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Effect of Basicity on Consolidation Behavior and Phase Evolution of Mg-Bearing Medium Silica Fluxed Pellets

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Abstract

Against the background of blast furnace burden optimization and the low-carbon transition of the steel industry, the development of high-quality Mg-bearing fluxed pellets is of great significance for the efficient utilization of medium-high silica iron ore concentrates. In this study, Mg-bearing medium-high silica fluxed pellets with a fixed SiO_2 content of 5.5% were prepared, and the effect of basicity in the range of R = 1.0–1.4 on compressive strength, liquid phase behavior, slag phase composition, and pore structure evolution was systematically investigated. The results showed that the compressive strength of the pellets decreased from 2527 N/pellet to 2079 N/pellet as the basicity increased from 1.0 to 1.4. At 1250 °C, the liquid phase content first decreased from 2.66% to 1.30% and then increased to 7.38%, while the liquid phase viscosity decreased continuously. Meanwhile, the liquid phase composition evolved from a SiO_2-rich calcium–iron silicate system to a $Fe_2O_3{}^-$ and CaO-rich system. XRD results indicated that Fe_2O_3 was the dominant crystalline phase in the pellets, accompanied by a small amount of Fe_3O_4, whereas no distinct highly crystalline slag phase was detected. The slag phase was mainly a Fe-Ca-Si composite slag, in which the Fe_2O_3 content increased and the SiO_2 content decreased with increasing basicity. At higher basicity, the number and size of pores increased, and the pore morphology evolved from dispersed fine pores to irregular large pores and locally connected pores. Meanwhile, the slag phase became more widely distributed and locally enriched, weakening the continuity of the iron oxide load-bearing skeleton, which was the main reason for the decrease in compressive strength. This study provides a theoretical basis for preparing high-quality Mg-bearing fluxed pellets from medium-high silica iron ore concentrates.

Keywords: Mg-bearing fluxed pellets; medium-silica iron ore concentrate; basicity; compressive strength; consolidation behavior

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Academic Editor: Petros E. Tsakiridis

Received: 20 May 2026
Revised: 4 June 2026
Accepted: 7 June 2026
Published: 16 June 2026

1. Introduction

With the continuous development of blast furnace ironmaking, increasingly stringent requirements have been imposed on burden quality, particularly in terms of strength, reducibility, softening-melting behavior, and chemical composition stability [1,2]. Owing to their high iron grade, uniform particle size, favorable reducibility, and high cold strength, iron ore pellets have become an important burden material for optimizing blast furnace

Metals **2026**, *16*, 665 https://doi.org/10.3390/met16060665

burden structure and promoting green, low-carbon ironmaking. Accordingly, the proportion of pellets used in blast furnaces in China has increased steadily in recent years [3]. Compared with sinter, pellet production generally features lower energy consumption and fewer pollutant emissions [4,5]. Under China's carbon peaking and carbon neutrality strategy, the steel industry is facing major targets for energy conservation and carbon reduction. In this context, optimizing the blast furnace burden structure, increasing the proportion of pellets in the furnace burden, and reducing the carbon emission intensity of ironmaking have become key pathways for the green and low-carbon transformation of the steel industry [6,7].

Fluxed pellets can not only reduce process energy consumption, decrease the consumption of fluxes charged into the blast furnace, and increase the permissible pellet proportion in the burden, but also form an appropriate slag phase in the high-temperature zone, thereby improving the permeability and dripping behavior of the cohesive zone. These effects are beneficial for lowering the coke rate and increasing the blast furnace productivity [8–10]. In recent years, Mg-bearing pellets have attracted increasing attention as an important direction for the development of high-quality pellets, because they can optimize slag fluidity, mitigate refractory erosion, improve the reduction swelling behavior of pellets, and increase their softening-melting temperature [11,12]. Meanwhile, with the increasing scarcity of high-quality iron ore concentrates, the efficient utilization of medium-high silica iron ore concentrates, typically containing approximately 5–8% SiO_2, is of practical significance for reducing raw material costs and expanding the usable range of iron ore resources [13]. However, a higher SiO_2 content increases the slag phase fraction in pellets and, without appropriate regulation, may lead to a decrease in compressive strength and deterioration of metallurgical properties [14]. Therefore, preparing Mg-bearing fluxed pellets by introducing both CaO and MgO into medium-high silica systems provides a feasible approach to optimizing slag composition, liquid phase behavior, and microstructure, thereby achieving a synergistic improvement in strength and metallurgical performance.

Extensive studies have been conducted on the induration and consolidation behavior of Mg-bearing medium-high silica fluxed pellets [15,16]. Most previous investigations have focused on roasting experiments to examine the evolution of mineral structure [17], pore distribution, and phase composition during pellet induration [18], thereby clarifying the general phase evolution behavior of fluxed pellets during oxidative roasting [11].

In China, many researchers have systematically investigated the preparation and performance optimization of fluxed pellets. Jiang Tao et al. [19] studied the effect of calcium-bearing fluxes on the strength of roasted pellets and found that the compressive strength first increased and then decreased with increasing dosage of calcium additives. Hydrated lime had a particularly pronounced effect on roasted pellet strength. Even when relatively coarse hematite particles were used, the compressive strength of roasted pellets exceeded 2000 N after adding 0.5% hydrated lime. However, when the addition exceeded 6%, a glassy structure appeared inside the pellets, leading to a decline in strength. Fan Xiaohui et al. [20] prepared pellets using magnetite concentrate with a SiO_2 content of 5.00% and different fluxes, including limestone, quicklime, magnesite, MgO, dolomite, and light-burned dolomite. Their results showed that calcium-bearing fluxes promoted the formation of calcium ferrite bonding phases, and an appropriate amount of liquid phase improved hematite recrystallization. In contrast, excessive liquid phase damaged the pellet structure, causing the compressive strength to first increase and then decrease. Tian Junqing et al. [21] prepared fluxed pellets using high-grade magnetite concentrate with a SiO_2 content of 1.89% and limestone. They found that when the limestone proportion was below 4.0%, the compressive strength could exceed 2500 N at 1265 °C, whereas a higher temperature of 1280 °C was required when the limestone proportion increased to

4.5–5.0%. With increasing limestone addition, Fe_2O_3 crystals became increasingly dispersed and failed to form continuous intergrowths, which weakened the bonding strength and reduced the compressive strength. Zhang Yuanbo et al. [22] prepared fluxed pellets using high-silica magnetite concentrate with a SiO_2 content of 5.6%, limestone, and reagent-grade MgO, and investigated the effect of liquid phase on the properties of high-silica fluxed pellets by combining FactSage calculations with experiments. Their results showed that increasing the MgO content from 0 to 2.50% reduced the reduction swelling index, but the formation of magnesioferrite spinel caused a sharp decrease in compressive strength. However, adding CaO to pellets containing 2.50% MgO significantly improved pellet quality. This improvement was attributed to the substantial increase in silicate liquid phase, which effectively acted as a bonding phase and enhanced pellet strength.

