than 25 wt%, there is a lack of relevant studies about the properties of slag. The melting behavior, viscosity, structural property, and crystallization behavior of high-alumina slag with the fixed MgO content of 11.13 wt% and Al$_2$O$_3$ content from 27.61 wt% to 40 wt% were investigated. The results revealed that the liquidus temperatures and complete solidification temperatures of slag increased with the increasing binary basicity and Al$_2$O$_3$ content. The melting temperature and viscosity of the CaO-SiO$_2$-11.13wt%MgO-Al$_2$O$_3$ slag system increased with the increasing basicity from 0.8 to 1 and Al$_2$O$_3$ content from 27.61 wt% to 40 wt%. The increase in Al$_2$O$_3$ caused the formation of high-crystallinity and high melting point materials in the slag, such as spinel and Åkermanite. A large number of non-uniform phases could quickly crystallize out of the solids present in the slag melt, thereby increasing the slag viscosity and deteriorating the fluidity of the slag.

Keywords: viscosity; crystallization behavior; high-alumina slag; basicity; spinel

1. Introduction

Viscosity is a critical property of slag that affects the metallurgical process[1–7]. The CaO-SiO$_2$-MgO-Al$_2$O$_3$ slag system is well-known for its widespread use in pyrometallurgical operations[8–10]. The amount of high-quality iron resources decreases with the continuous exploitation in the world; thus, the low-quality iron ores with high Al$_2$O$_3$ become a choice. The high-alumina iron ore is also employed as the raw material in the ironmaking process[11–15]. Furthermore, the high-alumina slag is used to recover platinum group metals (PGMs) from alumina-based spent catalysts with metals collection methods[16–18]. Moreover, a tremendous amount of slag with high Al$_2$O$_3$ is produced during the ferro-nickel alloy and ferrochromium alloy production process[19–21]. As we know, the fluidity property of slag has a considerable influence on the smelting process and separation of metals from slag[22–26]. Therefore, it is vital to study the viscosity and crystallization behavior of high-alumina slag.

At present, the effects of basicity and Al$_2$O$_3$ on viscosity have been reported by some researchers. Chen et al. [27] studied the viscosity of SiO$_2$-MgO-FeO-Al$_2$O$_3$-MgO slag with the Al$_2$O$_3$ content from 4 wt% to 10 wt%, and the results revealed that Al$_2$O$_3$ was a network former and could polymerize the slag, increasing viscosity. Gao et al. [9] measured the viscosity of SiO$_2$-CaO-MgO-9wt% Al$_2$O$_3$ slag and pointed out that the complex network structure of the molten slag was disaggregated into simple network units as the basicity increased from 0.4 to 1.0. The viscosity experiments of CaO-SiO$_2$-MgO-Al$_2$O$_3$ slag [28] suggested the slag viscosity decreased with the increasing basicity from 0.5 to 0.9 and in-
creased with the increase in alumina content from 5% to 20%. However, the effects of basicity and Al₂O₃ content on slag viscosity and crystallization behavior have not been sufficiently investigated for high-alumina slag with Al₂O₃ content above 25%.

In this work, the effects of binary basicity and Al₂O₃ content on the melting behavior, viscosity, structural property, and crystallization behavior of the CaO-SiO₂-Al₂O₃-11.13wt%MgO system were investigated. The melting behavior and viscosity of slag with different binary basicity (0.8–1.1) and alumina (27.61–40 wt%) were measured. In a high Al₂O₃ and MgO slag system, it is easy to form a high melting point and high-crystallinity phases. Therefore, the viscosity behavior of slag is inseparable from the melting and crystallization behavior of slag. This work can deepen the realization of basicity and Al₂O₃ content on melting behavior, viscosity, and phase transformation of super-high Al₂O₃ (27.61–40 wt%) and high MgO (11.13 wt%) slag, and the interaction between these properties. In addition, this study can provide a technical basis for the efficient utilization of low-quality iron ores with high Al₂O₃ content.

