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Sintering and Smelting Property Investigations of Ludwigite

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Abstract: In this paper, orthogonal experiments are designed to study the sintering and smelting characteristics of the ludwigite ore. The predominant influencing factors of the optimal ratio, basicity and carbon content on different single sintering indexes, including the vertical sintering speed, yield rate, drum strength and low-temperature reduction pulverization index, are firstly explored by the range analysis method, and the main influencing factors on comprehensive indexes are obtained by a weighted scoring method based on different single index investigation. Considering the sintering characteristics, the primary and secondary influencing factors are: ordinary ore ratio, carbon content and basicity, and the optimal ore blending scheme is: basicity 1.7, ordinary ore blending ratio 60% and carbon content 5%. In terms of the smelting characteristics, the research obtains the order of the influencing factors on the softening start temperature, softening end temperature, softening zone, smelting start temperature, dripping temperature, smelting-dripping zone, maximum pressure difference and gas permeability index of the ludwigite sinters by simply considering various single smelting indexes. On this basis, considering the comprehensive softening-melting-dripping characteristics, the primary and secondary influencing factors are: carbon content, ordinary ore ratio and basicity, and the optimal ore blending scheme is: basicity 1.9, ordinary ore blending ratio 60% and a carbon content of 5.5%. Comprehensively, considering the sintering and smelting property of the ludwigite ore, the primary and secondary influencing factors are: carbon content, ordinary ore ratio and basicity, and the optimal ore blending scheme is: basicity 1.9, ordinary ore blending ratio 60% and a carbon content of 5.5%.

Keywords: ludwigite; sintering; smelting

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Citation: Cheng, G.; Liu, X.; Yang, H.; Xue, X.; Li, L. Sintering and Smelting Property Investigations of Ludwigite. *Processes* **2022**, *10*, 159. https://doi.org/10.3390/pr10010159

Academic Editor: Bipro R. Dhar

Received: 16 November 2021
Accepted: 11 January 2022
Published: 13 January 2022

1. Introduction

Ludwigite iron ore is a multi-element, symbiotic iron ore containing mainly iron, boron and magnesium elements and containing aluminum, calcium, chromium and radioactive uranium. It has a high comprehensive utilization value and an important strategic position [1–6]. Boron resources are widely distributed worldwide with abundant reserves, but it is mainly concentrated in a few countries. It is estimated that there are 1.2 billion tons in the world [7], of which there are about 24 million tons (accounting for B_2O_3) in China. Wengquangou, Fengcheng in Liaoning, is a large ludwigite resource base, accounting for about 60% of the country's total reserves, where there are also small amounts of exhausted szaibelyite resources. The salt-lake-type boron ore resources in Qinghai and Tibet contain 33% of the country's boron resources [8,9]. Ludwigite is not only an important iron ore resource in China's steel industry but also an important resource in China's non-ferrous metal industry.

Ludwigite, as a resource, makes up the main body of boron resource development and utilization in China, but the grade is low (average B_2O_3: 7–8%). Additionally, the mineral composition is complex, with magnetite, szaibelyite, taxoite, etc., and the crystal size is fine and uneven, contributing to the difficulty of mineral separation and smelting. In order to solve the problem of processing and utilization of ludwigite ore, previous workers have carried out research on the comprehensive utilization of ludwigite ore in Fengcheng, Liaoning province, since 1976, and have made breakthroughs in conventional separation, wet separation and pyrometallurgy separation, forming the principal process as shown in Figure 1. For the utilization of boron-bearing iron concentrate, on the one hand, a great deal of research work has been carried out on the efficient recovery of boron as a chemical product, including the pre-reduction electric furnace melting method, granular iron method, reduction-magnetic separation method and other representative technologies [10–13]. On the other hand, the traditional method applies a boron-bearing additive to improve the metallurgical properties of sinters and pellets [14]. However, large-scale utilization in sintering or pelletizing and further application in the blast furnace are scarcely researched in previous studies as some problems exist in this process that limit industrial application, such as low capacity, high coke ratio, severe brasque erosion and low activity of the boron-rich slag [15–19]. Thus, it is necessary to fill in the blanks of sintering and pelletizing systematic studies.

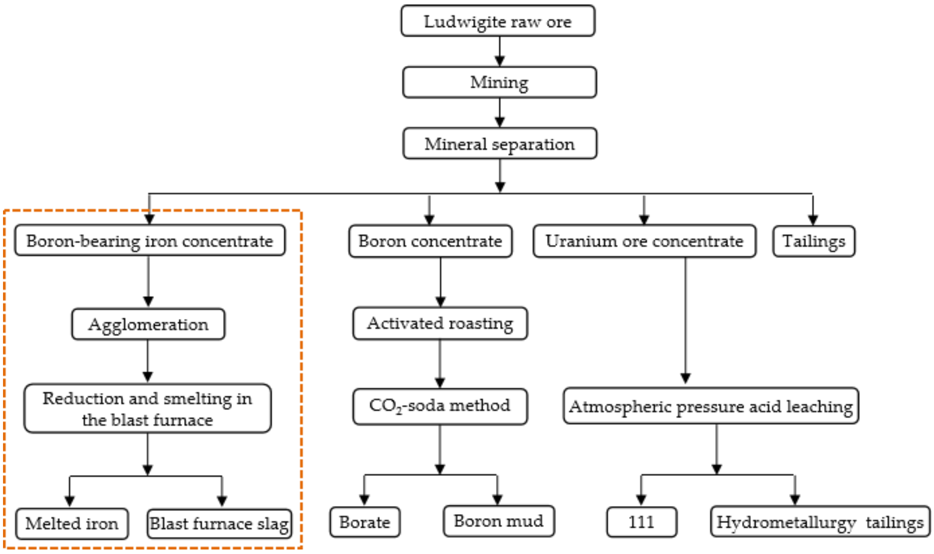

Figure 1. Present, predominantly utilized route of ludwigite ore.

In this paper, the sintering characteristics of ludwigite ore are firstly studied, and the feasibility of using ludwigite ore in the blast furnace is further explored. The research results can provide reference for efficient utilization of ludwigite ore on a large scale.

2. Experimental Materials and Methods

2.1. Experimental Materials

The ludwigite ore studied in this paper was taken from Fengcheng, Liaoning province, and was used for sintering experiments with ordinary ore powder, returned sinter below 5 mm, flux (quicklime, etc.) and coke powder. The chemical composition of raw materials is shown in Table 1, in which TFe represents total Fe content, and VM represents volatile matter. The chemical composition of the materials was determined via X-ray fluorescence (XRF, ZSXPrimus II; Rigaku, Japan) and inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Optima 8300DV; PerkinElmer, Waltham, MA, USA).

2.2. Experimental Methods

The sintering experiment was carried out by adopting a large sintering cup of 100 kg level, and the sintering experimental conditions are shown in Table 2. The flow chart of laboratory sinter production is shown in Figure 2.

Table 1. Chemical composition of sintering materials/wt%.