International researchers have also conducted systematic studies on the preparation of Mg-bearing fluxed pellets. Jagannath Pal et al. [23] prepared fluxed pellets using high-grade magnetite concentrate with a SiO_2 content of 1.4%, in which calcined lime and MgO were used as composite fluxes to replace limestone and bentonite. The decomposition of limestone ($CaCO_3$) at high temperature is an endothermic process, and additional energy is also required to grind limestone into fine powder. In contrast, calcined lime releases heat during hydration to form hydrated lime, which exhibits favorable binding properties. By optimizing the MgO addition and basicity, fluxed pellets were successfully developed using calcined lime instead of limestone. Dwarapudi et al. [18] prepared pellets from magnetite concentrates containing 1.9–4.2% SiO_2 with different fluxes, including limestone, dolomite, and magnesite, and investigated the effects of flux type on liquid phase formation, microstructure, and reduction degradation behavior of fluxed pellets. Their results showed that a higher pellet basicity promoted the formation of more liquid phase and significantly reduced the low-temperature reduction degradation index. T. Umadevi et al. [24] used magnetite concentrate with a SiO_2 content of approximately 5.0% to prepare fluxed pellets with a basicity of 0.40–0.50, and analyzed the effect of limestone addition on pellet consolidation behavior. Their results indicated that the introduction of CaO altered the formation temperature, amount, and distribution of the liquid phase during roasting, thereby affecting the bonding mode of mineral phases inside the pellets. An appropriate amount of liquid phase promoted interparticle bonding and structural densification, increasing the compressive strength of fired pellets from approximately 1760 N/pellet to 2640 N/pellet. This suggests that rational control of flux addition is beneficial for improving pellet induration quality. Panigrahy et al. [25] investigated pellets prepared from specular hematite concentrate with a SiO_2 content of 5.05% and a basicity range of 0.2–1.6. Pellet basicity was adjusted by adding limestone or a mixture of dolomite and limestone. SEM-EDS analysis showed that calcium ferrite was observed in limestone-fluxed pellets at a basicity of 0.8, whereas substantial calcium ferrite formation occurred only at a basicity of 1.6. For pellets prepared with the dolomite-limestone mixture, only a small amount of calcium ferrite was observed even at a basicity of 1.6. In these pellets, magnesioferrite spinel ($MgO{\cdot}Fe_2O_3$) was formed, and the silicate glass phase served as the main bonding phase. The silicate phase and magnesioferrite regions were clearly separated. In contrast, such phase separation was not obvious in pellets fluxed only with limestone because of their low Mg content.

Representative international producers of fluxed pellets include Vale in Brazil, IOC in Canada, Minntac in the United States, and Kobe Steel in Japan [26]. These producers commonly use high-grade magnetite concentrates with limestone to prepare fluxed pellets. The SiO_2 content of the finished pellets is typically in the range of 2.37–4.20%, while their compressive strength is relatively low, generally around 2300–2800 N/pellet. Their reduction swelling index is usually below 20%, and the pellet basicity is generally higher than

0.9. In China, to meet the operating requirements of large blast furnaces, the compressive strength of fluxed pellets is generally required to be higher than that of foreign fluxed pellets. At present, representative Chinese producers of fluxed pellets usually have access to imported high-grade iron ore resources, which provide the basis for producing low-silica fluxed pellets. For example, Shougang Jingtang [27] and Hesteel Tangsteel [28] rely on high-quality Peruvian magnetite concentrate and use hydrated lime as the calcium-bearing flux to produce fluxed pellets with SiO_2 contents of 2.01–3.25% using straight-grate induration machines. The compressive strength of these pellets can exceed 3000 N/pellet, while the reduction swelling index remains below 20%. Baosteel Zhanjiang [29] uses low-silica imported ore and limestone as raw materials to produce fluxed pellets with a basicity of 0.85 through the grate-kiln process, achieving a compressive strength of approximately 2800 N/pellet. However, due to limitations in resource availability, the production experience of low-silica fluxed pellets cannot be readily applied to many steel enterprises. Domestic iron ore resources in China generally contain relatively high SiO_2 contents because of limitations in beneficiation technology. The production of fluxed pellets from such ores tends to increase liquid phase formation during induration. Therefore, regulating the composition and amount of liquid phase in pellets and developing high-quality Mg-bearing fluxed pellets have become key issues in the field of iron ore pelletization.

In summary, although extensive studies have been conducted on the effects of flux type, MgO addition, and basicity regulation on pellet properties, the consolidation behavior of Mg-bearing medium-high silica fluxed pellets remains insufficiently understood. In this system, the relatively high slag phase fraction caused by elevated SiO_2 content, together with the combined effects of MgO and CaO, makes liquid phase formation and mineral structure evolution during induration more complex. At present, the mechanisms by which basicity regulates hematite intergrowth, the formation of Ca- and Mg-bearing bonding phases, slag network distribution, and pore structure evolution in medium-silica fluxed pellets remain unclear. Therefore, in this study, Mg-bearing medium-high silica fluxed pellets with a SiO_2 content of 5.5% were prepared to investigate the effect of basicity on their induration consolidation behavior and phase evolution. Particular attention was paid to the relationships among compressive strength, hematite recrystallization, liquid/slag phase distribution, and pore structure. This work aims to elucidate the mechanism by which basicity controls pellet consolidation behavior and to provide theoretical support for the efficient utilization of medium-high silica iron ore concentrates and the preparation of Mg-bearing fluxed pellets.

2. Materials and Methods

2.1. Raw Materials

Five iron ore concentrates were used as raw materials in this study. Iron ore A was Kimkan iron ore concentrate sourced from Russia. Iron ore B was Chita iron ore concentrate sourced from Russia. Iron ore C was lateritic nickel ore supplied by Yichun Fuxiang Technology Co., Ltd. (Yichun, Heilongjiang, China). Iron ore D was Jinshu Investment iron ore concentrate supplied by Yichun Fuxiang Technology Co., Ltd. (Yichun, Heilongjiang, China). Iron ore E was Qing'an high-sulfur iron ore concentrate supplied by Qing'an Shangyuan Mining Co., Ltd. (Qiangan, Heilongjiang, China).

Iron ore A was a typical high-silica concentrate with a SiO_2 content of 7.32%. Iron ore B was a medium-silica, high-MgO concentrate, containing 3.37% MgO. Iron ore C was a lateritic nickel ore with a relatively high limonite content and a loss on ignition (LOI) of 14.33%; a small addition of this ore was beneficial for improving the balling performance of the mixture. Iron ore D was a typical medium-silica concentrate with a SiO_2 content of 4.75%. Iron ore E was characterized by relatively high sulfur and MgO contents, with 2.59% S and

2.71% MgO. Limestone powder was used as the calcium-bearing flux, and bentonite was used as the binder at a fixed dosage of 1.6%. The chemical compositions of the raw materials are listed in Table 1. The chemical compositions of the raw materials were determined by standard chemical analysis methods. The major oxide contents were analyzed by X-ray fluorescence spectroscopy (XRF, RIGAKU ZSX Primus, Rigaku Corporation, Tokyo, Japan), TFe and FeO were determined by wet chemical titration methods, and the loss on ignition (LOI) was measured by the gravimetric method after high-temperature calcination.

Table 1. Chemical composition and burning loss analysis of experimental raw materials %.

