minerals

Article

Study on Grinding Additives in Cassiterite–Polymetallic Sulfide Ore Grinding

Jinlin Yang [1,2], Shaojian Ma [1,2,*], Wentao Zhou [3] and Pengyan Zhu [1]

[1] College of Resources, Environment and Materials, Guangxi University, Nanning 530004, China; jlyang523@126.com (J.Y.); 13840541273@163.com (P.Z.)
[2] Guangxi Key Laboratory of Processing for Nonferrous Metallic and Featured Materials, Guangxi University, Nanning 530004, China
[3] College of Chemical and Biological Engineering, Shandong University of Science and Technology, Qingdao 266590, China; neuzhouwentao@163.com
* Correspondence: 1615391004@alu.gxu.edu.cn; Tel.: +86-131-5266-0958

Abstract: To attempt a new approach to improve the grinding of cassiterite–polymetallic sulfide ores while simultaneously reducing cassiterite overgrinding and sulfide undergrinding, this article looked into the effects of grinding chemical additives on the distribution of grinding product size. Six chemicals, namely sodium hexametaphosphate, triethanolamine, ferric sulphate, aluminum chloride, polyaluminum chloride and polyacrylamide, were compared in terms of their influence on the grinding product size distribution. The results showed that the six chemicals changed the distribution results with varying orientations and degrees and that the addition of polyacrylamide achieved the most satisfactory effect by decreasing the production of both coarse and fine size fractions and increasing the production of qualified particles. The effect of the molecular weight of polyacrylamide on the grinding was also discussed. The polyacrylamides with molecular weights of about 3×10^6, 5×10^6, 8×10^6 and 12×10^6 could help to produce less of the coarse size fraction and more of the qualified size fraction, but only the polyacrylamides with molecular weights of 3×10^6 and 5×10^6 produced pronounced changes. Moreover, the polyacrylamides could slightly reduce the production of the fine size fraction. Polyacrylamide with a 5×10^6 molecular weight was better than that with a 3×10^6 molecular weight in aiding the grinding of the discussed ore. It was also found that the aid action of the polyacrylamide with a 5×10^6 molecular weight was related to grinding concentration and that a low grinding concentration of less than 70% solid mass was helpful in exerting its aid action. Using polyacrylamide could shorten the grinding time that is needed to achieve the same, or even improved, product size distribution.

Keywords: grinding; cassiterite–polymetallic sulfide ore; overgrinding; undergrinding; grinding additive

check for updates

Citation: Yang, J.; Ma, S.; Zhou, W.; Zhu, P. Study on Grinding Additives in Cassiterite–Polymetallic Sulfide Ore Grinding. *Minerals* **2022**, *12*, 472. https://doi.org/10.3390/min12040472

Academic Editor: Chiharu Tokoro

Received: 7 March 2022
Accepted: 8 April 2022
Published: 12 April 2022

1. Introduction

Grinding is one of the most important unit operations in mineral processing plants due to its vast capital cost and consumption of energy and materials [1]. However, the two essential tasks for grinding are liberation and size reduction, which means that the grinding product size seriously affects the downstream separation. Thus, the optimization of the grinding operation to achieve the desired product size distribution attracts the attention of mineral processors. The addition of chemicals into the mill is one of the methods that is used to improve the grinding operation, which has been tested and practiced since the 1960s [2–7]. The chemicals that are added into the grinding process are called grinding additives or grinding aids. In addition, the application of grinding aids is mainly adopted in the cement and calcite industry [8–14]. Previous work has shown that using grinding additives can change the hardness of the ground particles or the rheology of the slurry, thereby increasing the breakage rate of particles, mill throughput and the fineness of the grind. Nevertheless, most studies have focused on the enhancement of mill throughput, which is the most effective approach for reducing the total production costs and increasing profits; therefore, it is the most popular approach among mineral processing plants [15–20].

Guangxi, a province in south China, is rich in cassiterite–polymetallic sulfide ore, which contains several important metals, such as tin, lead, zinc, antimony, silver, indium, etc. This type of ore is one of the most important valuable minerals and is an oxide of great brittleness with large specific gravity, which is commonly collected using gravity separation. The polymetallic sulfide ore minerals have large hardness values and a smaller specific gravity and are recovered using froth flotation. However, a big problem that is involved in the mineral processing plants that treat this type of ore is that the grinding operation is difficult to design and control. The most commonly encountered cases involve either cassiterite that is overground, which leads to inefficient gravity concentration and the loss of the tailings, or sulfide minerals that do not separate enough from each other or from the gangue (called "undergrinding" for the sake of convenient expression), which results in the lowering of the grades of the concentrates. Therefore, the mineral processing plants have been seeking solutions to this problem so as to enhance the separation efficiency and recovery of the metal minerals. Considering that the addition of chemicals that alter the slurry rheology and the breakage rate of particles is possible, according to previous work, this article looked into the effects of the addition of grinding additives on the grinding product size when grinding this type of cassiterite–polymetallic sulfides ore in an attempt to simultaneously reduce cassiterite overgrinding and sulfide undergrinding.

