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Effect of Milling Process Variables on the Size of Hematite Ore Particles

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Keywords:
Al-Hussainiyat iron ore; Hematite; Liberation; Milling; Particle Size; Sieving.

Highlights:
- *Al-Husseiniyat iron ore processing.*
- *Crushing and grinding hematite ore to free valuable ore particles from impurities.*
- *Reach a particle size of 20 microns with the appropriate parameters, i.e., grinding speed, input weight, and grinding time.*

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Abstract: Hematite is one of the iron ores, and its chemical formula is (Fe2O3). The present research studies the hematite processing and the effect of grinding factors on it. Hematite ore is considered a low-grade iron ore due to its low iron percentage. The hematite comprised Fe (30.36%), Fe2O3 (43.41%), and other minerals, such as (CaO, SiO2, and Al2O3). It is essential to clean the valuable metal from impurities by making its closed components intertwined with impurities liberated through processing and grinding processes to increase its surface area, which is the research goal. The research methodology included collecting a sample of hematite ore from the Al-Hussainiyat area in (Anbar-Iraq). The hematite ore sample was crushed and ground. Then, samples were sieved using a vibrating sieve to analyze the raw particles based on their particle size distribution. Weight, time, and rotational speed were investigated to obtain the right balance between the input weight, grinding time, and mill speed to get the required particle size. The present research also aims to reduce the ore's particle size to less than 75 µm and grind it to maximize its surface area. The findings of the milling process showed that the particle size reduced with increasing speed and duration. Also, it was found that the laboratory ball mill produced raw materials with a size of 20 microns and a maximum weight of 21.6 grams. These gains were achieved when a weight of 50 grams was added to 4 balls, a suitable number of balls, and the mixture was left inside for 30 minutes. The maximum weight achieved at 500 rpm for 10 minutes was 41 grams, with an internal weight of 100 grams and a particle size of 150 microns.

تأثير متغيرات عملية الطحن على حجم جزيئات خام الهيماتيت

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الخلاصة

الهيماتيت هو أحد خامات الحديد وصيغته الكيميائية (Fe_2O_3). يدرس هذا البحث الهيماتيت وتأثير عوامل الطحن عليه. يعتبر خام الهيماتيت خام الحديد منخفض الدرجة لأن نسبة الحديد فيه منخفضة. يتكون الهيماتيت من الحديد (٣٠,٣٦٪)e و(Fe_2O_3 (43.41%) ومعادن أخرى مثل (CaO, SiO_2, Al_2O_3). ولذلك يتم طحنها لتحرير المعدن الثمين من الشوائب بجعل مكوناته المغلقة والمتشابكة مع الشوائب تتحرر من خلال عمليات المعالجة والطحن لزيادة مساحة سطحه وهو هدف البحث. تتضمن منهجية البحث أخذ عينة من خام الهيماتيت من منطقة الحسينيات في (الأنبار- العراق). تم سحق عينة الهيماتيت طحنها. ومن ثم تم غربلة العينات باستعمال المنخل الاهتزازي لتحليل الجزيئات الخام بناءً على توزيع حجم الجسيمات. تم دراسة الوزن، الوقت، وسرعة الدوران للحصول على التوازن الصحيح بين الوزن المدخل، وزمن الطحن، وسرعة المطحنة للحصول على حجم الحبيبات المطلوب. كما يهدف البحث إلى تقليل حجم جزيئات الخام إلى أقل من ٧٥ ميكرومتر، فضلًا عن طحنه لزيادة لمساحته السطحية الى حد اعلى. وفقا لنتائج عملية الطحن، فإن حجم الجسيمات يقل مع زيادة السرعة والمدة. وبناء على ذلك تبين أن مطحنة الكرات المختبرية تنتج مواد خام بحجم ٢٠ ميكرون ووزن أقصى ٢١,٦ جرام عند إضافة وزن محدد ٥٠ جرام إلى ٤ كرات عدد مناسب من الكرات وترك الخليط داخل لمدة ٣٠ دقيقة. وكان الحد الأقصى للوزن الذي تم تحقيقه عند ٥٠٠ دورة في الدقيقة لمدة ١٠ دقائق هو ٤١ جرامًا، مع وزن داخلي ١٠٠ جرام وحجم جسيمات ١٥٠ ميكرون.

الكلمات الدالة: خام حديد الحسينيات، هيماتيت، تحرر، الطحن، حجم الجزيئات، غربلة.