Raw Material	TFe	FeO	CaO	SiO_2	MgO	Al_2O_3	K_2O	Na_2O	TiO_2	LOSS
Iron ore A	65.06	26.90	0.33	7.32	0.67	0.42	0.089	0.038	0.068	−2.22
Iron ore B	62.86	27.24	1.20	4.38	3.37	0.68	0.148	0.042	0.066	−0.81
Iron ore C	52.40	0.36	0.72	2.62	0.92	6.07	0.012	0.007	0.184	14.33
Iron ore D	68.41	28.70	0.13	4.75	0.34	0.10	0.037	0.024	0.011	−2.17
Iron ore E	64.72	31.12	0.84	2.93	2.71	0.55	0.046	0.010	0.064	−1.23
Limestone	–	–	52.88	2.41	0.48	–	–	–	–	39.86
Bentonite	2.77	–	3.49	54.27	2.38	13.92	1.49	3.94	–	7.27

2.2. Experimental Design and Procedure

In the experimental design, as shown in Table 2, the proportions of iron ores C, D, and E were kept constant at 4.98%, 14.44%, and 4.98%, respectively. The blending ratio of iron ores A and B was adjusted to maintain the SiO_2 content of the pellets at 5.5%. Meanwhile, the pellet basicity was regulated by varying the addition amount of limestone powder. No external Mg-bearing flux was added; thus, all MgO in the pellets originated from the iron ore concentrates themselves.

Table 2. Theoretical chemical compositions and basicity of pellets in different experimental groups, wt.%.

Raw Material	TFe	CaO	SiO_2	MgO	Al_2O_3	R
Pellet 1	58.93	5.50	5.50	1.84	0.90	1.0
Pellet 2	58.51	6.05	5.50	1.81	0.90	1.1
Pellet 3	58.10	6.60	5.50	1.78	0.90	1.2
Pellet 4	57.70	7.13	5.50	1.75	0.90	1.3
Pellet 5	57.52	7.73	5.50	1.72	0.90	1.4

Before the experiments, all raw materials were dried in an oven. The raw materials were then weighed according to the designed proportions and mixed three times using the coning and quartering method. Subsequently, 7.5 wt.% water was added, and the mixture was thoroughly homogenized. The moist mixture was passed through a 0.05 mm square-hole sieve to break up large agglomerates, followed by three additional mixing cycles using the coning and quartering method to ensure uniform moisture distribution. For each experiment, 10 kg of the mixture was used to prepare green pellets in a disc pelletizer. The disc pelletizer had a diameter of 800 mm and a side-wall height of 150 mm, and it was operated at a rotation speed of 38 r/min and an inclination angle of 47°. Green pellets with a particle size of 10–12.5 mm were selected as qualified pellets and placed in a roasting pot for subsequent induration tests. The preheating temperature was set at 900 °C with a holding time of 10 min, and the roasting temperature was set at 1250 °C with a holding time of 10 min. The final roasted pellets were then obtained. The experimental procedure is illustrated in Figure 1. The complete thermal profile and process parameters of the induration procedure are shown in Figure 2.

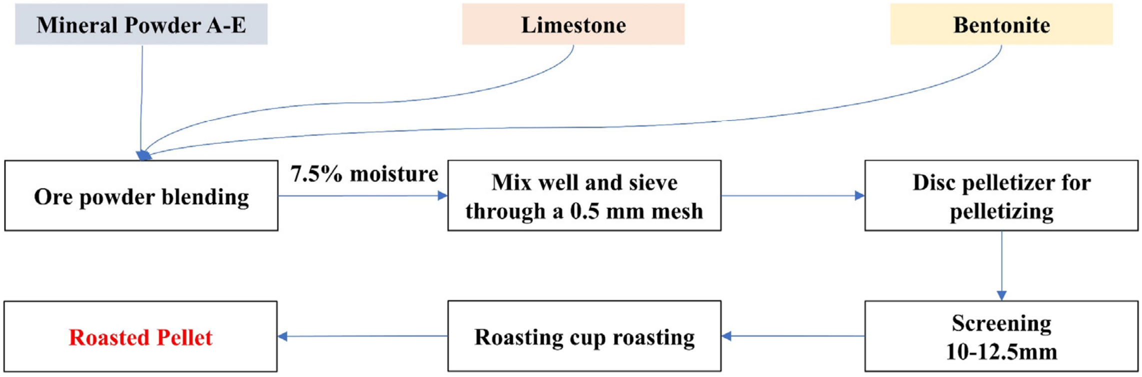

Figure 1. Experimental process for preparing roasted pellets.

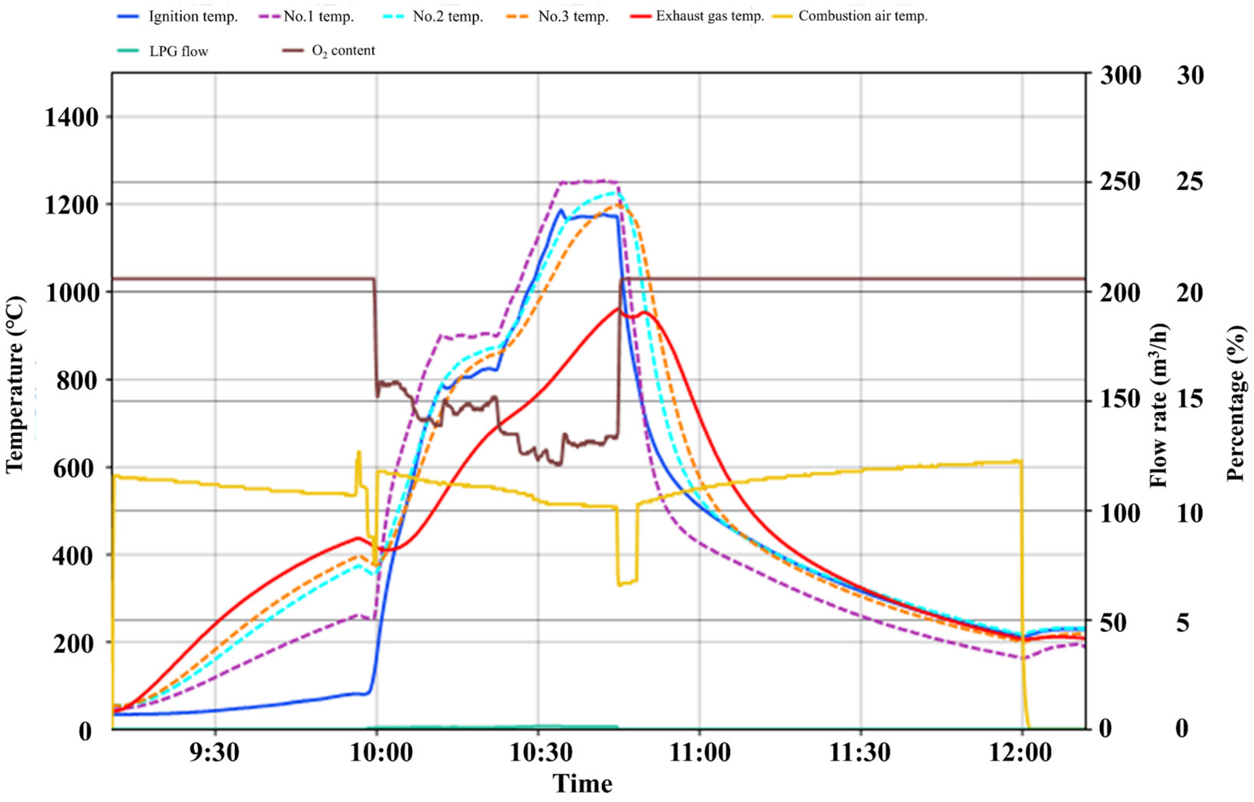

Figure 2. Thermal profile and process parameters for pellet preheating, roasting, and cooling.

