Bulk density of industrial minerals:
Reporting in accordance with the 2007 SME Guide

by Andrew Scogings

Bulk density determination is often one of the most neglected parameters during industrial mineral exploration, generally not receiving the attention devoted to other measures such as sample width, chemical analysis or product performance testing. As noted by Lipton and Horton (2014, pp.97), "estimation of density commonly receives less attention than is paid to geochemical data and may be based on fewer data points derived from less controlled measurement practices."

Geological resources are typically modeled as volumes which must be converted to mass using density values; thus the measurement of density should be an integral part of the resource estimation process.

The author's intention is to address certain aspects concerning bulk density listed in Section B of The 2007 SME Guide Table 1, and the first part of the article describes bulk density and some of the methods most commonly used for measuring the density of rocks and materials. This is supported by several case studies from Minerals Technologies Inc. (MTI) mines where the author was previously involved in Australia and South Africa. An additional study investigates barite diluted with quartz impurities, in order to compare mineralogy with American Petroleum Industry (API) oil-drilling barite SG specifications.

The 2007 SME Guide

The Society for Mining, Metallurgy and Exploration Inc. (SME) Guide for reporting exploration results, mineral resources and mineral reserves includes Table 1 which is a useful checklist of evaluation criteria that the competent person (CP) should address (Table 1). Section B of Table 1 refers specifically to sampling and includes the criteria "Specific Gravity and Bulk Tonnage."

When reporting a resource, the CP should discuss how the tonnage factor was determined (assumed or measured) so that, "If assumed, which assumptions were made and on which basis. If measured, by what method and how frequently. Discussion of whether different tonnage factors were used in different parts of the deposit and why."

In the case of reporting a reserve, the CP should note that, "The specific gravity and bulk tonnage must have been measured by methods that adequately account for void spaces and differences between rock and alteration zones in a deposit."

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Figure 1

Uncoated chromitite sample being weighed in air, (Source: MTI).

What is bulk density?

Bulk density is a measure of mass per unit volume of rock and may be expressed, for example, as metric tonnes per cubic meter (t/m^3) or pounds per cubic foot (lbs/cu ft).

Density is determined by measuring the mass of a sample and dividing this by its volume. As a general rule, the dry mass is obtained by drying the sample and then weighing it, which is the 'easy' part of the process. The challenge arises when trying to determine the volume of a sample especially when it has an irregular shape, is friable, soft or porous.

Density may be defined in a number of ways (Table 2), and it is important to ensure that the appropriate density measurement is used for any specific project. Assays for constituents such as Cr_2O_3 and SiO_2 (in a chromitite seam); MgO, CaO, SiO_2 and Fe_2O_3 (in magnesite) or graphitic carbon (in graphite schist) are normally reported on a dry weight basis and therefore in such cases the 'dry bulk density' (DBD) is applicable. Lipton and Horton (2014) describe DBD as the mass per unit volume, including pore spaces but excluding natural water content. Abzolov (2013) notes that DBD is often referred to as SG, which he considers to be an obsolete term.

The in situ bulk density (ISBD) includes natural water content and should be applied when estimating tonnages of material to be mined (Lipton and Horton, 2104). ISBD could apply to a commodity such as bentonite, which may typically contain 25 to 35 percent moisture before being mined.

Specific gravity (SG) is a term commonly used in place of density but caution should be exercised, as SG (also known as relative density) is often measured using pulverised samples in equipment known as a pycnometer. A limitation of this method is that it does not account for porosity or natural water content.

Determining bulk density from small samples

The geologist frequently has only small drill samples to use for density measurement and there are several practical methods available, essentially based around the issue of measuring volume. Each density method has its own potential source of error and it is useful to verify the results of one method against a second if at all possible. It is important to ensure that samples are representative and that a particular type of rock is not sampled preferentially, e.g. hard material relative to soft material (Lipton and Horton, 2014).

