Designing Shotcrete As Primary Support in Tunnels

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ABSTRACT

Since the advent of New Austrian Tunneling Method (NATM), shotcrete as a primary means of support in tunnels has been widely applied. It's most important features are durability, speed of application and cost effectiveness. This paper introduces some tables that provide guidelines for the thickness of shotcrete required in some common situations of mine roadways.

In order to devise such tables, two different arch sections, together with three different overburden types, were considered. Geotechnical parameters such as apparent cohesion and angle of internal friction of surrounding rocks were chosen, based on the five-category classification of Bieniawski. Two K_0 factors (the ratio of horizontal stress to vertical stress) and an average rock density were utilized. Using numerical methods, 60 models were then devised in this way.

By applying interaction diagrams of axial force and the bending moment for different thicknesses of shotcrete, appropriate shotcrete thickness for these models were calculated. The results of this research, as well as the methodology applied, can be used in mining roadway support design and all types of civil engineering tunnels.

INTRODUCTION

Having popularized the NATM technique, shotcrete as the first choice for primary support in tunnels has been extensively applied. Reasonable prices, quick and simple installation and permanence are some features that make this type of support most preferable amongst all kinds of supports in the new tunneling method. Reviews of the development of shotcrete technology have been presented in some papers (Rose, 1985; Franzén, 1992; Morgan, 1993).

Although the use of shotcrete as support for underground excavations was pioneered by the civil engineering industry, the mining industry has become a major user in recent years. An important area of shotcrete application in underground mining is in the support of permanent openings such as ramps, haulages, shaft stations and crusher chambers.

Rehabilitation of conventional rock bolt and mesh support can be very disruptive and expensive. Increasing numbers of these excavations are being shotcreted immediately after excavation. Trials and observations suggest that shotcrete can provide effective support in mild rock burst conditions (McCreath and Kaiser, 1992; Langille and Burtney, 1992). While the results from these studies are still too limited to permit definite conclusions to be drawn, the indications are encouraging enough that more serious attention will probably need to be paid to shotcrete support in the future.

In spite of increasing importance of shotcrete, a complete guidance reference for its application, in which shotcrete is designed as primary support in different conditions, is not yet available. The supports proposed by experiment classifications are also based on the databases in which a steel frame is dominated and suggested shotcrete thickness by them should be reconsidered. These factors made the authors analyze tunnel stability in some common geotechnical conditions by numerical methods and using FLAC software; in each case, appropriate thickness of shotcrete as a primary support is suggested.

IN-SITU STRESS

Before digging underground spaces, adjacent rocks are already under stress. As a matter of fact, the stress imposed after drilling is in direct relationship with that primitive stress; hence, it is necessary to determine the initial stresses at the first step of underground excavation support design. Different techniques for measuring in-situ stresses are presented namely over coring, hydraulic failure and flat jacking. All of these methods require an access way, drilling very expensive boreholes or pilot tunnels, and these studies are economically feasible only for tunnels of considerable length.

In-situ stresses based on the amount of tunnel overburden, the average density of rock surrounding and the ratio of horizontal stress to vertical stress (K_0) is estimated (Equation 1). Measuring vertical stress in construction and mining projects around the world confirms the equation.

$$\sigma_v(Pa) = \gamma(N/m^3)\times Z(m) \quad \sigma_H = \sigma_V \times k_0 \qquad (1)$$

In 1952, Richard and Terzaqy presented a relationship between vertical and lateral stresses (σ_x and σ_x) in areas where sedimentary rocks and sequences of layers are intact and horizontal and their dimensions have remained unchanged. This relationship is shown in Equation 2.

$$\sigma_x = \sigma_z = \sigma_H = v/(1\text{-}v) \times \sigma_v \qquad (2)$$

Hook and Brown in 1978, and Herget in 1988, showed that K_0 depends on depth and its value decreases with an increase in depth. Sheory also confirms this relationship and presents Equation 3, in which Z is depth (m) and is the average deformation modulus (GPa) measured in the horizontal direction (Sheory, 1994).

$$k_0 = 0.25 + 7E_h(0.001+1/Z) \qquad (3)$$

In this paper, the in-situ stress is calculated according to the values of 1 and 0.7 for K_0, the average density of 2,500 kg/m^3 (156 lbs/ft^3) for neighboring rocks and overburdens of 50, 100 and 150 m (164, 328 and 492 ft).