2. Materials and Experimental Methods
2.1. Slag Sample Preparation

The slag samples in the experiment were half-synthetic slag based on a blast furnace slag from one steel company in China. The reagents used to modify the composition of slag include CaCO₃ (≥98 wt%), SiO₂ (≥99 wt%), MgO (≥98 wt%), and Al₂O₃ (≥99 wt%) reagents. The chemical composition of blast furnace slag is shown in Table 1. The chemical methods [29] were adopted for the chemical composition of blast furnace slag. The converted main compositions of the slag are 32.37 wt% SiO₂, 27.61 wt% Al₂O₃, 28.89 wt% CaO, 11.13 wt% MgO, and the binary basicity (CaO/SiO₂) is 0.89. The XRD pattern of the blast furnace slag is shown in Figure 1. As shown in Figure 1, the main phase of blast furnace slag is spinel (MgAl₂O₄). The half-synthetic slags were prepared by mixing the practical blast furnace slag and chemical reagents with a fixed mass ratio of 2:1. In this way, the chemical compositions of the slag sample are closer to the actual slag compositions. The designed chemical compositions of the half-synthetic slags are shown in Table 2. It could be seen that the CaO/SiO₂ ratio ranged from 0.8 to 1.1, and alumina ranged from 27.61 wt% to 40 wt%. All reagents except CaCO₃ powder were roasted at 1000 °C for one hour to remove carbonate and water. Appropriate amounts of the blast furnace slag powder and reagents were weighed and then mixed in an agate mortar to ensure composition uniformity. After that, one part of the mixtures was premelted in an electric furnace at 1500 °C for 1 h to attain the homogeneous samples. These pre-melted samples were used for subsequent viscosity measurement experiments. Additionally, another part of the mixtures were placed in a graphite crucible lined with molybdenum sheets and smelted in the electric furnace at 1500 °C for 1 h under the protection of N₂ gas (>99.9). Thereafter, the sample was removed from the furnace and quenched in cool water. After drying, the sample was crushed and ground for the melting properties tests.

Table 1. Chemical composition of blast furnace slag (mass fraction, %).

<table>
<thead>
<tr>
<th>SiO₂</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>FeO</th>
<th>TiO₂</th>
<th>MnO</th>
<th>S</th>
<th>Cr₂O₃</th>
<th>MFe</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.9</td>
<td>24.90</td>
<td>23.8</td>
<td>9.59</td>
<td>1.63</td>
<td>1.40</td>
<td>1.36</td>
<td>0.97</td>
<td>0.58</td>
<td>0.57</td>
</tr>
</tbody>
</table>
Figure 1. XRD pattern of blast furnace slag.

Table 2. Design of composition of high-alumina slag (mass fraction, %).

<table>
<thead>
<tr>
<th>No.</th>
<th>Slag Composition</th>
<th>Binary Basicity (B = CaO/SiO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CaO</td>
<td>SiO₂</td>
</tr>
<tr>
<td>1#</td>
<td>27.23</td>
<td>34.03</td>
</tr>
<tr>
<td>2#</td>
<td>29.02</td>
<td>32.24</td>
</tr>
<tr>
<td>3#</td>
<td>30.63</td>
<td>30.63</td>
</tr>
<tr>
<td>4#</td>
<td>32.09</td>
<td>29.17</td>
</tr>
<tr>
<td>5#</td>
<td>25.52</td>
<td>28.35</td>
</tr>
<tr>
<td>6#</td>
<td>23.15</td>
<td>25.72</td>
</tr>
<tr>
<td>7#</td>
<td>25.60</td>
<td>23.27</td>
</tr>
</tbody>
</table>