Water displacement method: there are several methods which rely on displacement of water to estimate sample volume and are described in detail by Lipton and Horton (2014, pp. 99-101) who list six water displacement methods. One of the most common methods for exploration samples is based on the Archimedes principle in which sample is first weighed in air, after which it is weighed in water (Figs. 1 and 2). The density is calculated as the mass of the sample in air, divided by the volume (difference between the sample mass in air and in water). Samples should be competent and not absorb water; if porous, they should be waterproofed with substances such as paraffin wax or beeswax which melt at approximately 60 º C (Figs. 3; and 4) spray lacquer or hairspray (Fig. 5) vacuum packed in plastic (Fig. 6) or wrapped in 'cling wrap' film (Fig. 7).

Caliper method: This is applicable for drill core samples that can be trimmed at right angles to form a regular cylinder. A vernier caliper is used to measure the core diameter at several points to estimate an average result, while the core length is determined using a tape measure or ruler (Figs. 8 and 9). The core is then weighed and the density determined simply by using the formula of weight divided by volume. The caliper method has the advantage of simplicity, but it is cautioned that using small diameter core or short core lengths may result in errors (Lipton and Horton, 2014). Care should also be

Figure 2

Beeswax coated weathered pyroxenite core sample being weighed in water, (source: MTI).

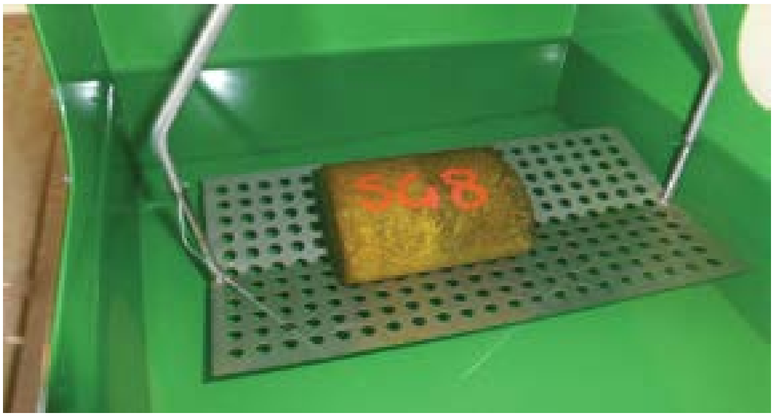

Table 1

Check list of assessment criteria.

Evaluation criteria	Exploration results	Mineral resource	Mineral reserve
B. Project Data 4. Sampling d. Specific Gravity and Bulk Tonnage	Generally not determined.	Discussion of how the tonnage factor was determined (assumed or measured). If assumed, which assumptions were made and on which basis. If measured, by what method and how frequently. Discussion of whether different tonnage factors were used in different parts of the deposit and why.	See Mineral Resource. The specific gravity and bulk tonnage must have been measured by methods that adequately account for void spaces (vugs, porosity, etc.) and for differences between rock and alteration zones within the deposit

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Table 2

Description of some commonly used density terms (adapted from Lipton & Horton, 2014).

Term	Units	Definition
Specific gravity		Relative density: the ratio of the density of the material to the density of water at 4ºC
Density	t/m³	Mass per unit volume
In situ bulk density ISBD)	t/m³	Density of the material at natural moisture content
Dry bulk density (DBD)	t/m³	Density of the material after all free moisture content has been removed

Figure 3

Paraffin wax block being melted in disposable tray.

Figure 4

Coating a friable chromitite core sample with molten paraffin wax (Source: MTI).

taken with materials that swell after removal from the core barrel. In such cases, the core diameter should be corrected to match the internal diameter of the core barrel. It may not be possible to determine a reference point for expansion along the length of the core but it is suggested to use the same correction as applied to the diameter.

Pulp sample method: Density of competent rocks that have very low porosity and low natural water content may be measured using a gas pycnometer and rock pulp samples (finely milled rock) but this method is not suitable for porous rocks, as the fabric is destroyed by the milling process. The gas pycnometer method determines volume within the sample chamber from which an inert gas is excluded. The pycnometer gives volumes for samples weighed into plastic vials (Fig. 10), which are in turn dropped into the sample chamber. Best precision is obtained from the largest possible volume of sample which is typically around 30 grams. Density data derived from a gas pycnometer may form a useful part of the density database and in the author's experience such 'SG' data can be a valuable QC tool.

