# A Review on Application of Shotcrete in Tunnel Construction for Better Performance

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*Abstract*— in tunnel construction Shotcrete is using as a support & stabilization of excavated section and also as a lining inner. Shotcrete is a process where concrete is likely to apply under pressure, using a gun onto a surface to form structural shapes including walls, floors, and roofs. This paper highlights shotcrete technology with admixtures effects, strength development control and its importance, spraying & flow processes, proportions of ingredients, mechanical properties, application criteria's, advantages and advancement. It also covers a case study of Hong Kong Tunnel works.

*Key words:* Tunnel construction, shotcrete, Spraying process, Advancements

## I. INTRODUCTION

Shotcrete is a pneumatically applied sprayed concrete mixture, applied through hose, and projected at a high velocity to a surface to produce a compacted material which is self-supporting.

Shotcrete is used in all areas of tunnel construction for road or rail tunnels, water drainage and underground military structures, in addition to slope stabilization. In tunnel construction shotcrete is using as a support & stabilization of excavated section and also as a lining inner. Its unique flexibility in the choice of application thickness, material formulation, output capacity, very early strength development and the ability to re-spray at any time makes it complete material for excavation stabilization. Shotcrete was used for the first time in 1914 and has been permanently developed and improved over recent decades.

Fig. 1: Shotcrete application

## II. SHOTCRETE TECHNIQUE

### A. Suitability

Shotcrete is advantageous in situ when form work is cost prohibitive or impractical and where forms can be reduced or eliminated, access to the work area is difficult, thin layers or variable thicknesses required, or normal casting techniques cannot be employed.

Additional savings are possible because shotcrete requires only a small, portable plant for manufacture and placement.

Shotcreting operations can often be accomplished in areas of limited access to make repairs to structures.

### B. Admixtures & its effects

Cement, Additives (Fly ash, Micro silica, Stone dust, Slag) Aggregates, water & admixtures are ingredients of shotcrete. Admixtures are added as a percentage of the cement to shotcrete during the spraying process to regulate the start of setting. They are added in an approximate range of 0.5 % to 6.0 %. This gives quantities of 2 kg/m$^3$ to 30 kg/m$^3$. All the admixtures used are fed into the concrete during its production at the mixing plant after the initial water metering. Main exception is the setting accelerator, which is adding immediately before spraying.

#### 1) Liquid, alkali-free setting accelerator

Used for heading stabilization in tunneling, rock and slope stabilization, high quality lining shotcrete. Effects are very high early strength, increased water tightness, reduced quantity, better health and safety.

#### 2) Liquid, alkaline setting accelerator

Used for heading stabilization in tunneling, rock and slope stabilization. Effects are very high early strength, Lower rebound. It can be sprayed on a wet substrate.

#### 3) Super plasticizers

Effects are high water reduction, better workability, time controlled workability, rapid increase in strength, better shrinkage and creep properties and higher water tightness.

#### 4) Retarder

Effects are adjustable workability & no cleaning of pumps and hoses necessary during the retarding phase.

#### 5) Silica fume slurries Silica fume powder

Effects are improved fresh concrete homogeneity, much higher water tightness, improved adhesion between aggregate and hardened cement, high frost and freeze / thaw resistance and lower rebound.

#### 6) Polymer-modified Silica fume powder

Used for very high quality specifications. An effect is significant water reduction.

#### 7) Pumping agents and stabilizers

Effects are improvement in homogeneity and internal cohesion for unsuitable concrete mixes, increase in spraying output with lower energy consumption, even for mixes with crushed aggregate.

### C. Strength Development, control and its importance

Very early strength development in the range of a few minutes to about 1 hour & early strength development in the range of about 1 hour to max. 1 day. Final strength develops after 28 days.

In the first few minutes after application of the shotcrete, the adhesive strength is decisive. Accurate dosage of the amount of air determines the rate of application (thickness).

The insufficient air creates insufficient compaction and creates negative effect on final strength of shotcrete. Too much air produces much dust and high rebound losses. Fine cement and accelerator particles lost in the dust are important components missing for optimal strength development. The very early strength development determines the speed of advance and therefore the performance of the contractor.

A measurable compressive strength is obtained after about 1 hour (in special cases or in immediate stabilization after only a few minutes). This strength development determines when heading can continue to advance. The early strength development determines the progress with tunneling. The compressive strength is measured on cores taken from the structure or from sprayed panels.

## III. SPREYING PROCESS & FLOW PROCESS OF SHOTCRETE

### A. *Spraying Process*

#### 1) *Dry Sprayed Shotcrete Process*

Dry sprayed shotcrete process means delivery (transport) of a ready mixed sprayed concrete consisting of aggregate, cement and any sprayed concrete admixtures but without mixing water. This ready-mixed formulation is either completely dry (oven dry) or is wetted by the inherent moisture in the aggregate. Special rapid hardening cements that set in a very short time after wetting with water can be used in the dry spraying process. The thin flow process must be used for delivery of dry sprayed concrete.