2.2. Experimental Methods

2.2.1. Viscosity Tests

The RTW-10 melt physical properties comprehensive testing instrument was applied to measure the viscosity value of the slag samples listed in Table 2. The schematic diagram of the experimental apparatus is illustrated in Figure 2, which consists of a high-temperature furnace, measuring system, gas purification system, and data acquisition system. The MoSi₂ heating element was used to heat the samples. The slag samples were placed into a molybdenum crucible surrounded by a graphite crucible, and a disassembled graphite sleeve was wrapped in the graphite crucible to hold the extra slag sample. The Mo spindle consisted of a bob and a shaft connected to a viscometer head. The viscometer was validated before the measurements adopting castor oil (A.R.) of known viscosity at room temperature.
During the experiment, about 125 g of premelted slag was added to the molybdenum crucible and then transferred to the furnace, and then it was set to heat at the rate of 5 °C min⁻¹ under the Ar atmosphere (>99.99%). The slag sample was premelted at 1550 °C for 30 min to sustain the temperature and completely melt the slag sample. The rotating spindle was slowly immersed into the molten slag and rotated at a fixed rate of 200 r/min. The tip of the bob was positioned approximately 10 mm away from the bottom of the molybdenum crucible. The measurement was performed to cool down at a rate of 3 °C/min, and the target temperature was maintained for 0.5 h to ensure thermal equilibrium. The temperature and viscosity were recorded every 10 s by the data acquisition system. Furthermore, the final slag viscosity at each target temperature was the average of the measured value. When viscosity tests were over, the slag sample was reheated to 1500 °C and then cooled to room temperature with the furnace to complete the slag crystallization.

2.2.2. Melting Properties Tests

The slag sample was shaped into a triangular cone using a mold, and the samples were heated in a tube furnace with a camera. The shape change in the slag samples during the softening and melting process was observed by a camera. Figure 3 exhibited the morphologic changes in a sample at spherical temperature, hemispherical temperature, and flowing temperature, defined by the Chinese Standard GB/T 219-2008 [30]. The hemispherical temperature (HT) implies the melting temperature of the slag at which the solid phase begins to precipitate out of the molten slag. Correspondingly, the flowing temperature can also be called the liquefaction temperature [31].

2.3. Characterization Methods

The FactSage 8.0 software [32–35] was utilized to draw the phase diagram and calculate the crystallization and phase transformation of slags. The used modules were “Phase Diagram” and “Equilibrium”, with the corresponding databases being “FToxid” and “FactPS”. The locations of the slag composition in the diagram are marked in Figure 4. The phase composition of the crystallized slag was determined by X-ray diffraction (XRD, Advance D8, Brock Company, Zürich, Switzerland), operation at 40 kV and 4 mA with CuKα radiation, step 4°/min and range of angles analyzed from 10 to 80°. The slag structure was
analyzed using FT-IR spectroscopy (Spectrum Two, PerkinElmer, Groningen, the Netherlands) with a frequency between 1200 and 400 cm\(^{-1}\). The size and proportion of crystal phases in slags were observed and counted by LEICA optical microscope and Image J Software, respectively.

**Figure 4.** Phase diagram of CaO-SiO\(_2\)-Al\(_2\)O\(_3\)-MgO calculated by 8.0.

### 3. Results

#### 3.1. Crystallization and Phase Transformation of Slags

In this part, the FactSage 8.0 was used to calculate the equilibrium phase and precipitated solid mass fraction in the slag from 2000 °C to 1000 °C with 100 °C intervals. The Equilib module was adopted with the FToxid database based on the Gibbs minimum free energy principle [36,37].

