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Full Length Research Paper

Analysis of Ore Hand-Crushed Size Distribution for Grinding Process in the Artisanal and Small-Scale Gold Mines Production: A Case Study of Nholi Mine, Bahi District

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ABSTRACT

In many parts of the world, artisanal and small-scale gold mines (ASGM) employed numbers of people compared to large-scale mines. The ASGM has been played a crucial role in poverty alleviation and rural development, particularly in developing countries. The mined ore is crushed and ground for beneficiation of gold. The grinding process involved the size reduction of blasted materials to acquire minerals of interest. This paper presents the size distribution of hand-crushed for blasted materials using sieve analysis and digital image processing. The sieve test results for hand-crushed blasted material of three muck-piles were ranged between 17 mm and 36 mm that is equivalent to 20% and 80% passings respectively, with an average of 26 mm. The digital image processing results were about 19.8 mm for 20% passing and 58 mm for 80% passing, with an average of 36.06 mm. The hand-crushed provided a wide range of material distribution than the required size in the grinding unit and increased oversize by 18%. The hand-crushed of blasted materials provides different sizes distribution leading to increase the residence time and power consumption of the grinding units.

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INTRODUCTION

Artisanal and small-scale gold mining (ASGM) is typically characterized as the activity of individuals or groups extracting alluvial and placer mineral deposits, it can be illegal or legal, formal or informal, and inefficiently (Labonne 1996, Gunson and Jian 2001). This mining activity has been around since the history of civilization to produce ornaments, decoration, tools, and shelter, as well as stimulate economic growth (Hilson 2009).

Tanzania has a diverse range of mineral resources that cater to small-scale miners. These include gold, gemstones (including diamond), metallic ore, and industrial minerals. Gold extraction accounts for around two-thirds of miners in Tanzania (Mutagwaba, Tindyebwa et al. 2018). The miners have conducted their daily activities without any geological or technical knowledge. Most of the ASGMs of Tanzania are located in the greenstone belt which is south, east, and west of Lake

Victoria, the central zone (Singida and Dodoma region), and alluvial gold in Chunya. The market-based approach to mineral sector development has been in place since the late 1980s and opened up Tanzania's resources to new organizational actors and interests, significantly altering the role of mining in the economy (Fisher 2008). Currently; the contribution of the mining sector in Tanzania is about 15.3% to the country's GDP as a result of mineral sector reforms made late in 2017 (AMM 2020). The reforms also have benefited the ASGMs following the provision of mining licenses and put in place guidelines and policies and exemption from some tax payments (withholding tax 5% and 18% VAT) for their empowerment. The production cycle for Tanzanian ASGMs goes through drilling, blasting, rock support (mostly using timbers), hoisting, crushing, milling, sluicing, or panning and heating of obtained gold amalgamate to evaporate the mercury.

Several methods have been applied to predict and analyze the distribution of material sizes in mining including direct and indirect methods. Direct methods involve sieving of the muck pile and weighs the different sizes; normally the method conducted at the site or using representative sample. Indirect method involves the use of observational methods like counting the particles and so forth, use of empirical methods, imagery analysis, and shovel loading rate method (Bamford, Esmaeili et al. 2016, Babaeian, Ataei et al. 2019, Nanda and Pal 2020). The sieve analysis techniques among the mentioned methods is the one that generates more consistent result (Bamford, Esmaeili et al. 2016). The evolution of computers has facilitated the use of an image and computer languages in analyzing blasted rock distribution.

The crushed materials were fed into grinding mills without controlling the particle size and shape (Govender, Rajamani et al. 2018). The uncontrolled particle sizes lead to increase the residence time of the material in the mill or grinding time, increase in power consumption, clogging of the hopper, and generally increasing the operating cost of the mill. Knowing that the purpose of grinding is to reduce the ore to the size that it can liberate the mineral of interest. The grinding increases the surface area hence increasing the rate of a chemical reaction during the dressing of the mineral (Stamboliadis, Pantelaki et al. 2009, Guo, Yan et al. 2016). Over milling and under milling result in the loss of minerals of interest as fine or as a middling respectively (Bradley, Lloyd et al. 1972).