SHOTCRETE

Shotcrete Technology

Shotcrete is the generic name for cement, sand and fine aggregate concretes which are applied pneumatically and compacted dynamically under high velocity.

Dry Mix Shotcrete

As illustrated in Figure 1, dry shotcrete components – which may be slightly pre-dampened to reduce dust – are fed into a hopper with continuous agitation. Compressed air is introduced through a rotating barrel or feed bowl to convey the materials in a continuous stream through the delivery hose. Water is added to the mix at the nozzle. Gunite, a proprietary name for dry-sprayed mortar used in the early 1900s, has fallen into disuse in favor of the more general term shotcrete (Mahar et al., 1975).

Wet Mix Shotcrete

In this case, shotcrete components and water are mixed (usually in a truck-mounted mixer) before delivery into a positive displacement pumping unit, which then delivers the mix hydraulically to the nozzle where air is added to project the material onto the rock surface (see Figure 2).

The final product of either the dry or wet shotcrete process is very similar. The dry mix system tends to be more widely used in mining because of inaccessibility for large transit mix trucks and also because it generally uses smaller and more compact equipment. This can be moved around relatively easily in an underground mine environment. The wet mix system is ideal for high production applications in mining and civil engineering where a deep shaft or long tunnel is being driven and where access allows the application equipment and delivery trucks to operate on a relatively continuous basis. Decisions to use dry or wet mix shotcrete processes are usually made on a site-by-site basis (Mahar et al., 1975).

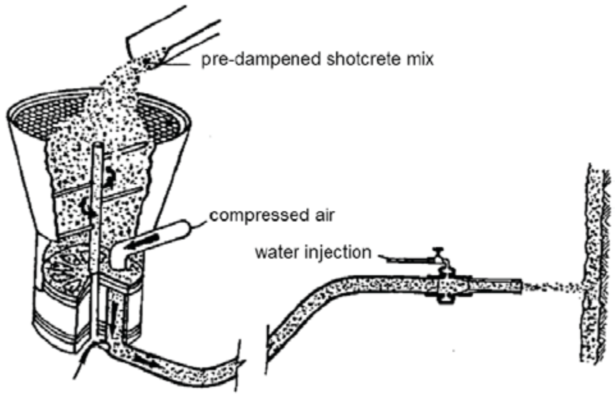

Figure 1. Simplified sketch of a typical dry mix shotcrete system.

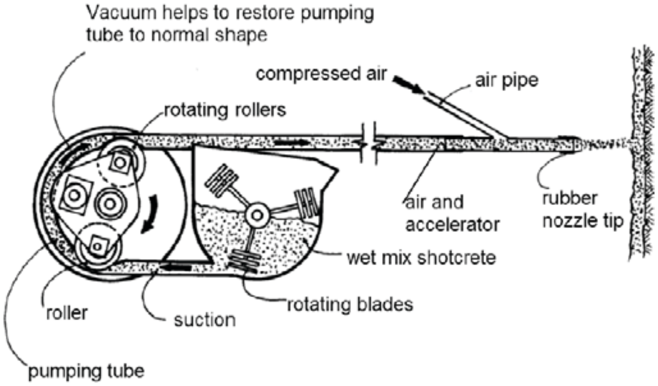

Figure 2. One typical type of wet mix shotcrete.

Steel Fiber-Reinforced Shotcrete

Steel fiber-reinforced shotcrete was introduced in the 1970s and has since gained world-wide acceptance as a replacement for traditional wire mesh-reinforced plain shotcrete. The main role that reinforcement plays in shotcrete is to impart ductility to an otherwise brittle material (Papworth, 2002).

Mesh-Reinforced Shotcrete

While steel fiber-reinforced shotcrete has been widely accepted in both civil and mining engineering, mesh-reinforced shotcrete is still widely used and is preferred in some applications. In very poor quality loose rock masses, where adhesion of the shotcrete to the rock surface is poor, the mesh provides a significant amount of reinforcement, even without shotcrete. Therefore, when stabilizing slopes in very poor quality rock masses or when building bulkheads for underground fill, mesh is frequently used to stabilize the surface or to provide reinforcement. In such cases, plain shotcrete is applied later to provide additional support and to protect the mesh against corrosion.