As shown in Figure 5, the initial phase of the slag precipitation is spinel. The amount of spinel precipitation does not change significantly as the slag basicity increases from 0.8 to 1.1 with the fixed Al\(_2\)O\(_3\) and MgO contents of 27.61 wt% and 11.13 wt%, respectively. Moreover, the precipitation silicate phase changes from CaAl\(_2\)Si\(_2\)O\(_6\) to melilite (Ca\(_2\)Mg\(_2\)Si\(_2\)O\(_7\)) when the basicity increases from 0.8 to 1.1. The amount of spinel phase increases as the Al\(_2\)O\(_3\) content increases from 27.61 wt% to 40 wt% with the fixed slag basicity of 0.9. Furthermore, a small number of CaMg\(_2\)Al\(_5\)O\(_{16}\) appear when the Al\(_2\)O\(_3\) content of slag is up to 40 wt%. Moreover, as illustrated in Figure 5f,g, the CaAl\(_2\)Si\(_2\)O\(_6\) disappears, and the Ca\(_2\)Mg\(_2\)Si\(_2\)O\(_7\) generates when the slag basicity increases from 0.9 to 1.1 at the fixed Al\(_2\)O\(_3\) content of 40 wt%. Figure 5h shows the liquidus temperatures and complete solidification temperatures of slags with various basicity and Al\(_2\)O\(_3\) contents. As shown in Figure 5h, both the liquidus temperature and complete solidification temperature of the slags increase with the basicity of slag increases from 0.8 to 1.1. In addition, the liquidus temperatures and complete solidification temperatures of the slags also increase with the increasing Al\(_2\)O\(_3\) content, and this result is similar to the calculations of Ma et al. [31].
Figure 5. Equilibrium phase compositions of the high-alumina slags at various temperatures. (a) B = 0.8, (b) B = 0.9, (c) B = 1.0, (d) B = 1.1, (e) B = 0.9, Al₂O₃ = 35 wt%, (f) B = 0.9, Al₂O₃ = 40 wt%, (g) B = 1.1, Al₂O₃ = 40 wt%, and (h) the liquidus temperatures and complete solidification temperatures.

3.2. Melting Properties

Figure 6 shows the effects of the slag basicity on the melting temperatures of slags. It can be seen that the melting temperatures ranged from 1220 °C to 1340 °C, and the basicity had a significant influence on the melting temperature of the high-alumina slag. The spherical temperature, hemispherical temperature, and flowing temperature increased gradually with the increasing binary basicity. When the basicity increased from 0.8 to 1.1, the hemispherical temperature increased from 1228 °C to 1327 °C, and the flowing temperature increased from 1242 °C to 1338 °C.
Figure 6. Effects of the slag basicity on the melting temperature of high-alumina slag (Al$_2$O$_3$ = 27.61 wt%; MgO = 11.13 wt%).

Figure 7 illustrates the influence of the Al$_2$O$_3$ content on the melting temperatures of the high-alumina slag. It indicates that the trends illustrated by the spherical temperature, hemispherical temperature, and flowing temperature with changing Al$_2$O$_3$ content were similar, and they significantly increased with increasing Al$_2$O$_3$ content. The hemispherical temperature of slag increases from 1253 °C to 1375 °C, and the flowing temperature increases from 1268 °C to 1402 °C as the Al$_2$O$_3$ content increases from 27.6 wt% to 40 wt%. The spherical temperature, hemispherical temperature, and flowing temperature reflect the melting properties of the slag, and high melting temperatures of slag may produce a solid phase during the smelting process, thus affecting the viscosity and fluidity of the slag. In our study, all characteristic temperatures increased with the increasing basicity from 0.8 to 1.1 and Al$_2$O$_3$ content from 27.6 wt% to 40 wt% in CaO-SiO$_2$-11.13 wt%MgO-Al$_2$O$_3$ slag, which indirectly mirrored the possibility of the existence of the solid phase in the smelting process.

Figure 7. Effects of the Al$_2$O$_3$ content on the melting temperature of high-alumina slag. (B = 0.9, Al$_2$O$_3$ = 27.61 wt%).
3.3. Slag Viscosity