Stoichiometric method: There may be an obvious correlation between bulk density and rock chemistry, such as with relatively simple mineral assemblages such as some barite and chromite ores. For example, assuming that a chromitite ore consists essentially of chromite with density of approximately 4.5 g/mL and pyroxene with density around 3.3 g/mL, it should be possible to estimate bulk density based on XRF 'whole rock' analyses. A further example may be impure barite ore, in which pure barite has a density of approximately 4.5 g/mL compared with quartz that has a much lower density of close to 2.7 g/mL.

The calculated density must be based on mineral volumes in order to maintain a constant volume, as density is expressed in terms of volume and XRF whole-rock analyses are expressed on a weight percentage basis,. The relationship between density and whole-rock chemistry is nonlinear (Lipton and Horton,

Table 3

DBD of chromitite and pyroxenite drill cores estimated by various methods (Source: MTI).

Method	Diameter	Length	Volume	Mass in air	Mass in wated	Sealant mass	Sealant density	Sealant volume	DBD	DBD
	cm	cm	cm³	g	g	g	g/cm³	cm³	g/cm³	lbs/ cu ft
SG2 oxidised pyroxenite										
Caliper	6.3	11.35	353.95	880.25					2.49	151
Vacuum pack				887.85	530.75	7.6	0.92	8.26	2.52	157
Paraffin Wax				887.35	536.9	7.1	0.9	7.89	2.57	160
SG6 competent pyroxenite										
Caliper	4.76	19.6	348.93	1145.85					3.28	205
Archimedes				1145.85	801.05				3.32	206
Cling Wrap				1147.95	786.1	2.1	0.92	2.28	3.19	200
Vacuum pack				1153.5	796.4	7.65	0.92	8.32	3.29	205
Paraffin Wax				1154.85	800.2	9	0.9	10	3.32	206
11R0007 22.1-22.8m (LG6 chromitite, friable)										
Paraffin wax (1/2 coore) 175.8					132.65	1.55	0.9	1.72	4.21	262
Spray Lacquer (1/4 core) 94.45					71.85	0.4	0.9	0.44	4.24	265

2014), which is especially obvious when there is a marked difference in density between the different mineral phases.

Determining bulk density from larger samples

Bulk samples may be obtained if trial mining or production is already in progress at a site. The in situ volume of bulk samples can be estimated by surveying an excavated void (for example an extracted bentonite or chromitite seam) or by surveying a stockpile before and after removal. The sample mass may be determined by directly measuring truckloads across a weighbridge. However, subsamples will have to be taken to determine moisture content as it is impractical to measure the moisture of an entire stockpile or run of mine material.

Operating mines generally measure raw material stockpile volumes for audit and reconciliation purposes, but the question arises of selecting an appropriate bulk density for conversion of volume to mass. Bulk density values for free-flowing powders and granular materials can vary significantly according to particle size distribution and on how closely the particles are packed. In practical terms, the bulk density of a powder tends to increase the more it is subjected to tapping, vibration or other action which causes particles to become better packed, with less void space between larger particles; this is known as the 'tapped bulk density.' Bulk density of free-flowing powders or granular materials can be determined by filling a container of known volume, after which the material is weighed and the 'loose bulk density' can be estimated (Fig. 13). The container is then tapped and refilled until the

Figure 5

Spray lacquer-coated friable chromitite core sample, (source: MTI).

Figure 6

Vacuum-packed pyroxenite core sample being weighed in air (Source: MTI).

Figure 7

Pyroxenite core sealed with cling wrap, (source: MTI)

material stops settling at which stage the tapped bulk density can be estimated.

QAQC

QAQC methods commonly applied to other factors in an exploration program such as equipment calibration, duplicates, standards and external laboratory tests should also apply to density measurements (Fig. 11).

Case study: chromitite in South Africa

The main aim of this article is to give practical examples of density measurement and the first example is of drill core from a chromite mine that produces a range of premium-grade chromite sands for foundry, chemical, metallurgical and refractory applications. In this case, the chromitite being tested was unweathered competent rock from the underground part of the mine. Hence, the Archimedes water displacement method was deemed suitable. Given that the chromitite seams and associated chromiferous pyroxenite in this particular example were nonporous and competent, a set of milled samples was also analyzed by gas pycnometer as a check. This data set demonstrated good correlation between methods (Fig. 12) with all samples comfortably within +/-10 percent tolerance between methods.

