The influence of mix design on boundary conditions of applied sprayed concrete for underground mine and civil tunnels.

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Abstract

Sprayed concrete or typical known as shotcrete in the world of civil and mine tunnels has been used for a number of years and for various problematic issues. The issue that intrigues me most, is the fact that boundary condition is inevitably, neglected by most tunnel and geotechnical design engineers. It is without a doubt the most important aspect of implementing a proper design including the acquisition or control of boundary conditions from design to application.

Introduction

Shotcrete or sprayed concrete was apparently invented in 1907 as a means of applying a cementitious material onto wire frames to construct animal models. The Cement-Gun Company in Allentown conducted the first sprayed concrete job in the United States. The first device made for spraying of dry materials for new constructions was invented in Pennsylvania in 1907 by Carl Ethan Akelay, who needed a machine to spray onto mesh to build dinosaurs. His company, the Cement Gun Company, protected the brand name "Gunite' for their sprayed mortar. This mortar contained fine aggregates and a rather high percentage of cement. The name Gunite is still used. In some classification Gunite stands for sprayed mortar, but grain size limits are not consistent. Depending on the country, the limit for the maximum aggregate is defined as 4mm, 5mm or even 8mm. To avoid this confusion between sprayed mortar and sprayed concrete, the expression "Sprayed Concrete" for every sprayed mixture of cement and aggregates is used (Melbye, T. and Garsholl, K.F., 1999, p9-10).

Dry-mix spraying developed from there, but in the 1960's wet-mix sparing gained popularity. This development was essentially an adaptation of conventional concrete pumping with compressed air added at the nozzle. The term "shotcrete" can be correctly used to describe either dry-mix or wet-mix spraying. However dry-mix was originally and is still often referred to as "gunite" while wet-mix applicators often prefer the term "sprayed concrete" to differentiate their product (Clements, M.J.K., 1998).

Wet-mix spraying in Australia was used widely in 1970's for swimming pool construction. The introduction of the EE steel fibre by Australian Wire Industries in 1972 enabled conventional steel reinforcement to be eliminated in low-end structural uses. The skills learned by swimming pool constructors in the 1970's were quickly turned to good use in the booming construction industry of the mid to late 1980's in Sydney in particular (Clements, M.J.K., 1998).

In the 1980's some builders recognised that the fastest means of transporting ready mix concrete to its final position in walls was by sprayed application. Only rear

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formwork was required, and in basements, the concrete could be sprayed directly onto the excavated surface, eliminating formwork completely (Clements, M.J.K., 1998).

By 1987, shotcrete was widely used in the building industry in the following ways: -

- To construct underpinning columns under buildings adjacent to high rise excavations
- To construct shoring panels that achieved the two-fold purpose of ground support and permanent car park walls
- To construct vertical concrete walls in high rise buildings, especially fire rated walls and lift wells
- To construct free-form shapes difficult to form up such as fancy facades and rooftop pools

A unique ability of shotcrete is its capability of being used in a free-form fashion. This is after all why it was invented in the first place. Fancy building facades and rooftop swimming pools on city hotels are examples of shotcrete being used in this form. Other good examples are found at Sydney's Taronga Park Zoo where animal enclosures are built to simulate natural environments. A variety of surface finishing's have been adapted by skilled operators to enable natural rock-like appearances to be fashioned (Clements, M.J.K., 1998).

However, by 1990 the building industry had collapsed spectacularly as commercial property prices plunged. CBD construction in Sydney and Melbourne ground to a halt completely. Building construction moved to the suburbs, but the emphasis was now on economy rather than speed (Clements, M.J.K., 1998).

The benefits of shotcrete as surface support in mining tunnels and the need for it to enable ultra deep mining have come to be realised at tremendous speed in the industry in the past number of years. Developments accordingly have been focused, simultaneously in two directions, viz. Structural competency and design on the one hand and manufacture and application at the job site on the other. The aspects of structural competency and design that have been pursued on a collaborative research basis comprise system ductility, conjunctive functions of shotcrete and rock reinforcement, flexural resistance of shotcrete, design of shotcrete and accounting for parameter variability.