1.INTRODUCTION

Humans have used iron since the dawn of time. A nation's economic and social development depends on the availability of iron [1]. Although it is only the fourth most prevalent element in the Earth's crust, iron is its most abundant and significant metal. Iron is concentrated mostly in the core [2]. Numerous materials containing iron can be found in nature. However, only a few of them are economically relevant [3]. In all iron-making processes, the iron comes from ores where it mostly resides as oxides, such as hematite (Fe_2O_3), magnetite (Fe_3O_4), or goethite ($Fe_2O_3.H_2O$), with siderite ($FeCO_3$) occasionally present in minute amounts. Particle size, crystal structure, processing methods, and impurities can all affect hematite's mechanical properties. Some general mechanical properties of hematite ore-based particles are that Hematite's Mohs hardness ranges from 5 to 6.5, making it a relatively hard mineral. Hematite is a brittle substance that breaks more readily along some planes or directions than others. It also has a noticeable cleavage plane. With a normal density of 4.9 to 5.3 grams per cubic centimeter, it has a comparatively high density. However, the hardness can also change within this range according to conditions and composition. The ore density varies depending on its purity and content [4, 5]. Worldwide, iron ore is found in various places, including Austria, South Africa, Brazil, Iran, Iraq, England, India, China, and Canada [1, 6]. The two main ironstone deposits in Iraq are the Al-Hussainiyat deposits, close to Rutba, and the older Ga'ara Formation, in the Western Desert-Alanbar. Since the 1980s, the area around the ironstone deposits in the Ga'ara Depression and AlHussainiyat has been extensively studied by the Iraq Geological Survey. According to the findings of this study, Al- Hussainiyat Deposit and the Ga'ara contain low-grade iron ores. Although the Ga'ara Deposit's reserves are almost depleted, the Al-Hussainiyat Deposit's mine is still operating. Low-grade sedimentary deposits from Iraq's Al-Hussayniat iron ore have an average iron content of 26% Fe. The ore deposit under investigation is 18 kilometers from the Baghdad-Rutba highway, close to Wadi Al-Hussaynait in the southeast of the Rutba uplift. Over the past 25 years, Al-Hussaynait low-grade iron ore has undergone numerous beneficiation operations. Several physical methods have been studied in these operations. The focus of the present beneficiation studies is on determining whether upgrading the iron ore from Al Hussainiyat to generate iron concentrate for use as a feed in a traditional blast furnace or a direct reduction process to produce iron and steel [7, 8]. Important iron ore-producing nations have improved their production by taking steps to use low-grade iron ores, fines, and slimes in response to the rising demand for iron ores due to the enormous demand for steel worldwide. Low-grade iron ores require several processing steps and face use challenges due to their silica content, soft nature, and unique mineralogical properties. Therefore, it makes sense to benefit low-grade iron ores to remove gangue minerals and raise their grade [9, 10]. Mineral processing is a multi-step process consisting of multiple processes like grinding, classifying, and sorting [11]. The degree of enrichment and the upgrading of iron ore have received the attention of mineral processing researchers. The mineralogical composition, liberation size, and interactions between various components, such as iron, silica, and alumina, are all related to the study of the value of low-grade iron ores. Crushing, grinding, gravimetric separation, magnetic separation, and flotation are all methods that can be used to enrich low-grade iron ores so that gangue minerals are removed [12-14]. The objective of beneficiation of iron ore, fines, and slimes is to treat mechanically, chemically, and through other methods [15]. Crushing and grinding are frequently necessary to separate iron minerals from the gangue mineral. The ore is first crushed in a size-reduction process in which large lumps are broken into smaller pieces or fragments using a crusher. Next, the ore is ground in a process in which relatively coarse particles are reduced to the desired fineness using a mill. Particle size is a critical factor in mineral enrichment; therefore, sieve analysis is used, i.e., a technique used to separate ore particles by size, from the largest to smallest. Sieves used are with a distinctly sized aperture (opening). This method is used to separate ore particles according to size. Excessive grinding not only increases processing costs but also creates fine particles that harm product quality and recovery [16-18]. Sieve analysis is still the most often used technique for measuring particle size distribution due to its simplicity [19]. The present study investigates the hematite ore processing and the effect of grinding process variables on the ore particle size. The main objectives are processing hematite ore to clean the iron metal from impurities so that it can be easily separated by one of the separation methods, obtaining the lowest particle size from the ore, and determining the best speed, time, and weight entering the mill obtained at the lowest particle size. The weight of the hematite ore, mill speed, and grinding time are three important factors that significantly impact the quality of the output produced by a ball mill during the grinding. The weight of the ore entering the mill determines the grinding efficiency and overall load. While too much feed might cause overloading and reduced efficiency, the right ore feed rate ensures effective mill operation. Insufficient feed could result in the mill not using its full potential. A key factor in the grinding process is mill speed. Because it can affect both the raw particles and the grinding medium, a low or high speed might negatively influence the mill's parts or hinder effective grinding. The grinding time is an important factor that affects the final product's accuracy. However, there is a limit to it. This study aims to find the ideal balance between mill speed, grinding time, and input weight. Experimental testing can be performed to grind hematite ore to achieve the desired product qualities, reduce energy consumption, and boost production.

2. EXPERIMENTAL PROGRAM

2.1. Materials

The material used in this experiment was a sample of hematite, an iron ore, extracted and collected from Wadi Al-Hussainiyat, northeast of Rutba (Anbar, Iraq). The sample was pulverized by a jaw crusher and ground by a ball mill to provide an acceptable range of particle size for use in other subsequent processes, such as physical separation and physicochemical separation, as well as to separate valuable minerals from associated gangue minerals, which are the most expensive parts of mineral processing. The ore sample's chemical composition was studied using X-ray fluorescence (XRF). Figure 1 shows the hematite ore processing steps flowchart.

