1. Introduction

The iron and steel industry occupies approximately 15% of the anthropogenic greenhouse gas emissions of Japan. For the mitigating global warming, the reduction of carbon dioxide emissions is urgently required. However, it is essential to utilize fossil fuel energy, especially coal, in the conventional ironmaking processes, because carbon plays an important role in the heat generation, reduction of iron oxide and carburization. An innovative ironmaking process is highly desired to solve such problems. Lowering the thermal reserve zone temperature in blast furnace by decreasing the distance between iron oxide and carbonaceous particles may be one of the effective methods. The mixed charging of iron ore with coke to the blast furnace and the utilization of iron ore–carbon composites have attracted significant attention. A number of studies have been conducted on the reduction behavior of composites containing iron oxide and carbonaceous materials from the viewpoint of blast furnaces burdens\(^2\)–\(^4\), waste utilization as raw materials\(^5\)–\(^6\), grinding/milling effect\(^7\)–\(^8\) and so on. Kondo et al. studied the gasification and reduction behavior of a composite of the powder mixture of hematite ore and coke, at a heating rate of 20 K/min\(^9\). Kasai et al. studied the effect of the hot briquetting composite charging to the blast furnace on the thermal reserve zone temperature and the ratio of CO gas utilization.\(^10\) When the conventional sinter was used, the thermal reserve zone temperature was estimated at 1323 K. However, the temperature decreased to 1133 K and the ratio of CO gas utilization increased as the reduction reaction progressed.

Below 1200 K, the reduction of iron oxide in Marra Mamba ore–coal and pisolite ore–coal composites proceeded faster than that in hematite ore–coal composite. It can be attributed to the larger specific surface area of the ores after decomposition of the combined water. Metallic iron also formed at lower temperature in the composites containing Marra Mamba and pisolite ores. The generation rate of CO gas from these composites showed the maximum value at approximately 1170 K; however, that from the hematite-coal composite gave no peak, because formed metallic iron could act as a catalyst for the gasification of carbon. These results indicate that the reduction of ores with high combined water concentration can proceed at lower temperature. Above 1373 K, however, the reduction rate of these ores in the composite significantly decreased due to a drastic decrease in the specific surface area of the ores and the formation of slag.

The steel industry is facing two difficult and urgent tasks to reduce CO\(_2\) emissions and to use low-grade iron resources effectively. The utilization of an iron ore–carbon composite is one of the promising methods to solve the former. The latter is concerning to goethite ores such as Australian Marra Mamba and pisolite ores, which contain high concentration of combined water. In this study, the effect of combined water on the reduction behavior of the iron ore–coal composites at elevating temperature was examined under inert gas flow.

Below 1200 K, the reduction of iron oxide in Marra Mamba ore–coal and pisolite ore–coal composites proceeded faster than that in hematite ore–coal composite. It can be attributed to the larger specific surface area of the ores after decomposition of the combined water. Metallic iron also formed at lower temperature in the composites containing Marra Mamba and pisolite ores. The generation rate of CO gas from these composites showed the maximum value at approximately 1170 K; however, that from the hematite-coal composite gave no peak, because formed metallic iron could act as a catalyst for the gasification of carbon. These results indicate that the reduction of ores with high combined water concentration can proceed at lower temperature. Above 1373 K, however, the reduction rate of these ores in the composite significantly decreased due to a drastic decrease in the specific surface area of the ores and the formation of slag.

KEY WORDS: ironmaking; iron ore–coal composite; reduction degree; combined water.
centrations of combined water and gangue minerals in different iron ores on the reduction and gasification behaviors of various composites were systematically evaluated at a constant heating rate.

2. Experimental Procedure

Five types of iron ores: one hematite (H1), two Marra Mamba (M1 and M2) and two pisolite (P1 and P2) ores with particle sizes from 105 to 250 μm were used to prepare the composites. The chemical composition and loss on ignition (LOI) of these ores are shown in Table 1. The weight change in these ores was measured by TG-DTA (20 K/min, Ar: 1.66 × 10⁻⁶ Nm³/s) to understand the dehydration behavior. The ores were heat-treated for 1.8 ks under Ar atmosphere at 673 K and for 3.6 ks in air at 1073 K. And, the specific surface area of these ores was measured. Noncoking coal (VM: 36%, fixed carbon: 56%, ash: 8%) having size of <44 μm and graphite reagent (average particle size: 20 μm) were used as a carbonaceous reductant.

