Bulk Density: neglected but essential

Bulk density is frequently one of the most neglected parameters during industrial mineral exploration compared with other measures such as sample width in borehole intersections, chemical analysis and product performance testing. *Industrial Minerals Consultant, Andrew Scogings,* explores bulk density and some of the methods most commonly used for measurement.

Bulk density is a measure of mass per unit volume of rock; in exploration and mining projects, it is generally expressed as metric tonnes per cubic metre or, in the US, as pounds per cubic foot.

Density is determined by measuring the mass of a sample and dividing this by its volume. Generally the dry mass is obtained by drying the sample and then weighing it, which is the easy part. The challenging part comes when trying to determine the volume of a sample, especially when specimens have irregular shapes, are friable, soft or porous.

Density may be defined in a number of ways (*Table 1*) and it is important to ensure that the appropriate density measurement is used for any specific project. Assays for elements, such as chromium (Cr) in a chromitite seam and calcium (Ca) in limestone, are normally reported on a dry weight basis and therefore in such cases the 'dry bulk density' (DBD) is applicable. The DBD is defined as the mass per unit volume, including pore spaces but excluding natural water content (Lipton and Horton, 2014). Abzolov (2013) notes that DBD is often referred to as specific gravity (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, 2014). ISBD could apply to a commodity such as bentonite, which may typically contain 25-35% moisture before being mined.

SG is commonly used to describe density, but caution should be exercised, as SG, also known as relative density, is often measured using powdered (milled) samples in equipment known as a pycnometer. This method does not take into account porosity or natural water content, which is a limitation of the method for use in geological resource estimations. SG is, however, used as a metric to qualify drilling-grade barite (barytes) products to meet industry specifications (i.e. SG 4.1 and SG 4.2) and may also provide useful data for un-weathered, non-porous rocks.

Why measure bulk density?

As a general rule, geological resources are modeled as volumes in three-dimensional space, after which the estimated volume must be converted to mass using density values and, as noted by Lipton and Horton (2014, p 97):

Figure 1. Archimedes (water displacement) equipment. Chromitite sample being weighed in air.

"There are three fundamental inputs to any Mineral Resource estimate: grade, volume and bulk density." They also state that "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".

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 rock/mineralised samples are representative and that a particular type of rock is not sampled preferentially, such as 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 the sample is first weighed in air, after which it is weighed in water (*Figures 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 ~60^{o}C (*Figure 3*) spray lacquer or hairspray, wrapped in cling wrap film or vacuum packed in plastic to prevent ingress of water (*Figure 4*).

Calliper method

This is applicable for drill core samples that can be trimmed at right angles to form a regular cylinder. A pair of callipers 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 (*Figures 5 and 6*). The core is weighed and the density determined simply by using the formula of weight/volume.

The calliper method has the advantage of simplicity, but it is cautioned that using small diameter core or short core lengths may result in errors. Care should also be 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

Figure 2. Wax-coated friable chromitite core sample being weighed in water.

possible to determine a reference point for expansion along the length of the core but it is suggested to apply the same correction 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 the gas is excluded. The pycnometer will accurately give volumes for samples weighed into plastic vials, 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. SG data derived from a gas pycnometer may form a useful part of the density database and can be a valuable quality control (QC) tool.

Stoichiometric method

There may be an obvious correlation between SG or bulk density and rock chemistry, for example, with relatively simple mineral assemblages such as some barite and chromite ores. Assuming that a barite ore consists of discrete barite ($BaSO_4$) and quartz (SiO_2) or that chromitite ore consists essentially of chromite and pyroxene minerals, it should be possible to estimate bulk density based on X-ray fluorescence (XRF) whole rock analyses. An example is barite ore in which pure barite has a density of ~4.5 g/ml compared with quartz, which has a much lower density of ~2.7 g/ml.

Seeing that density is expressed in terms of volume and that XRF whole rock analyses are expressed on a weight percentage basis, the calculated density must be based on mineral volumes in order to maintain a constant volume. The relationship between whole-rock chemistry and density is non-linear, which is especially obvious when there is a marked difference in SG between the different mineral phases (Lipton and Horton, 2014).

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 sub-samples 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. Reconciliation of tonnage mined against the mineral resource or ore reserve is also a good check, not only of the three-dimensional geological model, but also of bulk density.

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. Since powders and granular materials are composed of particles and voids, the volume of a given mass of particles depends on how closely they 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/granular materials can be determined by filling a container of known volume, at which stage the material is weighed and the 'loose bulk density' can be estimated. The container is then tapped and refilled until the material stops settling, at which stage the tapped bulk density can be estimated.