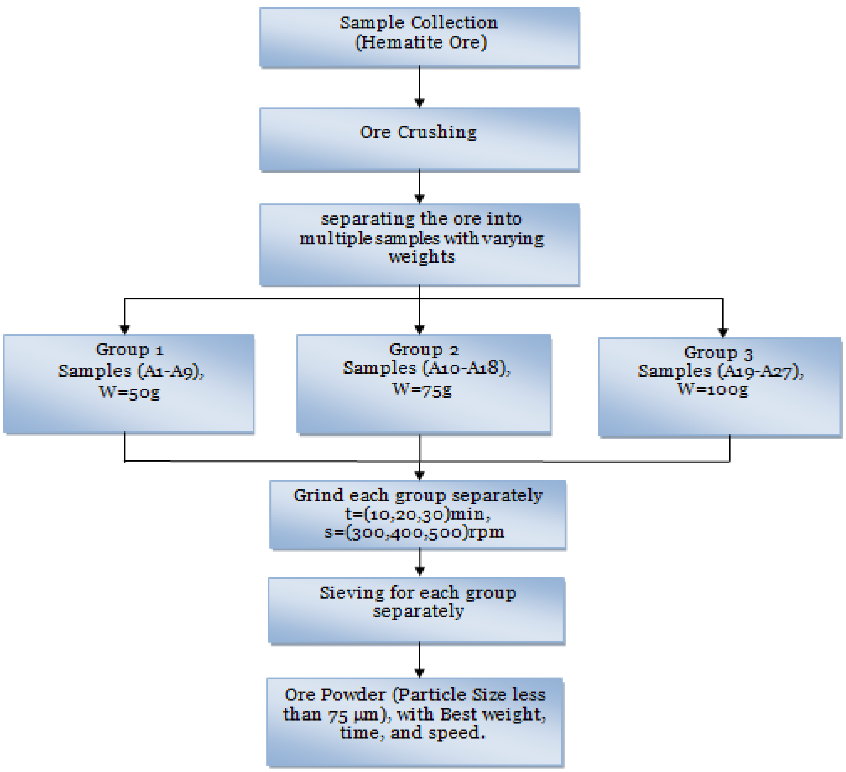

Fig. 1 Flowchart of Hematite Ore Processing Steps.

2.2. Chemical Analyses

The chemical composition study of the ore sample was conducted using X-ray fluorescence (XRF) by the Ministry of Science and Technology (Baghdad, Iraq) (model XEPOS Power 100VA). XRF analysis results showed that iron oxides in the form of Fe_2O_3 constituted about 43.41% of the sample by weight, Fe (30.36%), SiO_2 (4.506%), Al_2O_3 (2.043%), and CaO (3.365%), which were the second and third main oxides. In addition, the sample had small quantities of Mn, Ti, Na, S, and Mg oxides, as shown in Table 1. Hematite was identified as an abundant, economical iron-bearing mineral.

Table 1 Chemical Composition of the Sample by XRF Technique.

Compound	Concentration (%)
Fe	30.36
Fe_2O_3	43.41
Al_2O_3	2.043
SiO_2	4.506
CaO	3.365
MgO	3.442
K_2O	3.343
Na_2O	3.341
TiO_2	2.998
MnO	3.011
S	0.18

2.3. Crushing

As indicated in Fig. 2, a sample was loaded into a jaw crusher (Retsch-Allee 1-5, type BB200 rostfrei, Germany) to crush it to a size that could be handled in subsequent operations. The sample weighs approximately (5) kilograms and was charged in batches. Before the crushing process, the particle size was approximately (10) mm; however, after the crushing process, the particle size decreased to approximately (2) mm, as shown in Fig. 3. After crushing, the sample was divided into several samples with different weights (50, 75, and 100) g, as shown in Fig. 4. They were stored to be used in subsequent operations.

Fig. 2 Laboratory Jaw Crusher.

(a) (b)

Fig. 3 Particle Size of the Sample (Hematite Ore), (a) Particle Size before Crushing (10mm), (b) Particle Size after Crushing (2mm).

Fig. 4 Sample Weight and Divided into Several Samples and Weight.

2.4. Grinding

The experiments performed in the present study determine the important grinding parameters, i.e., the input weight of the mill, the grinding time, the rotational speed of the mill, the grinding medium, and the type of material to be ground. In this experiment, a laboratory ball mill (Retsch-Alle 1-5, Type PM100, Germany) was used, as shown in Fig. 5. The grinding media used in the present study were four steel balls with a diameter of 2.5 cm. The grinding process was dry. Three experimental sets (groups) were used. Each group included nine experiments. The total number of experiments was 27 experiments. The experiment code was (A), which means (A1-A27). The first group had a fixed weight of 50 grams, with different times, i.e., 10, 20, and 30 minutes, and different speeds, i.e., 300, 400, and 500 rpm. Also, the second group consisted of nine experiments weighing 75 grams at different times and speeds. The third group included the last nine experiments with a weight of 100 grams and different times and speeds, as specified above. As shown in Fig. 6, a hematite ore sample under zoom 0.7x-4.5x, working distance 95mm, was obtained using a laboratory stereoscope (Serial Number: 8542-30, Italy) at the Department of Production and Metallurgy Engineering, University of Technology (Baghdad, Iraq). The image demonstrates the characteristic reddish-brown hue of hematite ore. The ore particles were spherical. Some irregular particles lacked a clear geometric shape and may have random edges. The ore particles were about 75 μm in size. Needle-like particles were elongated and resembled needles or rods.

(a)

(b)

(c)

Fig. 5 Laboratory Ball Mill. (a) From Outside. (b) From Inside. (c) the Grinding Medium Balls and the Ore after Grind.

Fig. 6 Hematite Ore Grains after Grinding Operations.

2.5.Sieve Analysis

Sieve analysis is a technique or method of size analysis. A sample of the material is run through several test laboratory vibration sieves (Retsch-Alle 1-5, 42781 Haan, Germany) according to American Society for Testing and Material (ASTM) E-11-01, as shown in Fig. 7, to calculate the weight percentage of a close-sized fraction. Sieving is usually done under dry conditions, and the sieves selected for testing are stacked with a coarse sieve on top and a finer sieve on the bottom. To prevent the material from leaking into the air, a cover is placed over the coarse sieve. The nest is then placed in a shaker and sieved for a predetermined period. On each sieve, the collected materials are taken out and weighed. The particle size distribution data is the total set of values. Particle size distribution is a statistical correlation between quantity (g) and size (μm) that describes how particles are distributed quantitatively between different sizes [20]. Sieves with aperture sizes of 250, 212, 150, 106, 75, 53, 20, and Pan μm were used.