The developments on manufacture and application were traced in a number of case studies that include "shotcreting" in a bored ventilation shaft, development of logistics to apply shotcrete in high-speed development at depth, use of shotcrete in a vertically sided open shaft as novel method of extraction, introduction of monofilament polypropylene fibre in a highly corrosive ventilation shaft, and the use of shotcrete in heavily stressed and deformed production tunnels in a block cave diamond mine (Kirsten, H.A.D., 1998).

The potential benefits of shotcrete as surface support have been realised to a progressively increasing extent in the mining industry over the past decade. Versatility is the main attraction of shotcrete in this regard. It can, for example, be applied close to the advancing face as early support where it is utilised to close the apertures in mesh against a loss of fines, reinforced with fibre to reduce the number of supporting operations, and it can be augmented with rope lacing to improve its resistance to impact loading (Kirsten, H.A.D., 1998).

Shotcrete may further be used to clad the rock surface, fill in undulations in the rock surface, control water seepage, thermally insulate tunnels when made with perlite aggregate, protect other steel components against vehicle impact and provide a tough wearing surface with the addition of reinforcing fibres and silica fume. Additional material can be applied at any subsequent stage to upgrade the support or to repair damaged or cracked sections loading (Kirsten, H.A.D., 1998).

It has been found that plain shotcrete is effective in static stress environments at moderate depth and that it stops scaling and weathering of the rock. Surface support systems that consist of an application of shotcrete followed by wire mesh and lacing are very effective in excavations that are subject to stress change and moderate seismic impact, but are subject to blast damage and corrosion. The initial application of shotcrete close to the face stabilises the ground and promotes quality bolting, meshing and lacing. The alternative of first applying the wire mesh and lacing and then the shotcrete is widely practiced in the industry but is relatively ineffective and time consuming. It should only be considered if the sidewalls are competent to start with and if mesh can be closely pinned to the rock. Highly stressed and fractured ground in a dynamic environment requires shotcrete to be applied before and after the mesh and lacing are installed. Such support is very effective, but is very expensive and is a logistical nightmare, if not impossible, in high-speed development. It is accordingly hoped that fibre-reinforced shotcrete, possibly reinforced with lacing, will encompass all the benefits of construction of the other systems without compromising any of their structural attributes (Kirsten, H.A.D., 1998).

Tunnel support is always expensive and “shotcreting” only worsens the situations. Whereas over-supporting may be unduly costly, under-supporting in demanding circumstances is invariably even more costly. The costliness of support and the retarding effect that it has on the speed of development often lead to it being delayed and/or partly installed. Such course of action has to some extent been pursued in the past in the industry to pay for support as maintenance rather than capital cost, which has had the effect of reducing capital expenditure, but invariably resulted in the overall costs of support being far more than had it been done correctly and in time the first instance.

It is now firmly accepted, that the costs of properly designed and installed support should be fully provided for in project budgets, schedules and construction logistics. The sizes and operational equipment of shafts and access ways in ultra deep mines, are now designed in extensive detail to cater for the requirements of support. This is due to the one dimensionality of a mine as construction site, the great distances of the working faces from the shaft head, the number of working faces involved and the required speed of development and production.

Because of the far-reaching effects on the costs and operational logistics of mines, it is now realised that the type of support required should be determined far more reliably and the design thereof be based on far more rational considerations than in the past. Awareness has arisen that support types should be varied as frequently along the length of a tunnel as intrinsic and mining induced ground conditions may dictate. It is accepted that the specification of support and shotcrete as part thereof has become a sophisticated business. The ability to quantitatively determine the likelihood of support failure under static and dynamic conditions and the associate risk of injury has been identified as a further requirement (Kirsten, H.A.D., 1998).

Problem

When conditions are good shotcrete without reinforcement and rock anchors are supposed to provide a high load carrying capacity. This capacity is not only dependent on the mix design of the sprayed concrete but also the workmanship of the contractor. This may result in conflicts between the owner and the contractor since the owner "delivers" the work. There are no evident solutions to this problem. In Sweden it is normally specified that three cores shall be pulled to determine adhesion for a certain area of the tunnel length. The average of the adhesion strength for the accepted cores is calculated and it is normally stated that this average shall exceed the required value. No single value must be lower than half the required value. The reason why this type of tensile test should not be treated like ordinary tension tests on concrete is the large variations in rock properties even within a limited area.