2. Materials and Methods

2.1. Materials

The gross sample material was taken from a mineral processing plant that treats cassiterite–polymetallic sulfide ore and it was the product of the second compartment of a jig concentrator roughing the grinding product of the primary mill to pre-discard part of the tailings. After it was naturally dried, the gross sample material was crushed to <2 mm for further blending and subdivision into test samples using high pressure roller mill (XPSF-Φ400 × 250). Each subdivided test sample was 500 g and was put into a paper bag. The main valuable ore minerals are cassiterite, jamesonite, marmatite, pyrite, pyrrhotite and arsenopyrite. The gangue minerals include quartz, calcite, carbonaceous shale, etc. The elemental constituents of the test samples are listed in Table 1 through semi-quantitative analysis. The chemical analysis indicated that the assaying of Sn, Pb and Zn in the test samples was 0.2%, 0.1% and 1.2%, respectively. The size analysis through test sieving showed that 92.4% of the particles in the test sample were in the range of 0.2 mm to 2 mm in size and only 2.2% of the particles were smaller than 0.038 mm.

Table 1. The chemical composition of the test samples through semi-quantitative analysis.

Ingredient	Percent (%)	Ingredient	Percent (%)	Ingredient	Percent (%)	Ingredient	Percent (%)
SiO_2	46	Zn	1.2	Pb	0.1	Na_2O	0.01
$CaCO_3$	33	MgO	1.1	As	0.1	Cd	0.01
Al_2O_3	6.5	Mn	0.3	Sb	0.1	Sr	0.01
Fe_2O_3	4.8	Sn	0.2	Ni	0.02	Zr	0.01
SO_3	4	P_2O_5	0.2	Cu	0.02	Y	<0.01
K_2O	1.4	Ti	0.2	Rb	0.02		

2.2. Methods

A laboratory-scale conical-type ball mill with a cylinder of 240 mm in outer diameter and 90 mm in length was employed to carry out the grinding tests. The inner wall of the mill cylinder was smooth and the cylinder wall was 5 mm in thickness. The mill had 6300 mL of effective volume and was run at 85 rev/min, which was equivalent to 96% of its critical rotary speed. The grinding media consisted of several sizes of balls with weight composition percentages of (%):

Φ 38 mm:Φ33 mm:Φ31 mm:Φ25 mm:Φ21 mm:Φ14 mm:Φ13 mm = 3%:13%:16%:15%:29%:12%:10%. The ball filling fraction was set at 23.5%.

A grinding aid is an additive for the grinding process. Adding an appropriate amount of a grinding aid to the grinding process can change the physical and chemical properties of the surface of the mineral particles, the hardness of the materials and the dispersion of pulp so as to improve the grinding efficiency and reduce the grinding energy consumption. As these changes have different effects on different minerals, the use of grinding aids can expand the difference between the mechanical strengths of various minerals in the ore and strengthen or reduce the selective grinding between minerals. Therefore, according to the action mechanism of grinding aids, agents that can change the fluidity of pulp and polar surfactants with large dipole moments should be selected as grinding aids. According to the selection requirements of grinding aids, six chemicals (Analytical purity from Tianjin Kemio Chemical Reagent Development Center) were employed in grinding tests to look into their effects on the distribution of grinding product size. The chemicals were sodium hexametaphosphate, triethanolamine, ferric sulphate, aluminum chloride, polyaluminum chloride and polyacrylamides with molecular weights of 3×10^6, 5×10^6, 8×10^6 and 12×10^6. Among these chemicals, the polyaluminum chloride and polyacrylamides with molecular weights of 8×10^6 and 12×10^6 were of industrial grade purity and the others were of analytical grade purity. For the sake of convenience, the polyacrylamides with molecular weights of 3×10^6, 5×10^6, 8×10^6 and 12×10^6 are henceforth written as PAM300, PAM500, PAM800 and PAM1200, respectively. Wet batch grinding tests were used in this study. Each grinding test used 500 g of solid sample. Pure water was added based on the designated grinding concentration. The solid material, water and the selected additives were added into the mill simultaneously before the mill was run. The grinding time was set at 6 min. After the grinding time was complete, the mill was switched off and the ground contents were carefully collected together with the flush water. The size analysis of the ground product was performed using wet sieving. Each ground product was sieved into five size fractions: >0.2 mm, 0.2 to 0.154 mm, 0.154 to 0.074 mm, 0.074 mm to 0.038 mm and <0.038 mm.