Fig. 7 Laboratory Vibrating Sieves Device.

3.RESULTS AND DISCUSSION

When experiments (A1-A27) were conducted, each experiment (sample) was entered separately into the ball mill. The input weight factor of the sample was 50, 75, and 100 grams. The grinding time was 10, 20, and 30 min. The mill's rotational speed was 300, 400, and 500 rpm. After grinding, each sample was taken and placed in vibrating sieves to analyze the particle size. The remaining weight on each sieve was weighed and calculated. The graph between particle size and weight on each sieve for samples and with the conditions of each experiment are illustrated in figures, and the performance comparison results of the groups are shown and discussed as follows:

3.1.Insights from the First Group

The results describe a series of experiments, i.e., A1-A9, conducted under different conditions to investigate particle size and weight recovery samples. The experiments had a fixed input weight of 50g for each round. The results are presented in Figs. 8, 9, and 10. In Fig. 8, experiments A1, A2, and A3 are shown along with their respective conditions. Experiment A1 yielded the smallest particle size of 20μm with a weight recovery of 16.8g. The conditions for A1 included a speed of 300 rpm, a time of 10 minutes, and a fixed weight of 50g. It is noted that this weight recovery is the highest among the samples presented in Fig. 8. Figure 9 depicts experiments A4, A5, and A6.

Experiment A4 resulted in a particle size 20µm with a weight recovery of 17.9g. The conditions for A4 included a time of 20 minutes, a speed of 300 rpm, and a fixed weight of 50g. This weight recovery is highlighted as the highest among the experiments, as shown in Fig. 9. Finally, Fig. 10 displays experiments A7, A8, and A9. Particles having a size of 20µm and a weight recovery of 21.6g were created by experiment A7. For A7, the parameters were as follows: a fixed weight of 50g, a speed of 300 rpm, and a duration of 30 minutes. The weight recovery, shown in Fig. 10, is determined to be the highest among the experiments. These findings showed that, under the specified experimental conditions, experiments A1, A4, and A7 produced particles with a size of 20µm—obtained the largest weight recoveries. It implies that the samples' weight recovery increased due to these circumstances. Figures 8, 9, and 10 present the weight recovery and particle size comparison. Identifying the ideal experimental settings that produce the desired results is essential. Overall, these findings imply that the particle size and weight recovery of the samples were influenced by the speed, time, and weight. Particularly, among their groups, experiments A1, A4, and A7 conducted at a speed of 300 rpm—produced the highest weight recoveries. Also, particles with a size of 20µm were consistently produced by these trials.

3.2.The Second Group

The weight sample for each experiment in the second batch, consisting of experiments A10–A18, was 75 grams. Figure 11 shows experiments (A10-A12) with their conditions. The smallest particle size (20µm) and weight (3.2g) were obtained in experiment A10 at a speed of 300 rpm and 10 minutes. As for the highest weight, it was (29.7 g) for experiment A10 at 300 revolutions per minute with a time of 10 minutes and a particle size of (150µm). Figure 12 shows experiments (A13-A15). The particle size was (20µm) in experiment A15 with a weight of (6.8 g) at a time of 20 minutes and a speed of 400 rpm. The highest weight obtained was (29.4 g) for experiment A13 at a speed of 300 revolutions per minute, a time of 20 minutes, and a particle size of (106 µm. Figure 13 shows experiments (A16-A18), where the particle size was (20µm) in experiment A18 and weighed (10.977 g) at a speed of 500 revolutions per minute and a time of 30 minutes. The highest weight was (24.5 grams) for experiment A17, size 150 microns, time 30 minutes, speed 400 rpm. These results show that the experimental conditions, including speed, time, and particle size, influenced the samples' particle size and weight recovery. The smallest particle size achieved across all figures was consistently 20µm. However, the highest weight recovery varied among the experiments, depending on the specific conditions employed. The results presented here provide insights into the relationship between the experimental parameters and the resulting particle size and weight recovery.