Item	TFe	CaO	MgO	SiO_2	Al_2O_3	TiO_2	V_2O_5	P	Cr_2O_3	B_2O_3	VM	C Fix	$CaCO_3$
Ludwigite	51.47	0.32	12.65	5.33	0.36			0.016	0.81	6.34			
Ordinary ore	67.67	0.075	0.3	4.06	0.73			0.02	0				
Returned sinter below 5 mm	47.24	13.56	2.42	5.89	2.19	5.23	0.53	0.02	0.34				
Quicklime		60.8	2.87	3.42	1.11								12.35
Coke		3.27	0.14	5.5	3.77			0.02			76.90	0.559	

Table 2. Cold preparation, prepelletization stage and sintering parameters.

Parameter	Index	Parameter	Index
Material height	700 mm	Sintering cup diameter	320 mm
Ignition negative pressure	8.0 kPa	Ventilation negative Pressure	10.0 kPa
Ignition temperature	1050 °C	Ignition time	2.0 min
Carbon content	4.5~5.5%	Mixture moisture	8.0 ± 0.1%
Percent of return sinter below 5 mm	15.00%	Thickness of base material	30 mm
Basicity	1.7~2.1	Granulation time	10 min

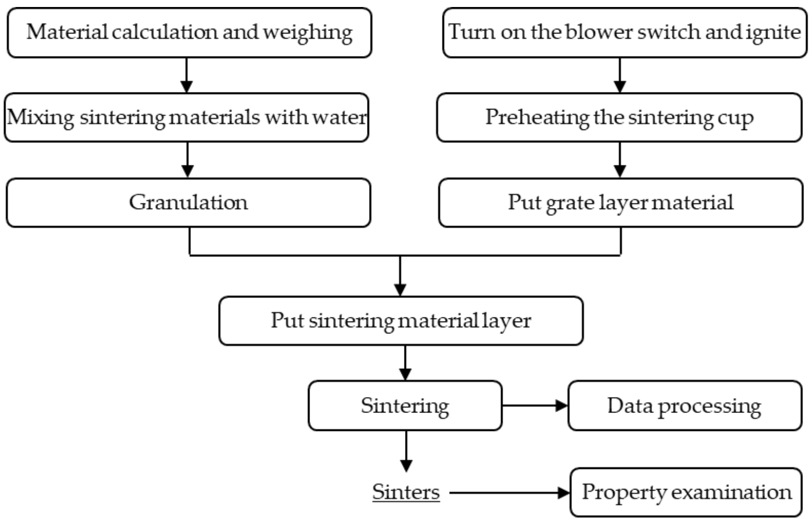

Figure 2. Flow chart of laboratory sinter production.

Orthogonal experimental research method was used to design the sintering and ore blending scheme of ludwigite ore. Three factors were selected, namely: basicity, carbon content and ordinary ore ratio. Three levels were chosen for each factor. According to the three factors and three levels, the orthogonal experiment table was established (Table 3), and there were 9 sets of ore blending experiments. The three-factor, three-level, orthogonal experiment selected the L_9 (3^4) orthogonal experiment table, as shown in Table 4. In the experiment, the added amount of returned sinter below 5 mm in the control mixture was constant. The experiment designed nine groups of ore blending, and the blending amounts of raw materials are listed in Table 5.

Table 3. Setting of sinter cup test factor and level.

Level	Factor		
	A (Basicity/-)	C (Ordinary Ore Ratio/%)	B (Carbon Content/%)
I	1.7	0	4.5
II	1.9	30	5.0
III	2.1	60	5.5

Table 4. Orthogonal experiment scheme of L_9 (3^4).

Item	1	2	3	4	5	6	7	8	9
Basicity	1.7	1.7	1.7	1.9	1.9	1.9	2.1	2.1	2.1
Ordinary ore ratio	0	30%	60%	0	30%	60%	0	30%	60%
Carbon content	4.5%	5%	5.5%	5%	5.5%	4.5%	5.5%	4.5%	5%

Table 5. Raw material adding scheme/wt%.

Item	1	2	3	4	5	6	7	8	9
Ludwigite	73.35	44.2	15.1	71.6	42.7	13.7	69.9	41	12.3
Ordinary ore	0	30	60	0	30	60	0	30	60
Carbon content	4.5	5	5.5	5	5.5	4.5	5.5	4.5	5
Returned sinter below 5 mm	15	15	15	15	15	15	15	15	15
Quicklime	11.65	10.8	9.9	13.4	12.3	11.3	15.1	14	12.7
Total	104.5	105	105.5	105.5	104.5	105	105	105.5	104.5
Basicity	1.7	1.7	1.7	1.9	1.9	1.9	2.1	2.1	2.1

The smelting was carried out by adopting a self-designed RDL-2000A ore softening-melting-dripping tester, and the schematic diagram of the equipment is shown in Figure 3, together with the temperature and gas atmosphere regime in Table 6. The size of the graphite crucible used in the experiment was: the inner diameter was 75 mm; the inner height was 160 mm; the bottom hole diameter was 10 mm. During the measurement of the softening-melting-dripping experiment, the heating rate, the amount of reducing gas and the load were all simulated in actual blast furnace production conditions. During the measurement, the equipment recorded the softening start temperature (T_4), softening temperature (T_{40}) and softening zone (T_{40}-T_4) of different sinters, in which T_4 and T_{40} are the temperatures that the shrinkage ratio of the raw sinter layer reaches at 4% and 40%, respectively. The shrinkage rate was calculated based on the material layer displacement. The equipment also recorded the temperature point when the instantaneous pressure difference was 0.8 kPa as T_s and recorded the temperature point when the mass of the drop was 5 g as T_d. (T_s-T_4) and (T_d-T_s) represent the melting interval and melting-dripping zone, respectively. The specific experimental steps were the same as previous study [20].

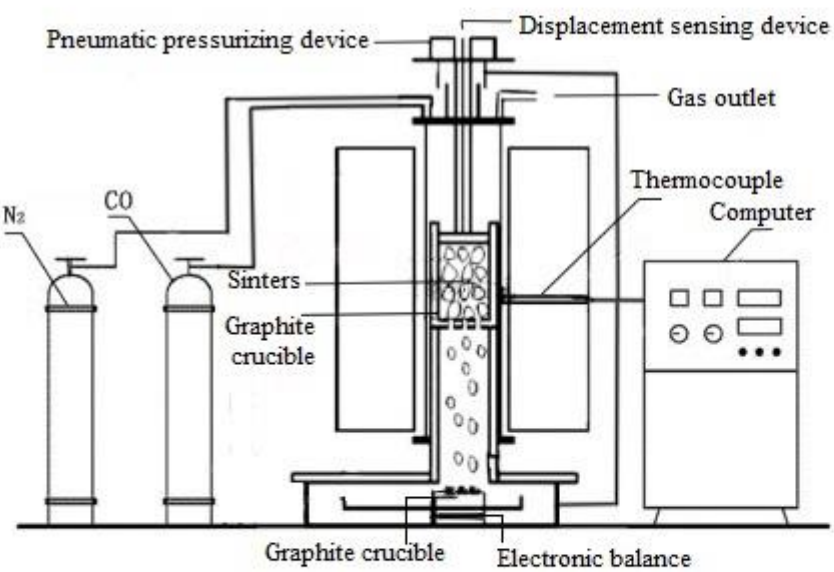

Figure 3. Schematic diagram of softening-melting-dripping tester.