The essential purpose of the study was to explore how to simultaneously reduce the overgrinding of cassiterite and enhance the liberation of sulfide minerals. However, in a strict sense, is difficult to assign a clear definition to the size at which overgrinding occurs, as it depends on the concentration methods. Similarly, the undergrinding size is also difficult to determine because it is affected by several factors, such as the mineralogy and dissemination of the mineral particles in the ore. In most industrial practices, cassiterite is commonly concentrated using gravity concentration and the best particle size for concentration is about 0.038 mm. Frequently, the size fraction of less than 0.019 mm is considered as slime due to the very low concentration efficiency by gravity separation. Therefore, this study—took particles of less than 0.038 mm as the overgrinding size fraction, or fine size fraction, mainly in terms of cassiterite concentration. Pb, Zn and Sb minerals are primarily sulfides and are able to be concentrated using froth flotation. For most concentrations for the froth flotation of sulfides, particles in the range of 0.01 mm to 0.2 mm in size are able to float; thus, the authors considered the 0.2 mm size fraction as the underground size fraction, or coarse size fraction, mainly in terms of the sulfide concentration. The overgrinding of the sulfides was not the concern of this study. Moreover, the 0.01 mm size fraction was covered in the 0.038 mm size fraction of, which was used to judge the overgrinding of cassiterite. After the definition of the overgrinding and undergrinding size fractions, the three size fractions of 0.2 to 0.154 mm, 0.154 to 0.074 mm and 0.074 to 0.038 mm were combined into one wide size fraction of 0.2 to 0.038 mm, which was considered to be the qualified size fraction for the grinding products. Although these size definitions for the particle grouping were not very strict, they were feasible in terms of optimal concentration size and separation efficiency. Thus, the percentages of the three size fractions were employed to evaluate the grinding results.

3. Results and Discussion

3.1. Effects of Type of Grinding Additives

Six chemicals were selected to add into the mill as grinding aids in order to investigate their influences on the distribution of grinding product size. The grinding concentration (denoted as the weight of ore in the mill as a percentage of the weight of the whole pulp) was set as 65%. The results are plotted in Figure 1.

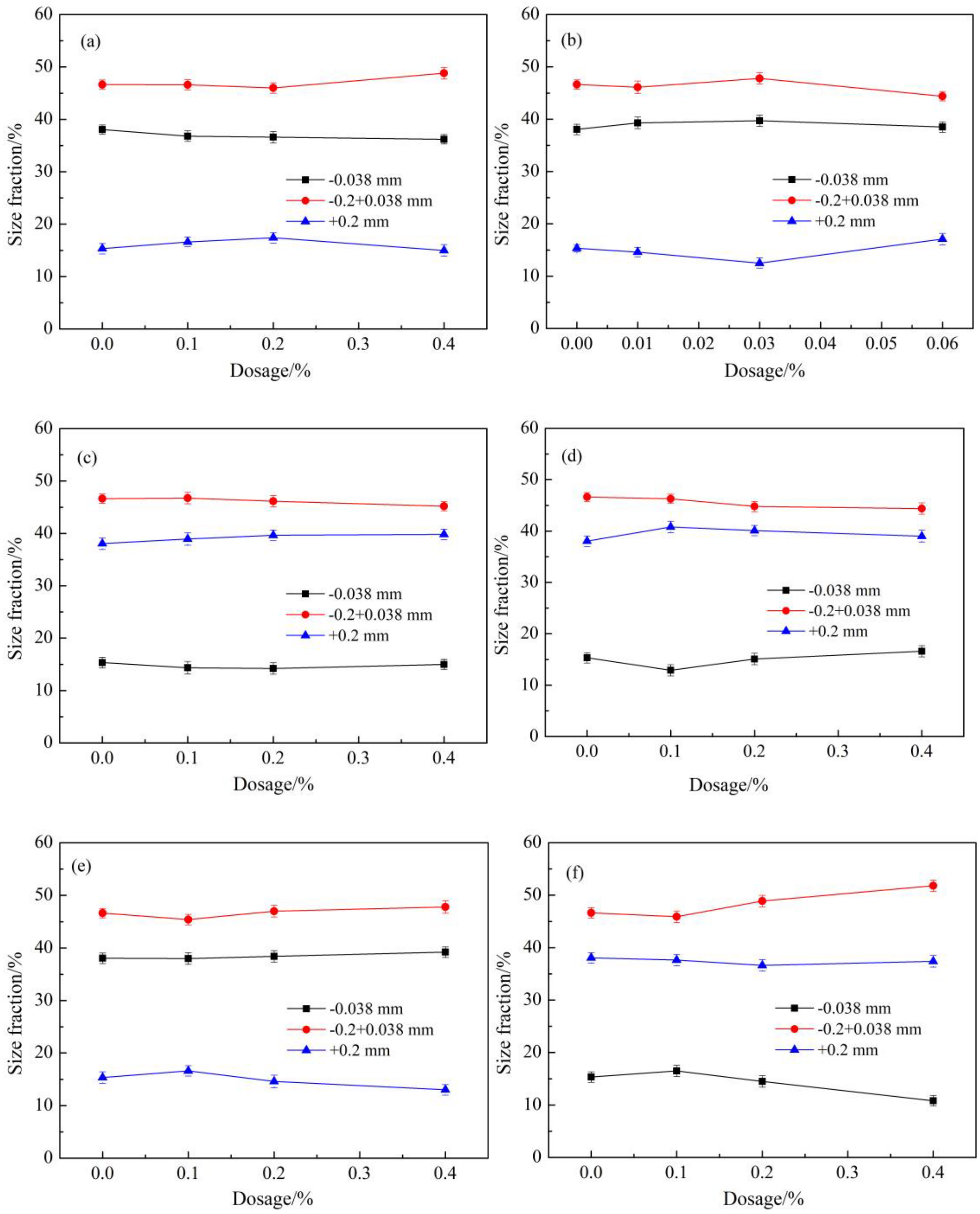

Figure 1. The plots of the yields of product size fractions against the dosage of (**a**) sodium hexametaphosphate, (**b**) triethanolamine, (**c**) ferric sulphate, (**d**) aluminum chloride, (**e**) polyaluminum chloride and (**f**) PAM300.