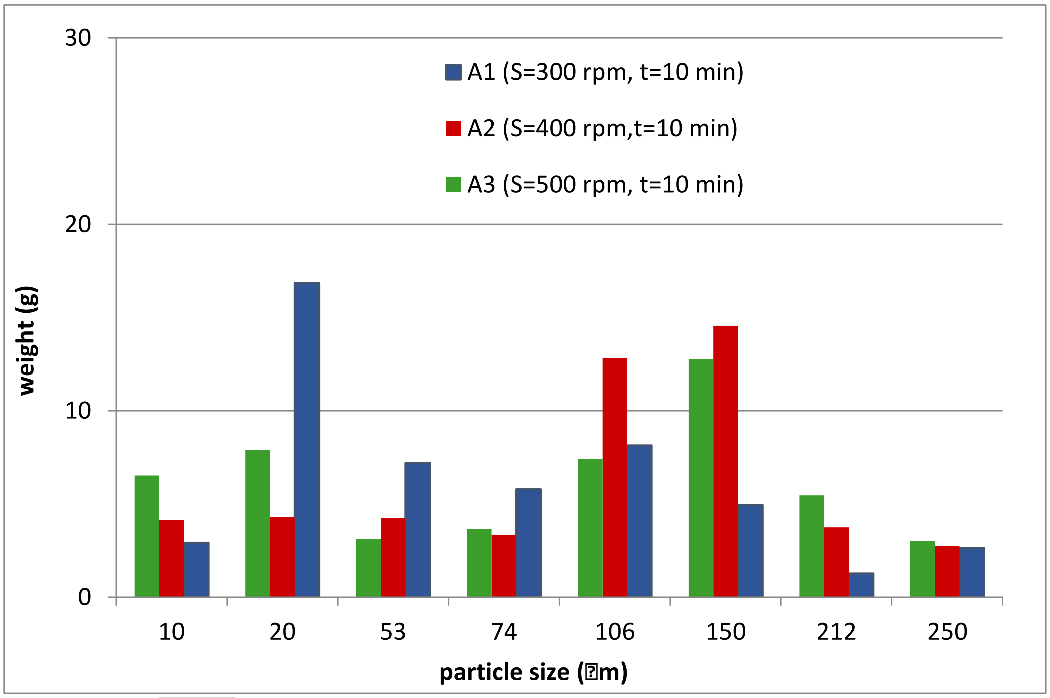

Fig. 8 Product Size Distribution for Samples (A1, A2, and A3).

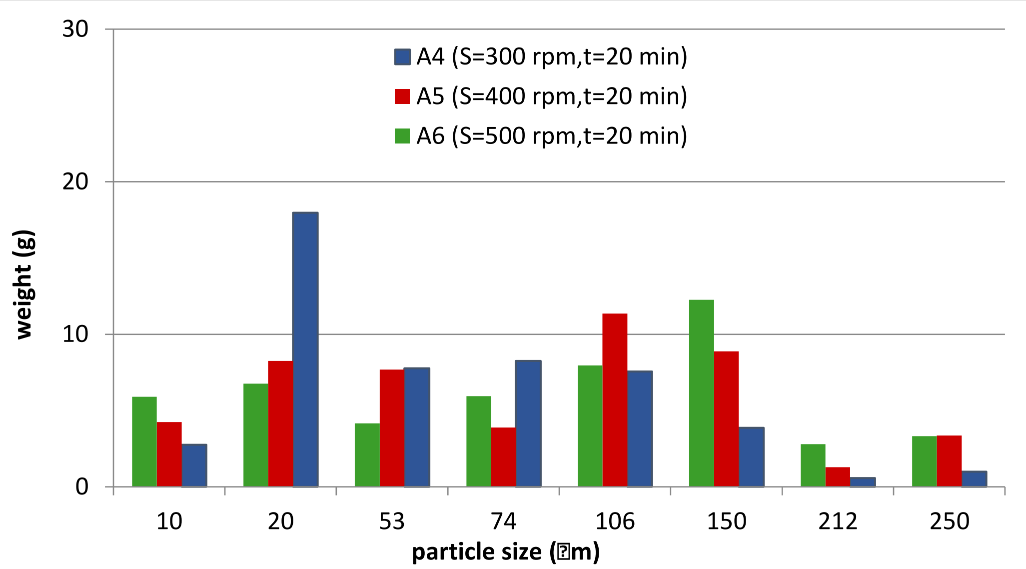

Fig. 9 Product Size Distribution for Samples (A4, A5, and A6).

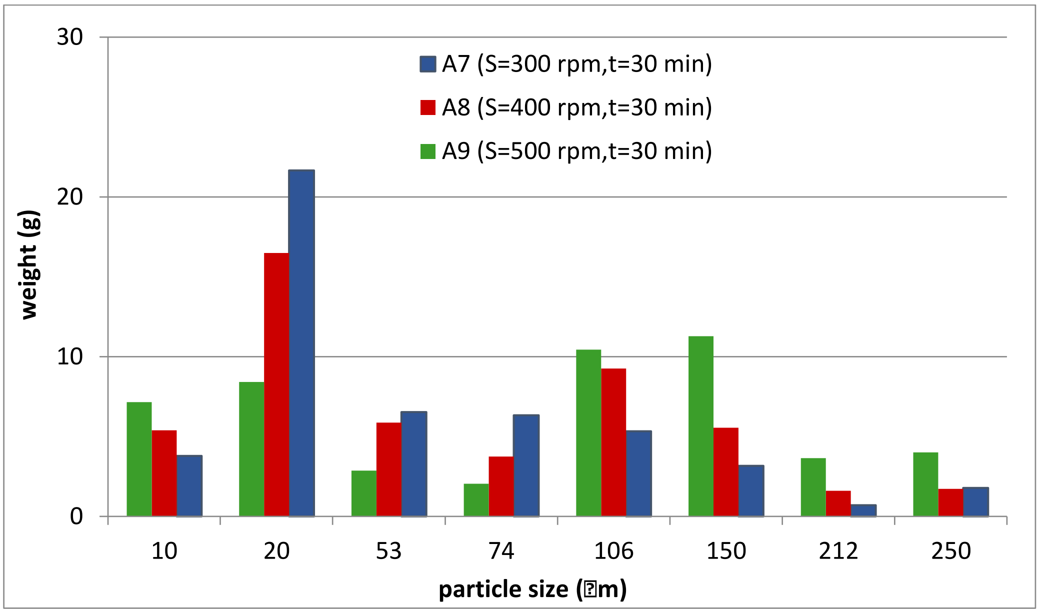

Fig. 10 Product Size Distribution for Samples (A7, A8, and A9).