Table 6. Experimental conditions for softening-melting-dripping properties.

Temperature/°C	Room Temperature→200	200→500	500→900	900→1020	1020→T_d
Temperature increasing rate/°C·min	10	10	10	3	5
Gas atmosphere	-	N_2, 5 L/min	N_2, 3.5 L/min CO, 1.5 L/min	N_2, 3.5 L/min CO, 1.5 L/min	N_2, 3.5 L/min CO, 1.5 L/min

3. Results and Discussion

3.1. Sintering Properties

Table 7 exhibits the chemical composition of the ludwigite sinters.

Table 7. Chemical composition of ludwigite sinters/wt%.

Item	TFe	B_2O_3	CaO	SiO_2	MgO	Al_2O_3	MnO
1	48.90	5.57	10.55	7.47	9.29	1.00	0.74
2	47.65	3.68	12.24	7.94	9.01	1.67	0.60
3	51.77	1.82	9.93	10.04	3.09	1.70	0.77
4	48.85	5.46	11.50	8.21	8.65	0.86	0.53
5	52.91	3.63	8.85	10.01	3.04	1.41	0.62
6	50.38	1.73	10.70	8.53	6.38	1.20	0.45
7	50.92	5.36	10.86	8.73	5.25	1.13	0.72
8	51.59	3.36	10.98	9.75	3.14	1.27	0.66
9	51.12	1.68	9.49	8.76	6.48	1.08	0.62

3.1.1. Cold Metallurgical Properties

In the sintering process, the speed at which the sintered layer moves down per unit of time is called the vertical sintering speed (VSS). In the actual sintering process, with the gradual progress of physical and chemical reactions, the vertical sintering speed is constantly changing. It is generally expressed by the average speed value obtained by dividing the thickness of the sintering mixture layer by the sintering time. The vertical sintering speed of ludwigite agglomeration mixture is shown in Table 8. According to the results of the vertical sintering speed of ludwigite ore, the influencing factors were analyzed by range. According to the range analysis, from large to small, the order of influence on the vertical sintering speed of ludwigite ore is: basicity, carbon content, ordinary ore ratio. The optimal ore blending scheme that simply considers the vertical sintering speed is: basicity 2.1, ordinary ore blending ratio 30% and carbon content 5%.

Yield rate (YR) is calculated according to the following Equation (1).

$$\eta = \frac{q}{Q} \times 100\% \tag{1}$$

In the equation, η—yield rate, %; q—mass of the part with a particle size ≥5 mm after sintering, kg; Q—total mass of sintered ore, kg.

According to the yield rate results of ludwigite sintered ore, the influencing factors were analyzed by range, as shown in Table 8. According to the range analysis, from large to small, the order of influence on ludwigite sinter yield rate is: ordinary ore ratio, carbon content, basicity. The optimal ore blending scheme that simply considers the yield rate is: basicity 1.9, ordinary ore blending ratio 60% and carbon content 5.5%.

The drum index obtained by the drum experiment is a measurement of the impact resistance and wear resistance of the sinter at room temperature. According to the testing standard of GB/T8029-1987, the sinter drum strength test was carried out. After the sinter was crushed and screened, according to the mass percentage of each particle size level, three particle sizes of 25–40 mm, 16–25 mm and 10–16 mm were correspondingly taken out for sintered ore samples. A total of 0.75 kg sinters were put into the drum and were continuously rotated for 200 r at a speed of (25 ± 1) r/min. The samples were taken out at the end of the drum and classified by mechanical shaker. The drum strength (T) was calculated with the masses of >6.3 mm and <6.3 mm grain fractions, respectively. The calculation Equation (2) is as follows:

$$T = (>6.3 \text{ mm particle mass/total mass of sample entering drum}) \times 100\% \quad (2)$$

According to the results of the drum strength (T) of the ludwigite sintered ore, the influencing factors were analyzed by range, as shown in Table 8. According to the range analysis, the order of influences on the drum strength (T) of ludwigite sinters from large to small is: carbon content, ordinary ore ratio and basicity. The optimal ore blending scheme that simply considers the drum strength (T) is: basicity 2.1, ordinary ore blending ratio 60% and carbon content 5%.

The abrasion index −0.5 mm of nine ludwigite sintered ores was lower than 1.34%, which is a superb index, so no further analysis was made.

Table 8. Experimental results of cold metallurgical properties and range analysis.

Item	Basicity/-	Ordinary Ore Ratio/%	Carbon Content/%	Vertical Sintering Speed (VSS)/mm·min^{-1}	Yield Rate (YR)/%	Drum Strength (DS)/%
Experiment #1	1.7	0	4.5	15.70	73.32	53.44
Experiment #2	1.7	30	5.0	19.44	75.34	62.21
Experiment #3	1.7	60	5.5	14.58	83.13	62.85
Experiment #4	1.9	0	5.0	21.21	78.36	60.41
Experiment #5	1.9	30	5.5	17.95	77.51	56.50
Experiment #6	1.9	60	4.5	17.5	82.31	59.24
Experiment #7	2.1	0	5.5	18.92	80.88	63.78
Experiment #8	2.1	30	4.5	21.21	73.40	54.21
Experiment #9	2.1	60	5	21.73	75.69	60.97
Average value 1 of VSS	16.573	18.610	18.137			
Average value 2 of VSS	18.887	19.533	20.793			
Average value 3 of VSS	20.620	17.937	17.150			
Range analyzing value of VSS	4.047	1.596	3.643			
Average value 1 of YR	77.263	77.520	76.343			
Average value 2 of YR	79.393	75.417	76.463			
Average value 3 of YR	76.657	80.377	80.507			
Range analyzing value of YR	2.736	4.960	4.164			
Average value 1 of DS	59.500	59.210	55.630			
Average value 2 of DS	58.717	57.640	61.197			
Average value 3 of DS	59.653	61.020	61.043			
Range analyzing value of DS	0.936	3.380	5.567			

3.1.2. Low-Temperature Reduction and Pulverization

According to the standard of GB/T 13242-1991, nine groups of ludwigite sinters were measured by low-temperature reduction and pulverization. The low-temperature reduction pulverization experimental data of ludwigite sinters are shown in Table 9, from which it was found that the low-temperature pulverization index $RDI_{+3.15}$ was at quite a high level of above 97%, indicating that ludwigite sinters have eminent resistance of pulverization compared with ordinary sinters and even vanadium-titanium magnetite sinters [21,22]. The chemical composition of ludwigite sinters after reduction is presented in Table 10.