2.3. Characterization Methods

The compressive strength of the pellets was measured as follows. Sixty pellets with a uniform size in the range of 10–12.5 mm were selected for each test, and the measurement was conducted using an automatic pellet compressive strength tester. The maximum load capacity of the tester was 10 KN, and the arithmetic mean of all measured values was taken as the final compressive strength, expressed in N/pellet. Phase analysis was performed using an X-ray diffractometer (XRD, Rigaku Ultima IV, Rigaku Corporation, Tokyo, Japan), with a divergence slit of 2/3°, a 2θ step size of 0.02°, and a scanning rate of 1°/min. The microstructure and elemental distribution of the samples were characterized using scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS, Phenom, Eindhoven, The Netherlands).

3. Results and Discussion

3.1. Effect of Basicity on the Compressive Strength of Mg-Bearing Fluxed Pellets

For Mg-bearing medium-high silica fluxed pellets, the relatively high gangue content promotes the formation of a considerable amount of liquid phase during high-temperature induration. The generation and spreading of this liquid phase within the pellets can affect the intergrowth of iron oxide grains, the distribution of pore structure, and the type and amount of slag phases, all of which exert significant influences on pellet compressive strength. Therefore, the following section focuses on these aspects to clarify the effect of basicity on the strength development of Mg-bearing fluxed pellets.

For Mg-bearing medium-high silica fluxed pellets, the relatively high contents of gangue components such as CaO, SiO_2, and MgO in the raw materials facilitate the formation of a certain amount of liquid phase during high-temperature induration. The generation, migration, and spreading of the liquid phase within the pellets directly affect the intergrowth of iron oxide particles, the evolution of pore structure, and the composition and distribution of slag and bonding phases. In particular, variations in basicity significantly influence the reaction sequence among CaO, SiO_2, Fe_2O_3, and MgO, thereby regulating the formation of calcium ferrites, silicates, and Mg-bearing composite phases. These factors jointly determine the densification degree and intergrowth state of the internal pellet structure, which are ultimately reflected in the compressive strength of the roasted pellets. Therefore, it is necessary to systematically examine the variation in compressive strength of Mg-bearing medium-high silica fluxed pellets under different basicity conditions, so as to clarify the mechanism by which basicity affects pellet consolidation behavior.

To clarify the effect of basicity on the compressive strength of Mg-bearing fluxed pellets, compressive strength tests were conducted on roasted pellets from different experimental groups. The results are shown in Figure 3. For Mg-bearing medium-high silica fluxed pellets, the compressive strength gradually decreased from 2527 N/pellet to 2079 N/pellet as the basicity R increased from 1.0 to 1.4, indicating that increasing basicity is unfavorable for maintaining compressive strength in this medium-high silica system. This deterioration may be related to changes in the type of liquid phase induced by increasing basicity, which may inhibit hematite recrystallization and weaken the intrinsic strength of the solidified slag phase after cooling. To verify this mechanism, XRD phase analysis, SEM-EDS microstructural and elemental distribution characterization, and thermodynamic calculations were further performed to quantitatively analyze the liquid phase amount and liquid phase type at different basicity, thereby elucidating the influence mechanism of basicity on the consolidation behavior of Mg-bearing fluxed pellets.

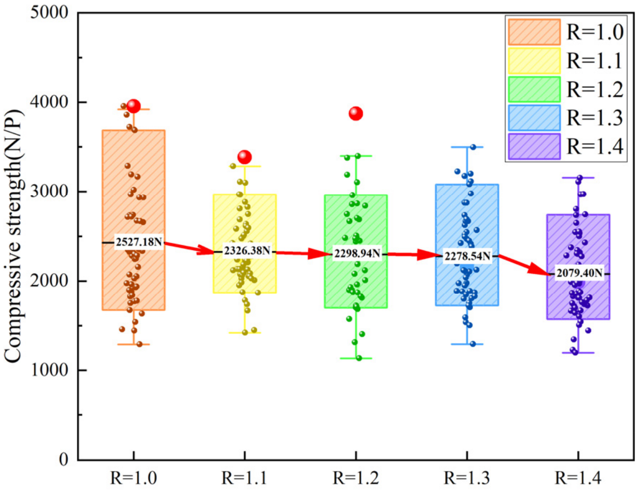

Figure 3. The influence of basicity on the compressive strength of pellet ore.

https://doi.org/10.3390/met16060665

3.2. Effect of Basicity on Liquid Phase Formation Behavior

For Mg-bearing medium-high silica fluxed pellets, the internal structure is mainly composed of Fe_2O_3, slag phases, and pores. Variations in basicity can alter both the amount and type of liquid phase formed inside the pellets. On the one hand, differences in liquid phase content during high-temperature induration can significantly affect pore structure reconstruction, thereby changing the pore distribution in roasted pellets and influencing their consolidation behavior. On the other hand, different types of liquid phase may crystallize into different mineral phases during cooling, and the intrinsic mechanical properties of these phases can strongly affect pellet performance. Therefore, to clarify the mechanism by which basicity affects the compressive strength of Mg-bearing medium-high silica fluxed pellets, thermodynamic calculations were first performed to determine the liquid phase content and liquid phase type at different basicity. The calculated liquid phase content and liquid phase characteristics at 1250 °C are shown in Figure 4, and the detailed liquid phase compositions are listed in Table 3.

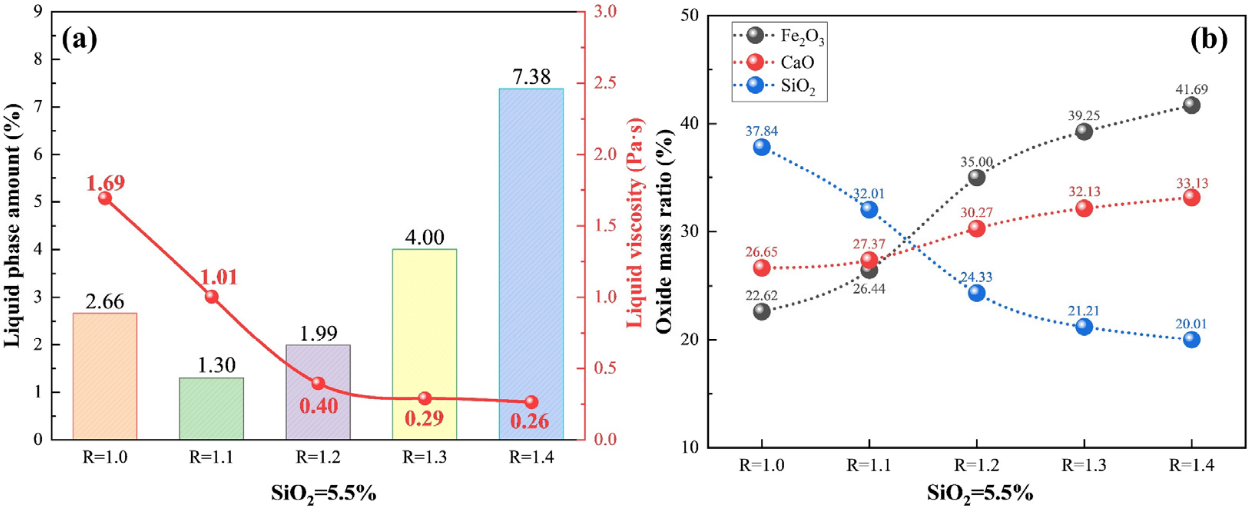

Figure 4. The influence of basicity on the compressive strength of pellet ore: (**a**) liquid phase amount and liquid phase viscosity; (**b**) mass ratios of Fe_2O_3, CaO, and SiO_2.