A further example from the chromite mine concerns pyroxenite drill core from the chromitite hangingwall, which the mine planners wished to evaluate for an openpit situation. In this case, the pyroxenite ranged from weathered (friable and porous) to fresh (competent and nonporous). Hence, there were several options, including water displacement of sealed samples and the caliper method. An unweathered pyroxenite core sample 'SG6' was chosen as a control and density was estimated using the caliper and various water displacement methods (Table 3).

Table 4

ISBD of bentonite 5D estimated using the caliper method, (source: MTI).

Bentonite	Length	Diameter	Volume	Mass	Moisture	ISBD	ISBD
	cm	cm	cm³	g	%	tonnes/m³	lbs/cu ft
5D	4.6	6.4	148.0	254.6	27.3	1.72	107
5D	2.3	6.4	74.0	135.9	27.0	1.84	114

Table 5

Bentonite 5D ISBD estimated from a surveyed openpit, (source: MTI).

Description	Tonnes hauled (over weighbridge)	Volume m³ (surveyed)	Volume m³ (geology model)	Difference in volume	ISBD tonnes /m³	ISBD lbs/cu/ft
NP Block 3	10.017	5,773	5,947	3%	1.74	109

The caliper method yielded comparable results to the Archimedes method (uncoated, vacuum packed and paraffin wax). However, the 'cling wrap' method proved to be unreliable as it entrained air (reducing the density) and was not completely waterproof.

Following the initial tests on control sample SG6, a range of pyroxenites and friable chromitites were tested, which illustrated that densities were generally within 1 to 3 percent of the caliper method (Table 3). The significantly lower DBD of weathered material (e.g. sample SG2) highlighted the need to test density across a range of weathering domains within a mineral deposit.

It was concluded that for competent, non-porous core samples at the chromite mine the caliper, water immersion and gas pycnometer methods are suitable, while porous core sample densities are best measured using the caliper or wax-coated, spray lacquered or vacuum-packed water displacement methods.

Case study: bentonite in Australia

Measuring the ISBD of sodium bentonite presents a whole set of challenges related to the fact that such material absorbs water and swells. Therefore direct immersion in water is not a practical option.

In the case of the MTI Australian bentonite example, all exploration drilling was carried out by a method known as rotary air blast (RAB) using a bladed bit, which results in small drill chips unsuitable for water immersion or the caliper method. An alternative drilling method had to be considered in order to measure ISBD. After discussion with the contractor, the RAB rig was modified to drill core (without water) at several strategic locations. On reclaiming the cores, all samples were sealed in plastic bags to retain in situ moisture before estimating density. The core samples were then trimmed with a hacksaw to yield regular cylindrical shapes, from which volumes could be estimated using the caliper method. The shavings were used to measure the moisture content (Fig. 9). The resultant densities of 1.72 to 1.84 t/m^3 (107 to 114 lbs/cu ft) indicated that 1.8 t/m^3 (112 lbs/cu ft) should be appropriate for estimation of in-situ 'wet' bentonite resources in the 5D bed at the Australian mine (Table 4).

Once a mine is in operation, it is possible (and advisable) to verify densities that were

Figure 8

Pyroxenite core sample being measured using a caliper, (source: MTI).

Figure 9

Bentonite core trimmed for caliper method. The core shavings were used for moisture analysis (source: MTI).

Table 6

Bentonite stockpile BD measured using cubic meter box, (source: MTI).

Bentonite	Location	Untapped mass (tonnes)	Tapped mass (tonnes)	Volume (m^3)	Moisture (%)	Density untapped t/m^3 (lbs/cuft)	Density tapped t/m^3 (lbs/cuft)
5B OP	Dry stockpile	1.253	1.41	1	10.4	1.25 (78)	1.41 (88)
5D OPW	Dry stockpile	1.306	1.43	1	11.9	1.31 (81)	1.43 (88)

Figure 10

Gas pycnometer cell with plastic vial of pulverised sample (source: Intertek, Perth).

estimated during the exploration phase of the project. This can be achieved by surveying the volume of an excavated void, for example an extracted bentonite seam in an opencast pit and using this in conjunction with truckloads of mined material measured on a weighbridge.