The crushed size distribution fed to the grinding unit affects the grinding process throughout (Workman and Eloranta 2003). The increase in operating cost and loss of mineral of interest due to poor crushing decreased the gross profit. This study aims on evaluating the hand-performed crushing activity on the blasted or mined ore by analyzing the size distribution and shape angularity. This would help the small-scale miners to optimize the crushed size of the material before feeding to the grinding unit. The sieving method and digital image analysis were used to analyze the hand crushed distribution. Several images were taken from muck piles after crushing handly and been analyzed using WipFrag software. The same sample was sieved for size distribution using mesh of different sizes.

Distribution of Crushed Materials

The purpose of crushing is to obtain material that fits the requirement for the grinding unit. There are two types of means of crushing blasted rocks includes using a machine powered with diesel oil or electricity or using manual means. In large-scale mines, the crushing is done by using mechanized crushing equipment such as jaw crusher, gyratory crusher, cone crusher, and so forth. The control of the size of the material as a feed to the grinding unit in a large scale mine is done by using a size control unit which is a screen for coarser material and a spiral classifier for fines. In the case of small-scale miners, this is rarely, crushing is done using the sledgehammer of a different type (Figure 1) and different location as shown in Figure 2. The sledgehammer crushing production ranges between 2 to 3 bags (Figure 3) of 50–70 kg depending on the productivity of the worker, working hours, and availability of the ore (Merket 2018). The crushed materials are fed directly to the grinding unit. Crushing and grinding are energy consumer processes in mineral extraction. About 36% of the energy used in mining is consumed by crushing and grinding units (Somani, Nandi et al. 2017).