The ratio, C/O, which was defined as the molar ratio of fixed carbon in coal to oxygen in iron oxide, was 0.8. Powders of ore and coal were well mixed without reducing the particle size. Then, the mixed powder was press-shaped under a pressure of 9.8 × 10⁶ Pa. A composite sample with 10 mm in diameter and 10 mm in height was obtained. Figure 1 shows a schematic diagram of the a) sample holder and b) experimental system used for the reduction of the composite. The holder consisted of an alumina tube coated by platinum paste. Fifty alumina balls with 2 mm in diameter were packed at the bottom part of the holder. This part has a function as preheating the up flow gas. A setting zone for the composite was formed at the center of the holder using a platinum wire with a diameter of 0.3 mm. The ore–coal composite sample was placed in the holder, and the holder was set in a chamber made of fused silica. Then, Ar–5%N₂ gas was introduced in the chamber at a rate of 8.33 × 10⁻⁶ Nm³/s after evacuating the air in the chamber. N₂ gas was used as a tracer to estimate the amount of gas generated from the composite. The chamber was then heated up to 1 573 K at a heating rate of 0.33 K/s using an infrared image furnace. The temperature was measured at a height of 1 mm from the composite sample using a Pt/Pt–13%Rh thermocouple. A fused silica spacer was set in the holder in order to decrease the dead space volume. The micro- and macro-structures of the composite sample were observed using optical and scanning electron microscopes. The chemical compositions of oxide and slag phases in the composite were measured by energy dispersive X-ray spectroscopy (EDX).

Table 1. Chemical composition of iron ore used.

<table>
<thead>
<tr>
<th></th>
<th>T-Fe</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>68.0</td>
<td>13.5</td>
<td>0.7</td>
<td>0.01</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>M1</td>
<td>63.8</td>
<td>27.1</td>
<td>1.8</td>
<td>0.01</td>
<td>0.1</td>
<td>4.2</td>
</tr>
<tr>
<td>M2</td>
<td>59.9</td>
<td>37.7</td>
<td>2.7</td>
<td>0.02</td>
<td>0.0</td>
<td>7.8</td>
</tr>
<tr>
<td>P1</td>
<td>58.4</td>
<td>50.1</td>
<td>1.2</td>
<td>0.02</td>
<td>0.1</td>
<td>8.7</td>
</tr>
<tr>
<td>P2</td>
<td>57.2</td>
<td>55.5</td>
<td>2.5</td>
<td>0.01</td>
<td>0.1</td>
<td>10.1</td>
</tr>
</tbody>
</table>

The effect of concentration of combined water on the specific surface area of the ores with particle sizes from 105 to 250 μm is shown in Fig. 2. The specific surface area increases with increasing the concentration of combined water. P2, which was heated at 623 K, shows the maximum specific surface area of 60 m²/g. The type of iron oxide in P2 was found to be FeOOH from total Fe content (T-Fe) following formula.

\[ RD(T) = \left( \int_{T_0}^{T} n_{\text{comp}}dT - \int_{T_0}^{T} n_{\text{coal}}dT - \int_{T_0}^{T} n_{\text{oxygen}}dT \right) \times 100 \]

Here, \( n_{\text{comp}} \) and \( n_{\text{oxygen}} \) are the molar amounts of oxygen atom in the CO, CO₂, and H₂O gases generated from the composite and that form coal, respectively, \( n_{\text{coal}} \) and \( n_{\text{oxygen}} \) are that of oxygen atom in H₂O generated from the ore and that originally contained in iron oxide in the composite, respectively. \( T_0 \) is the initial experimental temperature. \( n_{\text{coal}} \) and \( n_{\text{oxygen}} \) were determined by the gasification behavior of the Al₂O₃–coal and ore samples, respectively. The reduction degree was also calculated from the composition analyzed chemically, and it was compared with that calculated from the gas composition.

3. Results and Discussions

3.1. Specific Surface Area of Iron Ores

The effect of concentration of combined water on the specific surface area of the ores with particle sizes from 105 to 250 μm is shown in Fig. 2. The specific surface area increases with increasing the concentration of combined water. P2, which was heated at 623 K, shows the maximum specific surface area of 60 m²/g. The type of iron oxide in P2 was found to be FeOOH from total Fe content (T-Fe)
shown in Table 1, assuming that the LOI was equaled to the concentration of combined water. The effect of the thermal decomposition of synthesized FeOOH on the pore morphology and the specific surface area was examined by Hirokawa et al. They found that a disk-like pore with a diameter of approximately 10 nm was formed at 673 K under inert atmosphere. The formation of these pores increased the specific surface area. The specific surface area measured at 1 073 K is less than that measured at 673 K. The reason for this difference was that the coalescence of small pores led the formation of large pore.