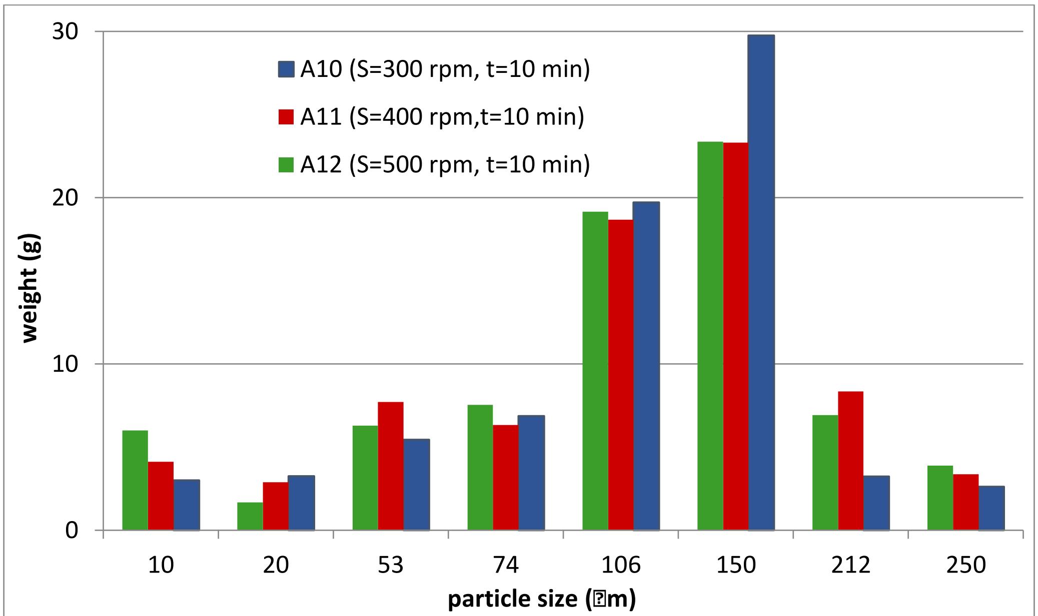

Fig. 11 Product Size Distribution for Samples (A10, A11, and A12).

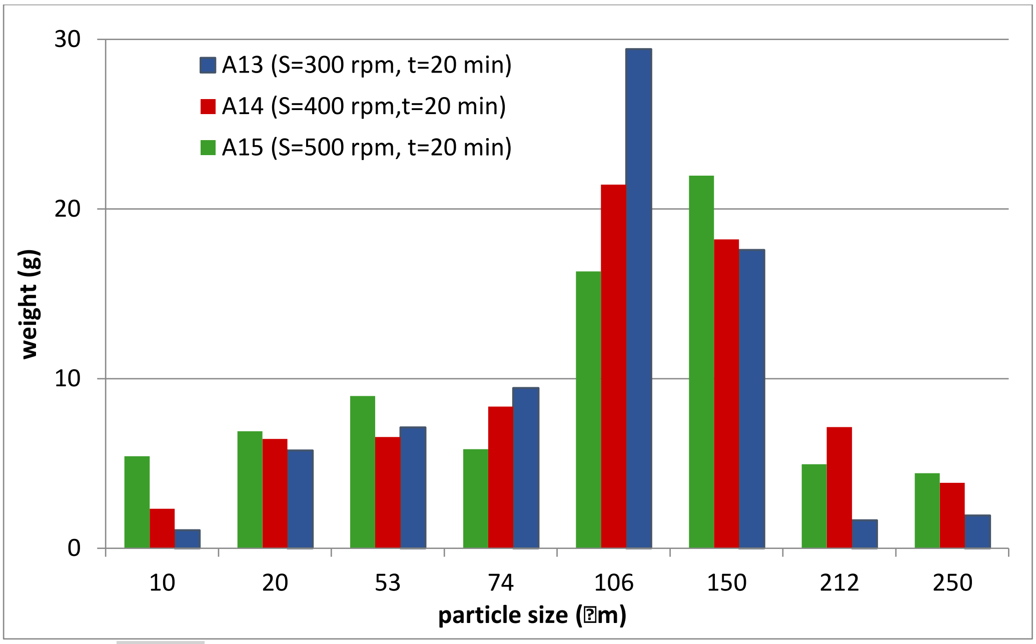

Fig. 12 Product Size Distribution for Samples (A13, A14, and A15).

