Estimating Volume of Shotcrete for Mining Applications

Traditionally, there has been a rather *ad hoc* attitude towards technical supervision of mining engineering ground control programs, to the extent that the preparation and enforcement of specifications has not been a major issue. In certain locations, however, the dominant use of contracting companies to provide mining-related services has meant that structured specifications are needed to ensure the high quality of the end-product. This is perhaps particularly the case with shotcrete (1) now that more and more mines are using the process and product to enhance the ground control regime within the mine.

by David F. Wood

The principal objective of this paper is to develop a rigorous method of estimating the volume of shotcrete needed for any particular mining project. The paper starts with an assessment of the rock mass and excavation conditions, and continues with an evaluation of the shotcrete placement process as it relates to wastage of shotcrete through rebound. Design charts are presented to assist in the challenging task of estimating shotcrete volumes based on different concepts of "thickness."

Finally, when considering terminology, a clear distinction is required between:

- Placement—which is the act of spraying shot/concrete, and
- Application—which deals with the suitability of using shotcrete under different rock engineering conditions.

Effect of Shape of Mined Excavation

Once the design engineer has planned the excavation dimensions and shape, the theoretical excavation perimeter can be determined. An estimate of the volume of shotcrete required per linear metre of drift can be made for a given thickness of shotcrete and a predetermined allowance for rebound. There are two issues, however, which have an impact on the final excavated perimeter. They are the irregularities of the excavated surface caused by the condition of the rock mass (such characteristics cannot be engineered) and the irregularities of the excavated surface caused by the excavation process itself (which can be engineered).

The first issue is referred to as the Ground Condition Irregularity and is primarily a function of the rock mass quality. The second is referred to as the Drill and Blast Process and is wholly a function of the mining or development contractor's ability to accurately and consistently carry out high quality controlled blasting. These two components comprise the Roughness Factor.

Ground Condition Irregularity

The irregularity of the rock mass surface after excavation as a function of the natural condition of the ground is a function of the following parameters:

- The blockiness of ground, predominantly due to block size and block shape
- The tightness of ground, predominantly due to the aperture of discontinuity surfaces
- The orientations of natural structures, especially relative to the orientation of the mining excavations
- The presence of faults and their interaction with the excavation profile
- The presence of groundwater
- The presence of clay seams
- The degree of foliation in metamorphic rocks, and
- The presence of minerals on slip planes

Four discreet combinations are proposed which reflect decreasing rock mass quality:

Excellent Condition—No geological effect. The rock mass does not influence the final perimeter of the excavation.

Good Surface Condition—Some jointing with slightlyrough surfaces. The rock mass has a low influence on the perimeter of the excavation.

Fair Surface Condition—Blocky ground and smooth surfaces. The rock mass has a significant influence on the perimeter of the excavation.

Poor Surface Condition—Very blocky ground, polished surfaces, possible fault zones and wet ground. The rock mass has a significant influence on the perimeter of the excavation.

The effect of the inherent character of the rock mass is that a certain amount of overbreak outside design is inevitable and the surface area of the rock mass for a certain drive length is increased. For each ground condition irregularity, the length of the perimeter of the surface is increased by the factors shown on Figure 1.