Figure 1a indicates that in the case of addition of sodium hexametaphosphate to the mill, the percentage of the 0.2 mm size fraction increased and both the 0.2 to 0.038 mm and 0.038 mm size fractions decreased with a dosage of less than 0.2% of the sodium hexametaphosphate in terms of the ground solid mass, which implies that sodium hexametaphosphate did not aid in grinding at this dosage. When as much as 0.4% of the ground solid mass of the sodium hexametaphosphate was added, the qualified size fraction increased and the fine size fraction decreased, with the coarse size fraction being close to that without sodium hexametaphosphate. This suggests that the addition of sodium hexametaphosphate in this dosage improved the grinding product size distribution a little. Thus, it could be concluded that sodium hexametaphosphate has a small effect on the grinding of this type of ore by only improving the grinding product size distribution when at a 0.4% dosage.

Figure 1b shows the results of adding triethanolamine to the grinding process. In its low dosage of less than 0.03% of the ground solid mass, triethanolamine resulted in a decrease in the percentage of the 0.2 mm coarse size fraction and a slight increase in the qualified particle and fine size fractions, which demonstrates the limited aid of triethanolamine in grinding. However, increasing the dosage of triethanolamine to 0.06% of the ground solid mass caused a decrease in the qualified size fraction and an increase in the coarse particles, with the fine size fraction remaining almost unchanged. This result was converse to our expectation. Thus, we could conclude that triethanolamine is not an ideal choice for improving the grinding operation.

As seen in Figure 1c, the addition of ferric sulphate to the grinding process caused a decrease in the 0.2 to 0.038 mm size fraction and an increase in the 0.038 mm fine particles, with the percentage of the 0.2 mm size fraction being hardly affected. Obviously, this is also not the result that this research expected. Aluminum chloride produced a similar effect to ferric sulphate (Figure 1d). Therefore, we concluded that ferric sulphate and aluminum chloride are not suitable as candidates for grinding additives when grinding this type of ore.

Figure 1e shows that when the addition of polyaluminum chloride was in the range of 0.1% to 0.4% of the ground solid mass, the increase in polyaluminum chloride dosage led to a slight decrease in the 0.2 mm size fraction and a slight increase in the 0.2 to 0.038 mm size fraction, while the 0.038 mm fine size fraction was much less affected. However, compared to the result without addition of polyaluminum chloride, the changes that were caused by the addition of polyaluminum chloride were so small that they could be neglected. Thus, it could be concluded that polyaluminum chloride does not meet the requirements for a good grinding additive.

The addition of PAM300 produced different results compared to the other chemicals (Figure 1f). When the addition of PAM300 was in the range of 0.1% to 0.4% of the ground solid mass, the increase in PAM300 dosage caused a pronounced decrease in the 0.2 mm size fraction and a marked increase in the 0.2 to 0.038 mm size fraction. Moreover, the 0.038 mm fine size fraction was also slightly reduced. Compared to the results without PAM300, the maximum increase in the percentage of the 0.2 to 0.038 mm size fraction was 5.17% and the maximum decrease in the percentage of the 0.2 mm size fraction was 4.53% at a 0.4% PAM300 dosage. There was no doubt that these changes satisfied the demands for a good grinding additive. Thus, out of the six chemicals in question, PAM300 was the best candidate as a grinding aid for the grinding of the discussed ore.

3.2. Effects of Polyacrylamide Molecular Weight

PAM is a polymer with a variable molecular weight. Its properties are related to its molecular weight, so it was worth looking into the effects of the molecular weight of PAM on the grinding product size. Here, PAM300, PAM500, PAM800 and PAM1200 were selected to compare the effects of polyacrylamide molecular weight. The test results are shown in Figure 2.

For the sake of convenient comparison, Figure 1e is reoccurs in Figure 2 as the sub-diagram Figure 2a. Thus, it is unnecessary to repeat the description of the results of using PAM300 as the grinding additive.

Figure 2b indicates that in the case of the addition of PAM500 with a dosage in the range of 0 to 0.2%, with the increase in the dosage of PAM500, the yield of the 0.2 mm coarse size fraction rapidly decreased with a maximum change of 8.93%, the percentage of the 0.2 to 0.038 mm qualified size fraction greatly increased with a maximum change of 9.57% and the 0.038 mm fine particles decreased a little with a maximum change of 1.04%. These three altered values exceeded 4.4%, 4.4% and 0.38%, respectively, compared to those that were caused by using PAM300. Therefore, the use of PAM500 as the grinding aid caused the production of more of the qualified size fraction and less of both the fine and coarse size fractions compared to the use of PAM300. However, when the dosage of PAM500 was larger than 0.2% of the ground solid mass, the grinding results became a little worse, which suggests the importance of controlling the dosage of PAM500 in order to take full advantage of the aid action of PAM500.