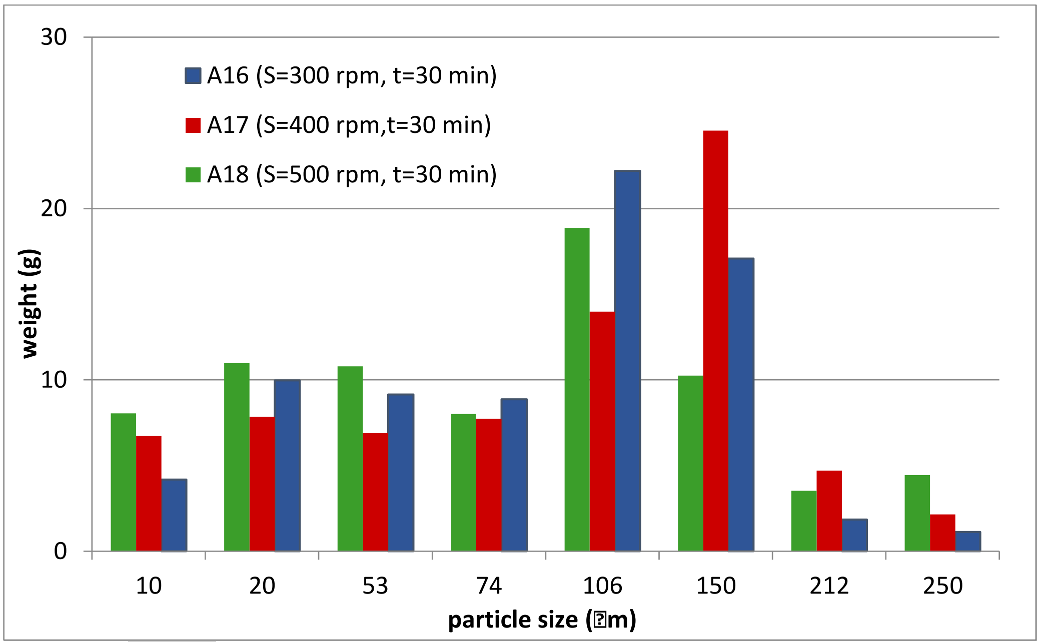

Fig. 13 Product Size Distribution for Samples (A16, A17, and A18).

3.3.Insights from the Third Group

As for the experiments (A19-A27), i.e., the third group, each sample from these experiments weighed 100 grams. Figure 14 shows the experiments (A19-A21) with their conditions. The experiment A19, at a speed of 300 revolutions per minute and a time of (10 minutes), had the lowest particle size (20μm), and its weight was (6.841 grams). The highest weight obtained was obtained in experiment A21, i.e., (38 grams), particle size (150 microns), speed 500 rpm, time 10 minutes. As shown in Fig. 15 shows experiments (A22-A24). In experiment A22, the smallest particle size, i.e., 20 microns, and weight (8.5 grams) were obtained at a speed of 300 rpm and 20 minutes. The highest weight obtained among the three experiments was (41 grams) for experiment A24 at a speed of 500 rpm and a time of 20 minutes. Figure 16 shows experiments (A25-A27). A particle size (20μm) and weight (19.8g) were obtained for experiment A26 with a time of 30 minutes and a speed of 400 rpm. The highest weight obtained was (37.6 g) and volume (106μm) in experiment A25 at a speed of 300 rpm and time of 30 minutes.

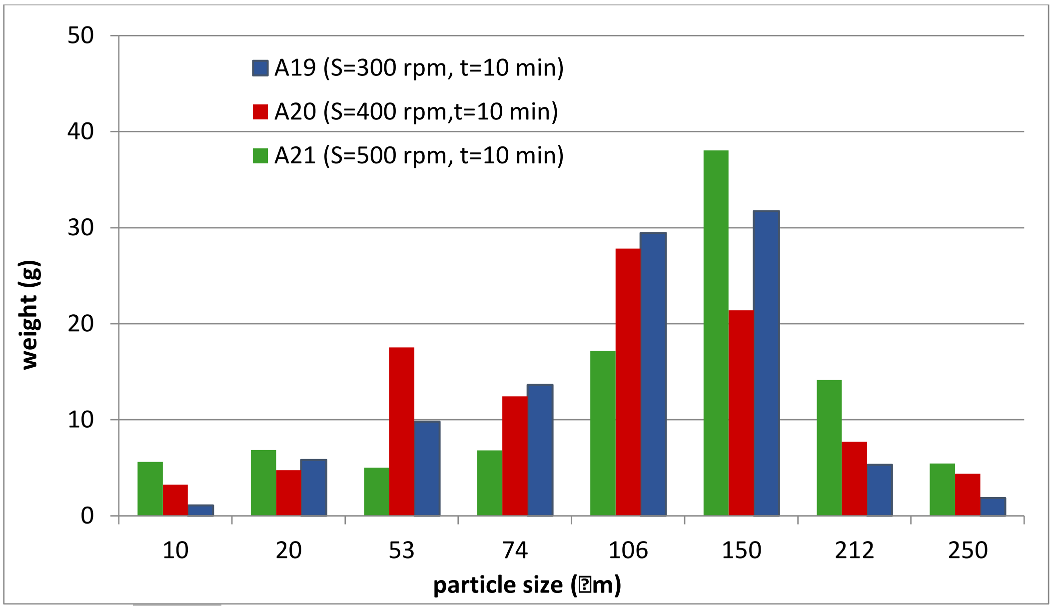

Fig. 14 Product Size Distribution for Samples (A19, A20, and A21).