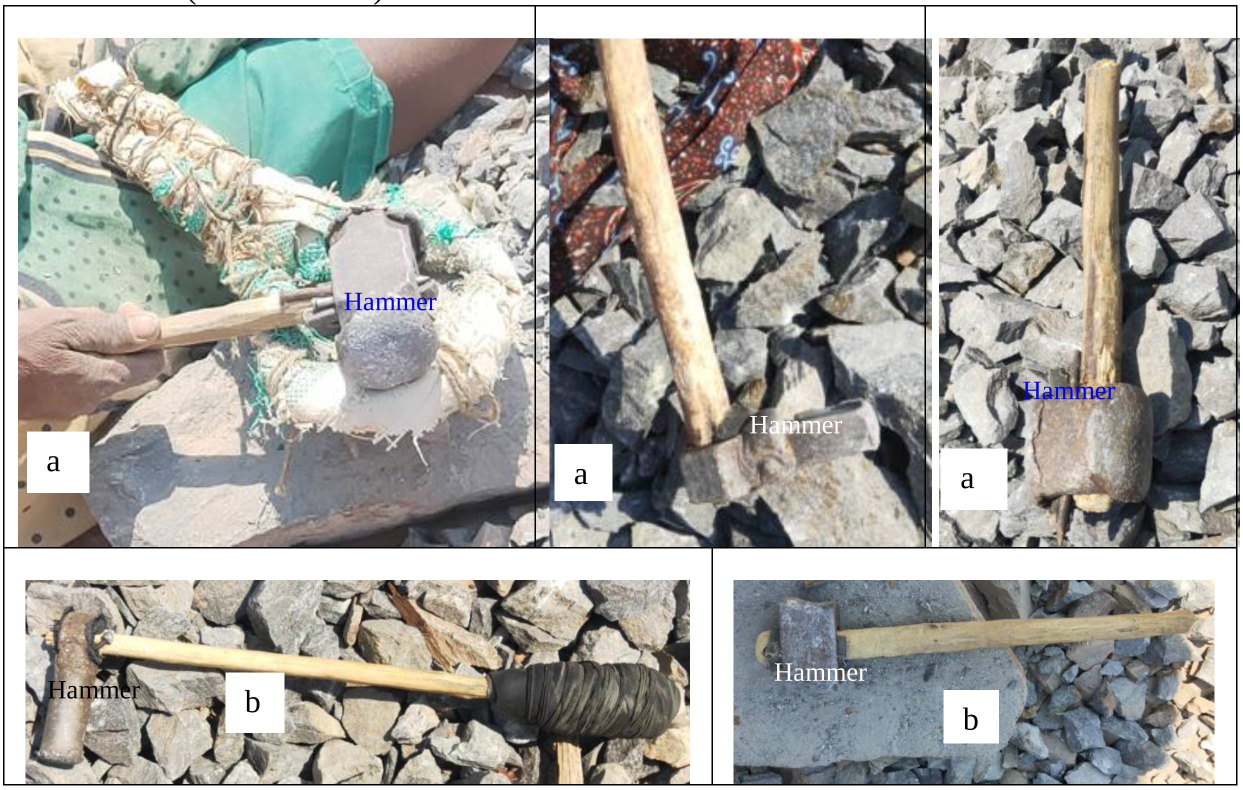

Figure 1: Different types of hand-hammers with wood handles for crushing rocks (a) with two sides for crushing rocks (b) One side for crushing rocks.

a) Sledgehammer at Nholi mine

b) Sledgehammer in Shinyanga (Merket 2018)

c) Mortar and pestle in Mozambique (Veiga, Metcalf et al. 2006)

Figure 2: Ore crushing using different manual techniques in different ASMG.

Figure 3: Bags of blasted rocks after hand crushed.

MATERIAL AND METHODS

Study area

The study area is located in the central part of Tanzania in the Dodoma region in the Bahi district. The Nholi mine is at the Mpangala ward in the Nholi village approximately 50 Km South-West of Dodoma city with the 35°18' longitude and 5°18' latitude. The gold mining operations in the area are done by small-scale miners using low technology with low investment capital. The geological setting of the area is dominated by granulated and sheared synorogenic granites as well as unsheared late-orogenic granites (Gabert 1990, Kabete, Groves et al. 2012, Macheyeki, Delvaux et al. 2012).

Design and fabrication of wire mesh

Mechanical process of separating particles of varying sizes was done using a screening surface known as mesh. A mesh accepts particles that pass through and rejects or retains material that is larger than the mesh's size. The design and fabrication of a wire mesh pass through several steps: (i) determination of the length and width of the screen deck for efficiency and capacity determination and (ii) determination of the size of the mesh. The ratio of the length of the deck to the width of the deck ranges between 2.5 and 3 for effective screening. The size of the mesh is determined by dividing the length of the deck by the number of pitches and then subtracting the diameter of the wire used.

Data type and collection

To meet the objective of the study different data were collected, this includes different images from the different hand-crushed stockpiles and screened material per mesh size. The image was taken using the Canon EOS 60D camera. The net mass retained by each mesh after sieving was obtained using the beam balance and dimensions of the crushed rock obtained using the ruler. Sieving was done using the fabricated wire mesh.

Site measurement for hand-crushed rocks

A sieve is a wire screen with a uniform specific size of openings. Four wire mesh tray sized 74 mm, 39 mm, 23 mm and 16 mm were arranged in order of decreasing in size; the large mesh was placed at the top and the small mesh at the bottom as shown in Figure 6. A known mass of the hand-crushed material was placed to the top mesh and the mesh was shaken. The smaller size than the mesh size passed to the next mesh and so on up to the bottom container for collection. The mass of the crushed material that remained on the mesh was determined by measuring using a mass balance and the percentage retained was obtained using equation 1. The cumulative percentage pass of the material is obtained by subtracting the cumulative percentage retained from 100% as shown in equation 2. The graph of cumulative percentage pass against mesh size is plotted on a semi-logarithmic scale for particle size distribution analysis.

$$\%\ Retained = \frac{weight\ of\ retained\ material}{Total\ weight} \times 100\% \quad (1)$$

$$\%\ Commulative\ pass = 100\% - \%\ commulative\ retained \quad (2)$$

The WipFrag software

The Wipfrag software was used to analyze the particle size distribution of the crushed material using digital image analysis. Wipfrag is a program for analyzing digital images captured with a digital camera and evaluating the particle size distribution of fragments. WipFrag and its predecessor WIEP have been designed to take full advantage of the flexibility of general-purpose microcomputers since their inception about ten years ago. In contrast to a purpose-designed image analyzing computers, which because they are designed for metallurgical or medical use impose several undesirable constraints on their use in mining and quarrying (Maerz, Palangio et al. 2018). The acquired image for analyzing particle size distribution passed through several stages, including loading, assign a scale, generating nets, editing and finally output generation. The image was scaled using a control object whose length was known and placed in the material during the image capturing process. The generated aggregate net was edited to correct the disintegration and fusion error. The image used in this software covers the entire dimensional spectrum of fragments (including large- to fine-sized fragments), obtained in such a way that there is no shade and benefits from uniform lighting, and the camera lens was placed as normal as possible to the muck pile during imaging.