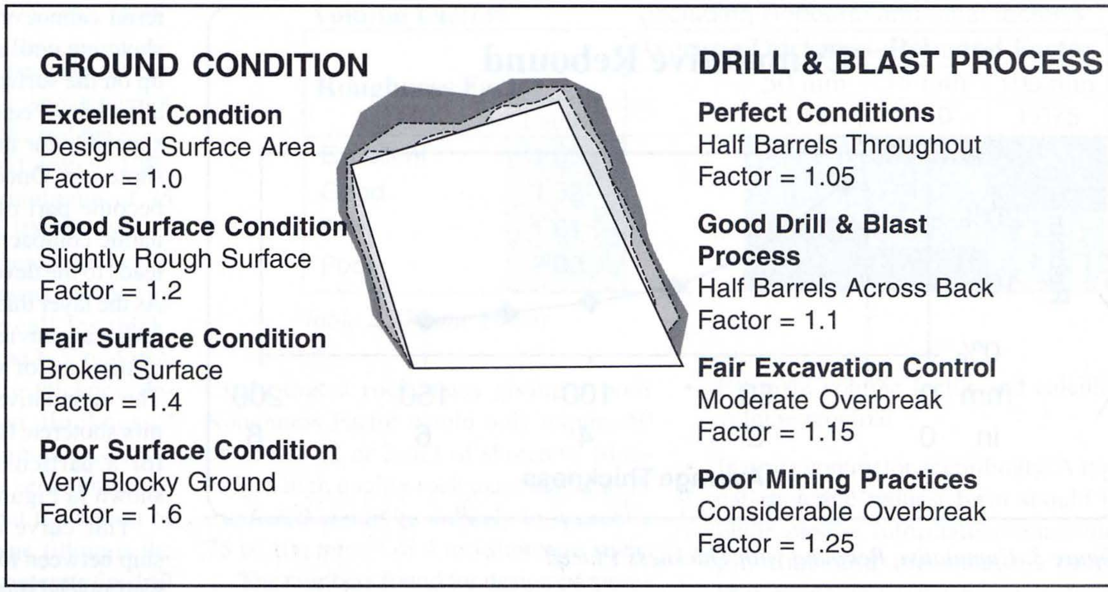


Figure 1. Ground Condition Irregularity and Drill and Blast Process.

Drill and Blast Process

The control of the excavation process may be considered a function of:

- The design of blasting pattern, particularly the location and charging design of the blast holes
- The layout of the blast design, especially the accuracy of surveying or estimating the locations of the blast holes
- The drilling orientation, especially of the controlled blasting perimeter holes across the back and down the sidewalls
- The charging accuracy. This refers to the accuracy with which the explosives are located within the blast holes and the types of explosives used in various holes
- The initiation sequence. If the holes are loaded properly but the millisecond delay times and the initiation sequence are flawed, then the rock mass will suffer more than the minimum amount of overbreak.

Four discreet combinations are proposed which reflect decreasing excavation process quality:

Perfect—Half barrels visible throughout. Only a small amount of additional excavation perimeter is generated from the inevitable "lookout" of the drill holes.

Good—75% half barrels visible across back. Some deficiencies in the excavation process lead to additional overbreak beyond design.

Fair—Moderate overbreak outside design.

Poor—Considerable overbreak outside design. Profound difficulties in the excavation process lead to considerable overbreak.

The effect of the excavation process on the rock mass is that a certain additional amount of overbreak outside design is caused and the surface area of the rock mass for a certain drive length is increased. For each drill and blast combination, the length of the perimeter of the surface is increased by the factors shown on Figure 2. It is noted that these factors are smaller than those for the ground condition irregularity since the influence of the excavation process is considered to be lower than that of the ground condition. It is also noted that the two processes act independently of each other and should be considered separately.

The Roughness Factor

The Roughness Factor is found by multiplying the two factors found from an evaluation of the natural rock mass conditions and the excavation process, as shown on Table 1.

The prime diagonal has been highlighted as a likely combination of the two factors. The Roughness Factors from the prime diagonal are used in Table 2.

Rebound

Up to this point, no consideration has been made for the influence of the installation of any ground support system. However, the placement of shotcrete will inevitably lead to some rebound and overspray that will increase the volume of shotcrete that needs to be ordered to achieve the desired results. This section will also introduce different concepts of "thickness."

Shotcrete rebound is primarily a function of the particle size distribution of the coarse and fine aggregates, and the velocity of impact of the shotcrete materials.

