Investigation of Grain Size Distribution of Conveyed Copper Ore for Modelling Ore Flow through a Bunker

Piotr J. Bardziński¹, Błażej Doroszuk¹, Witold Kawalec¹,* and Robert Król¹

¹ Department of Mining and Geodesy, Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
witold.kawalec@pwr.edu.pl

Abstract. Knowledge of the particle size distribution of mined ore enables improvement of the main processes of the whole mining value chain: blasting, ore loading and haulage and ore processing. Photogrammetry with image analysis techniques was proposed for the on-line identification of grain size distribution of conveyed ore. Preliminary laboratory tests were performed on the experimental belt conveyor to evaluate the quality of photographs for various camera settings. Grain size distribution of transported copper ore was determined on the basis of photographs taken over the main haulage conveyor that feeds mined material to the underground ore bin located at skip-filling station of the winding shaft. Size distribution slope was calculated using the Split Desktop 4.0 software package to estimate the degree of rock fragmentation. Fine fractions (<10 mm) accounted for more than 40% of transported bulk material. Such a large portion of fine fraction may be attributed to the lithology of conveyed material. Individual rock lumps 600 mm or larger constituted a minor part of the total amount of mined ore. The actual ore granulation influences ore flow through the bin, which was simulated using a discrete element method model to obtain information about the ore stream leaving the winding shaft.

1. Introduction
Information about grain size distribution is important for process optimisation in numerous industries [1–3]. In the mining industry, methods used for the analysis of the particle size distribution in the run-of-mine material are used to effectively evaluate the quality of drilling and blasting operations [4]. The development of technologies focused on measuring parameters related to the particle size distribution in the mined material is not only useful in adjusting blasting parameters to the particular geological and mining conditions but also enables continuous monitoring and evaluation of the effects of blasting operations [5–7], [8], [1], [9]. To maintain high productivity levels in modern mining facilities, information about grain size distribution is also used to select suitable haulage equipment and to improve the efficiency of bulk material delivery processes [10] as well as to reduce energy consumption in ore processing operations [5], [11].

Setting new energy efficiency standards for ore processing has become an objective for improving ore processing control in ore concentration plants [12], [13]. This improvement, however, depends on the level of identification of ore batches supplied to the ore processing plants. Because the transported ore is mixed in ore bins, the discrete element method (DEM) is used to model the ore flow there [14]. For this purpose, the size of the rocks that compose the modelled stream of material loaded into the ore bin must be precisely determined.
Available methods for measuring the size of transported materials can be classified as either direct or indirect methods [15], [16]. The direct methods involve screen classification or flow classification, which requires direct contact between the particles and the screening sieve to enable their comparison [17]. Because of the mass of the transported run-of-mine material and the substantial labour demand of the screening procedures, the current research has been based on an indirect method involving image analysis [18], [1], the accuracy of this method relies on a comparison of the size of the fragmented rock with the size of known objects. Computer applications for this purpose are under constant development and improvement and are becoming increasingly popular [19], [8], [1].

This paper presents the results of research into the grain size distribution of copper ore transported on belt conveyors. The results enable the determination of the time required for the ore grains to flow through the bunker as it is filled to various degrees. The grain size distribution was measured with the Split Desktop 4.0 computer application using photogrammetric techniques. The analysis was performed on photographs collected in situ by the authors.

2. Materials and Methods
To avoid time-consuming methods that require direct contact with the mined ore, its fragmentation was assessed using a photogrammetric method. The grain size distribution in the transported material was determined on the basis of photographs taken over the main haulage conveyor that feeds mined ore to the ore underground bunker located at the skip-filling station of the winding shaft. The photographs were taken at uniform time intervals for 1.5 h, which is equivalent to the time needed to fill the bunker to its full capacity. The aforementioned step enables the slope of the grain size distribution to be determined for the amount of rock material needed to completely fill the bunker.

The size distribution slope was calculated with the Split Desktop 4.0 software, which enables the degree of rock fragmentation to be estimated. The application uses its embedded algorithms to find lumps of rock material and provides them with the third dimension by rotating the ellipse formed on the axes drawn on the surface of the lump. In the subsequent step, a special statistical algorithm adds corrections to the marked area. In the case when forming a solid body on a certain area is impossible, the application generates a hypothetical grain size slope for fine fractions [9]. The possibility of forming a solid body on a particular area is largely determined by the quality of the base material: the higher the quality of the photographs, the more accurate the grain size slope. The choice was also influenced by the recommendations of Maerz and Zhou [7], [1], and Sanchidrian et al. [9], who suggested that the photographs should be taken of rock material on belt conveyors to eliminate the error caused by a substantial portion of material remaining hidden from view after being piled into the bunker.