Kirsten (1992, 1993) carried out a comprehensive set of laboratory bending tests on both mesh and fiber reinforced shotcrete slabs. The loads versus deflection curves that he obtained were similar to those reported by Kompen (Kirsten, 1992, 1993;

Kompen, 1989). He found that the load-carrying capacity of the mesh and fiber-reinforced shotcrete samples were not significantly different, but that the mesh-reinforced samples were superior in bending with both point loads and uniformly distributed loads. He concluded that this was due to the more favorable location of the mesh reinforcement in the slabs subjected to bending.

Kirsten also concluded that the quality control required to obtain a consistent dosage and uniform distribution of fibers in shotcrete is more easily achieved in civil engineering than in mining applications. This is a reflection of the multiple working headings and access difficulties common at mines. Under these circumstances, more reliable reinforcement will be obtained with mesh-reinforced rather than fiber-reinforced shotcrete. However, in large mines, in which many of the 'permanent' openings are similar to those on large civil engineering sites, these problems of quality control should not arise.

In this research, only mesh reinforced shotcrete is applied as tunnel support in different conditions (Papworth, 2002).

Technical Characteristics of Shotcrete

Some of the technical and engineering traits of shotcrete used in support design are compressive strength, tensile strength, elastic modulus and inertia moment. Elastic modulus is related to the compressive strength and increases over time in consistence with it.

In this study, elastic modulus, compressive strength and tensile strength for shotcrete are respectively assumed at 20 GPa (2.9 million psi), 280 and 20 kg/cm^2 (3,983 and 285 lb/in^2). Because of the great length of tunnels compared with their width and, hence, considerable stiffness in the direction of the tunnel length, the strain in this direction can be ignored and all designs are done under two-dimensional strain circumstances. Under these conditions, tunnel length is considered as length unit. Shotcrete inertia moment is like a rectangular cross-section where length unit and width equal the shotcrete thickness (Hook and Brown, 1978).

Interaction Diagrams of Axial Force and the Bending Moment

Final strength calculation of a cross-section when axial force and the bending moment are combined is complicated. This combination creates an area ranging from the pure axial force ($M=0$, $P=P_{no}$) to pure bending moment ($M=M_{no}$, $P=0$) including pressure control area, balanced failure state and tensile control area. These areas are easily detectable if final strength calculation results are shown by interaction diagrams of axial force and the bending moment. Such diagrams are suitable means for quick and proper support design.

For a cross-section with certain dimensions, the interaction diagram will generally look like that in Figure 3, where the vertical and horizontal axis is axial force and the bending moment corresponds. Each point on the graph, such as point A, represents a combination of P_n and M_n that, according to the theory, show the disruptive point of the cross-section. The diagram begins from the point O with the pure axial force of P_{no} ($M=0$). Ob-related area belongs to the pressure control zone. Point B represents the balanced failure state and the bc-related region is the tensile control area. Finally, C shows the end point of flexural capacity, M_{no}, at the pure bending moment ($P=0$). According to ACI regulations, the safety factor for pressure area and pure bending is 0.7 and 0.9, respectively. The reason for this difference is the fact that pressure failure is more sensitive to fluctuations of shotcrete's compressive strength as compared with tensile failure (Tahuny, 1990).

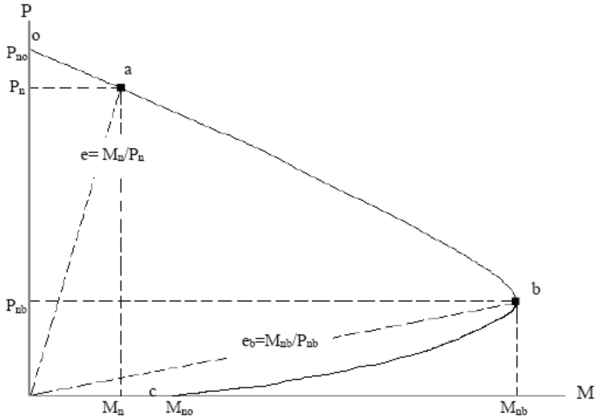

Figure 3. Interaction diagrams of axial force and the bending moment.