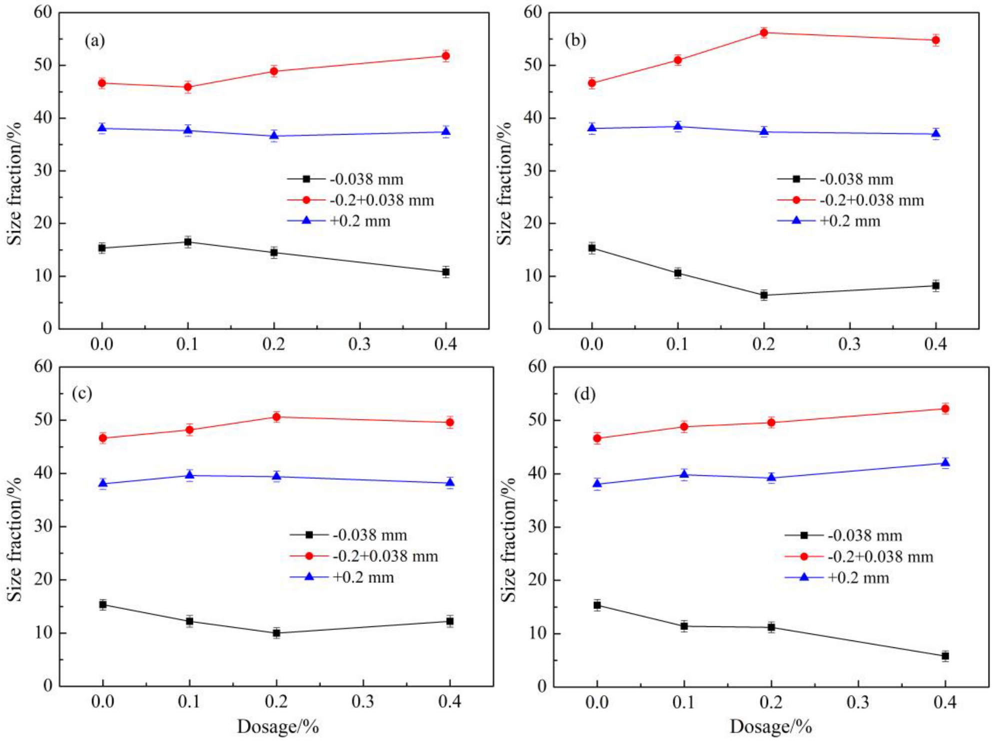

Figure 2. The effects of polyacrylamide molecular weight on the grinding product size with (**a**) PAM300, (**b**) PAM500, (**c**) PAM800 and (**d**) PAM1200.

Figure 2c shows that in the case of the addition of PAM800 as the grinding aid, the yield of the 0.2 mm size fraction decreased with a dosage of less than 0.2% of the ground solid mass of PAM800, with the largest reduction being 5.33%, and then slowly increased when the dosage was larger than 0.2%. The percentage of the 0.2 to 0.038 mm size fraction increased with the dosage of the PAM800 at first, with the largest increase being 3.97% at a 0.2% dosage, and then maintained at a relatively stable level. The overall trend of the percentage of the 0.038 mm size fraction was an increase with the dosage of the PAM800, although the increase was very small. This shows that the use of PAM800 as the grinding aid resulted in a reduction in the 0.2 mm coarse size fraction, an increase in the qualified size fraction and a small increase in the fine size. Overall, PAM800 demonstrated a sufficient aid action when grinding the ore in question.

Figure 2d shows that when the PAM1200 was used in the grinding, the yield of the 0.2 mm size fraction decreased with the dosage of PAM1200, with the maximum change in value being 9.53%. With the increasing dosage of PAM1200, the percentages of the 0.2 to 0.038 mm and 0.038 mm size fractions increased simultaneously, which signified a more serious overgrinding. Thus, we could conclude that PAM1200 is a strong aid for grinding in terms of the enhancement of grinding ability, but it does not improve the distribution of the grinding product size because it produces more overground particles.

By comparing these four polyacrylamides with different molecular weights, it could be concluded that they can all decrease the production of the 0.2 mm coarse size fraction and increase the production of the 0.2 to 0.038 mm qualified size fraction, but they have different effects on the production of the 0.038 mm fine size fraction. PAM1200 achieved the largest reduction in the production of the 0.2 mm coarse size fraction (9.53%), but it also increased the production of the 0.038 mm fine size fraction. PAM800 was similar to PAM1200 in the production of the 0.038 mm fine size fraction. PAM500 and PAM300 achieved an increase in the production of the qualified size fraction and a decrease in the production of the coarse and fine size fractions, for which this study was aiming. The addition of PAM500 provided a greater aid in the grinding of the cassiterite–polymetallic sulfide ore than the addition of PAM300.

3.3. Effects of Grinding Concentration on the Effectiveness of PAM500

Batch grinding tests were carried out using PAM500 as the grinding additive. The grinding concentrations were set at 60%, 70% and 75%. The grinding results are listed in Table 2.