According to the results of the low-temperature reduction pulverization index of ludwigite ore, the influencing factors were analyzed by range, as shown in Table 11. According to the range analysis, from large to small, the order of influence on the low-temperature reduction pulverization index $RDI_{+3.15}$ of ludwigite sinter is: ordinary ore ratio, basicity and carbon content. The optimal ore blending scheme that simply considers the low-temperature reduction pulverization index $RDI_{+3.15}$ is: basicity 1.7, ordinary ore blending ratio 60% and carbon content 5%.

Table 9. Data of low-temperature reduction and pulverization index.

Item	m_{D0} /g	$m_{+6.3}$ /g	$m_{3.15\sim6.3}$ /g	$m_{0.5\sim3.15}$ /g	$m_{-0.5}$ /g	$RDI_{+6.3}$ /%	$RDI_{+3.15}$ /%	$RDI_{-0.5}$ /%
1	499.59	482.82	5.53	4.34	6.90	96.64	97.75	1.38
2	498.62	485.23	6.97	2.69	3.73	97.31	98.71	0.75
3	498.72	479.01	12.37	3.86	3.48	96.05	98.53	0.70
4	500.32	476.49	13.54	5.68	4.61	95.24	97.95	0.92
5	499.02	464.35	19.59	8.98	6.10	93.05	96.98	1.22
6	501.79	486.83	7.48	2.69	4.79	97.02	98.51	0.95
7	500.32	476.49	13.54	5.68	4.61	95.24	97.95	0.92
8	501.00	488.46	5.19	3.10	4.25	97.50	98.54	0.85
9	497.26	482.03	6.96	3.35	4.92	96.94	98.34	0.99

Table 10. Chemical composition of ludwigite sinters after reduction/wt%.

Item	TFe	B_2O_3	CaO	SiO_2	MgO	Al_2O_3	MnO
1	48.01	6.02	10.70	7.468	11.14	0.71	0.74
2	46.24	4.10	12.58	8.07	11.44	0.76	0.57
3	50.40	2.04	10.00	10.31	5.17	1.29	0.69
4	47.81	5.98	9.92	9.50	9.33	1.51	0.66
5	51.74	4.15	9.20	10.29	3.92	1.35	0.72
6	49.43	2.09	10.53	8.46	8.38	0.89	0.66
7	49.70	5.89	10.89	8.56	7.72	0.95	0.44
8	49.83	3.95	10.93	10.20	5.29	1.36	0.48
9	50.24	2.01	9.38	8.46	8.41	0.91	0.63

Table 11. Range analysis of low-temperature reduction and pulverization index.

Item	Basicity	Ordinary Ore Ratio/%	Carbon Content/%	$RDI_{+3.15}$/%
Experiment #1	1.7	0	4.5	97.75
Experiment #2	1.7	30	5.0	98.71
Experiment #3	1.7	60	5.5	98.53
Experiment #4	1.9	0	5.0	97.95
Experiment #5	1.9	30	5.5	96.98
Experiment #6	1.9	60	4.5	98.51
Experiment #7	2.1	0	5.5	97.95
Experiment #8	2.1	30	4.5	98.54
Experiment #9	2.1	60	5.0	98.34
Average value 1 of $RDI_{+3.15}$	98.883	97.883	98.267	
Average value 2 of $RDI_{+3.15}$	97.813	98.077	98.333	
Average value 3 of $RDI_{+3.15}$	98.277	98.460	97.820	
Range analyzing value of $RDI_{+3.15}$	0.517	0.577	0.513	

3.1.3. Comprehensive Weighted Scoring Method Analysis of Sintering Characteristics

Considering the sintering index, including the vertical sintering speed, yield rate, drum strength and low-temperature reduction pulverization index of the ludwigite sinter, the comprehensive weighted scoring method was adopted to analyze the factor order and the optimal conditions, and the results are shown in Table 12.

The evaluation matrix $X = (x_{ij})$ can be obtained from the orthogonal test results. In order to unify the trend requirements of each index and eliminate the incommensurability of each index, the evaluation matrix X was standardized (Equation (3)). This study required higher index values of the vertical sintering speed, yield rate, drum strength and low-temperature reduction pulverization index. According to the comprehensive weighted scoring method, the larger the score, the better the criterion, and the standardized evaluation matrix Z was obtained (Equation (4)).

$$X = \begin{cases} 15.70 & 73.32 & 53.44 & 97.75 \\ 19.44 & 75.34 & 62.21 & 98.71 \\ 14.58 & 83.13 & 62.85 & 98.53 \\ 21.21 & 78.56 & 60.41 & 97.95 \\ 19.95 & 77.51 & 56.50 & 96.98 \\ 17.50 & 82.31 & 59.24 & 98.51 \\ 18.92 & 80.88 & 63.78 & 97.95 \\ 21.21 & 73.40 & 54.21 & 98.54 \\ 21.73 & 75.69 & 60.97 & 98.34 \end{cases} \quad (3)$$

$$Z = \begin{cases} 15.66 & 0.00 & 0.00 & 44.51 \\ 69.97 & 20.59 & 84.82 & 100.00 \\ 0.00 & 100.00 & 91.01 & 89.60 \\ 92.73 & 51.38 & 67.41 & 56.07 \\ 47.13 & 42.71 & 29.59 & 0.00 \\ 40.84 & 91.64 & 56.09 & 88.44 \\ 60.70 & 77.06 & 100.00 & 56.07 \\ 92.73 & 0.82 & 7.45 & 90.17 \\ 100.00 & 24.16 & 72.82 & 78.61 \end{cases} \quad (4)$$

Among the four indexes in the test, the subjective weights of the indexes obtained by the expert survey method were: the vertical sintering speed α_1 = 0.1, yield rate α_2 = 0.1, drum strength α_3 = 0.3, low-temperature reduction pulverization index α_4 = 0.5, that is, α = (0.1, 0.1, 0.3, 0.5)^T. Secondly, the objective weight of each index obtained by the entropy method was: β = (0.22, 0.37, 0.25, 0.15)^T. Finally, taking the preference coefficient as 0.5, the comprehensive weight of each index was obtained as: w = (0.16, 0.24, 0.28, 0.33)^T. The comprehensive weighted score value (f_i) of the test can be calculated by Equation (5).

$$f_i = \sum_{j=1}^{3} w_j z_{ij} \qquad i = 1, 2, \cdots 16 \quad (5)$$

where w_j is the (j)th comprehensive weight, and the calculation result is shown in Table 12. According to the comprehensive weighted scoring value and the individual index test analysis and evaluation method, the conclusion is shown in Table 12. The primary and secondary factors that affect the sintering characteristics of the ludwigite ore are carbon content, ordinary ore ratio and basicity. Considering the sintering property, the optimal ore blending scheme is: basicity 1.7, ordinary ore blending ratio 60% and carbon content 5.0%.

Table 12. Comprehensive weighted scoring analysis.