Gradation of hand-crushed rock

The particle shape classification of hand crushed material is important for the effectiveness of the grinding unit (Govender, Rajamani et al. 2018). The variable edges and irregular surfaces bringing the challenge during particle measurement. To classify the particle shape, many indices such as particle parameter, convexity, sphericity, and shape factor have been proposed (Park, Lee et al. 2020). However, in this study, classification of particle shape using the sphericity index has been adopted as described in (Krumbein 1941). A particle's sphericity is the ratio of the surface area of a sphere of the same volume to the actual surface area of the particle (Park, Lee et al. 2020). The sphericity index (ψ) is calculated using Equation (3) and coefficients ranged between 0.1 and 0.9. A very irregular particle has a sphericity of 0.45, a near-sphere particle has a sphericity of 0.9, and a spherical particle has a sphericity of 1. The particle shape is angular when the sphericity index is less than 0.1. The particulate's largest, middle, and smallest diameters are shown in Figure 4.

$$\psi^3 = \frac{b \times c}{a^2} \quad (3)$$

The uniformity coefficient (C_u) and coefficient of gradation (C_g) from equations 4 and 5 are used to define the distribution of fines, mediums, and courses in the pile (Azizi 1999).

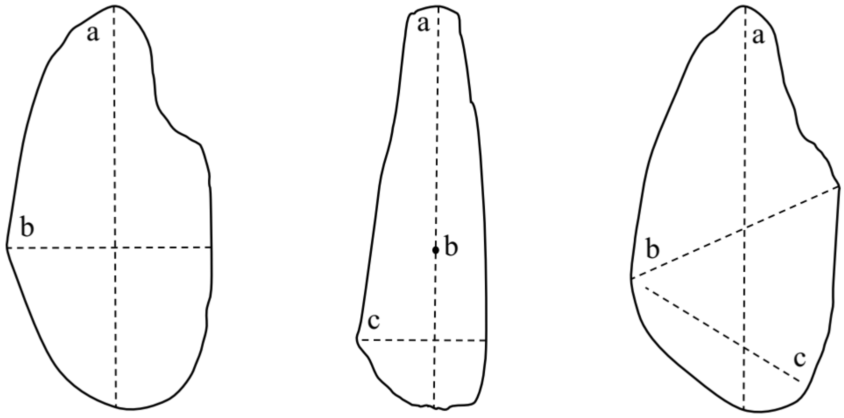

Figure 4: Definition of particle dimension (Park, Lee et al. 2020).

The coefficient of uniformity is used to determine the dominant size, whereas the coefficient of gradation is used to determine the shape of the particle size curve (Nanda and Pal 2020). The grain size distribution is uniform for C_u values less than 5, medium uniform for C_u values 5 to 15, and nonuniform for C_u values greater than 15. C_g values of 1-3 indicate that the crushed rock is well-graded(Azizi 1999); otherwise, it is poorly graded.

$$C_u = \frac{D_{60}}{D_{10}} \tag{4}$$

$$C_g = \frac{{D_{30}}^2}{C_u \times {D_{10}}^2} \tag{5}$$

where D_{10}, D_{30}, and D_{60} are the grain sizes that correspond to 10%, 30%, and 60% of the sample passing by weight, respectively.

RESULTS AND DISCUSSION

Design and fabrication of wire mesh

Four-wire meshes tray were fabricated with an average aperture size of 74 mm, 39mm, 23 mm, and 16 mm as shown in Figure 5. Steel of 6 mm diameter was used to develop interconnects for each tray. The designed length of the deck was 70 cm and the ratio of length to the width was 2.5. During the data collection the mesh trays were arranged from the largest to smallest in size as shown in Figure 6.

a) 16 mm sized tray	b) 23 mm sized tray	c) 39 mm sized tray	d) 74 mm sized tray

Figure 5: Fabricated mesh trays.