Table 3. Calculated liquid phase composition and liquid phase content of pellets at 1250 °C obtained by FactSage 8.4 thermodynamic calculations, wt.%.

	FeO	Fe_2O_3	SiO_2	CaO	MgO	Al_2O_3	K_2O	Na_2O	$NaAlO_2$	$KAlO_2$	$NaFeO_2$
R = 1.0	1.841	22.615	37.838	26.650	3.760	2.832	0.288	0.228	0.526	1.855	0.948
R = 1.1	1.668	26.443	32.010	27.367	2.341	1.707	0.662	0.610	0.756	3.494	2.119
R = 1.2	1.418	34.997	24.331	30.271	1.512	0.985	0.555	0.596	0.237	1.858	1.297
R = 1.3	1.248	39.254	21.213	32.128	1.225	0.781	0.308	0.353	0.073	0.793	0.586
R = 1.4	1.102	41.692	20.006	33.132	1.093	0.738	0.173	0.195	0.032	0.416	0.306

For Mg-bearing fluxed pellets, in view of the continuous decrease in compressive strength with increasing basicity, the liquid phase formation behavior was further analyzed. The results show that the liquid phase content first decreased and then increased with increasing basicity. When the basicity increased from 1.0 to 1.1, the liquid phase content decreased from 2.66% to 1.30%, and then increased to 7.38% at a basicity of 1.4. In contrast, the viscosity of the liquid phase showed a continuous decreasing trend with increasing basicity. Combined with the compressive strength results, these findings indicate that the deterioration in pellet strength is not simply governed by the amount of liquid phase, but is closely related to changes in liquid phase viscosity and composition. With increasing basicity, the increase in liquid phase content and the decrease in viscosity may promote atomic migration between the liquid phase and iron oxides at high temperature and enhance elemental penetration. In principle, the formation of a larger amount of low-viscosity liquid phase could facilitate the development of a slag bonding network and thus improve pellet strength. However, the measured compressive strength decreased continuously with increasing basicity, suggesting that the solidified slag phase formed during cooling at higher basicity may be a key factor responsible for the deterioration of pellet strength.

Furthermore, FactSage calculations were used to determine the chemical composition of the liquid phase at a high temperature under different basicity conditions, as shown in Figure 4b and Table 3. The data in Table 3 are calculated equilibrium results obtained using FactSage and should not be regarded as directly measured experimental values. With the decrease in pellet compressive strength, the Fe_2O_3 and CaO contents in the liquid phase increased markedly, whereas the SiO_2 content decreased. This indicates that the liquid phase gradually transformed from a high-viscosity, SiO_2-rich calcium–iron silicate system to a low-viscosity, Fe-rich calcium–iron silicate system. The low-viscosity and highly fluid ferrite-bearing liquid phase may crystallize into iron oxide phases during cooling after induration, which is less effective at forming a high-strength slag bonding network. This may further contribute to the pronounced decrease in pellet compressive strength.

3.3. Effect of Basicity on Phase Evolution

Thermodynamic calculations revealed the overall effect of increasing basicity on liquid phase formation, including an initial decrease followed by an increase in liquid phase content, a continuous decrease in liquid phase viscosity, and a compositional transition of the liquid phase from a Si-rich system to an Fe-rich system. However, the crystallization behavior of the liquid phase during cooling and the resulting slag mineral phases are directly related to the consolidation strength of the pellets. In other words, changes in the high-temperature equilibrium liquid phase can significantly influence the mineralogical characteristics of the solidified slag phase after cooling. To identify the actual mineral composition of the slag phase in roasted pellets with different basicity and clarify its relationship with compressive strength, X-ray diffraction (XRD) analysis was conducted on the roasted pellets. This analysis was intended to further explore the underlying cause of strength deterioration at higher basicity from the perspective of phase structure.

As shown in Figure 5, the XRD patterns of pellets with different basicity all exhibit distinct diffraction peaks corresponding to iron oxides. Fe_2O_3 is the dominant crystalline phase, accompanied by a small amount of Fe_3O_4. This indicates that, after oxidative induration at 1250 °C, the main mineral phases in the pellets remain iron oxides. As the basicity increased from $R = 1.0$ to $R = 1.4$, no strong diffraction peaks corresponding to slag minerals such as calcium silicates, magnesium silicates, or calcium ferrites were observed. This suggests that these slag or bonding phases did not exist in the pellets as abundant, highly crystalline phases. Instead, the slag phase may mainly be distributed among iron oxide particles in the form of glassy or poorly crystalline phases. From the perspective of consolidation behavior, iron oxides remain the dominant phases in pellets with different basicity. Therefore, the decrease in compressive strength with increasing basicity is unlikely to be caused by a fundamental transformation of the major crystalline phases. Instead, it may be more closely related to changes in the interconnection state of iron oxide grains, pore structure, and the composition and distribution of microscale slag phases. Poorly crystalline slag phases may significantly affect pellet consolidation strength by altering the bonding interfaces between particles and the morphology of pores.

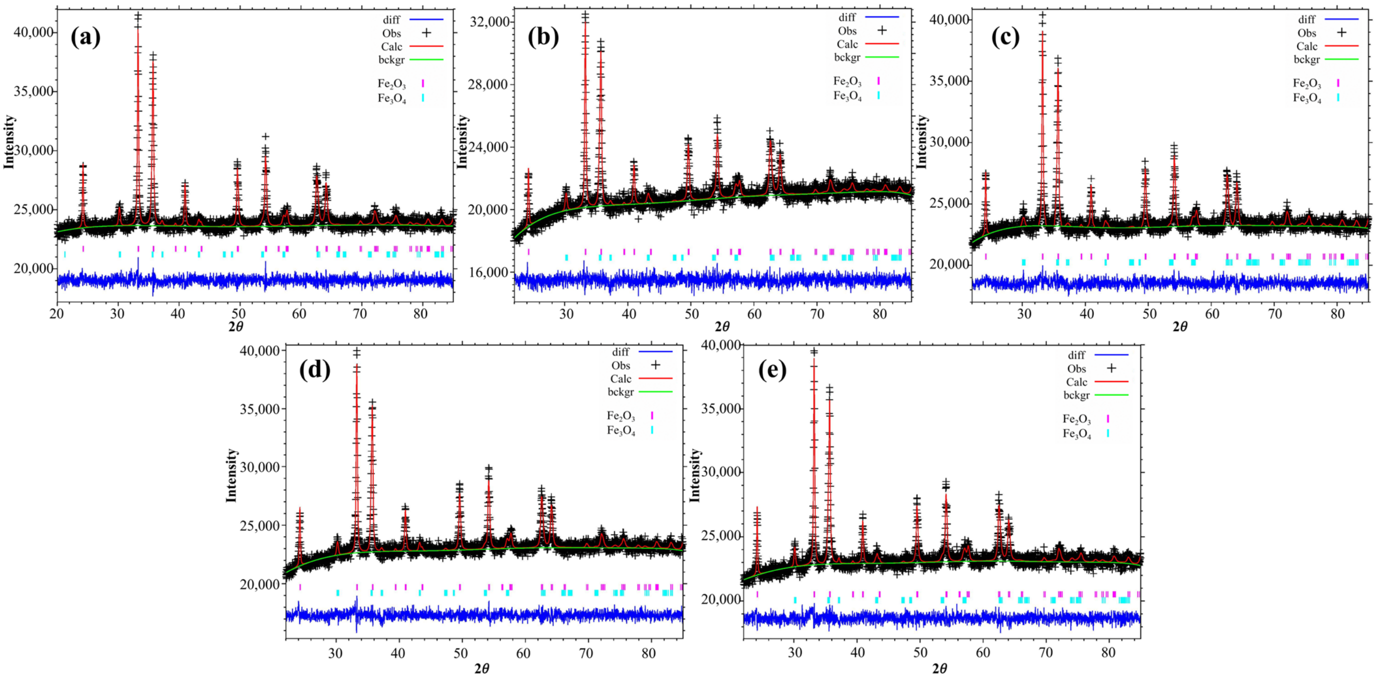

Figure 5. XRD patterns of Mg-bearing medium silica fluxed pellets with different basicity: (**a**) R = 1.0; (**b**) R = 1.1; (**c**) R = 1.2; (**d**) R = 1.3; (**e**) R = 1.4.