Taking photographs of rock material on belt conveyors also enables adjustment of the light intensity, which is impossible in the case of piled material [4], [9]. Therefore, prior to in situ tests, preliminary laboratory tests were performed to verify the camera settings suggested in the literature [20–23], [7], and to select an optimal variant. These tests were carried out on an experimental belt conveyor [24–25] equipped with a frequency converter that enabled control of the belt speed. A conveyor belt with specially prepared and marked defects was used to evaluate the quality of photographs for various camera settings. A darkened room simulated the conditions characteristic for an actual belt conveyor operated in an underground mine (Figure 2a).

After testing alternative camera settings in the laboratory, further industrial tests were based on a variant in which both the defects and their marks exhibited the highest sharpness. The in situ tests were performed on the P1 belt conveyor, which functions as the main haulage conveyor and transports mined copper ore to shaft L-II from the LW (Lubin-East) area (Figure 1).
Grain size distribution was measured on a section of the belt conveyor line located approximately 300 m from the discharge station, from where mined ore is fed through a boom conveyor to bunker S. The measurement apparatus comprised a camera mounted on a tripod to allow adjustment of the field of view to cover the full belt width. For safety reasons and to eliminate the vibrations on the camera caused by pushing the shutter release button, the photographs were taken using a remote control.

The camera was positioned in a plane perpendicular to the plane of the belt conveyor to eliminate unwanted distortions and errors related to the camera settings (Figure 2b).

In the next step, a series of 15 photographs were taken at 6 min intervals. With the conveyor capacity of 800 Mg/h, this time corresponded to the time required to completely fill underground bunker S (which has a capacity of 1040 Mg). A stop watch was used to properly time the intervals. Figure 3 shows sample photographs representing various fragmentation levels of the transported ore.

**Figure 1.** A fragment of the underground transportation system of the Lubin copper ore mine with indicated belt conveyor P1.

**Figure 2.** The measuring apparatus in the two test locations: a) laboratory and b) in situ.
3. Results and Discussion

The size of rocks visible in the photographs was preliminarily scaled using two techniques. The first technique used added objects of known size to the transported ore. The objects were orange table-tennis balls with a diameter of 40 ± 0.4 mm. The second technique involved using the known belt width, which was averaged (because of local edge defects) on the basis of three measurements performed on various belt sections, in accordance with the approach suggested in the literature [7]. The accuracy of the two methods was similar, and the choice of belt width as reference was dictated by the fact that photographs involving table-tennis balls need to be taken while the belt conveyor is stopped, which is problematic under real operating conditions. Moreover, to increase the effectiveness of contour detection in the fragmented rock, the photographs were sharpened by applying an adequate contrast in the Split Desktop application. The obtained results are shown in Figure 4.

![Figure 4](image)

**Figure 4.** Comparison of photographs before (on the left) and after (on the right) the contrast was applied

To generate a combined size distribution slope, all of the photographs were imported into and subsequently processed in the Split Desktop 4.0 application. Each of the photographs was processed in an identical sequence of steps, which included scaling the photograph and providing it, in the location where the idler set was visible, with a length calculated from three measurements of the known belt width, and subsequently performing manual delineation, i.e., marking the contours of the rock fragments.

As a result, each photograph produced a fully delineated image. Examples of fully delineated images are shown in Figure 5. In each photograph, the objects that are not the mined ore (e.g. the belt, idlers
and structural members of the belt conveyor line) were masked with blue. Red represents finer particles whose structure was not detected by the dedicated software.

The Split Desktop application calculated the grain size distribution of the ore transported in those sectors using its own algorithms, on the basis of the estimated grain size distribution for the remaining part of the mined ore [1].

Figure 5. Contours of the fragmented rock for selected photographs: a) IMG_7, b) IMG_9 and c) IMG_13

The comparison of the contours of the fragmented rocks in Figure 6 reveals that grain size distribution of the mined ore varies to a great degree. Figure 6c shows the domination of fine fraction (0 ÷ 2 mm), which accounts for approximately 70% of the analysed part, whereas Figs. 6a and 6b show the presence of some coarse material in which the rocks reach 600 mm. Short time intervals between subsequent photographs indicate that the size of mined ore particles transported to the bunker changes substantially over time. In this case, rock properties prove to be the decisive factor. Individual layers of ore-bearing rocks and the surrounding rocks exhibit various resistances to drilling and blasting. The excavation profile comprises three types of rocks with various thickness: dolomite, shale and sandstone, all of which have different strength characteristics.