Figure 3 shows the weight change in the five types of ores, which was measured by TG in air, with temperature. The weight of all the ores gradually decreases with increasing temperature up to 523 K, though the change in the weight of H1 is very small. Thereafter, the weight rapidly decreases around 623 K. The initial gradual decrease and the subsequent rapid decrease in the weight are caused by the vaporization of free/adsorbed water and the dehydration of combined water, respectively. Therefore, the rapid decrease in the weight of P2 with a high LOI is more apparent than that in the weight of ores with a low LOI, such as H1. The weight loss ceases at approximately 1 073 K. It can be considered that the generation of oxygen from the composite is caused by the reduction of oxide without dehydration above 1 073 K. In other words, the elucidation of the dehydration behavior of the ore is required in order to calculate the reduction degree below 1 073 K. Similarly, the gasification behavior of the volatile matter in the coal should be considered, because the volatile matter contains oxygen. In this study, the reduction degree was calculated by considering these behaviors.

3.2. Gas Generation Behavior of the H1–Coal Composite

Figure 4 shows the changes in the generation rate of gases from the H1–coal composite with temperature. The vertical axis on the right-hand side represents only the generation rate of CO gas, because the amount of CO gas generated was higher than the other gases. Above 700 K, CH4 gas starts to generate from coal because it contains volatile matter, and the generation rate of CH4 gas is the maximum at approximately 820 K. C2H4 and C2H6 gases are also detected above 700 K, though the generation rate of these gases is lower than that of CH4 gas. The temperature at which the generation rate is the maximum is also lower than that at which CH4 gas is generated. H2 and CO2 gases sequentially generate from the composite, and the local maximum values of the generation rates of CO2 and H2 gases are at approximately 920 and 1 040 K, respectively. After the dehydration of combined water, water vapor generates continuously during heating as shown in Fig. 3. These results suggest that the reduction reaction of iron oxide by carbon and hydrogen, which were produced from the volatile matter present in coal, proceeded below 1 100 K. The peaks of generation rate of CO2 gas are also obtained at approximately 1 170 K and 1 380 K. The generation rate of CO gas starts to increase gradually at approximately 1 000 K, and the maximum generation rate of CO gas is at approximately 1 400 K. Thereafter, the amount of generated gases abruptly decreases.

This gasification behavior of the composites depends on many phenomena such as the dehydration of free, adsorbed and combined water, reduction of iron oxide and gasification of volatile matter present in coal. The gasification behavior of coal will be dealt with separately from the gasification behavior of the entire composite by examining the gasification behavior of the Al2O3–coal composite, assuming that Al2O3 behaves as a spacer only, because the Al2O3 particles do not appear to affect the generation rate of gases from the Al2O3–coal composite. Figure 5 shows the difference between the generation rate of the gases from the H1–coal and Al2O3–coal composites. The generation rate is defined as the number of moles per gram of coal in the composite. In the temperature range from 700 to 900 K, the difference in the generation rate of CH4 gas shows a nega-
tive value. This implies that the CH$_4$ gas generated from coal was decomposed in the presence of iron ore. On the other hand, the difference in the generation rate of H$_2$ gas increases. These results indicate that the cracking reaction of CH$_4$ gas, as given in formula (2), proceeds in this temperature range.

\[
\text{CH}_4 = \text{C} + 2\text{H}_2
\]  

(2)

It is known that the formation of carbon from CH$_4$ proceeds at 773 K in the presence of a nickel catalyst. The catalytic reactivity of iron oxide for the formation of carbon from ethane and acetylene was investigated. Therefore, there is a possibility that the formation of carbon from CH$_4$ gas may have proceeded on the surface of iron oxide particles in the temperature range from 700 to 900 K. Formula (2) indicates that 2 mol of H$_2$ generates from 1 mol of CH$_4$. However, the amount of H$_2$ gas generated was smaller than that estimated by formula (2). In addition, water vapor was detected after the dehydration from the ore, as described above. This implies that the H$_2$ gas generated from CH$_4$ gas was consumed in the reduction of iron oxide.