Table 1: Description of some commonly used density terms

Term	Units	Definition
Specific Gravity	-	Relative density: the ratio of the density of the material to the density of water at 4°C
Density	t/m^3	Mass per unit volume
In situ bulk density (ISBD)	t/m^3	Density of the material at natural moisture content
Dry bulk density (DBD)	t/m^3	Density of the material after all free moisture content has been removed

Source: Adapted from Lipton & Horton, 2014

Figure 3. Coating a friable chromitite core sample with molten paraffin wax.

Case study: chromitite in South Africa

One example of density measurement is of chromitite drill core from an MTI mine that produces a range of premium-grade chromite sands for foundry, chemical, metallurgical and refractory applications. In this case the chromitite is 'fresh' or unweathered competent rock consisting predominantly of chromite with interstitial pyroxenes; hence the Archimedes water displacement method was deemed suitable.

Given that the chromitite seams in this particular example were unweathered, non-porous and competent, a set of milled samples was also analysed by gas pycnometer as a check. This data set demonstrated reasonable correlation between methods with all samples comfortably within 10% tolerance between methods (correlation coefficient = 0.75; Archimedes method mean = 4.35 g/mL; gas pycnometer method mean = 4.37 g/mL).

A further example from the chromite mine concerns pyroxenite drill core from the chromitite hanging wall, which the mine planners wished to evaluate for an open pit situation. In this case the pyroxenite ranged from weathered (friable and porous) to fresh (competent and non-porous) hence there were several options, including water displacement of sealed samples and the calliper method. An unweathered pyroxenite core sample was chosen as a control and density was estimated using the calliper and various water displacement methods. The calliper method yielded comparable results to the Archimedes method (uncoated, vacuum packed and paraffin wax yielded DBD ~ 3.3 t/m^3). However the 'cling wrap' method proved to be unreliable as it entrained air (reducing the density) and was not 100% waterproof.

Following the initial tests on the control sample, a range of pyroxenites and friable chromitites were tested, which illustrated that densities were generally within 1 to 3% of the calliper method. The significantly lower DBD of weathered pyroxenite 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 calliper, water immersion and gas pycnometer methods are suitable, while porous core sample densities are best measured using calliper and wax-coated, spray lacquered or vacuum-packed water displacement methods.

Case study: bentonite in Australia

Measuring the ISBD of sodium bentonite presents a set of challenges related to the fact that such material absorbs water and swells; therefore direct immersion in water cannot be used with much confidence.

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 calliper method.

Figure 4. Vacuum-packing a pyroxenite core sample.

Figure 5. Pyroxenite core sample being measured using a calliper.

Figure 6. Bentonite core trimmed for calliper method and core 'shavings' for moisture analysis.

An alternative drilling method had to be considered in order to measure ISBD and, after discussion with the contractor, the RAB rig was modified to drill core (without water) at several strategic locations where the overburden had been partly stripped. 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 calliper method, and moisture content derived from the 'shavings'. Density values of between 1.72 and 1.84 t/m^3 were obtained and it was elected to use 1.8 t/m^3 (112 lbs/cu ft) for estimation of *in situ* 'wet' bentonite resources.

Once a mine is in operation, it is possible (and advisable) to verify densities that were 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 verified that an ISBD range of 1.74 to 1.8 t/m^3 (109 to 112 lbs/cu ft) is applicable for this type of bentonite (~27% moisture; ~ 80% montmorillonite). It is to be expected that ISBD would vary across such a deposit according to mineralogical composition, degree of weathering, moisture content and overburden thickness.

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% of the modelled volume, which indicates that the drilling, logging, sampling and modelling methods are reasonable for this bedded style of mineralisation.

Another example from the Australian mine addresses the estimation of the bulk density of sun-dried (granular) bentonite stockpiles. Bulk density values for granular materials can vary significantly according to particle size distribution, mineralogical composition and moisture content; therefore it is to be anticipated that different bentonite stockpiles might have individual densities.

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 and it was estimated from filling a box of one cubic metre volume that loose (untapped) density is ~1.3 t/m^3 (80lbs/cu ft) and that tapped density is ~1.4 t/m^3 (88lbs/cu ft).

Essential for estimates

Mineral resource estimations rely on three main inputs; grade, volume and bulk density, but bulk density measurement is often a neglected component of mineral exploration. Poor bulk density estimates can result in unreliable tonnage estimates, which may impact negatively on mine scheduling and reconciliation of mineral production against reserves.

Determination of sample mass is the easy part of estimating density. The challenging part lies in trying to determine the volume of a sample, especially when specimens have irregular shapes, are friable, soft or porous. The methods chosen to determine the volume of rocks and materials should take into account physical and chemical variations across the deposit such as weathering, porosity, mineralogy and moisture content. QAQC methods commonly applied to other factors in an exploration programme such as equipment calibration, duplicates, standards and external laboratory tests should also apply to density measurements.

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