Figure 6: Arrangement of mesh during measurement of hand crushed rocks.

Size distribution of hand-crushed material for different mesh sizes

Percentage mass of measured hand-crushed rock

During the sieving, a known mass of crushed ore was fed into a mesh arranged in ascending order and shook for some minutes. Afterward, the material retained in each mesh its net weight was obtained using the beam balance as presented in Table 1. The cumulative percentage pass of hand-crushed rock per mesh was obtained using Equation (2). The distribution of crushed ore was analyzed by plotting the graph of a cumulative pass against mesh size in a semi-logarithmic scale as shown in Figure 7.

Table 1: Crushed ore distribution after sieving per mesh size

Wire mesh size (mm)	Material distribution by weight (kg)		
	Sample 1	Sample 2	Sample 3
74 mesh tray 1	0	0	0
39..mesh tray 2	8	8	8
23..mesh tray 3	35	27	28
16 mesh tray 4	10	12	11
Container/Pan	5	17	18
Total	58	64	65

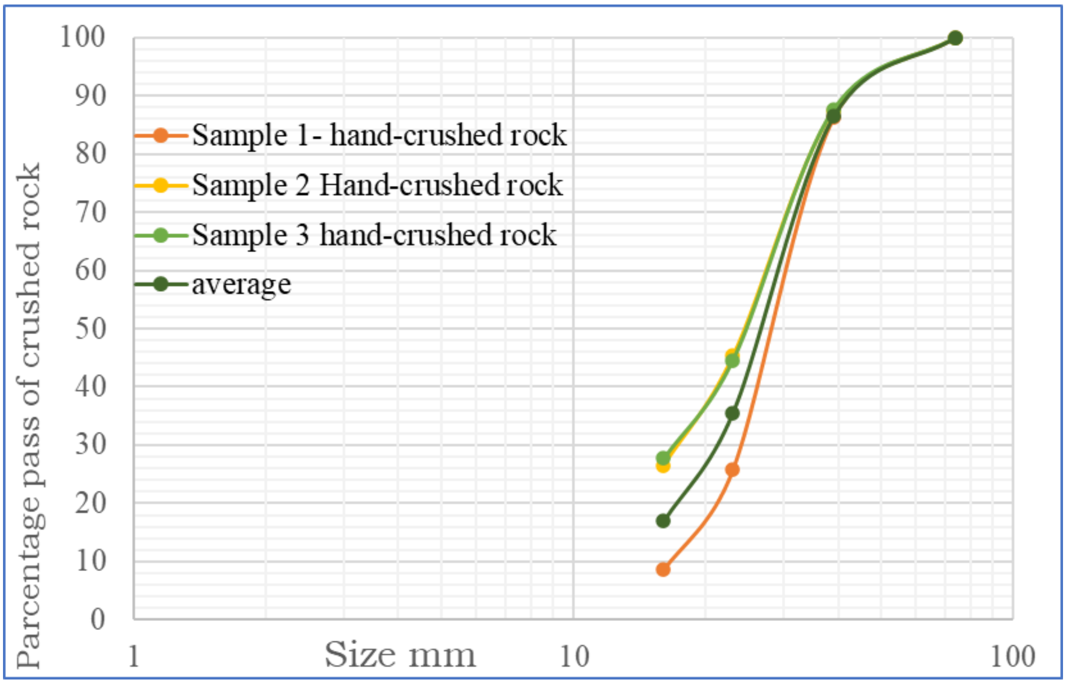

Figure 7: Cumulative curves of three sieved hand-crushed sample.

Crushed rock distribution analysis for each mesh using Wipfrag software

The distribution of hand-crushed rock retained in each mesh is presented in Figure

8. When the mesh size of 16 mm, the average crushed size (X_{50}) was 19.98 mm, and the characteristic size, which was defined at 63.2% of passing size was 25.73 mm. With the mesh size of 23 mm, the mean crushed was 24.22 mm, and the characteristic size of 31.15 mm. Again, using a mesh size of 39 mm, the mean size crushed size was 39.12 mm, and the characteristic size of 39.82 mm.