Experiences have shown that there is a great risk to test only a few cores for determining the adhesion strength in a way that is acceptable for a contractor who stands the risk of being forced to take costly measures due to unacceptably low adhesion results. It is therefore stated that the adhesion strength of sprayed concrete with the rock face varies with mix design, application, rock type, rock surface preparation and curing.

Sprayed Concrete Technique

Only a clean surface should be sprayed, as the adhesion of sprayed concrete is very greatly impaired if sprayed onto contaminated substrates. In case of several layers of sprayed concrete are applied it is necessary to obtain a good adherence between all of them. Before spraying a next layer of concrete the surface has to be cleaned each time mainly from dust produced during blasting and/or excavation. Simply using the spraying nozzle with compressed air and water, or in severe cases by sand blasting cleans the surface.

Care should be taken to always spray onto a well-damped surface, otherwise there exists the danger that an excessively dry surface will draw too much water out of the freshly concrete or mortar. On the other hand, the water must no longer flow on the surface since, otherwise, the sprayed mortar or concrete would tend to flow off. Surfaces on which water flows have to be sealed of first or the water drained using draining channels and gunite to which an accelerator has been added (Vandewalle, M., 1998, p42).

If concrete is to be sprayed or applied to a soft substrate as, for example sand, it is advisable to consolidate this surface beforehand with a very thin layer of mortar and only then should one apply thicker coatings. This prevents segregation between layer and the substrate.

i) Personnel

Successful concrete spraying not only depends on the machinery but also on the skill of the operator at the spray nozzle, as he largely controls the rebound and keeps it to a minimum. It is important to employ competent and reliable personnel as the work of a nozzle operator is not easy.

Spray dust and considerable rebound have to be combated when dry spraying; when wet spraying, holding the heavy hose filled with concrete is a great physical exertion. The gunman or pump operator is responsible for providing a constant flow of properly mixed material to the nozzle man.

It must however be pointed out that the safety of the driving team depends on the quality of the sprayed concrete.

ii) Robot

Up to some years ago, shotcreting was a manual operation. This required an operator for each nozzle, plus a driver to operate the shotcreter's work platform, which gave them close access to the entire profile. The resulting shotcrete was not always of the best quality. Cover was not uniform, particular over the irregular surfaces of the girders, and the work was arduous for the shotcrete's. They were hampered by protective gear worn against the fierce rebound and the dust, and they had to fight against high pressures involved in shotcrete delivery.

The wet-mix process with spray robots is preferred to the dry-mix process whenever a large amount of concrete has to be sprayed, especially for large diameter tunnels. Because one of the secrets behind a successful shotcreting system is a high capacity accommodated by high-pressure delivery for good compaction, manual control of the nozzle has become impossible. The demand for faster tunnel excavation, with a shotcrete application of more than 10 m^3 per hour, has promoted the development of the manipulated shotcrete systems. A high capacity system has to be automated and the nozzle remotely

A robot or spray arm is of considerable advantage, especially in tunnel construction as it does not only replace the work of the nozzle operator but it is also capable of utilising the full capacity of the machine.

This means that the shotcreting time can be halved. Total construction time in big tunnel projects can be reduced by approximately 10-15%. Reducing shotcreting time reduces the whole operation period for all other tunnelling machines and consequently reduces the total hire cost.

The sequence movements for spraying can even be programmed. This new technology makes it possible not only to drive the tunnel by machines but also to carry out the work outside the danger area. Some manufacturers have incorporates a cabin on the shotcreting boom to keep the operator as close to the nozzle as possible. Others have kept the operator on the ground with a remote control console, which can be free standing or strapped around the operator's neck allowing him freedom of movement to choose the best point of observation. With the portable console the operator can stand well back from the face under a supported roof, away from the dust and rebound, where visibility is higher (Vandewalle, M., 1998, p46).

iii) Nozzle distance, spraying angle

The distance of the nozzle from the work should be preferably between 0.60m and 1,8m to give the best results for work requirements: highest degree of compaction at the lowest rebound.