Design Diagrams

In this support design study, four shotcrete thicknesses are used: 5, 10, 15 and 20 cm (2, 4, 6 and 8 in). To determine the suitable thickness, interaction diagrams of axial force and the bending moment for the shotcrete thicknesses of 10, 15 and 20 cm (4, 6 and 8 in) are plotted (see Figure 4); for the 5-cm (2–in) thickness, Equation 4 is the criterion for the support design being considered.

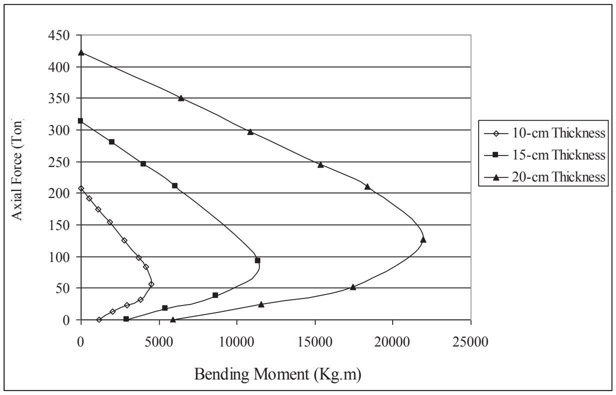

Figure 4. Interaction diagrams of shotcrete thicknesses of 10, 15 and 20 cm (4, 6, and 8 in).

$$F/A \pm M.C/I \qquad (4)$$

In which F, A, M, C and I is axial force, the cross-section area, the torque, the distance between axial force and neutral line, and inertia moment.

According to regulations of ACI, total proportion of mesh cross-section area to the total cross-section area should be one to eight percent. The reason for the one percent limit is that it prevents sudden failures, and the limit of eight percent is used because of installation matters and keeping a minimum distance between longitudinal meshes. In this study, meshes are symmetrically placed in a shotcrete cross-section and they cover up 1–1.5% of total cross-section (Tahuny, 1990).

NUMERICAL MODELING WITH FLAC SOFTWARE

FLAC software is fitting for the modeling and analysis of soil and stone structures' behavior, which have the same behavior as continuous structures. As long as the displacement of rock along the joint surface compared with rock mass displacement is negligible, this software can be utilized for modeling.

Tunnel Geometry

In this study, two types of tunnels have been studied (see Figure 5):

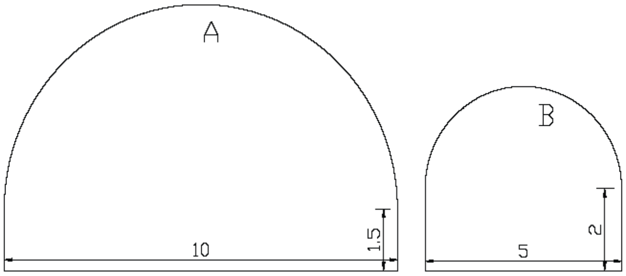

Figure 5. (A) Geometry of road tunnel (m); (B) geometry of mining tunnel (m).

A. A road tunnel where geometry is chosen based on typical roads with two ways, and where every line has a width of 3.65 m (12 ft).
B. A mining tunnel where the geometry is chosen based on typical main tunnels in underground mines.

Determination of Stress Released Before Support Installation

Determination of tunnel displacement or stress discharged before installing a support is not a simple issue, and three-dimensional modeling is required. Chern and his colleagues analyzed the performance of instruments installed in different tunnels to achieve results, and Hook presented their results in a graph (see Figure 6) (Chern et al., 1998).

Rock Mass Geotechnical Parameters

In this comprehensive research, geotechnical parameters of rock mass are selected based on the classification of Bieniawski. Bieniawski has classified rocks into five categories: very good, good, moderate, weak and very weak and for each category, apparent cohesion and angle of internal friction are suggested. Table 1 shows the average amount of these parameters for each category (Farooqh Hosseini, 2000).