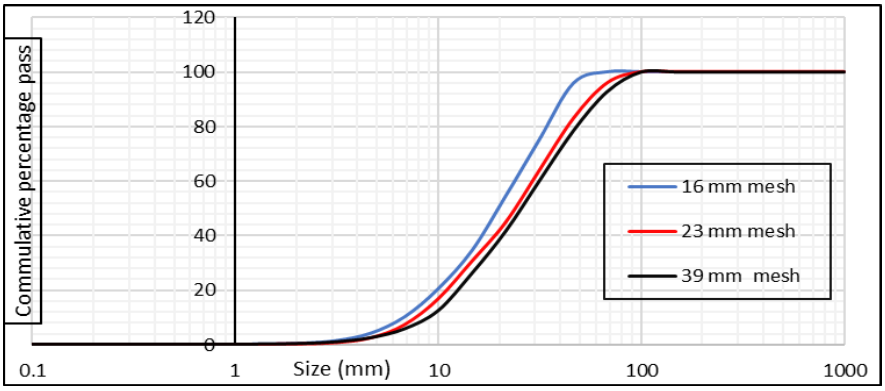

Figure 8: Distribution of retained hand-crushed rock by size in each mesh.

Size distribution of hand-crushed material for different stockpiles using WipFrag software

The rocks were crushed into ten different locations within the study area. Figure 9 presents the distribution of the crushed rocks with a mean of 36.06 mm and a characteristic size of 43.52 mm. About 3.47% of the material had a size less than 2.15 mm and 9.06% of the material with a size between 68.10 mm and 147 mm. Most of the material (86.84%) had a size between 2.15 mm and 68.10 mm with an average size of 36.06 mm. 80% of the crushed rock passed through the mesh size of 58 mm and 20% passed through a mesh size of 19 mm as shown in Figure 9 analyzed using WipFrag software.

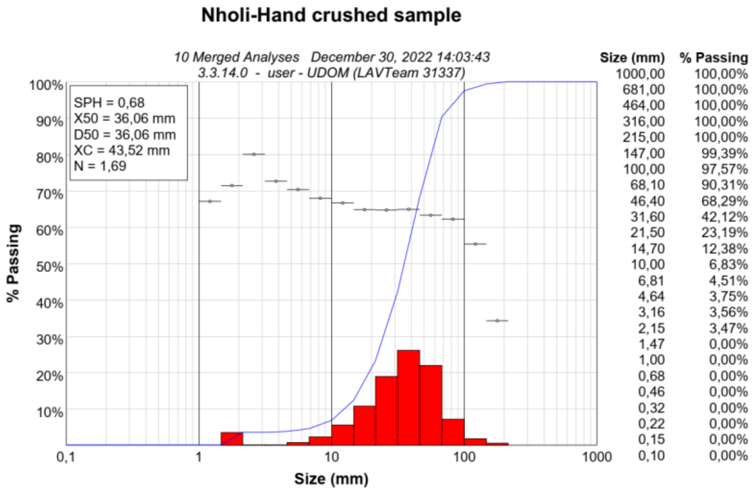

Figure 9: Histogram and cumulative size curve of eleven merged image.

Hand-crushed rock gradation

A total of 14 samples were analyzed. Table 2 shows the calculation of the sphericity index using Equation (3). The selection of the sample was performed randomly in a hand crushed rock pile. An average of the value of 0.72 of sphericity was obtained.

Analysis of sphericity index using the WipFrag software gives an average value of 0.68 as shown in Figure 9. The average value of Cu and Cg was calculated from 9 samples and obtained as shown in Table 3. An average value of 2.7 for Cu and 1.0 for C_g indicates that the hand-crushed rock material was uniformly distributed and well graded.