Above 800 K, the difference in the generation rate of H$_2$ gas shows a negative value, and the difference in the generation rate of H$_2$O gas markedly increases. The difference in the generation rate of CO$_2$ gas also increases. These results indicate that reduction by both H$_2$ and CO gases proceeds at increased temperature.

### 3.3. Effect of Ore Type on the Reduction Behavior in the Composite

Figure 6 shows the changes in the generation rate of gases from the M1–coal and M2–coal composites with temperature. The generation rate of water vapor from both composites in the temperature range from 600 to 800 K is considerably larger than that from the H1–coal composite, as shown in Fig. 4, because the concentration of combined water of M1 and M2 is higher than that of H1. Further, the generation rate of water vapor form the M2–coal composite is larger than that from the M1–coal composite since the concentration of combined water in the former is higher than that in the latter. The generation rate of H$_2$ gas from the M1–coal and M2–coal composites is larger than that from the H1–coal composite in this temperature range. It should be noted that the generation rate of CO gas from the M1–coal and M2–coal composites shows the local maximum value at approximately 1 170 K; however, the generation rate of CO gas from the H1–coal composite remains constant up to this temperature. Moreover, the generation rate of CO$_2$ gas from the M1–coal and M2–coal composites is larger than that from the H1–coal composite in this temperature range. These results suggest that the reduction reaction of iron oxide in the M1–coal and M2–coal composites proceeds faster than that in the H1–coal composite. However, at approximately 1 373 K, the maximum generation rate of CO gas generated from the M2–coal composite is less than that generated from the M1–coal and H1–coal composites. The changes in the gasification rate of the composites with temperature are shown in Fig. 7. Except for the H1–coal composite, all the composites show the local maximum of the gasification rate at approximately 1 170 K. The maximum gasification rate in the temperature from 1 300 to 1 400 K decreases with increasing the concentration of combined water in the ore. The temperature at which the gasification rate is the maximum reduced with increasing the concentration of combined water. These results also suggest that these composites show different reduction behaviors.

Changes in the reduction degree of the H1–coal, M1–
coal, M2–coal, P1–coal and P2–coal composites with temperature are shown in Fig. 8. The open marks denote the reduction degree calculated by chemically analyzing the composites after heating them up to a certain temperature. The reduction degree estimated from the gas concentration agrees with that estimated by the chemical analysis. **Figure 9** shows changes in the partial pressure ratio of \((\text{CO}+\text{H}_2)\) to \((\text{CO}+\text{CO}_2+\text{H}_2+\text{H}_2\text{O})\) in the outlet gas generated from the composites with increasing temperature on the phase diagram of an Fe–O system. That of CO to \((\text{CO}+\text{CO}_2)\) from the previous composite reported by Kondo et al.\(^3\) and the H1–graphite composite is also plotted. They used powders of hematite ore and coke as the ore and carbonaceous material, respectively; however, they did not state the particle size of these powders. The heating rate was 0.33 K/s, which was the same as that employed in this study. Therefore, the gas ratio measured in this study could be compared with their values. The gas ratio of the ore–coke composite starts to increase at approximately 750 K and it reaches the coexistence line of \(\text{Fe}_3\text{O}_4\) and \(\text{FeO}\) at approximately 1200 K. The gas ratio of the H1–graphite composite starts to increase at approximately 1150 K. This is the maximum temperature employed in this study, because graphite contains little volatile matter and its gasification rate is lower than that of coke and coal.\(^16\) On the other hand, the gas ratio of the ore–coal composites starts to increase at approximately 700 K. This behavior is caused by both the gasification of \(\text{H}_2\) gas from coal, as shown in Fig. 5(a)), and the generation of \(\text{H}_2\) gas by the cracking reaction of CH\(_4\) gas, which generates from the coal present in the composites. The gas ratio shows the local maximum value at approximately 770 K, and it decreases with increasing concentration of combined water. This decrease in the gas ratio is caused by the difference in the amount of \(\text{H}_2\text{O}\) generated by the dehydration reaction of \(\text{FeOOH}\). The gas ratio slightly decreases with increasing temperature because of the \(\text{CO}_2\) and \(\text{H}_2\text{O}\) gases generated by the reduction reaction, as shown in Figs. 4 and 6. The gas ratio increases again with temperature at around 900 K. This increase is attributed to the increase in the amount of \(\text{H}_2\) gas generated from coal, as shown in Fig. 5(a)).