Figure 8 shows the viscosity-temperature curve of CaO-SiO\textsubscript{2}-MgO-Al\textsubscript{2}O\textsubscript{3} slag with basicity ranging from 0.8 to 1.1. It can be seen that the slag viscosity increases with the increasing basicity. As illustrated in Figure 9, the viscosity of the slags increases with the increasing Al\textsubscript{2}O\textsubscript{3} content of slag. When the Al\textsubscript{2}O\textsubscript{3} content of slag is fixed at 40 wt\%, the measured slag viscosity is high and exceeds 5 Pa·s at 1522 °C. Figure 10 shows the effects of basicity on the viscosity of the slag system at 1500 °C and the effects of Al\textsubscript{2}O\textsubscript{3} content on the viscosity of the slag system at 1520 °C, respectively. There is a linear relationship between viscosity and basicity of slag with fixed Al\textsubscript{2}O\textsubscript{3} content of 27.61 wt\% and MgO content of 11.13 wt\% at 1500 °C, the viscosity of slag increased by approximately 0.14 Pa·s for every additional CaO/SiO\textsubscript{2} ratio of 0.1. The effect of Al\textsubscript{2}O\textsubscript{3} content on the viscosity of slag is more significant.

Figure 8. Effects of temperature on the viscosity of slag with different basicity (Al\textsubscript{2}O\textsubscript{3} = 27.61 wt\%; MgO = 11.13 wt\%).

Figure 9. Effects of temperature on the viscosity of slag with different Al\textsubscript{2}O\textsubscript{3} content (B = 0.9; MgO = 11.13 wt\%).
Figure 10. Effects of basicity (a) and Al$_2$O$_3$ content (b) on the viscosity of the CaO-SiO$_2$-MgO-Al$_2$O$_3$ slags.

Comparisons between the measured viscosities in the present study and other reports of the CaO-SiO$_2$-MgO-Al$_2$O$_3$ slags at 1500 °C are shown in Figure 11. From Figure 11a, it was noted that the slag viscosity increases with increasing basicity for the CaO-SiO$_2$-11.13 wt%MgO-27.61 wt%Al$_2$O$_3$ slags, a trend that is contrary to the results obtained by Hyuk Kim et al. [38] for CaO-SiO$_2$-10 wt%MgO-20 wt%Al$_2$O$_3$ slags and Y.M. Gao et al. [9] for CaO-SiO$_2$-13 wt%MgO-9 wt%Al$_2$O$_3$ slags. Moreover, it could be seen from Figure 11b that the viscosity of the slag increases with increasing Al$_2$O$_3$ content for the fixed MgO content of 11.13 wt% and basicity of 0.9. A similar observation was made by Lu Yao et al. [12] for the CaO-SiO$_2$-11 wt%MgO-Al$_2$O$_3$ slag and Hyuk Kim et al. [38] for the CaO-SiO$_2$-10 wt%MgO-Al$_2$O$_3$ slag, but the viscosities were lower than that in this study.

Figure 11. Comparisons of the effects of basicity (a) and Al$_2$O$_3$ content (b) on the viscosity of the CaO-SiO$_2$-MgO-Al$_2$O$_3$ slags at 1500 °C [9,12,38].

In addition, the structure of slags was determined by the FT-IR technique, and the results are shown in Figure 12. According to previous investigations [39–42], the FT-IR analysis of molten slag was typically situated in the wavenumber region between 1200 to 400 cm$^{-1}$. These regions at about 1200–800 cm$^{-1}$, 750–630 cm$^{-1}$, and 630–450 cm$^{-1}$, corresponding to [SiO$_4$]-tetrahedral stretching vibration bands, [AlO$_4$]-tetrahedral stretching vibration bands, and Si-O-Al bending, respectively. Furthermore, the [SiO$_4$]-tetrahedral stretching vibration bands can be classified depending on the values of NBO/Si, which corresponds to $Q^4_{Si}$ (monomers, NBO/Si = 4), $Q^5_{Si}$ (dimers, NBO/Si = 3), $Q^6_{Si}$ (chains, NBO/Si = 2), and $Q^7_{Si}$ (sheets, NBO/Si = 1), respectively. Figure 12a shows that the trough depth of [SiO$_4$]-tetrahedral band groups, [AlO$_4$]-tetrahedral band, and Si-O-Al bending...
were weakened when the CaO/SiO$_2$ ratio increased from 0.8 to 1. It indicated that the complicated network structures were disaggregated to simple structural units, which primarily attributed to the increase in free oxygen ions O$^2-$.