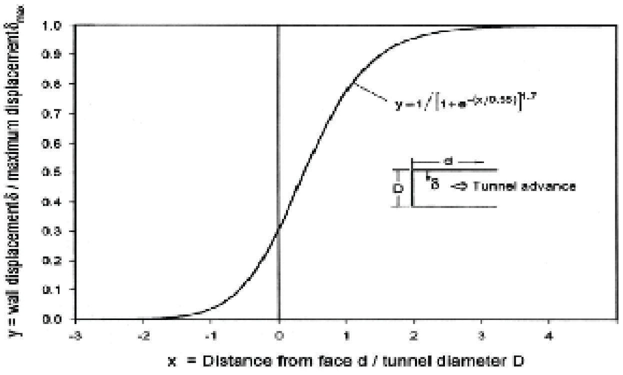

Figure 6. Tunnel displacement or stress discharged before installing the support.

Numerical Modeling

Using the five categories of rock, three overburdens, two K_0s and two tunnel cross-sections, 60 models were created and analyzed. It should be noted that modeling is done under a large deformation mode. The modeling process is as follows,

- According to the tunnel geometry and overburden, geometry of a model is determined in order not to influence the stress distribution around the tunnel, and be located in regions where stresses are the same as in-situ stresses.
- Tunnel geometry, rock properties, boundary conditions, in-situ stresses and gravity acceleration are applied to the model, and ground static conditions are also modeled before drilling.
- A tunnel is excavated and allowed to be displaced to about 40 percent of the total displacement, then a support is installed and, finally, the model is rotated to reach equilibrium.
- The determination of appropriate shotcrete thickness, axial force and the bending moment created in the support are compared with the corresponding interaction diagram. If the proper support was not installed (i.e., if corresponding points of axial force and the bending moment were located outside the interaction diagram or had a far distance to the interaction diagram), all previous stages would be repeated with another thickness in order to obtain the optimal shotcrete thickness.

CONCLUSION

The results of modeling based on the tunnel geometry and overburden are shown in Tables 2–7. In some conditions which are filled with aster, even the 20 cm (8 in) shotcrete thickness is insufficient, and lattice or a steel frame should be also used. According to the data represented in these tables, the following outcomes can also be achieved.

- Overburden plays a major role in determining the appropriate shotcrete thickness for weak and very weak rocks; the height of crushed rocks in these rocks increases in accordance with overburden height.
- Changing K_0 from 0.7 to 1 has a little effect on the required thickness of shotcrete. Increasing K_0 has both a positive and negative effect; the positive effect is making the uniform stress distribution around the tunnel, and the negative effect is increasing lateral stresses.

Table 1. Geotechnical parameters of rock mass.

Rock Mass Description	Very Hard	Hard	Moderate	Weak	Very Weak
Apparent Cohesion (K Pa)	400	350	250	150	100
Angle of Internal Friction (Degree)	40	35	30	20	15
Deformation Modulus (G Pa)	20	15	10	5	2

Table 2. Shotcret application for mining tunnels with the 50-m (164-ft) over burden (Cm).

Rock Mass Description	Very Hard	Hard	Moderate	Weak	Very Weak
$K_0 = 0.7$	5	5	5	10	20
$K_0 = 1$	5	5	5	10	20

Table 3. Shotcret application for mining tunnels with the 100-m (328-ft) over burden (Cm).

Rock Mass Description	Very Hard	Hard	Moderate	Weak	Very Weak
$K_0 = 0.7$	5	5	5	15	***
$K_0 = 1$	5	5	5	15	***

Table 4. Shotcret application for mining tunnels with the 150-m (492-ft) over burden (Cm)

Rock Mass Description	Very Hard	Hard	Moderate	Weak	Very Weak
$K_0 = 0.7$	5	5	5	***	***
$K_0 = 1$	5	5	5	***	***

Table 5. Shotcret application for road tunnels with the 50-m (164-ft) over burden (Cm).

Rock Mass Description	Very Hard	Hard	Moderate	Weak	Very Weak
$K_0 = 0.7$	5	5	5	15	20
$K_0 = 1$	5	5	5	15	20

Table 6. Shotcret application for road tunnels with the 100-m (328-ft) over burden (Cm)

Rock Mass Description	Very Hard	Hard	Moderate	Weak	Very Weak
$K_0 = 0.7$	5	5	5	20	***
$K_0 = 1$	5	5	5	20	***

Table 7. Shotcret application for road tunnels with the 150-m (492-ft) over burden (Cm).

Rock Mass Description	Very Hard	Hard	Moderate	Weak	Very Weak
$K_0 = 0.7$	5	5	15	***	***
$K_0 = 1$	5	5	15	***	***

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