Item	Basicity/-	Ordinary Ore Ratio/%	Carbon Content/%	Vertical Sintering Speed (VSS)/mm·min^{-1}	Yield Rate (YR)/%	Drum Strength (DS)/%	$RDI_{+3.15}$/%	Comprehensive Weighted Score f/-
Experiment #1	1.7	0	4.5	15.7	73.32	53.44	97.75	27.80
Experiment #2	1.7	30	5	19.44	75.34	62.21	98.71	63.72
Experiment #3	1.7	60	5.5	14.58	83.13	62.85	98.53	79.96
Experiment #4	1.9	0	5	21.21	78.36	60.41	97.95	56.20
Experiment #5	1.9	30	5.5	17.95	77.51	56.50	96.98	18.33
Experiment #6	1.9	60	4.5	17.5	82.31	59.24	98.51	70.06
Experiment #7	2.1	0	5.5	18.92	80.88	63.78	97.95	73.19
Experiment #8	2.1	30	4.5	21.21	73.40	54.21	98.54	38.90
Experiment #9	2.1	60	5	21.73	75.69	60.97	98.34	55.05
Average value 1	57.160	52.397	45.587	w_1 = 0.16; w_2 = 0.24; w_3 = 0.28; w_4 = 0.33				
Average value 2	48.197	40.317	58.323	Factor order: ordinary ore ratio, carbon content, basicity				
Average value 3	55.713	68.357	57.160	Optimal ore blending scheme: basicity 1.7, ordinary ore ratio 60%, carbon content 5.0%				
Range analyzing value	8.963	28.040	12.734					

3.2. Smelting Property of Ludwigite Sinters

3.2.1. Softening-Melting-Dripping Property

According to T_4, T_{40}, T_s T_d, T_{40}-T_4, T_s-T_4 and T_d-T_s of ludwigite sinters, the influencing factors were analyzed by range, as shown in Table 13. It was found that the overall indicator was better compared with the softening-melting-dripping property of vanadium-titanium magnetite sinters [23]. According to the range analysis, from large to small, the order of influence on the softening start temperature, melting start temperature and dripping temperature of the ludwigite sinter is: ordinary ore ratio, carbon content, basicity. The order of influence on the softening zone and melting-dripping zone is: carbon content, basicity and ordinary ore ratio. The order of influence on the melting interval is: carbon content, ordinary ore ratio and basicity. The optimal ore blending scheme that simply considers the softening start temperature is: basicity 1.9, ordinary ore blending ratio 60% and carbon content 5.5%; the optimal ore blending scheme that simply considers the melting start temperature is: basicity 2.1, ordinary ore blending ratio 60% and carbon content 5.5%. As the values of the dripping temperature, softening zone and melting-dripping zone are required to be as small as possible, the optimal ore blending scheme that simply considers the dripping temperature is: basicity 1.9, ordinary ore blending ratio 30% and carbon content 5.5%. The optimal ore blending scheme that simply considers the softening zone is: basicity 1.9, ordinary ore blending ratio 60% and carbon content 5%; the optimal ore blending scheme that simply considers the melting-dripping zone is: basicity 1.7, ordinary ore blending ratio 60% and carbon content 5.5%.

Table 13. Range analysis of softening and melting temperature zone.

Item	Basicity/-	Ordinary Ore Ratio/%	Carbon Content/%	T_4/°C	T_{40}/°C	T_s/°C	T_d/°C	T_{40}-T_4/°C	T_s-T_4/°C	T_d-T_s/°C
Experiment #1	1.7	0	4.5	606	966	1133	1410	360	527	277
Experiment #2	1.7	30	5	905	1072	1143	1360	167	238	217
Experiment #3	1.7	60	5.5	1032	1127	1186	1325	95	154	139
Experiment #4	1.9	0	5	898	951	1128	1351	53	230	223
Experiment #5	1.9	30	5.5	946	1080	1147	1316	136	201	169
Experiment #6	1.9	60	4.5	910	1072	1154	1378	162	244	224
Experiment #7	2.1	0	5.5	970	997	1216	1365	27	246	149
Experiment #8	2.1	30	4.5	630	970	1120	1339	340	490	219
Experiment #9	2.1	60	5	970	1086	1150	1375	116	180	225
Average value 1 of t_4	847.667	824.667	715.333							
Average value 2 of t_4	918.000	827.000	924.333							
Average value 3 of t_4	856.667	970.667	982.667							
Range analyzing value of t_4	70.333	146.000	87.666							
Average value 1 of t_s	1154.000	1159.000	1135.667							
Average value 2 of t_s	1143.000	1136.667	1144.333							
Average value 3 of t_s	1162.000	1163.333	1183.000							
Range analyzing value of t_s	19.000	26.667	47.333							
Average value 1 of t_d	1365.000	1375.333	1375.667							
Average value 2 of t_d	1348.333	1338.333	1362.000							
Average value 3 of t_d	1359.667	1359.333	1335.333							
Range analyzing value of t_d	16.667	37.000	40.334							
Average value 1 of t_{40}-t_4	207.333	146.667	287.333							
Average value 2 of t_{40}-t_4	117.000	214.333	112.000							
Average value 3 of t_{40}-t_4	161.000	124.333	86.000							
Range analyzing value of t_{40}-t_4	90.333	90.000	201.333							
Average value 1 of t_s-t_4	306.33	334.33	420.33							
Average value 2 of t_s-t_4	225.00	309.67	216.00							
Average value 3 of t_s-t_4	305.33	192.67	200.33							
Range analyzing value of t_s-t_4	81.33	141.66	220.00							
Average value 1 of t_d-t_s	194.333	199.667	223.333							
Average value 2 of t_d-t_s	205.333	201.667	221.667							
Average value 3 of t_d-t_s	197.667	196.000	152.333							
Range analyzing value of t_d-t_s	11.000	5.667	71.000							

3.2.2. Shrinkage Behavior and Gas Permeability

The shrinkage rate of the nine groups of ludwigite sinters in the softening-melting-dripping experiment is shown in Figure 4. It can be seen that, as the temperature rose, the volume of the sintered ludwigite ore first expanded. After reaching the softening temperature, the shrinkage rate curve began to gradually increase, indicating that it was changing from softening state to molten state, and the shrinkage rate increased until the melted iron dropped.

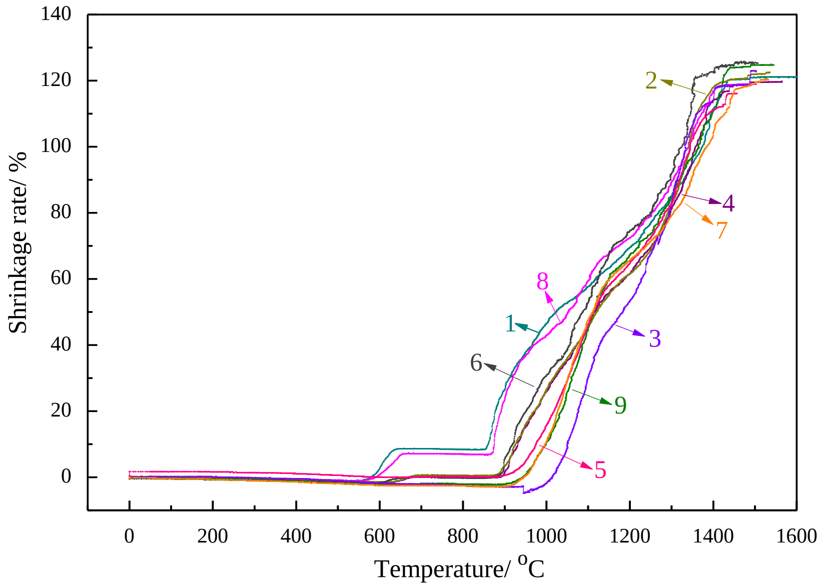

Figure 4. Shrinkage graph of ludwigite sinter.