In the case of the H1–coal composite, the gas ratio starts to decrease at 1050 K. After reaching the local minimum value at 1193 K, it starts to increase again. In the case of M2–coal, P1–coal and P2–coal composites, on the other hand, the gas ratio continuously increases above 1050 K, and reaches the coexistence line of metallic iron and \(\text{FeO}\) at 1120 K. It appears that the effect of the reduction reaction on the gas ratio increases above 1050 K, because the generation rate of \(\text{H}_2\) gas from coal starts to decrease, as described above, and the reduction rate increases with the temperature. Optical micrographs of the H1–coal, M2–coal and P1–coal composites obtained after heating at 1193 K, as shown in **Fig. 10**, to discuss the difference in the gas generation behavior; the gas ratio of the H1–coal composite is the local minimum at 1193 K. Metallic iron particles with a size of a few micrometers are observed in the M2–coal and P1–coal composites; however, no metallic iron is observed in the H1–coal composite. The reduction degree of the H1–coal composite at 1050 K and 1193 K was 12% and 22%, respectively, which indicates the coexistence of \(\text{Fe}_3\text{O}_4\) and \(\text{FeO}\). The reduction degree of the P1–coal and P2–coal composites is equivalent to that of single phase \(\text{FeO}\) at 1050 K. The reduction degree of the M2–coal composite is also equivalent to that of single phase \(\text{FeO}\) at the temperature where the gas ratio starts to increase. In the case of the H1–coal composite, however, the reduction degree becomes equivalent to that of single phase \(\text{FeO}\) above
200 K. Therefore, it is found that the gas ratio of the H1–coal composite decreased above 1,050 K because the gas ratio is higher than that controlled by the reduction degree.

The concentration of gases generated from the composites, except for the H1–coal composite, is almost equivalent to that at the boundary line of metallic iron and FeO in a temperature range from 1,100 to 1,250 K. In this temperature range, gasification reaction appears to be the rate-determining step. The reduction degree rapidly increases at approximately 1,100 K. Therefore, the catalytic effect of metallic iron on the gasification of coal seems to accelerate the generation reaction of CO gas from the composites except for the H1–coal, and it becomes the maximum at approximately 1,170 K, as shown in Fig. 7.

The relation between the temperature at which the reduction degree of the composites reached 30%, 70% and 80% and the concentration of combined water in the iron ores is shown in Fig. 11 to clarify the effect of the type of ores, and the concentration of combined water on the progress of the reduction reaction. A reduction degree of 30% indicates the beginning of metallic iron formation in the composite. The temperature, at which metallic iron starts to form, decreases with increasing concentration of combined water. It indicates that metallic iron formed below 1,170 K except for the H1–coal composite. The specific surface area of the ores increases with the concentration of combined water, as shown in Fig. 2. Below 1,050 K, the increase in the specific surface area directly causes the reduction reaction to proceed, because the rate of the reduction reaction is less than the supply rate of the reducing gas. Accordingly, the utilization of the ores with high concentration of combined water could reduce the temperature at which metallic iron started to form by approximately 150 K. This indicates that the ores with high concentration of combined water has the advantage for the progress of the reduction at lower temperature.

Above 1,250 K, there was no different trend in the change of the gas ratio from the composites, and the gas ratio increased with the temperature, as shown in Fig. 9. However, the reduction rate of the H1–coal composite is higher than that of the other composites in this temperature range. As a result, the temperature at which the reduction degree reaches 80% increases with the concentration of combined water, and in the case of the P2–coal composite, it occurs above 1,350 K.

The reason behind the decrease in the reduction rate of the ores with high concentration of combined water is discussed below. The gasification rate was kept at 20 μmol/s · g-coal above 1,500 K. The gas ratio was higher than that at the boundary line of metallic iron and FeO above 1,250 K. The oxygen potential calculated from the gas ratio indicates that the reduction reaction can proceed. In contrast, these ores have high amounts of not only com-

![Fig. 11. Relation between temperature at which the reduction degree of the composites reached 30%, 70% and 80% and the concentration of combined water in iron ores.](image)