Roughness Factor: (NOT including Rebound or other factors)

Ground Condition		Drill and Blast Process			
		Perfect	Good	Fair	Poor
	Factor	1.05	1.10	1.15	1.25
Excellent	1.00	1.05	1.10	1.15	1.25
Good	1.20	1.26	1.32	1.38	1.50
Fair	1.40	1.47	1.54	1.61	1.75
Poor	1.60	1.68	1.76	1.84	2.00

Table 1. Roughness Factor

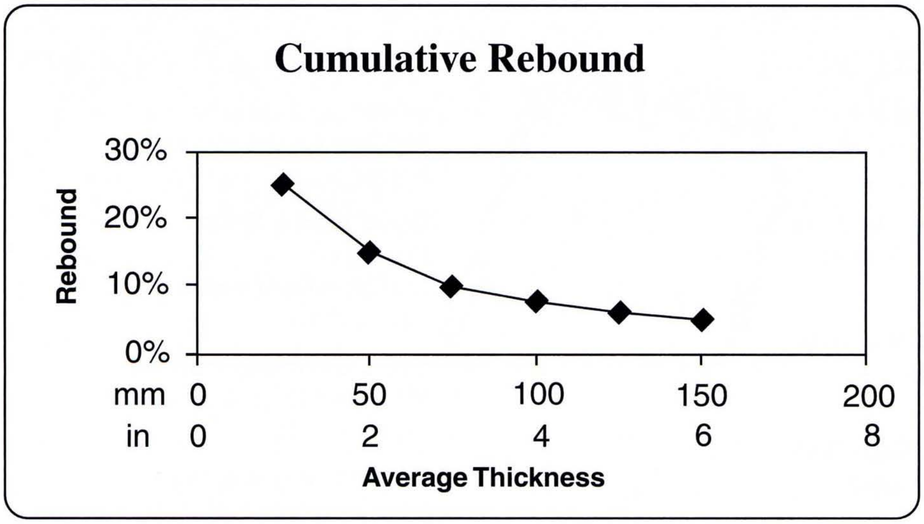


Figure 3. Cumulative Rebound with Thickness Placed

- Particle size distribution depends on the
  - Aggregate blend,
  - Sand,
  - Cement, and
  - Silica fume
- Velocity of impact depends on the
  - Pressure in the line or air flow,
  - Distance of the nozzle from the receiving surface, and
  - Orientation of the nozzle

A dense, well-placed shotcrete layer will usually exhibit a good distribution of aggregate particles including coarse aggregate to a maximum of about 10 mm (3/8 in.). The most common aggregate blend seen in international projects is close to the American Concrete Institute's Gradation No. 2 as shown in ACI 506R-90.

A well-designed shotcrete mix will also help to reduce rebound. There must be sufficient fine materials (cement and silica fume) to adequately cover the total surface area of the sand and aggregate particles. Since there is a high proportion of sand and relatively small aggregate in comparison with conventional cast concrete, the cement contents of shotcretes tend to be high. This is another reason that shotcrete strengths are high. If the cement content is too low, rebound will again increase since there will be too little sticky paste for embedment and dynamic compaction.

The relationships between rebound and velocity of impact are equipment dependent and so specific rebound values are not presented. In general, however, there will be an optimum air pressure or volume flow rate, an optimum distance between the nozzle and the receiving surface and the shotcrete stream should be maintained perpendicular to the receiving surface.

It is also noted that rebound is a function of the total placed thickness of shotcrete

- Rebound is high at the beginning of a shoot, and
- Rebound becomes lower with increasing thickness.

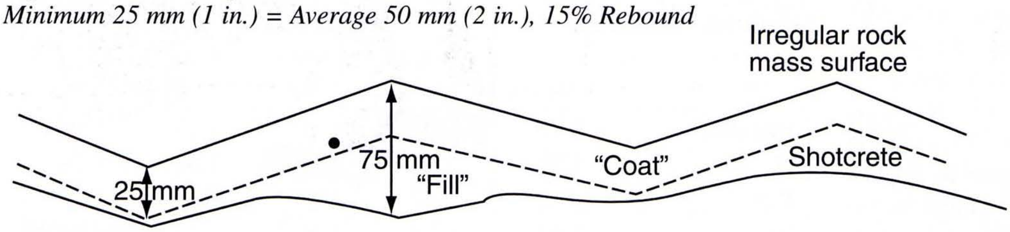
This concept is true for all shotcrete but is far more prevalent when using the dry-mix process. As the first material strikes the receiving surface a very high proportion of the coarse aggregate and steel fibers bounces off the surface. Coarser material cannot embed itself into the plastic shotcrete until a paste layer has been built up on the surface. This initial layer is usually rich in cement and is commonly responsible for the good bond developed by shotcrete. Once the coarser material can become part of the increasing layer, dynamic compaction starts to take place that leads to the development of high strengths. As the layer thickness increases further, the instantaneous rebound drops to almost zero in the case of wet-mix process shotcrete. The cumulative rebound figures for wet-mix shotcrete (the total amount of rebound for a particular section thickness) are shown in Figure 3.