This procedure was adopted at the Australian mine and confirmed that an ISBD range of 1.74 to 1.8 t/m^3 (107 to 114 lbs/cu ft) was appropriate for this specific bentonite bed (Table 5). A further benefit of reconciling actual volume and tonnes mined against the estimated mineral resource volume and tonnes is to verify the geology model. In this particular case the surveyed volume was within 3 percent of the modeled volume (Table 5) which indicated that the exploration and modelling methods were reasonable for this type of bedded mineralisation.

Another example from the Australian mine addressed the estimation of bulk density of sun-dried (granular) bentonite stockpiles. As with surveying the volume of bentonite mined from a pit, an option for stockpiles is to measure the stockpile before and after shipment and estimate the volume removed. An alternative is to extract some material from the stockpile and fill a container of known volume, which can then be weighed. This latter procedure was adopted at the Australian bentonite mine (Figs.13 and 14) and it was estimated from filling a box of one cubic meter volume that loose density was close to 1.3 t/m^3 (80 lbs/cu ft) compared with tapped density of approximately 1.4 t/m^3, or 88 lbs/cu ft (Table 6).

Case study - barite

Given the recent trend toward using lower SG barite for oil-drilling applications, this study evaluated the stoichiometric method of estimating density using a series of barite-silicate blends. Over the past few years, some experts in the oil industry expressed reservations that, as lower SG is related to dilution of barite by abrasive contaminants such as silica (quartz or chert), this would result in increased mill wear, increased tonnage requiring to be milled and more abrasive drilling mud. The consensus was that going to an even lower 4.0 SG standard would release more barite into the market, but could cause problems and increased costs for drilling fluids and waste management.

The author has calculated SG for a theoretical series of barite-quartz compositions between SG 2.7 and SG 4.5 to try and quantify the effect of dilution by silica contaminants. In addition, a series of barite-quartz dilutions (by mass) were prepared and measured by gas pycnometer at Intertek in Perth, Australia. The pycnometer results demonstrate i) the nonlinear relationship between whole-rock chemistry and density and; ii) that a barite product with density of 4.1 could have as much as 23

Figure 11

Calibration of a density balance using standard weights (Source: MTI).

percent silicate mineral by volume, rising to approximately 30 percent when SG is decreased to 4.0. This latter value for mineral impurities at SG 4.0 is higher than when assuming a straight-line relationship between chemistry and SG (Table 7; Fig. 15).

Conclusions

- Table 1 of the SME Guide for reporting exploration results, mineral resources, and mineral reserves refers specifically to measurement of density.
- Mineral resource estimations rely on three main inputs namely grade, volume and bulk density, of which the latter is often a neglected component during mineral exploration.
- Poor bulk density data will result in unreliable tonnage estimates and may impact negatively on mine scheduling, design and reconciliation of mineral production against reserves.
- Determination of sample mass is the ‘easy part’ of estimating density. The difficult step generally lies in trying to determine the volume of a sample.
- There are several methods for estimating the volume of rocks and materials, each of which has practical limitations. It is suggested that more than one method be used if possible, as a check. The method/s chosen should take into account physical and chemical variations across the deposit such as weathering, porosity, mineralogy and moisture content.
- The use of ‘cling wrap’ film to seal samples should be avoided, as entrapped air leads to significantly lower density results compared with other methods.
- QA/QC methods commonly applied to other factors in an exploration program

Figure 12

Scatterplot comparing SG (pycnometer) with DBD (Archimedes) for chromitite (source: MTI).