![Fig. 12. Microstructures of the H1–coal, M2–coal and P1–coal composites after heating up to 1,273 K, 1,373 K and 1,473 K.](image)
bined water but also gangue such as SiO₂ and Al₂O₃. Figure 12 shows the microstructures of the H1–coal, M2–coal and P1–coal composites after heating up to 1 273 K, 1 373 K and 1 473 K. In the case of the M2–coal and P1–coal composites, metallic iron particles with size less than 10 μm are observed with FeO phases at 1 273 K. FeO phases have a porous structure. Therefore, metallic iron was formed not only around the FeO phases but also inside the phases. On the other hand, no metallic iron is observed in the H1–coal composite at 1 273 K. Further, molten FeO phase, which forms during heating, was not found in these three composites. In the case of the composite containing M2 and P1 ores with large amounts of gangue, slag phase with metallic iron is observed at 1 373 K and 1 473 K. Figure 13 shows the composition of the oxide phase in the M2–coal composite after heating at 1 373 K and 1 473 K plotted on a ternary phase diagram of the Al₂O₃–FeO–SiO₂ system. The star symbols in the figure denote the ratio of SiO₂/Al₂O₃, which was calculated from the composition of gangue in the ore. The solid square and circle denote the average compositions of remained oxide, which was estimated from the gangue composition and the amount of remained FeO at 1 373 K and 1 473 K, respectively. The amount of remained FeO was calculated from the reduction degree. At 1 373 K, the major phases were FeO and Al₂O₃–SiO₂ with a low concentration of FeO as the gangue. Some points indicated the average composition of 2FeO·SiO₂, FeO·Al₂O₃ and slag. At 1 473 K, slag coexisted with 2FeO·SiO₂ and FeO·Al₂O₃. Approximately half of slag consisted of the FeO–SiO₂ system, which has low

Fig. 13. Chemical composition of the oxide phase in the M2–coal composite after heating at a) 1 373 K and b) 1 473 K plotted on the ternary phase diagram of Al₂O₃–FeO–SiO₂ system.
Therefore, above 1373 K, the formation of the FeO–SiO2 slag partially contributed to the decrease in the reduction rate of the composites containing ores with high concentration of combined water.

Figure 14 shows the effect of heating temperature on the surface length of the oxide particles per unit area in the case of the H1–coal, M2–coal and P1–coal composites. The oxide indicates both iron oxide particle and slag phase. The surface length corresponding to the two-dimensional surface area was calculated by image analysis of the microstructure. The surface length of the oxide particles in the H1–coal composite only slightly changes with increasing temperature. On the other hand, the surface length of the oxide particles in the M2–coal and P1–coal composites rapidly decreases in a temperature range from 1373 to 1473 K; little change is observed in the surface length below 1373 K. The reason for this change in the surface length is the formation of slag. The presence of a small amount of gangue in H1 prevented a rapid decrease in the surface length. Therefore, it is concluded that, above 1373 K, the rapid decrease in the surface area and the formation of the FeO–SiO2 slag system with low reducibility contribute to the decrease in the reduction rate of the composites containing ores with high concentration of combined water.

On the other hand, the effect of the combined water is not significant on the temperature at which the reduction degree reaches 70% as shown in Fig. 11. There are both positive and negative effects of concentration of combined water in the ore on the reduction of iron oxide. The positive effect is the progress of the reduction reaction below 1200 K in the case of the composites containing ores with high concentration of combined water. The negative effect is the decrease in the reduction rate due to the formation of slag above 1373 K. It is estimated that this negative effect cancelled the advantage for the progress of the reduction at lower temperature.

4. Conclusions

The effect of the combined water in iron ores on the reduction and gasification behaviors of the ore–coal composites at elevating temperature of 0.33 K/s was examined to find the effective methods for utilization of the low-grade iron ore. The following results were obtained:

(1) During the reduction of ore–coal composites, the rate of CO gas generation from the composites prepared by using ores containing high combined water, such as Marra Mamba and pisolite ores, showed the maximum value at approximately 1170 K, while that from a hematite–coal composite was low at that temperature. Such difference in the gasification behaviors can be attributed to the difference of the formation temperature of metallic iron, which has significant catalytic effect on the gasification reaction.

(2) It is clear that ores containing high combined water give advantage to promote the reduction reaction at lower temperatures, i.e., below 1200 K, since the formation temperature of the metallic iron decreases with increasing concentration of combined water. The reduction reaction by hydrogen and carbon, both generated by the decomposition of the volatile matters in coal, rapidly proceeds below 1200 K due to an increase in the surface area of the ores due to dehydration. Accordingly, the utilization of the ores containing high combined water could decrease the formation temperature of metallic iron by approximately 150 K.

(3) Above 1373 K, however, the reduction reaction of the composites of Marra Mamba and pisolite ores is suppressed mainly due to a rapid decrease in the surface area and the partial formation of FeO–SiO2 slag. On the other hand, hematite ore hardly show such phenomena.

Acknowledgments

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