Subsequently, to further reveal the mechanism responsible for the decrease in pellet compressive strength with increasing basicity, the microstructures of roasted pellets with different basicity (R = 1.0–1.4) were characterized by scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS).

Figure 6 shows the SEM-EDS elemental mapping results of the pellet with a basicity of R = 1.1. Fe and O are mainly distributed in the bright iron oxide regions, indicating that hematite remains the dominant phase in the pellet. In contrast, Ca and Si are primarily enriched in the gray regions between iron oxide particles, suggesting that CaO reacted with SiO_2 during induration to form calcium-bearing silicate slag phases. These phases are mainly distributed as local networks among iron oxide particles, indicating that an appropriate addition of calcium-bearing flux promotes the formation of interparticle bonding phases and participates in pellet consolidation.

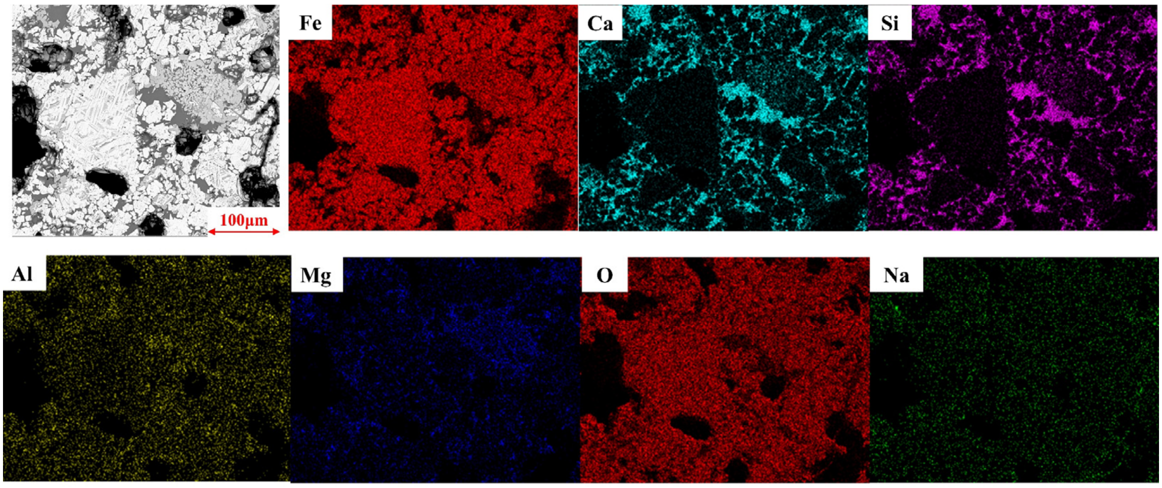

Figure 6. SEM-EDS elemental mapping of Mg-bearing medium-high silica fluxed pellet at R = 1.1.

In addition, Al shows a distribution similar to that of Si and Ca in some regions, suggesting that Al_2O_3 may enter the silicate slag phase and form a composite slag phase. Mg is relatively dispersed and no obvious independent Mg-rich regions are observed, indicating that Mg is likely incorporated into silicate phases, iron oxide phases, or minor Mg-bearing composite phases in a solid-solution or dispersed form, rather than forming abundant independent Mg-rich minerals.

To quantitatively characterize the effect of basicity on slag phase composition, EDS spot analysis was further performed on representative gray slag regions in pellets with different basicity based on the SEM-EDS mapping observations. By comparing the distribution characteristics of Fe, Ca, and Si in the slag phases, the composition of bonding phases formed after liquid phase solidification and their evolution with increasing basicity were further clarified. The EDS results of pellets with different basicity are shown in Figure 7.

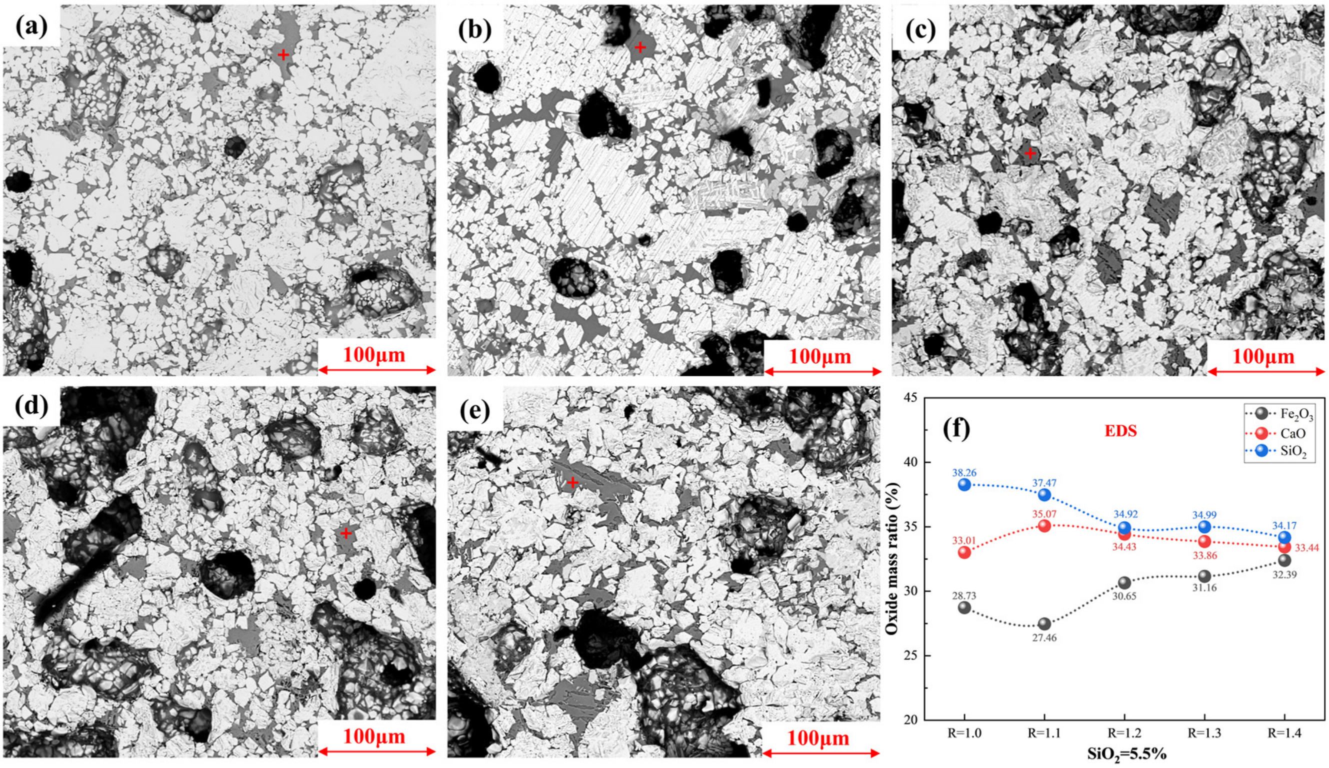

Figure 7. SEM-EDS spot analysis of representative slag phase regions in Mg-bearing medium-high silica fluxed pellets with different basicity: (**a**) R = 1.0; (**b**) R = 1.1; (**c**) R = 1.2; (**d**) R = 1.3; (**e**) R = 1.4; and (**f**) main oxide compositions of the slag phase regions.