Table 2. The relationship between the dosage of PAM500 and the percentages of the product size fractions using different grinding concentrations.

Grinding Concentration (%)	Dosage of PAM500 (%)	Percent of 0.2 mm Size Fraction (%)	Percent of 0.2 to 0.038 mm Size Fraction (%)	Percent of 0.038 mm Size Fraction (%)
60	0	14.80	47.60	37.60
	0.1	14.60	47.90	37.50
	0.2	12.90	50.80	36.30
	0.4	9.00	54.20	36.80
65	0	15.33	46.63	38.04
	0.1	10.60	51.00	38.40
	0.2	6.40	56.20	37.40
	0.4	8.20	54.80	37.00
70	0	10.30	48.80	40.90
	0.1	8.50	51.10	40.40
	0.2	10.10	50.30	39.60
	0.4	13.10	48.90	38.00
75	0	11.70	47.30	41.00
	0.1	14.10	46.90	39.00
	0.2	16.50	46.80	36.70
	0.4	19.20	44.00	36.80

It can be seen from Table 2 that when the grinding concentration was relatively low, such as 60% or 65%, the addition of PAM500 decreased the production of the 0.2 mm coarse size fraction and increased the production of the 0.2 to 0.038 mm qualified size fraction. With the grinding concentration increasing to 70%, the aid in grinding that was provided by PAM500 was weakened, with smaller changes occurring in the percentages of the qualified and coarse size fractions. When the grinding concentration was as large as 75%, the use of PAM500 led to an increase in the percentage of the 0.2 mm coarse size fraction and a decrease in the production of the 0.2 to 0.038 mm size fraction, which means that the addition of PAM500 no longer aided in the grinding and even deteriorated the grinding process. For all four grinding concentrations, the yield of the 0.038 mm size fraction decreased with the increase in PAM500 dosage, which verifies that PAM500 could decrease the production of the 0.038 mm fine size fraction in a wide slurry concentration.

3.4. Effects of Grinding Time on the Effectiveness of PAM500

The grinding time was set at 6 min and 8 min and the grinding concentration was fixed at 65%. The results are listed in Table 3.

It can be seen from Table 3 that in the case of no addition of PAM500, the yields of the 0.2 mm coarse size fraction demonstrated a big difference between the products from 6 min and 8 min of grinding, with the former being about 10% larger than the latter; however, the difference between the grinding products of these two grinding times became smaller when PAM500 was added into the grinding process. With regard to the qualified size fraction, there were very small differences between the yields of the size fractions of the products from 6 min and 8 min of grinding when no PAM500 was added. When PAM500 was used in the grinding, the yields of the qualified size fraction obviously increased with 6 min of grinding but were not affected with 8 min of grinding. This indicates that the PAM500 was only able to aid grinding over a relatively short grinding time.

Table 3. The relationship between the product size fractions and the dosage of PAM500 using different grinding times.

Grinding Time (min)	Dosage of PAM500 (%)	Percent of 0.2 mm Size Fraction (%)	Percent of 0.2 to 0.038 mm Size Fraction (%)	Percent of 0.038 mm Size Fraction (%)
6	0	15.33	46.63	38.04
	0.1	10.60	51.00	38.40
	0.2	6.40	56.20	37.40
	0.4	8.20	54.80	37.00
8	0	5.00	46.20	48.80
	0.1	4.00	47.00	49.00
	0.2	4.20	45.10	50.70
	0.4	4.40	45.80	49.80

As for the fine size fraction, the yield decreased overall with the addition of PAM500 when the grinding time was 6 min, while the yield of the fine size fraction slightly increased with 8 min of grinding time. However, compared to the other two size fractions, the change in the 0.038 mm size fraction that was caused by the addition of PAM500 was very small.

By summing up the above discussion, we could reach the conclusion that when PAM500 is used in grinding, it could exert an aid for grinding over relatively short grinding time, i.e., using PAM500 could shorten the grinding time that is needed to achieve the same, or even improved, product size distribution.

3.5. Mechanism Analysis of Grinding Aids

Scholars across the world have conducted a lot of research on the principle that grinding aids can optimize the grinding process [21,22]. At present, there are two main explanations. One is the explanation of "pulp rheological adjustment". Grinding aids change the viscosity of pulp and the dispersion of particles by adjusting the rheological properties of the pulp and the fluidity of the ore particles. The second is the explanation of "adsorption reduces hardness". It is considered that the adsorption of grinding aid molecules on the surface of the ore particles reduces the surface energy of the particles and causes the position migration of surface layer lattice, which results in point or line defects that reduce the strength and hardness of the particles, prevent the closure of new cracks and promote the propagation of cracks. Based on these theories, this study examined the influence of the grinding aids on the flow properties of the pulp, before and after the addition of the grinding aids, using viscosity tests.

Taking the grinding aid PAM500 as an example, under the conditions of 500 g of the sample, 6 min of grinding time, a 23.5% medium filling rate and a 65% slurry concentration, the change in the viscosity of cassiterite–polymetallic sulfide slurry after the addition of the grinding aid was studied. The results are shown in Figure 3. To investigate the influence of pulp viscosity on coarse particle (>2 mm) grinding effects, grinding tests were carried out under different pulp viscosities and the results are shown in Figure 4.