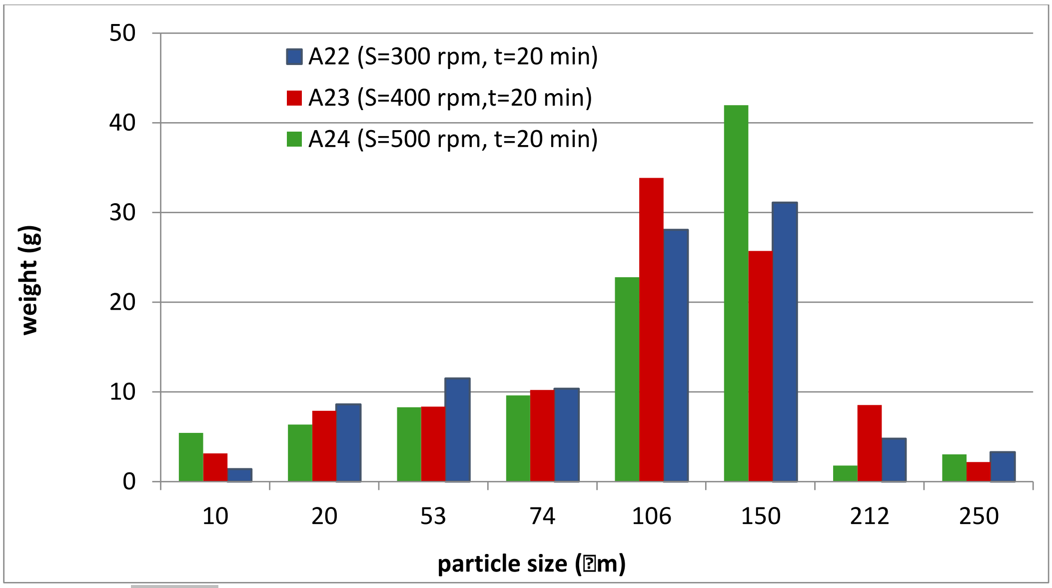

Fig. 15 Product Size Distribution for Samples (A22, A23, and A24).

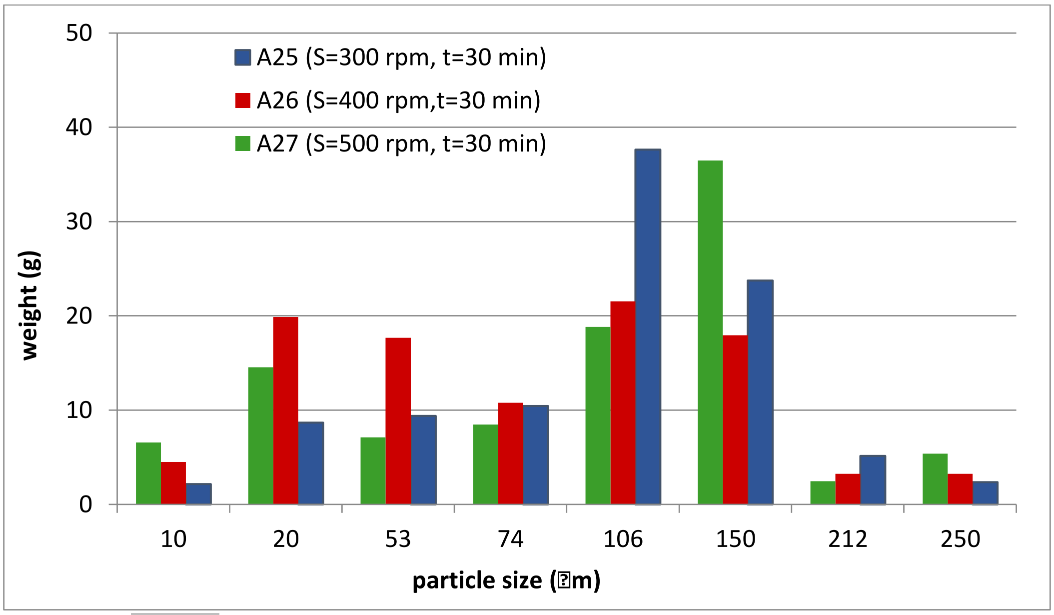

Fig. 16 Product Size Distribution for Samples (A25, A26, and A27).

From the above, it can be concluded that when the speed increased, the particle size decreased. Also, with the increase in grinding time, the particle size decreased due to the increase in the collisions between the particles with each other. On the other hand, the collisions between the particles and the grinding balls depleted their ability to maintain their size, and thus, the particles broke down, and their size decreased due to grinding. The smaller the particle size, the better the iron content through subsequent processes. The smaller the particle size, the greater the release of metal from impurities and the greater the percentage of free iron, leading to its easy separation in subsequent processes.

4.CONCLUSIONS

It can be concluded from the above that the smallest particle size obtained was 20 microns, and the highest weight was 21.6 grams in experiment A7, i.e., the time was 30 minutes, the speed was 300 rpm, and the internal weight was 50 grams. The highest recovered weight was 41 grams with a particle size of 150 microns in experiment A22, i.e., a time of 20 minutes, a speed of 500 revolutions per minute, and an internal weight of 100 grams. Therefore, as the grinding time increased, the size of the ore particles decreased, thus increasing the releasing of the closed ore particles leading to higher efficiency. The present investigation studied increasing the surface area and making it easily attracted to the magnetic field or during froth flotation. Therefore, the ore results from this study can be used in several processes, such as froth flotation, magnetic separation, and gravity separation. The new surface area decreased as the weight of the ore feed inside increased. The results are consistent with Tukarambi et al. [21] at similar speed and weight. However, at different times, it was noticed that the particles became smaller and finer as time increased. Therefore, it t optimizing the ore feed weight, mill speed, and grinding time is important to achieve the desired grinding efficiency, product fineness, and overall process performance. To conclude, the present study found the correct balance between the ore feed rate, mill speed, and grinding time.

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NOMENCLATURE

A	Experiment symbol
cm	Centimeter (unit of length measurement)
F	Figure
g	Gram (unit of measure for mass)
min	Minute (unit of measuring time)
mm	Millimeter (unit of length measurement)
rpm	*rotation per minute (Rotary speed measuring unit)*
s	Speed return, rpm
t	Time, min
w	Weight, g
ASTM	American Society for Testing and material
Greek Symbols	
μm	Micrometer (unit for measuring the size of particles)

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