The SEM-EDS spot analysis of the slag regions in pellets with different basicity indicates that the slag phase is mainly composed of Fe_2O_3, CaO, and SiO_2. As the basicity increased from R = 1.0 to R = 1.4, the Fe_2O_3 content in the slag phase generally increased from 28.73% to 32.39%, while the SiO_2 content decreased from 38.26% to 34.17%. In contrast, the CaO content remained relatively stable within the range of 33–35%, showing only minor variation. These results suggest that, with increasing basicity, the composition of the solidified slag phase gradually evolved from a relatively Si-rich calcium–iron silicate slag to a Fe-rich calcium–iron silicate slag.

Compared with the liquid phase composition calculated by FactSage at 1250 °C, the EDS results show a similar variation trend: the Fe_2O_3 content increases with increasing basicity, whereas the SiO_2 content decreases. However, clear differences exist between the experimental and calculated results, particularly at higher basicity. This discrepancy is mainly attributed to the different objects represented by the two methods. FactSage calculations reflect the composition of the high-temperature equilibrium liquid phase, whereas EDS analysis measures the composition of the solidified slag phase after cooling. During cooling, Fe in the liquid phase may re-precipitate as iron oxides, calcium ferrites, or Mg-bearing iron oxide phases, resulting in a lower Fe_2O_3 content and a relatively higher SiO_2 content in the residual slag phase.

With increasing basicity, some slag phases exhibit more pronounced aggregation between iron oxide particles. For pellet consolidation, an appropriate amount of uniformly distributed slag phase is beneficial for interparticle bonding. However, excessive continuity or local enrichment of the slag phase may reduce the direct contact between iron oxide particles and alter the continuity of the iron oxide-slag framework within the pellets. It is also noteworthy that, with increasing basicity, bright iron oxide crystals with relatively regular geometries become more abundant within the gray slag regions. This indicates that, under high-basicity conditions, the Fe-bearing liquid phase undergoes obvious precipitation of iron oxide phases during cooling. This observation is consistent with the increase in Fe_2O_3 content in the liquid phase predicted by thermodynamic calculations and the overall increase in Fe_2O_3 content in the slag phase measured by EDS. However, these precipitated iron oxide grains are mainly distributed within the slag regions or interparticle gaps, rather than forming a continuous hematite intergrowth skeleton. As a result, the compressive strength of the pellets decreases continuously with increasing basicity.

3.4. Effect of Basicity on the Pore Structure of Mg-Bearing Fluxed Pellets

As can be seen from the microstructural images of pellets with different basicity in Figure 8, the pore structure of the pellets underwent pronounced evolution with increasing basicity. At a basicity of 1.0, the pores were mainly composed of dispersed fine and medium-sized pores, with relatively weak interconnection. The iron oxide matrix and slag phase maintained good continuity, indicating that the pellets still possessed a relatively intact internal framework. As the basicity increased further, the number of large irregular pores, as highlighted in the red-marked regions, increased markedly. The pore morphology gradually changed from relatively rounded shapes to irregular, elongated, and aggregated forms, and some pores showed clear tendencies toward coalescence and interconnection. In particular, under high-basicity conditions, the pore boundaries became more tortuous, and locally large, interconnected pore clusters were formed, leading to a pronounced decline in the structural uniformity of the pellets.

The evolution of pore structure is closely related to liquid phase formation within the pellets at high temperature. For Mg-bearing medium-high silica fluxed pellets with a SiO_2 content of 5.5%, increasing basicity alters the composition, viscosity, and fluidity of the liquid phase in the calcium–iron silicate system. With increasing CaO content, the liquid phase viscosity decreases, enhancing the migration and spreading ability of the liquid phase within the pellets. An appropriate amount of liquid phase is beneficial for filling interparticle pores and promoting bonding between iron oxide particles. However, when the basicity is excessively high, the low-viscosity liquid phase tends to become locally enriched, causing originally dispersed fine pores to gradually evolve into coarse irregular pores. Pore coarsening directly weakens the compressive strength of pellets. On the one hand, large and connected pores reduce the structural integrity of the pellets. On the other hand, the edges of irregular pores can act as stress concentration sites, promoting crack initiation and propagation. In addition, pore coarsening is often accompanied by local enrichment of the slag phase and a decrease in the degree of hematite intergrowth, thereby reducing the overall structural stability of the pellets.

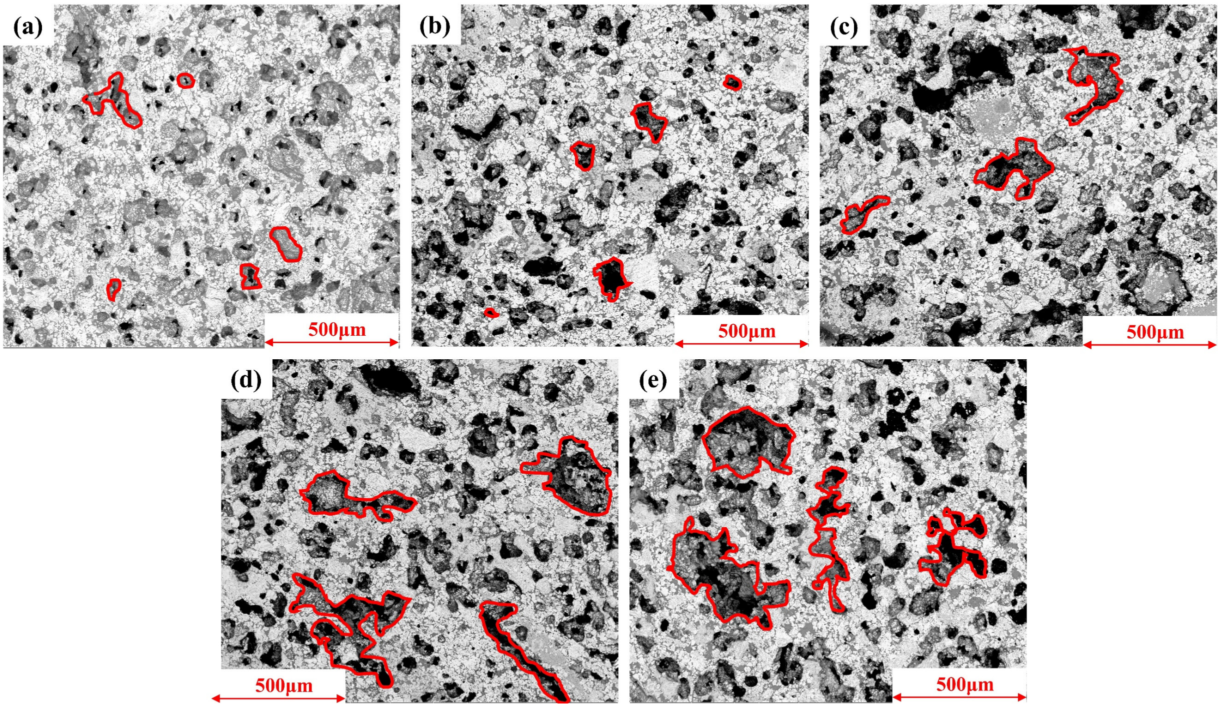

Figure 8. Evolution of pore structure in Mg-bearing medium-high silica fluxed pellets with different basicity: (**a**) R = 1.0; (**b**) R = 1.1; (**c**) R = 1.2; (**d**) R = 1.3; and (**e**) R = 1.4.