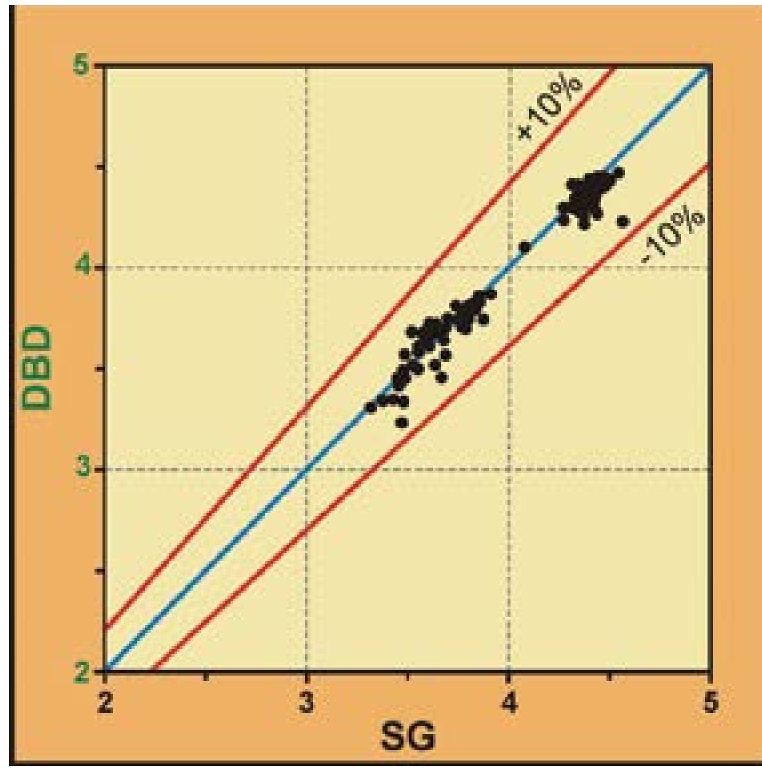


Table 7

Barite product: SG related to SiO_2 impurities, (source: IMR; Scogings 2015).

$BaSO_4$ (% by mass)	SiO_2 (% by mass)	SG (calculated) (g/mL by mass)	Barite (calculated) (% by volume)	Silicate (calculated) (% by volume)	SG (calculated) (g/mL by volume)	SG (pycnometer) (g/mL lab. blend)
100	0	4.50	100	0	4.50	4.50
95	5	4.41	92	8	4.35	4.38
90	10	4.32	84	16	4.22	4.22
85	15	4.23	77	23	4.09	4.04
80	20	4.14	71	29	3.97	4.01
75	25	4.05	64	36	3.86	3.78
50	50	3.60	38	63	3.38	3.46
25	75	3.15	17	83	3.00	3.02
0	100	2.70	0	100	2.70	2.71
Note: current API Section 13 drilling grade barite specifications are SG4.1 and SG4.2						

Figure 13

Filling a cubic meter box with sun-dried bentonite (source: MTI).

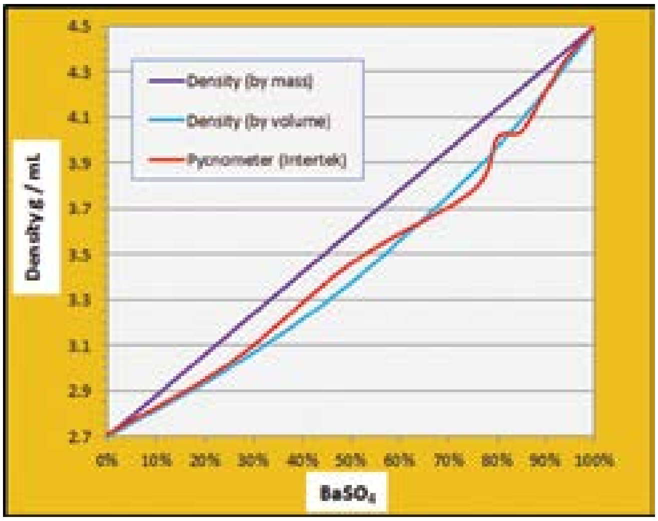
Figure 14

Bentonite being added after tapping the cubic meter steel box (source: MTI).

such as equipment calibration, duplicates, standards and external laboratory tests should also apply to density measurements. ■

Figure 15

Stoichiometric density estimates for barite-quartz blends (source: Industrial Minerals Research; Intertek Perth).



Acknowledgments

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