Table 2: Sphericity index measured for the randomly selected sample

Sample (1 – 7)							
Parameter	**1**	**2**	**3**	**4**	**5**	**6**	**7**
a (cm)	7.2	5.9	10	6	6.5	7	7.5
b (cm)	4.7	3.5	6	5	5.2	5	4
c (cm)	6	4	4	3	4.5	4	3
ψ	0.82	0.74	0.62	0.75	0.82	0.74	0.60
Sample (8 – 14)							
Parameter	8	9	10	11	12	13	14
a (cm)	8.3	5.1	6	7	6	4	5.5
b (cm)	5	2	3.2	5	3	4	3
c (cm)	5.2	3	3.1	4.2	4	3.2	2.2
ψ	0.72	0.61	0.65	0.75	0.69	0.93	0.60

Table 3. The calculated value of Cu and Cg

Parameter	**Image**									**Average**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
D_{10}	22.8	13.7	1.8	7.5	8.5	16.3	12.8	12.9	13.5	12.2
D_{30}	33	22	3.1	13	16	25	22	20	23	19.7
D_{60}	51	38	5	23	26	38	33	31	40	31.7
C_u	2.2	2.8	2.8	3.1	3.1	2.3	2.6	2.4	3.0	2.7
C_g	0.9	0.9	1.1	1.0	1.2	1.0	1.1	1.0	1.0	1.0

Post-grinding rocks that remain unground

This research was carried out using existing grinding mills and their daily operating conditions, which included an average rotational speed of 160 rpm, a material residence time of 45 to 60 minutes, and a total of 1300 balls, 400 of which had a diameter of 80 mm, 600 of 60 mm, and 300 of 40 to 50 mm. Figure 10 depicts the unground material that remains after grinding and is sorted at the ground material sluicing point. A WipFrag was used to analyze the size characteristic of the unground materia, and the distribution is illustrated in Figure 11. The unground rock has an average size of 26.07 mm, a characteristic size of 31.41 mm, and a sphericity index of 0.65.

Figure 10: Ungrounded material after grinding process.

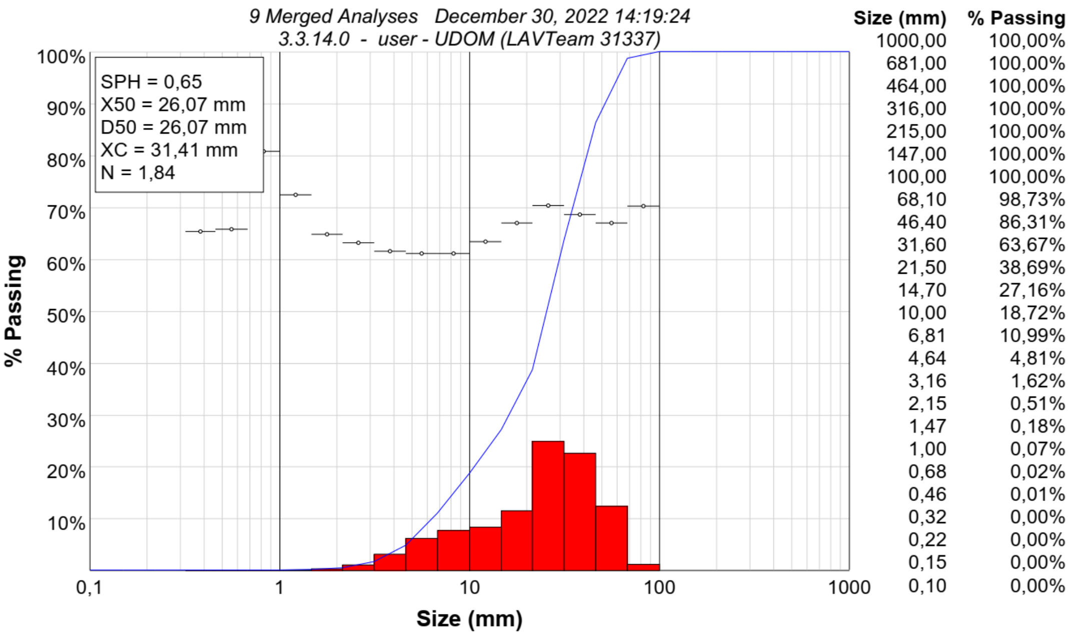

Figure 11: Size distribution of unground material after grinding.

CONCLUSION

The handcrushed rock has been analysed at Nholi small scale mine. The handcrushed for the surveyed muckpiles were uniformly distributed and well graded, but the activity accompanied with the closely supervisor to inspect each bag of hand-crushed ore materials. The emergency of unground material at the silucing point makes the further studies to be in the grinding mills operation conditions to analyze the number of balls, rotation speed, residence time and filled capacity of the grinding mill.

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