Figure 5 presents the gas permeability index (S) for the nine groups of ludwigite sinters obtained through the softening-melting-dripping experiments, in which the maximum pressure difference ($\triangle P_{max}$) can be found.

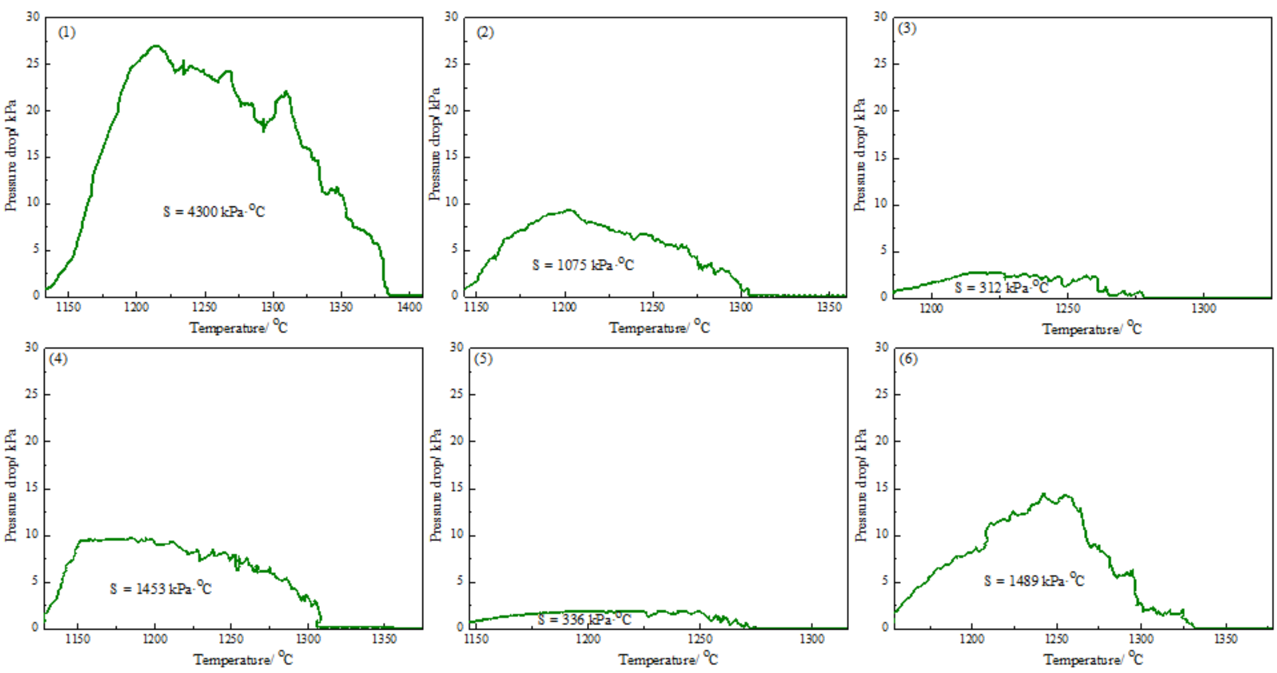

Figure 5. *Cont.*

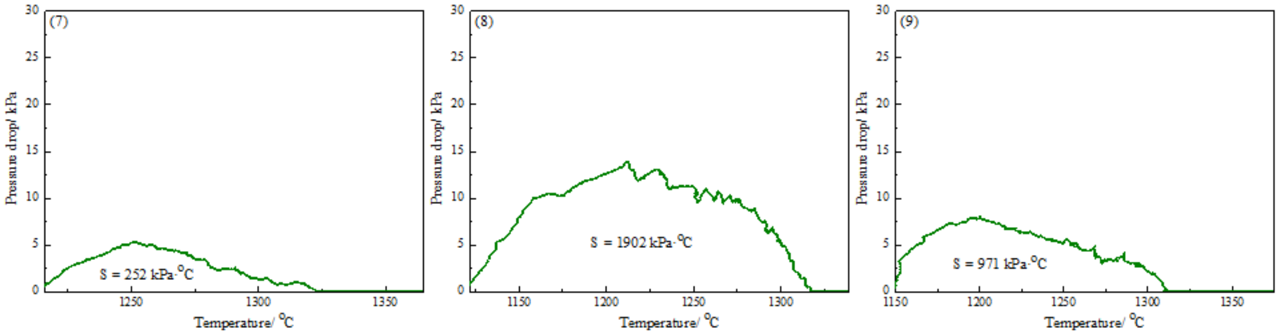

Figure 5. Characteristic number of gas permeability.

According to the results of the maximum pressure difference value and gas permeability index of the ludwigite sinter, the influencing factors were analyzed by range, as shown in Table 14.

Table 14. Range analysis of gas permeability index.

Item	Basicity/-	Ordinary Ore Ratio/%	Carbon Content/%	$\triangle P_{max}$/kPa	S/kPa·°C
Experiment #1	1.7	0	4.5	26.9	4300
Experiment #2	1.7	30	5	9.4	1075
Experiment #3	1.7	60	5.5	2.8	312
Experiment #4	1.9	0	5	9.7	1453
Experiment #5	1.9	30	5.5	2	336
Experiment #6	1.9	60	4.5	14.5	1489
Experiment #7	2.1	0	5.5	5.4	252
Experiment #8	2.1	30	4.5	13.9	1902
Experiment #9	2.1	60	5	8.1	971
Average value 1 of $\triangle P_{max}$	14.000	18.433	12.333		
Average value 1 of $\triangle P_{max}$	8.433	9.067	9.767		
Average value 1 of $\triangle P_{max}$	8.467	3.400	8.800		
Range analyzing value of $\triangle P_{max}$	5.567	15.033	3.533		
Average value 1 of S	2001.667	2563.667	1869.000		
Average value 2 of S	1104.333	1166.333	938.667		
Average value 3 of S	924.000	300.000	1222.333		
Range analyzing value of S	1077.667	2263.667	930.333		

According to the range analysis, from large to small, the order of influences on the maximum pressure difference and the gas permeability index of ludwigite sinter is: ordinary ore ratio, basicity, carbon content. As the maximum pressure difference and the gas permeability index are required to be as small as possible, the optimal ore blending scheme that simply considers the maximum pressure difference is: basicity 1.9, ordinary ore blending ratio 60% and carbon content 5.5%, and the optimal ore blending scheme that simply considers the gas permeability index is: basicity 2.1, ordinary ore ratio 60% and carbon content 5%.