The optimal distance between the nozzle and the surfaces to be sprayed is influenced by the :

- Aggregate size of the mix
- Grading curve
- Required or desired surface finish of the gunite or shotcrete
- Air pressure and speed of the conveyed material
- As a general rule, the nozzle should be held perpendicular to the receiving surface, but never more than 45 degree from the surface

When the nozzle is held at a too great an angle from the perpendicular, the shotcrete rolls or folds over, creating an uneven, wavy textured surface which can trap rebound and over spray. This technique is wasteful of material and may create porous and non-uniform shotcrete.

To uniformly distribute the shotcrete and minimise the effect of slugging, the nozzle is directed perpendicular to the surface and rotated steadily in a series of oval or circular patterns.

iv) Rebound

The following equation is a unique way to define rebound from a contractor's point of view (Vandewalle, M., 1998, p51) :

LOST SHOT CRETE = REBOUND + BACKFILL or OVERBREAK + WASTE

The total shotcrete often reaches 150-200% of the design quantity and is a significant factor in a contractor's cost. Rebound often takes an important part of it. In all types of shotcrete, the material travels at high velocity to the tunnel wall. The lighter particles of cement and sand are carried towards the wall with higher velocity than the heavier coarse aggregates. Initially upon striking the hard tunnel walls, rebound or blow away of almost 100% of all particles takes place (phase 1).

Finally a soft cushion of cement, sand and water is built up, and subsequent rebound drops to a constant percentage of perhaps 20% or less, as the new shotcrete strikes the soft cushion and adheres to it (phase 2).

If the shotcrete is placed in two lifts, there will again be initial high phase 1 rebound off the hardened shotcrete layer. If welded mesh is used it will vibrate and cause further rebound.

A spraying “mist” and rebound are avoided using high-grade nozzles with a compact spray jet. Higher performances, less wear on the machine, considerable energy saving due to lower air consumption and more safety for the nozzle operator are among the decisive advantages. It has been found that rebound of coarse aggregates on the wires of the mesh is much higher than elsewhere. This causes a poor shotcrete quality behind the wires and weak areas in the shotcrete layer; these are favorite places for groundwater drains. Not fully bonded layers generally have a reduced lifetime.

Less aggregate is found on the wall than exists at the nozzle due to rebound and blow away, but the percentage of cement finally sticking on the wall may increase. Rebound can be reduced in the field by the nozzle man shooting with added water and/or using a higher accelerator dosage. So commonly the initial layers may have a high water: cement ratio and a reduced strength. Strength is also negatively influenced by an increasing accelerator dosage.

It has been found, if the water ring is moved back from the end of the nozzle, it will ensure much better wetting of the dry shotcrete, reduce dust in the tunnel and produce a more consistent quality of shotcrete with less rebound and less tendency for the creation of dry pockets and sand lenses. To reduce phase 1 rebound, only relatively thick layers should be placed. No wire mesh should be used. Silica fume may be added, which increases “stickiness” and reduces rebound.

The rebound consists mainly of coarse aggregates of the mix. Under no circumstances should rebound be reused as it would invariably cause a distinct fall of the mechanical strengths. This is due to the fact that a portion of the rebound would be entirely coated with cement paste, which would have set by the time the rebound was removed.

The following conditions could reduce the rebound: higher cement content, more fines in the mixture, smaller maximum size aggregate, proper moisture content of the aggregate, a finer gradation, and inclusion of fly ash or silica fume. For dry mix process the most effective means to reduce rebound include reduction of air pressure, use of more fines, pre-damping and shooting at the wettest stable consistency. One of the bif advantages of wet-process shotcreting is the low rebound. The amount of rebound depends on the consistency of the concrete, the use of accelerators, spraying technique and last but not least aggregates grading.

In wet-process shotcreting a rebound between 15 and 20 percent by weight is experienced while in the dry process rebound can be as high as 50 percent.

References

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