Full delineation was followed by rock fragmentation estimation, which was demonstrated using an example of a Gaudin–Schumann distribution. At this stage, the computer application generates a log-linear graph representing grain size distribution slope for the ore in the investigated conveyor area. Figure 6 shows the sample size distribution slopes generated for some of the photographs.

Figure 6. Grain size distribution slopes generated for photographs IMG_7, IMG_9 and IMG_13
Table 1. Results of grain size distribution tests conducted with the complete photographic documentation.

| Upper limit grain size [mm] | D50 | D40 | D30 | D25 | D20 | D15 | D10 | D5  | D2  | Total percentage share [%] |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|----------------------------|
| 63.50                       | -   | -   | -   | -   | -   | -   | 100.0 | 100.0 | -   | 100.00                      |
| 381.00                      | 100.0 | -   | 100.0 | -   | -   | -   | 93.75 | 100.0 | 99.86 | 100.0                      |
| 254.00                      | 93.04 | 100.0 | 100.0 | 98.52 | -   | 100.0 | 100.0 | 74.35 | 83.17 | 81.01 | 98.00 | -   | 100.0 | 99.57 | 94.59 |
| 203.20                      | 84.46 | 98.73 | 97.57 | 93.77 | 100.0 | 98.76 | 97.51 | 71.38 | 70.46 | 93.09 | -   | 100.0 | 82.18 | 90.28 |
| 152.40                      | 69.72 | 94.34 | 91.73 | 85.97 | 97.43 | 87.36 | 90.63 | 59.43 | 57.80 | 61.76 | 84.02 | 100.0 | 91.52 | 73.10 | 83.23 |
| 101.60                      | 53.68 | 84.00 | 82.66 | 74.01 | 90.21 | 73.70 | 77.51 | 49.04 | 43.58 | 56.11 | 73.60 | 99.33 | 100.0 | 85.82 | 67.72 | 74.04 |
| 50.30                       | 40.14 | 61.82 | 71.87 | 57.83 | 71.62 | 60.89 | 52.42 | 37.05 | 32.12 | 48.05 | 66.52 | 91.06 | 95.24 | 72.64 | 64.62 | 61.56 |
| 25.40                       | 28.34 | 47.36 | 65.31 | 63.34 | 58.36 | 53.11 | 35.62 | 29.85 | 23.73 | 41.67 | 61.88 | 71.59 | 86.72 | 65.96 | 61.16 | 51.67 |
| 19.05                       | 24.47 | 42.13 | 62.55 | 42.14 | 51.58 | 49.35 | 30.33 | 27.21 | 20.51 | 39.16 | 59.09 | 64.78 | 83.98 | 63.79 | 58.62 | 47.95 |
| 12.70                       | 19.90 | 35.71 | 58.84 | 56.85 | 44.94 | 44.49 | 24.17 | 23.87 | 16.69 | 35.87 | 55.36 | 56.38 | 80.65 | 60.63 | 55.21 | 43.28 |
| 9.53                        | 17.17 | 31.75 | 56.34 | 53.49 | 40.74 | 41.53 | 20.56 | 21.75 | 14.42 | 33.71 | 52.85 | 51.13 | 78.16 | 58.48 | 52.91 | 40.29 |
| 6.35                        | 13.94 | 26.89 | 53.00 | 29.27 | 35.47 | 37.24 | 16.36 | 19.07 | 11.72 | 30.87 | 49.52 | 44.31 | 74.79 | 55.38 | 49.83 | 36.49 |
| 4.73                        | 12.01 | 23.88 | 50.74 | 26.58 | 32.12 | 34.57 | 13.89 | 17.35 | 10.10 | 28.99 | 47.27 | 39.99 | 72.47 | 53.60 | 47.73 | 34.06 |
| 2.00                        | 7.70  | 16.75 | 44.62 | 19.96 | 23.92 | 27.74 | 8.52  | 13.12 | 6.49  | 24.08 | 41.21 | 29.48 | 65.05 | 48.18 | 42.09 | 27.96 |
In the next step, the complete photographic documentation was used to generate, in Split Desktop 4.0, a combined size distribution slope (Figure 7) corresponding to the size of all rocks constituting a representative sample of the material discharged to the underground bunker until it was fully filled. Table I presents the total content of individual fractions, which served to generate a grain size distribution slope for the complete photographic documentation.