3.2.3. Comprehensive Weighted Scoring Method Analysis of Smelting Property

Similarly, considering the smelting index, including softening start temperature, melting start temperature, dripping start temperature, softening zone, melting-dripping zone, maximum pressure difference and gas permeability index, the comprehensive weighted scoring method was adopted to analyze the factor order and the optimal conditions, and the results are shown in Table 15.

The evaluation matrix $X = (x_{ij})$ can be obtained from the orthogonal test results. In order to unify the trend requirements of each index and eliminate the incommensurability of each index, the evaluation matrix X was standardized (Equation (6)). This study required higher index values of the softening start temperature and melting start temperature and lower index values of dripping temperature, softening zone, melting-dripping zone, maximum pressure difference and gas permeability index. According to the comprehensive weighted scoring method, the larger the score, the better the criterion, and the standardized evaluation matrix Z was obtained (Equation (7)).

Table 15. Comprehensive weighted scoring analysis.

Item	Basicity/-	Ordinary Ore Ratio/%	Carbon Content/%	Comprehensive Weighted Score f/-
Experiment #1	1.7	0	4.5	2.62
Experiment #2	1.7	30	5	51.85
Experiment #3	1.7	60	5.5	84.83
Experiment #4	1.9	0	5	52.89
Experiment #5	1.9	30	5.5	71.57
Experiment #6	1.9	60	4.5	47.69
Experiment #7	2.1	0	5.5	85.00
Experiment #8	2.1	30	4.5	30.95
Experiment #9	2.1	60	5	55.07
Average value 1	46.343	46.837	27.087	w_1 = 0.14; w_2 = 0.10; w_3 = 0.15; w_4 = 0.19; w_5 = 0.13; w_6 = 0.15; w_7 = 0.14
Average value 2	57.383	51.367	53.180	
Average value 3	57.007	62.530	80.467	Factor order: carbon content, ordinary ore ratio, basicity
Range analyzing value of t_4	11.040	15.693	53.380	Optimal ore blending scheme: basicity 1.9, ordinary ore ratio 60%, carbon content 5.5%

Among seven indexes in the test, the subjective weights of the indexes obtained by the expert survey method were: gas permeability index α_1 = 0.2, maximum pressure difference α_2 = 0.1, softening start temperature α_3 = 0.14, melting start temperature α_4 = 0.14, dripping start temperature α_5 = 0.14, softening zone α_6 = 0.14, melting-dripping zone α_7 = 0.14, that is, $\alpha = (0.2, 0.1, 0.14, 0.14, 0.14, 0.14, 0.14)^{\mathrm{T}}$. Secondly, the objective weight of each index obtained by the entropy method was: $\beta = (0.09, 0.10, 0.15, 0.25, 0.12, 0.15, 0.14)^{\mathrm{T}}$. Finally, taking the preference coefficient as 0.5, the comprehensive weight of each index was obtained as: $w = (0.14, 0.10, 0.15, 0.19, 0.13, 0.15, 0.14)^{\mathrm{T}}$. The comprehensive weighted score value of the test can be calculated by Equation (5), and the calculation result is shown in Table 15. According to the comprehensive weighted scoring value and the individual index test analysis and evaluation method, the conclusion is shown in Table 15. The primary and secondary factors that affected the softening-melting-dripping characteristics of the ludwigite sinter are carbon content, ordinary ore ratio and basicity. Comprehensively, considering the smelting property, the optimal ore blending scheme is: basicity 1.9, ordinary ore blending ratio 60% and carbon content 5.5%.

$$X = \left\{ \begin{array}{ccccccc} 4300 & 26.9 & 606 & 1133 & 1410 & 360 & 277 \\ 1075 & 9.4 & 905 & 1143 & 1360 & 167 & 217 \\ 312 & 2.8 & 1032 & 1186 & 1325 & 95 & 139 \\ 1453 & 9.7 & 898 & 1128 & 1351 & 53 & 223 \\ 336 & 2.0 & 946 & 1147 & 1316 & 136 & 169 \\ 1489 & 14.5 & 910 & 1154 & 1378 & 162 & 224 \\ 252 & 5.4 & 970 & 1216 & 1365 & 27 & 149 \\ 1902 & 13.9 & 630 & 1120 & 1339 & 340 & 219 \\ 971 & 8.1 & 970 & 1150 & 1375 & 116 & 225 \end{array} \right. . \quad (6)$$

$$Z = \left\{ \begin{array}{ccccccc} 0.00 & 0.00 & 0.00 & 13.54 & 0.00 & 0.00 & 0.00 \\ 79.67 & 70.28 & 70.19 & 23.96 & 53.19 & 57.96 & 43.48 \\ 98.52 & 96.79 & 100.00 & 68.75 & 90.43 & 79.58 & 100.00 \\ 70.33 & 69.08 & 68.54 & 8.33 & 62.77 & 92.19 & 39.13 \\ 97.92 & 100.00 & 79.81 & 28.13 & 100.00 & 67.27 & 78.26 \\ 69.44 & 49.80 & 71.36 & 35.42 & 34.04 & 59.46 & 38.41 \\ 100.00 & 86.35 & 85.45 & 100.00 & 47.87 & 100.00 & 92.75 \\ 59.24 & 52.21 & 5.63 & 0.00 & 75.53 & 6.01 & 42.03 \\ 82.24 & 75.50 & 85.45 & 32.25 & 37.23 & 73.27 & 37.68 \end{array} \right. \quad (7)$$

3.3. Comprehensive Weighted Scoring Method Analysis of Integrated Metallurgical Properties

Comprehensively, considering the cold metallurgical properties, low-temperature reduction and pulverization properties and softening-melting-dripping characteristics of the ludwigite sinter, the comprehensive weighted scoring method was adopted to analyze the factor order and the optimal conditions, and the results are shown in Table 16.

Table 16. Comprehensive weighted scoring analysis.

Item	Basicity/-	Ordinary Ore Ratio/%	Carbon Content/%	Comprehensive Weighted Score *f*/-
Experiment #1	1.7	0	4.5	8.38
Experiment #2	1.7	30	5	59.86
Experiment #3	1.7	60	5.5	82.12
Experiment #4	1.9	0	5	67.35
Experiment #5	1.9	30	5.5	63.24
Experiment #6	1.9	60	4.5	67.69
Experiment #7	2.1	0	5.5	80.57
Experiment #8	2.1	30	4.5	37.18
Experiment #9	2.1	60	5	60.07
Average value 1	50.120	52.100	37.750	$w_1 = 0.09$, $w_2 = 0.06$, $w_3 = 0.09$, $w_4 = 0.12$, $w_5 = 0.08$, $w_6 = 0.09$,
Average value 2	66.096	53.427	62.427	$w_7 = 0.08$, $w_8 = 0.10$, $w_9 = 0.10$, $w_{10} = 0.11$, $w_{11} = 0.13$
Average value 3	59.273	69.960	75.310	Factor order: carbon content, ordinary ore ratio, basicity
Range analyzing value	15.973	17.860	37.560	Optimal ore blending scheme: basicity 1.9, ordinary ore ratio 60%, carbon content 5.5%