This curve demonstrates the relationship between total anticipated rebound for well-placed shotcrete and the section thickness called for. Site specific versions of this chart could be produced by physically measuring the rebound values during pre-construction testing. The curve is based on field observations and various published values for rebound.

Thickness

The definition of thickness in mining engineering applications is not at all straightforward. For a smooth walled excavation such as a tunnel boring machine (TBM) driven civil engineering tunnel, the concept of a uniform layer of a specified thickness is reasonable. This would be considered to be a "coating" by Windsor and Thompson (1999) (2). The "coat and fill" suggested by Windsor and Thompson is more likely for mining applications in which a minimum coating thickness is required, but in order to successfully achieve this absolute minimum some additional filling of hollows in the rock mass is needed. The "fill" profile, in which all of the hollows are filled and the surface between is relatively smooth is unlikely in mining due to high volumes of material required.

Figure 4. Thickness of Shotcrete
Minimum 25 mm (1 in.) = Average 50 mm (2 in.), 15% Rebound



Thus, in a mining application of shotcrete in a drill and blast excavation, there is no single concept of "thickness" that applies. If the design engineer calls for an absolute minimum thickness of 25 mm (1 in.), then he will likely need an average of 50 mm (2 in.) to provide the desired cover. Figure 3 shows that this average layer thickness would probably be associated with a minimum of 15% rebound.

If the design is for a minimum of 50 mm (2 in.), then it is likely that an average of 75 mm (3 in.) will be needed and the associated rebound figure could drop to 10%. If the design calls for a minimum of 75 mm (3 in.), an average of 100 mm (4 in.) might apply and the rebound could drop further to 7.5%. The majority of mining applications of shotcrete call for thicknesses of 50, 75 or 100 mm (2, 3, or 4 in.). It is quite common to see the thickness described as a "minimum thickness," although estimating volumes based on minimum thickness is not recommended. It is strongly suggested that the notion of minimum coating plus some filling is the method used to specify shotcrete in drill and blast applications.

Figure 4 shows the placement of a minimum coating of 25 mm (1 in.) with local filling to 75 mm (3 in.). This illustrates how difficult it would be to assume that a uniform layer thickness could ever be successfully specified in a mining project.

Planning Process

It has been shown that the surface of an excavation driven by drill and blast methods is far from smooth and uniform, and the perimeter of the excavation boundary is much larger than designed. The amount of overbreak is a function of the inherent character of the ground-rock mass quality—and the actual excavation process—quality control of the drill and blast method. The impact of the placement of shotcrete can also be taken into consideration at the design phase by considering the required thickness, as both a minimum and an average. Different levels of rebound can be attributed to different total section thickness, so it is now possible to estimate a Volume Factor for a specific application using site specific values for Ground Condition, Drill and Blast Process and Rebound, using Table 2.

The Roughness Factors shown in Table 2 are taken from the prime diagonal from Table 1. It is noted that any combination of Ground Condition and Drill and Blast Process can be used to determine the Roughness Factor, and the Rebound Factor can then be used to generate a specific Volume Factor.

The grayed-out zones on Table 2 refer to matrix intersections that are not likely to exist in reality. For example, it is unlikely that a rock mass giving a poor Roughness Factor would only require 50 or 75 mm (2 or 3 in.) of shotcrete. Similarly, a high quality rock mass that is well-excavated would be unlikely to warrant a 75 or 100 mm (3 or 4 in.) shotcrete layer.