Figure 7. Combined grain size distribution slope generated for the complete photographic documentation from the belt conveyor P1 (see its location at Fig.1)

The recognized fragmentation of the conveyed ore was used to model the ore flow inside the ore bunker. Because of the phenomena known to influence the mixing of the grains of various sizes inside the bins, including the 'Brazilian nut effect' [14], the ore flow through the underground bunker (built at the entrance to the skip-filling station) was simulated using a DEM model (Figure 8). Sectors of the bunker displayed on the right-top window of Figure 8 represent the ore batches discharged through two ‘legs’ according to the given sequence of opening of two chutes (they are not opened simultaneously). The differentiated ore fragmentation causes different behaviours of the grains and influences the sequencing of discharging (refer to the grain size distributions in the sectors of the bunker in Figure 8). Therefore, the grain size distribution of the transported ore identified on the conveyor was used as the input data for the DEM model to estimate the granulation of the ore batches transported by skip to the ore processing plant at the shaft mouth (see Figure 1).

Figure 8. Grain size distributions in different sectors of the bunker, as obtained in DEM simulations
4. Conclusions
Ore mined via the blasting method typically has a very broad grain size distribution, where fine material coincides with coarse fragments. Identifying this distribution is important in analyzing transportation systems (i.e. the characteristics of the transported material and loads acting on the elements of the transportation system), in increasing the efficiency of ore processing and in estimating the quality of blasting operations.

The analysis of the currently used solutions and the known limitations due to operating conditions enabled the development and test of a method for indirect identification of grain size distribution in a complex transportation system of an underground mine. The employed measurement and analytical system is based on the image analysis of the transported ore, as documented in photographs. The reliability of the obtained results largely depends on proper sampling. Therefore, although the system involves substantial bias [7–8], it ensures a more effective evaluation of the ore fragmentation degree because it enables a practically unlimited increase of the sampling frequency.

The analysis covered the ore transported to the bunker via the main belt conveyor. The results point to substantial ore fragmentation: fine fractions (<10 mm) account for more than 40% of the transported bulk material. Such a large portion of fine fraction may be most convincingly attributed to the lithology of the material. Large individual fragments of rock, some larger than 600 mm, may prove to be important in such research. Such fragments constitute a minor part of the total amount of mined ore, whereas the analysis of their flow through the bunker may prove of great importance. Such a substantial difference between the smallest and largest grain size may bias estimations of the finest fraction based on Schumann distribution [7].

The results presented here are preliminary information required to build a simulation model representing the behaviour of unevenly granulated material in the nodes of the transportation system (i.e., in the bunkers) using the DEM. The results also demonstrate the effectiveness of the adopted solution, which will be used to further improve the simulation modelling of ore flow on the basis of the characteristics related to the flow of ore through the bunkers.

Acknowledgment(s)
The research work co-founded with the research subsidy of the Polish Ministry of Science and Higher Education granted for 2020.

References
[1] Maerz, N.H. Optical sizing analysis of blasted rock: lesson learned, Proceedings of 4th EFEE World Conference of Explosives and Blasting in Vienna, s. pp. 75–83, 2007
[2] Katterfeld, A., and Wensrich, C. 2017. Understanding granular media: from fundamentals and simulations to industrial application. Granular Matter, vol. 19, no. 4. p. 83.
[3] Chen, W., Williams, K., Donohue, T., and Katterfeld, A. Application of the image processing technique in identifying the particle dispersion from a centrifugal fertilizer spreader, Particulate Science and Technology, vol. 35, no. 5. pp. 607–615, 2017.
[4] Bessikirski, A., Dworzak, M., and Pyra, J. Pośrednia analiza fragmentacji urobku otrzymanego w wyniku robót strzałowych wykonywanych w kopalni dolomitu (Indirect analysis of fragmentation of spoil obtained as a result of blasting works carried out in the dolomite mine), Przegląd Górnicy (Geological Review) no. 7, p.1., 2016.
[5] Boujila, A., Bartolacci, G., Koch, N., Cayouette, J., and Cote, C. Toward the Improvement of Primary Grinding Productivity and Energy Investigation Consumption Efficiency, Mine to Mill 2000, Finland 5, 2000.
[6] Dance, A. The Importance of Primary Crushing in Mill Feed Size Optimization, Semiautogenous Grinding Technology, pp. 1–201, 2001.
[7] Maerz, N.H., and Zhou, W. Optical digital fragmentation measuring systems–inherent sources of error. *Fragblast*, vol. 2, no. 4. 415–431, 1998.