As can be seen from Figure 3, with the increase in the amount of grinding aid (PAM500), the pulp viscosity also increased rapidly. When the viscosity increased to a certain extent and the dosage continued to increase, the pulp viscosity changed slightly. It can be seen from Figure 4 that with the increase in pulp viscosity, the yield of the 0.2 mm particle size fraction in the grinding products gradually decreased. It can be seen that the increase in pulp viscosity was conducive to the crushing of coarse particles. In the grinding process, different pulp concentrations corresponded to different pulp viscosities. Pulp viscosities that are too high or too low were not conducive to grinding. The appropriate pulp viscosity had a great impact on the formation of a cover layer with an appropriate thickness on the surface of the grinding medium [23,24]. When the thickness of the cover layer was small, the probability of crushing the ore particles in the cover layer and the grinding efficiency increased with the increase in the thickness of the cover layer. When the thickness of the cover layer exceeded a certain critical value, the viscous resistance of the cover layer played a buffering role on the impact and collision of the grinding medium and the effective crushing probability and grinding efficiency were reduced. The addition of polyacrylamide into the grinding process increased the viscosity of the pulp and changed the thickness of the cover layer on the surface of the grinding medium. With the increase inf viscosity, the yield of coarse particles in the grinding products decreased gradually. When the addition dosage was 0.2%, the ore addition viscosity achieved the best viscosity and the yield of coarse particles in the grinding products reached the lowest value. With the continuous increase in the agent dosage, the yield of coarse particles increased.

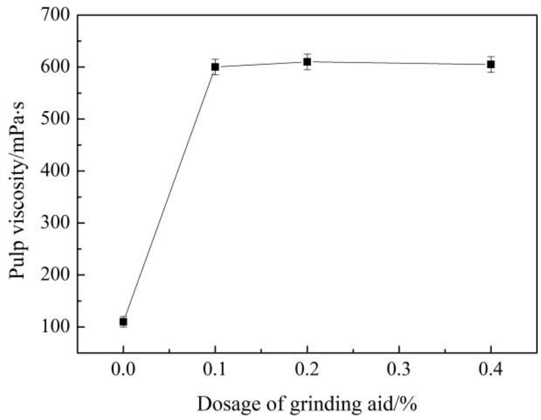

Figure 3. The relationship between pulp viscosity and grinding aid dosage.

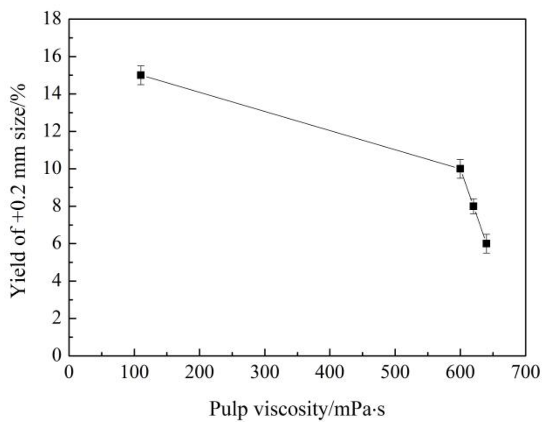

Figure 4. The relationship between pulp viscosity and the 0.2 mm size fraction yield.

4. Conclusions

The six chemicals that were discussed in this paper could affect the grinding results to some extent, but only the addition of polyacrylamide led to a decrease in the production of both the coarse and fine size fractions and an increase in the production of the qualified size fraction, which were the most satisfactory aid effects for the grinding process in this study.

The molecular weight of the polyacrylamide affected the grinding results. Both PAM800 and PAM1200 helped to produce less of the coarse size fraction and more of the qualified size fraction, but with the simultaneous increase in the fine size fraction. Both PAM300 and PAM500 demonstrated obvious aid in the grinding process by increasing the qualified size fraction and decreasing the fine and coarse size fractions, which means that they were the best candidates for grinding aids. PAM500 was better than PAM300. The aid action of PAM500 was related to the grinding concentration. A low grinding concentration was helpful in exerting the aid action of PAM500, but when the concentration was larger than 70%, the grinding was deteriorated by the addition of PAM500. When PAM500 was used in grinding, it could exert a greater aid in the grinding over a relatively short grinding time.

Author Contributions: Conceptualization, J.Y. and S.M.; methodology, J.Y.; software, J.Y.; validation, S.M.; formal analysis, W.Z.; writing—original draft preparation, W.Z.; writing—review and editing, J.Y.; visualization, P.Z.; supervision, J.Y.; project administration, J.Y.; funding acquisition, J.Y.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No.51874105) and the Guangxi Natural Science Foundation (No.2018GXNSFAA281204).