Combined with the compressive strength results, the continuous decrease in pellet strength with increasing basicity is consistent with the increase in pore number, enlargement of pore size, irregularization of pore morphology, and enhanced pore connectivity observed in Figure 8. Therefore, in the Mg-bearing medium-high silica fluxed pellet system, when the basicity exceeds 1.0, the strength deterioration caused by further increasing basicity is not due to insufficient liquid phase formation. Instead, the deterioration of pore structure induced by changes in liquid phase properties at high basicity is one of the key reasons for the decrease in strength. Under high-basicity conditions, the liquid phase content increases, its fluidity is enhanced, and its reactivity with iron oxides becomes stronger. The migration and local enrichment of excessive or low-viscosity liquid phase can induce pore coarsening, non-uniform slag network formation, and disruption of the hematite intergrowth skeleton, ultimately leading to a decrease in pellet compressive strength. Therefore, from the perspective of pore structure, the increase in pore number, enlargement of pore size, and local pore interconnection caused by increasing basicity are important factors responsible for the deterioration in compressive strength of Mg-bearing medium-high silica fluxed pellets.

In previous studies where an optimum basicity was reported [24,25], the basicity range usually covered low to medium basicity levels. In such cases, increasing the basicity from a low level can promote the formation of an appropriate liquid phase or bonding phase, thereby improving pellet strength. However, the present study focuses on a relatively high basicity range of R = 1.0–1.4. Within this range, the pellet system is already in a relatively high-basicity state. Further increasing the basicity changes the liquid phase from a relatively SiO_2-rich calcium–iron silicate system to a $Fe_2O_3^-$ and CaO-rich low-viscosity liquid phase. This promotes liquid-phase migration, local slag enrichment, pore coarsening, and the disruption of the continuous hematite skeleton. Therefore, the Mg-bearing medium-silica fluxed pellets in this study exhibited a continuous decrease in compressive strength with increasing basicity. It should be noted that this study mainly focuses on the consolidation behavior, liquid phase formation, phase evolution, and pore structure of

Mg-bearing medium-silica fluxed pellets. Heavy metals and other trace elements were not systematically analyzed in the present work. Therefore, before industrial application, further investigations on trace-element distribution, environmental compatibility, and compliance with relevant environmental regulations are required.

4. Conclusions

In this study, Mg-bearing medium-silica fluxed pellets with a fixed SiO_2 content of 5.5% were used to systematically investigate the effects of basicity in the range of R = 1.0–1.4 on compressive strength, liquid phase formation behavior, phase composition, slag phase composition, and pore structure evolution. The results show that increasing basicity significantly affects the liquid phase characteristics and microstructural evolution during pellet induration, ultimately altering the consolidation performance of the pellets. The main conclusions are as follows:

(1) Within the investigated high-basicity range, increasing basicity was unfavorable for the cold compressive strength of the pellets. As the basicity increased from R = 1.0 to R = 1.4, the average compressive strength decreased from 2527 N/pellet to 2079 N/pellet. This trend differs from the optimum-basicity behavior reported in some previous studies, mainly because the present work focuses on a higher basicity range. In this range, the pellet system is already in a relatively high-basicity state, and further increasing basicity tends to deteriorate the consolidation structure rather than improve bonding.

(2) FactSage thermodynamic calculations showed that the liquid phase content at 1250 °C first decreased from 2.66% at R = 1.0 to 1.30% at R = 1.1, and then increased to 7.38% at R = 1.4. Meanwhile, the liquid phase composition gradually changed from a relatively SiO_2-rich calcium–iron silicate system to a $Fe_2O_3^-$ and CaO-rich low-viscosity liquid phase. Therefore, the decrease in compressive strength was not controlled only by the amount of liquid phase, but was also closely associated with the composition, viscosity, and migration behavior of the liquid phase.

(3) XRD analysis showed that Fe_2O_3 was the dominant phase in pellets with different basicity, accompanied by a small amount of Fe_3O_4. No distinct diffraction peaks corresponding to highly crystalline slag minerals, such as calcium–iron silicates, magnesium silicates, or calcium ferrites, were detected, indicating that the slag or bonding phases in the pellets mainly existed between iron oxide particles in poorly crystalline or glassy forms. SEM-EDS spot analysis further revealed that the slag phases in pellets with different basicity were mainly Fe-Ca-Si-bearing composite slag phases. With increasing basicity, the Fe_2O_3 content in the slag phase generally increased, while the SiO_2 content decreased, and the CaO content changed only slightly. This suggests that the composition of the solidified slag phase gradually transformed from a relatively Si-rich calcium silicate-type slag to a composite slag phase with higher Fe content.

(4) Microstructural observations showed that, with increasing basicity, the number and size of pores inside the pellets increased, and the pore morphology gradually evolved from dispersed fine pores to irregular large pores and locally connected pores. Meanwhile, the distribution range of the slag phase expanded, accompanied by local continuity and enrichment. The non-uniform distribution of the slag network, together with the disruption of the hematite intergrowth skeleton, contributed to the decrease in pellet strength.

(5) The decrease in the strength of Mg-bearing medium-high silica fluxed pellets with increasing basicity was mainly associated with the transformation of liquid phase composition, the increased formation of low-viscosity liquid phase, the non-uniform distribution of slag phase, the coarsening of pore structure, and the reduced continuity

of the iron oxide skeleton at higher basicity. Therefore, for Mg-bearing medium-high silica fluxed pellets, excessive basicity should be avoided to maintain a favorable consolidation structure and cold compressive strength.

Author Contributions: Conceptualization, methodology, investigation, formal analysis, visualization, writing—original draft preparation, H.C.; methodology, resources, writing—review and editing, supervision, project administration, J.Z.; methodology, validation, resources, writing—review and editing, project administration, funding acquisition, Y.W.; investigation, data curation, formal analysis, writing—review and editing, J.H.; investigation, data curation, validation, visualization, writing—review and editing, R.D.; conceptualization, methodology, validation, resources, writing—review and editing, supervision, project administration, funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 52574368), the National Youth Talent Support Program (Grant No. GJRC2023008), the Young Elite Scientists Sponsorship Program by CAST (Grant No. YESS20230029), and the National Natural Science Foundation of China (Grant No. 52374319).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: Author Haoyu Cai was employed by the company Beijing Jianlong Heavy Industry Group Co., Ltd. Authors Jixiang Han and Rui Deng were employed by the company China Sinosteel Equipment and Engineering Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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