[8] Maerz, N.H. Automated Online Optical Sizing Analysis, SAG 2001, pp. 250–269, 2001.

[9] Sanchidrian, J.A., Segarra, P., Ouchterlony, F., and Lopez, L.M., On the accuracy of fragment size measurement by image analysis in combination with some distribution functions, Rock Mechanics and Rock Engineering, vol. 42, pp. 95–116, 2009.

[10] Bęben, A. O potrzebie weryfikacji określania wielkości bryły nadwymiarowej przy ładowaniu urobku łyżkami koparek hydraulicznych w kopalniach surowców skalnych. *Górniczo i Geoinżynieria (Mining and Geoenineering)*, Rok 28, Zeszyt 3/1, 2004.

[11] Saramak, D. Analysis of efficiency for chosen groups of enrichment operations with respect their cost-consumption on example of copper ore enrichment technology. *Mineral Resources Management*, T. 22, z. 1, (in Polish), 2006.

[12] Jurdziak L., Kaszuba D., Kawalec W., and Król R. Idea of identification of copper ore with the use of process analyser technology sensors. *IOP Conference Series: Earth and Environmental Science*, vol. 44, no. 4. p. 042037, 2016.

[13] Król R., Kawalec W., Zimroz R., Jurdziak L., Jach M., and Pilut R. Project DISIRE (H2020)–an idea of annotating of ore with sensors in the KGHM PM S.A. Underground copper ore mines. Mineral Engineering Conference (MEC2016), *E3S Web of Conferences*, ISSN (Electronic Edition), pp. 2267–1242, 2016.

[14] Walker, P., Kawalec, W., and Król, R. Application of the discrete element method (DEM) for simulation of the ore flow inside the shaft ore bunker in the underground copper ore mine. *Proceedings of the International Conference on Intelligent Systems in Production Engineering and Maintenance*, s. 633–644, 2018.

[15] Malewski, J. Technology and quality of screening. *Surowce i Materiały Budowlane*, vol. 2, pp. 36–40, 2016.

[16] Malewski, J. On accuracy of sieve analyzes. *Kruszywa Mineralne (Proceedings of the Conference of Mineral Aggregates)*, vol. 1, pp. 103–111, 2017.

[17] Drzymała, J. Podstawy mineralurii, Wyd. 2. zm., Ofic. Wyd. PWr, Wrocław (in Polish), 2009.

[18] Franklin, J.A., Kemeny, J.M., and Girdner, K.K. Evolution of measuring systems: a review. *Proceedings of the FRAGBLAST 5 Workshop on Measurement of Blast Fragmentation*, Montreal, Quebec, Canada, 1996.

[19] Palangio, T. C., and Maerz, N. H., Case studies using the WipFrag image analysis system. *Fragblast*, vol. 6, pp. 117–120, 1999.

[20] Batko, P., and Sołtys, A. O sposobach określania składu ziarnowego po strzelaniu (Methods of determining the grain composition after shooting), *Magazyn WUG: Bezpieczeństwo Pracy i Ochrona Środowiska w Górnictwie*” nr 9/1, s. pp. 125–139, 2007.

[21] Bessikirski, A., and Bessikirski, R. Wpływ warunków geologiczno-górniczych na fragmentację urobku w kopalniach wapienia (Impact of geological and mining conditions on the fragmentation of spoil in limestone mines), *Magazyn WUG: „Bezpieczeństwo Pracy i Ochrona Środowiska w Gó rnictwie”* nr 12, s. pp. 18–27, 2012.

[22] Esen, S., and Bilgin, H.A. Effect of Explosive on Fragmentation. *The 4th Drilling and Blasting Symposium*, Ankara, Turkey, vol. 6372, 2001.

[23] Ouchterloniy, F., Nyberg, U., Bergman, P., and Esen, S. Monitoring the blast fragmentation of Boliden Mineral’s Aitik mine, *4th EFEE World Conference of Explosives and Blasting in Vienna*, s. pp. 47–63, 2007.

[24] Błażej, R., Jurdziak, L., and Zimroz, R. Novel approaches for processing of multi-channels NDT signals for damage detection in conveyor belts with steel cords, *Damage Assessment of Structures X part 2*, Switzerland, 2013.

[25] Błażej, R. at al, W. Conveyor Belt Condition Evaluation via Non-Destructive Testing Techniques, *Mine Planning and Equipment Selection*, Dresden, 2013