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

References

1. Fuerstenau, D.W.; Phatak, P.B.; Kapur, P.C.; Abouzeid, A.Z.M. Simulation of the grinding of coarse/fine (heterogeneous) systems in a ball mill. *Int. J. Miner. Process.* **2011**, *99*, 32–36. [CrossRef]
2. Klimpel, R.R.; Austin, L.G. Chemical additives for wet grinding of minerals. *Powder Technol.* **1982**, *31*, 239–253. [CrossRef]
3. El-shall, H.; Somasundaran, P. Physico-chemical aspects of grinding: A review of use of additives. *Powder Technol.* **1984**, *38*, 275–293. [CrossRef]
4. Velamakanni, B.V.; Fuerstenau, D.W. The effect of the adsorption of polymeric additives on the wet grinding of minerals 1, mechanisms of suspension stabilization. *Powder Technol.* **1993**, *75*, 1–9. [CrossRef]
5. Velamakanni, B.V.; Fuerstenau, D.W. The effect of the adsorption of polymeric additives on the wet grinding of minerals 2, dispersion and fine grinding of concentrated suspensions. *Powder Technol.* **1993**, *75*, 11–19. [CrossRef]
6. Fuerstenau, D.W.; Venkataraman, K.S.; Velamakanni, B.V. Effect of chemical additives on the dynamics of grinding media in wet ball mill grinding. *Int. J. Miner. Processing* **1985**, *5*, 251–267. [CrossRef]
7. Sohoni, S.; Sridhar, R.; Mandal, G. The effect of grinding aids on the fine grinding of limestone, quartz and Portland cement clinker. *Powder Technol.* **1991**, *67*, 277–286. [CrossRef]
8. Toprak, N.A.; Altun, O.; Aydogan, N.; Benzer, H. The influences and selection of grinding chemicals in cement grinding circuits. *Constr. Build. Mater.* **2014**, *68*, 199–205. [CrossRef]
9. Sverak, T.S.; Baker, C.G.J.; Kozdas, O. Efficiency of grinding stabilizers in cement clinker processing. *Miner. Eng.* **2013**, *43–44*, 52–57. [CrossRef]
10. Hasegawa, M.; Kimata, M.; Shimane, M.; Shoji, T.; Tsuruta, M. The effect of liquid additives on dry ultrafine grinding of quartz. *Powder Technol.* **2001**, *114*, 145–151. [CrossRef]
11. Nair, P.B.R.; Paramasivam, R. Effect of grinding aids on the time-flow characteristics of the ground product from a batch ball mill. *Powder Technol.* **1999**, *101*, 31–42. [CrossRef]
12. Katsioti, M.; Tsakiridis, P.E.; Giannatos, P.; Tsibouki, Z.; Marinos, J. Characterization of various cement grinding aids and their impact on grindability and cement performance. *Constr. Build. Mater.* **2009**, *23*, 1954–1959. [CrossRef]
13. Choi, H.; Lee, W.; Kim, S. Effect of grinding aids on the kinetics of fine grinding energy consumed of calcite powders by a stirred ball mill. *Adv. Powder Technol.* **2009**, *20*, 350–354. [CrossRef]
14. Choi, H.; Lee, W.; Kim, D.U.; Kumar, S.; Kim, S.S.; Chung, H.S.; Kim, J.H.; Ahn, Y.C. Effect of grinding aids on the grinding energy consumed during grinding of calcite in a stirred ball mill. *Miner. Eng.* **2009**, *23*, 54–57. [CrossRef]
15. Hasegawa, M.; Kimata, M.; Yaguchi, M. Effect and behavior of liquid additive molecules in dry ultrafine grinding of limestone. *J. Soc. Powder Technol. Jpn.* **2005**, *24*, 178–184. [CrossRef]
16. Cheung, J.; Jeknavorian, A.; Roberts, L.; Silva, D. Impact of admixtures on the hydration kinetics of Portland cement. *Cem. Concr. Res.* **2011**, *41*, 1289–1309. [CrossRef]
17. Wang, Y.; Forssberg, E. Enhancement of energy efficiency for mechanical production of fine and ultra-fine particles in comminution. *China Particuology* **2007**, *5*, 193–201. [CrossRef]
18. Jeknavorian, A.A.; Barry, E.F.; Serafin, F. Determination of grinding aids in portland cement by pyrolysis gas chromatography-mass spectrometry. *Cem. Concr. Res.* **1998**, *28*, 1335–1345. [CrossRef]
19. Gao, X.J.; Yang, Y.Z.; Deng, H.W. Utilization of beet molasses as a grinding aid in blended cements. *Constr. Build. Mater.* **2011**, *25*, 3782–3789. [CrossRef]
20. Paramasivam, R.; Vedaraman, R. Effect of the physical properties of liquid additives on dry grinding. *Powder Technol.* **1992**, *70*, 43–50. [CrossRef]
21. Duan, X.X. *Selective Grinding and Its Application*; Metallurgical Industry Press: Beijing, China, 1991.
22. Chen, B.C. *Grinding Principle*; Metallurgical Industry Press: Beijing, China, 1989.

23. Li, T.P. Liu Jincai Control of grinding process parameters-Also on grinding aids. *Min. Mach.* **2005**, *33*, 14–17.
24. Frances, C.; Laguerie, C.; Mazzaotta, B. On the analysis of fine net grinding in a batch ball mill. *Chem. Eng. J.* **1996**, *63*, 141–147.