The evaluation matrix $X = (x_{ij})$ can be obtained from the orthogonal test results. In order to unify the trend requirements of each index and eliminate the incommensurability of each index, the evaluation matrix X was standardized (Equation (8)). This study required higher index values of the vertical sintering speed, yield rate, drum strength, low-temperature reduction pulverization index, softening start temperature, melting start temperature and lower gas permeability index values, maximum pressure difference, dripping start temperature, softening zone and melting-dripping zone. According to the comprehensive weighted scoring method, the larger the score, the better the criterion, and the standardized evaluation matrix Z was obtained (Equation (9)).

$$\mathrm{X} = \left\{ \begin{array}{ccccccccccc} 4300 & 26.9 & 606 & 1133 & 1410 & 360 & 277 & 15.70 & 73.32 & 53.44 & 97.75 \\ 1075 & 9.4 & 905 & 1143 & 1360 & 167 & 217 & 19.44 & 75.34 & 62.21 & 98.71 \\ 312 & 2.8 & 1032 & 1186 & 1325 & 95 & 139 & 14.58 & 83.13 & 62.85 & 98.53 \\ 1453 & 9.7 & 898 & 1128 & 1351 & 53 & 223 & 21.21 & 78.56 & 60.41 & 97.95 \\ 336 & 2.0 & 946 & 1147 & 1316 & 136 & 169 & 19.95 & 77.51 & 56.24 & 96.98 \\ 1489 & 14.5 & 910 & 1154 & 1378 & 162 & 224 & 17.50 & 82.31 & 59.24 & 98.51 \\ 252 & 5.4 & 970 & 1216 & 1365 & 27 & 149 & 18.92 & 80.88 & 63.78 & 97.95 \\ 1902 & 13.9 & 630 & 1120 & 1339 & 340 & 219 & 21.21 & 73.40 & 54.21 & 98.54 \\ 971 & 8.1 & 970 & 1150 & 1375 & 116 & 225 & 21.73 & 75.69 & 60.97 & 98.34 \end{array} \right. \quad (8)$$

$$\mathrm{Z} = \left\{ \begin{array}{ccccccccccc} 0.00 & 0.00 & 0.00 & 13.54 & 0.00 & 0.00 & 0.00 & 15.66 & 0.00 & 0.00 & 44.51 \\ 79.67 & 70.28 & 70.19 & 23.96 & 53.19 & 57.96 & 43.48 & 69.97 & 20.59 & 84.82 & 100.00 \\ 98.52 & 96.79 & 100.00 & 68.75 & 90.43 & 79.58 & 100.00 & 0.00 & 100.00 & 91.01 & 89.60 \\ 70.33 & 69.08 & 68.54 & 8.33 & 62.77 & 92.19 & 39.13 & 92.73 & 51.38 & 67.41 & 56.07 \\ 97.92 & 100.00 & 79.81 & 28.13 & 100.00 & 67.27 & 78.26 & 47.13 & 42.71 & 29.59 & 0.00 \\ 69.44 & 49.80 & 71.36 & 35.42 & 34.04 & 59.46 & 38.41 & 40.84 & 91.64 & 56.09 & 88.44 \\ 100.00 & 86.35 & 85.45 & 100.00 & 47.87 & 100.00 & 92.75 & 60.70 & 77.06 & 100.00 & 56.07 \\ 59.24 & 52.21 & 5.63 & 0.00 & 75.53 & 6.01 & 42.03 & 92.73 & 0.82 & 7.45 & 90.17 \\ 82.24 & 75.50 & 85.45 & 32.25 & 37.23 & 73.27 & 37.68 & 100.00 & 24.68 & 72.82 & 78.61 \end{array} \right. \quad (9)$$

Among eleven indexes in the test, the subjective weights of the indexes obtained by the expert survey method were: gas permeability index α_1 = 0.12, maximum pressure difference α_2 = 0.06, softening start temperature α_3 = 0.084, melting start temperature α_4 = 0.084, dripping start temperature α_5 = 0.084, softening zone α_6 = 0.084, melting-dripping zone α_7 = 0.084, vertical sintering speed α_8 = 0.04, yield rate α_9 = 0.04, drum strength α_{10} = 0.12, low temperature reduction pulverization index α_{11} = 0.2, that is, α = (0.12, 0.06, 0.084, 0.084, 0.084, 0.084, 0.084, 0.04, 0.04, 0.12, 0.2)^T. Secondly, the objective weight of each index obtained by the entropy method was: β = (0.05, 0.06, 0.09, 0.15, 0.07, 0.09, 0.08, 0.09, 0.15, 0.10, 0.06)^T. Finally, taking the preference coefficient as 0.5, the comprehensive weight of each index was obtained as: w = (0.09, 0.06, 0.09, 0.12, 0.08, 0.09, 0.08, 0.06, 0.10, 0.11, 0.13)^T. The comprehensive weighted score value of the test can be calculated by Equation (5), and the calculation result is shown in Table 16. According to the comprehensive weighted scoring value and the individual index test analysis and evaluation method, the conclusion is shown in Table 16. The primary and secondary factors that affect the cold metallurgical performance, low temperature reduction pulverization performance and softening-melting-dripping characteristics of the ludwigite sinter are carbon content, ordinary ore ratio and basicity. Comprehensively, considering the sintering and smelting property, the optimal ore blending scheme is: basicity 1.9, ordinary ore blending ratio 60% and carbon content 5.5%.

4. Conclusions

The sintering characteristics of ludwigite ore and smelting properties of ludwigite sinters were investigated in this paper. The main influencing factors were obtained by range analysis method, and the main influencing factors of comprehensive indexes were obtained by weighted scoring method. The conclusions are as follows:

(1) Considering the sintering characteristics of the vertical sintering speed, yield, drum strength and low-temperature reduction pulverization index for ludwigite ore, the primary and secondary influencing factors are: ordinary ore ratio, carbon content and basicity, and the optimal ore blending scheme is: basicity 1.7, ordinary ore blending ratio 60% and carbon content 5%.

(2) Considering the smelting property of the softening start temperature, softening end temperature, softening zone, smelting start temperature, dripping temperature, smelting-dripping zone, maximum pressure difference and gas permeability index for ludwigite sinters, the primary and secondary influencing factors are: the carbon content, ordinary ore blending ratio and the basicity, and the optimal ore blending scheme: basicity 1.9, ordinary ore blending ratio 60% and carbon content 5.5%.

(3) Comprehensively, considering the sintering characteristics and smelting properties of ludwigite sinters, the primary and secondary influencing factors are: carbon content, ordinary ore ratio and basicity, and the optimal ore blending plan is: basicity 1.9, ordinary ore blending ratio 60% and carbon content of 5.5%.

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

Funding: This research was funded by the national key research and development plan of China (grant no. 2020YFC1909803).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare no conflict of interest.

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