However, with the further increase in the CaO/SiO$_2$ ratio from 1 to 1.1, the trough depth of [SiO$_4$]-tetrahedral band groups, [AlO$_4$]-tetrahedral band, and Si-O-Al bending became more remarkable, which signified that the silicate network became more complex because the compensation effects of Ca$^{2+}$ on the [AlO$_4$] units are more pronounced when the CaO/SiO$_2$ ratio increases from 1 to 1.1. As shown in Figure 12b, both the trough depth of $Q^0_5$ and $Q^1_5$ bands decreased while the trough depth of $Q^0_6$ band increased with increasing Al$_2$O$_3$ content. The trough of [AlO$_4$]-tetrahedral stretching vibration bands had little change. This indicated that higher Al$_2$O$_3$ content tends to polymerize Si-O networks which play an active role in increasing viscosity [43,44].

![Figure 12. FT–IR transmittance spectra of CaO–SiO$_2$–MgO–Al$_2$O$_3$ slag with different basicity values.](image)

As the Si–O network structures depolymerized with increasing Al$_2$O$_3$ content, the viscosity increased, which agreed with the current study. While the silicate network structures showed a tendency that depolymerized firstly and then polymerized with increasing CaO/SiO$_2$ from 0.8 to 1.1, the viscosity of slag increased consistently, which was a contradiction.

Moreover, the proportions of the slag liquid phase and solid phase were calculated by FactSage 8.0. As shown in Figure 13, the proportion of slag liquid phase decreased with increasing CaO/SiO$_2$ and Al$_2$O$_3$ content, and the proportion of solid phase increased at 1500 °C. Combining the phase diagram (Figure 4) and Figure 13 indicated that the slag samples exhibited a mixture of liquid and solid phases at 1500 °C, and the solid phase mainly consists of spinel.
Figure 13. Variation of the main phases (liquid phase and solid phase) for high-alumina slag with different basicity and Al₂O₃ content at 1500 °C (FeO = 1.63%; MnO = 1.36%; TiO₂ = 0.58%; P (O₂) = 1.0 × 10⁻¹⁶ atm).

According to the above results, the inconsistency of viscosity changes that the viscosity of the slag increases with increasing basicity for the slags may be attributed to the high Al₂O₃ content and solid–liquid mixture behaviors. It is well known that partially molten materials or solid suspension liquids have a high viscosity value [27]. Additionally, the Roscoe model has been the most widely used to describe the viscosity of these melts [45,46]. The viscosity of the solid-containing melt is calculated by the following equation:

\[ \eta = \eta_0 (1 - af)^{-n} \]  

where \( \eta \) and \( \eta_0 \) are the viscosity of solid-containing and solid-free melt, respectively; \( f \) is the concentration of solid particles; \( a \) and \( n \) are constants that are dependent on solid particles size.

As shown in Figures 11 and 13, increasing Al₂O₃ content increased both the viscosity of solid-containing and solid-free slag melt, indicating that Al₂O₃ acts as a network former in the slag system. However, increasing basicity decreased the viscosity of the slag system by providing additional free oxygen ions (O²⁻) with Al₂O₃ content of slag was no more than 20 wt%. When the Al₂O₃ content of slag reached 27.61 wt%, slag samples exhibited a mixture of liquid and solid phases, resulting in high viscosity. It indicated that the effect of the solid phase on slag viscosity is predominant compared to the additional free oxygen and that effect is more pronounced at a higher Al₂O₃.

3.4. Determination of Crystalline phase

The phase compositions of slag with different Al₂O₃ content and basicity were investigated by XRD. It can be seen from Figure 14 that the main solid phases of CaO-SiO₂-MgO-Al₂O₃ slags are spinel (MgAl₂O₄) and Åkermanite (CaMgSi₂O₆).
Figure 14. XRD patterns of the slowly cooled slag with different basicity (S-Spinel (MgAl₂O₄); A-Åkermanite (Ca₂MgSi₂O₇)).