Volume Factor: (including Rebound and other factors)

Roughness Factor		Average Thickness–Rebound Factor		
		50 mm	75 mm	100 mm
	Factor	1.15	1.10	1.075
Excellent	1.05	1.2		
Good	1.32	1.5	1.5	
Fair	1.61		1.8	1.8
Poor	2.00			2.2

Table 2. Volume Factor

The numbers found for design purposes from this table are similar to those that have been developed empirically over the last few years by the mining industry in Australia. The process shown in this paper allows the engineer to determine where the different components of the overall Volume Factor come from.

Steps in the Planning Process

The following outline presents the planning process required for estimating shotcrete volumes in a drill and blast mining operation.

- Select location needing shotcrete
- Decide on plain or mesh reinforced shotcrete or fiber-reinforced shotcrete (Fibercrete)
- Determine area to be shot
- Confirm design shape per engineering
- Determine excavated shape by site review
- Estimate geological factors
- Estimate drill and blast factors
- Measure effective round/cut length (this may be more than the excavated cut length depending on loss of previously applied shotcrete, for example)
- Estimate design area needing shotcrete
- Estimate roughness factor
- Consider design thickness (minimum and average)
- Estimate rebound factor
- Estimate volume factor and calculate volume required
- Instruct contractor accordingly. A typical shotcrete request form should include precise information concerning the time and the location of the shotcreting, and a sketch on a cross section or plan view of the profile, including overbreak and fall outs. Above all, such a request form must include information on the length, the perimeter, the thickness, the factor , and the volume shotcreted, both as estimated and as shot. It then represents a hardcopy of the differences, if any, between the es-

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timated and the real quantity applied for every section of the opening shotcreted.

There are a number of other considerations that may come into play when designing a shotcrete program (quality of scaling walls and back, operator training, fall outs, presence of other support systems, etc.). They may all have an influence on the amount of shotcrete placed, and may or may not be under the control of the placement contractor.

Conclusions

One of the most demanding parts of a shotcrete program in the mining industry is determining what sort of contract to enter into with the placement contractor. One process commonly encountered in mining is for the design engineer to estimate the required volume of shotcrete based on the design profile of the excavation with a small allowance for rebound and wastage. Having made this estimate and instructed the contractor to place a certain volume of material on the rock mass around the excavation, the engineer is surprised to find that the volume requested did not cover the ground to the desired thickness. Almost inevitably, a conflict starts to develop between the two parties since the engineer and the contractor are looking at the problem from two different viewpoints.

It is hoped that by using a process such as that suggested in this paper, less conflict will arise by making both parties more aware of the considerations that need to be made during the design phase of the project. A clear understanding of the concept of thickness needs to be made before a decision is taken on how to word the "Payment" clause of the contract. If the contractor is to assume the majority of the risk, then unit costs will be high. If the owner and the contractor find a way to share the risk and agree to pay on "cubic metres through the pot," then both parties must use a shotcrete request form, and reach a consensus about the required volume of shotcrete materials to be placed.

Acknowledgements

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References

1. Throughout this article, the term "shotcrete" is used to include the process of pneumatically placing concrete and the product thus created. It includes "sprayed concrete" and does not infer the wet-mix or the dry-mix process. It usually implies a blended aggregate with up to 7-9 mm (1/2-1/3 in.) sized particles, although it may also be synonymous with the old term "gunite" (a term restricted to the use of dry-mix process and sand sized aggregate).

2. C.R. Windsor and A.G. Thompson, The design of shotcrete linings for excavations created by drill and blast methods in Rock Support and Reinforcement Practice in Mining, Eds. E. Villaescusa, C.R. Windsor and A.G. Thompson. Balkema, pp 231-242, 1999.

David Wood is a registered Professional and Chartered Engineer practicing in Rock Engineering and Engineering Geology with 25 years experience in consulting geotechnical engineering programs in North and South America, Europe, Australia, Africa and Asia. His experience comprises rock mass evaluation, rock hazard appraisal, rock engineering analysis and design, rock slope stability assessment and stabilization design, engineering geological and geotechnical field data-collection studies, and report preparation for small and large-scale civil and mining projects.