The amount of spinel precipitation does not change significantly as the slag basicity increases from 0.8 to 1.1 with the fixed Al₂O₃ and MgO contents of 27.61 wt% and 11.13 wt%, respectively. When the basicity of slag is 0.8, the main phase is the spinel phase, and the diffraction peak of the Åkermanite phase is not obvious. There are significant diffraction peaks of the Åkermanite phase when the basicity of slag increases to 1.0. As the basicity continues to increase to 1.1, the Åkermanite phase increases further. The XRD patterns of slag with different Al₂O₃ content and the fixed binary basicity of 0.9 and MgO content of 11.13 wt% are illustrated in Figure 15. As shown in Figure 15, the main phase of slag is the spinel phase, which also increases with the increasing Al₂O₃ content. These regulations of crystalline phases are fit with the thermodynamic calculations.

Figure 15. XRD patterns of the slowly cooled slag with different Al₂O₃ content and basicity (S-Spinel (MgAl₂O₄); A-Åkermanite (Ca₂MgSi₂O₇)).
The effects of basicity and Al₂O₃ content on the microstructure of high-alumina slag were observed, and the proportions of the solid phase in high-alumina slag were determined by Image J software and shown in Figure 16. As the basicity increased from 0.8 to 1.1, the size of solid particles became larger, and the proportion of solid phase in slag increased from 13.86% to 25.41%. This result agrees with the theoretical calculations in Figure 13 and also explains the increase in viscosity with increasing basicity. With higher Al₂O₃ content, a large number of fine solid phases emerged, and the percentage of crystals phase continues to increase, resulting in a more significant effect on viscosity.

Figure 16. The effects of basicity and Al₂O₃ content on the microstructure of high-alumina slag. (a) B = 0.8, (b) B = 0.9, (c) B = 1.0, (d) B = 1.1, (e) B = 0.9, Al₂O₃ = 35 wt%, (f) B = 0.9, Al₂O₃ = 40 wt%, (g) B = 1.1, Al₂O₃ = 40 wt%, and (h) proportion of solid phase in high-alumina slag (determined by Image J software).
Briefly, the increases in basicity and Al₂O₃ content caused an ascendance in the melting temperature and viscosity of slags, which are detrimental to reducing energy consumption and metal–slag separation. In addition, the Al₂O₃ content has a strong influence on the structure of slag. As the Al₂O₃ content increased, the number of aluminum oxide tetrahedra [AlO₄]⁻ which formed by the absorption of O²⁻ by the Al₂O₃ increased, causing the formation of complex compounds with high crystallinity and high melting points, such as spinel. As the Al₂O₃ content increased further, Åkermanite and other mineral phase components that have a greater impact on the slag emerge, making the internal structure more complex and thus forming many non-uniform phases that can easily crystallize out of the solids present in the slag melt, causing the viscosity of the slag to become greater and the fluidity of the slag to become worse.

4. Conclusions

The effects of basicity and Al₂O₃ content on the melting behavior, viscosity, structural property, and crystallization behavior of super-high-alumina (27.61–40 wt%) slag were investigated. At a fixed MgO content of 11.13 wt% and Al₂O₃ content of 27.61 wt%, the melting temperature, viscosity, and crystals phase (spinel and Åkermanite) increased when the basicity increased from 0.8 to 1.1. The viscosity of slag increased by approximately 0.14 Pa-s for every additional CaO/SiO₂ ratio of 0.1 at 1500 °C. The proportion of crystal phase in slag increased from 13.86% to 25.41%. At a fixed MgO content of 11.13 wt% and basicity of 0.9 or 1.1, the melting temperature, viscosity, and crystal phase (spinel and Åkermanite) increased with the increasing Al₂O₃ content from 27.61–40 wt%. The Al₂O₃ content has a strong influence on the slag. When the Al₂O₃ content of slag is fixed at 40 wt%, the measured slag viscosity is high and exceeds 5 Pa-s at 1522 °C, and the proportion of solid phase in slag increased to more than 35%.

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