Dry sprayed shotcrete is always used when smaller quantities and outputs are required and high very early strength is essential, for example for preliminary sealing against high water penetration with unites. It applies for concrete repairs, preliminary sealing against water in leakage, medium spraying works waterproofing works and local storage. Flexibility, high very early strength, unlimited holding time and no concrete waste are advantages of dry sprayed shotcrete.

#### 2) *Wet Sprayed Shotcrete Process*

Wet sprayed shotcrete means delivery (handling) of a ready mixed sprayed concrete consisting of aggregate, cement, water and sprayed concrete admixtures in a workable mix. For spraying, the wet sprayed concrete is mixed with air and shotcrete accelerators and then applied. The wet sprayed shotcrete can be processed by the dense flow or the thin flow method. Dense flow sprayed concrete is the latest high-performance process.

Wet sprayed shotcrete is always used when high set concrete quality is specified and high output is required. This process is by far the most popular in mechanical tunneling. Higher durability, sustainable working conditions due to less rebound & less dust generation, reduction in wear cost of equipment, constant water content are advantages of wet sprayed shotcrete process.

### B. *FLOW PROCESS*

#### 1) *Thin flow process*

Rotor machines convey concrete pneumatically by means of air, so that at the nozzle the concrete must not be additionally dispersed. The advantage of this method is that both wet and dry spray shotcrete can be applied in this manner. Since spray machines for the thin flow process are considerably smaller than those for dense flow processing, this technique is ideally appropriate for applications in the area of refurbishments, in which spatial limitations often impede work. The shotcrete accelerator is fed by the metering unit through separate hoses to the nozzle. The dosage is synchronized with the concrete quantity so that the set quantity of shotcrete accelerator is always added.

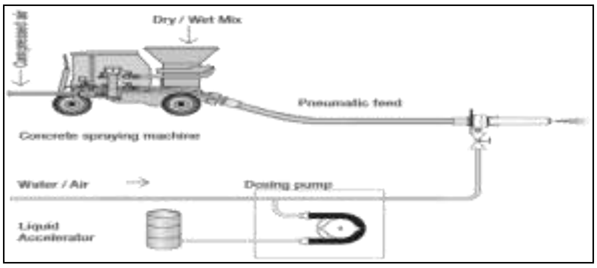


Fig. 2: Thin flow process for dry/ wet mix

#### 2) *Dense flow process*

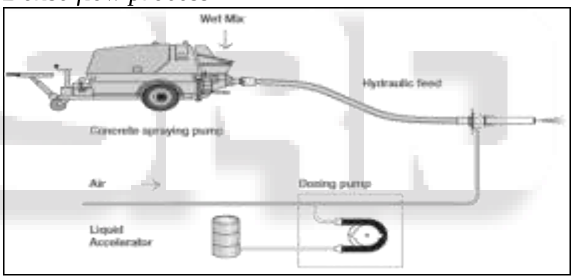


Fig. 3: Dense flow process for wet mix

When substantial quantities must be applied the concrete is pumped through pipelines in a dense-flow to the nozzle, where it is dispersed by compressed air. Accelerator is mixed into the concrete with the compressed air. The nozzle forms the concrete-accelerator mixture to a spray jet. Due to large output capacity this method is employed on one hand for excavation stabilization in tunnel construction and on the other for stabilization of large building pits.

The requirement for the pulsation is to be as low as possible during conveyance to obtain a constant spray at the nozzle. The compressed air is fed via an air compressor in separate hoses to the nozzle. The metering unit feeds the accelerator to the nozzle also in separate hoses. The dosage is synchronized with the concrete quantity so that the preset quantity of shotcrete accelerator is always added. Specially designed rotor machines are required for delivery of wet sprayed concrete by the thin flow process.

## IV. PROPORTION OF SHOTCRETE

### A. *Dry mix shotcrete*

There is no established method of proportioning dry-mix shotcrete. Since it is not practical to perform laboratory trial mixtures for dry-mix shotcrete, field testing of dry-mix proportions is highly advisable. The workability of the shotcrete is controlled by the nozzle man at the placement. Water adjustments may be made instantaneously at the placement by adjustment of the water valve.

Accelerators used in dry-mix shotcrete should be tested to determine that they are compatible with the cement being used and produce the required accelerated times of setting.

Cement contents are similar to those used in wet mix shotcrete. Batch weights for cement of 300 to 420 kg per cubic meter are typical, with 28-day compressive strengths of more than 31 N/mm$^2$ common for the mixtures used for vertical and overhead placement.

The batched water-cement ratio for coarse aggregate dry-mix shotcrete typically varies between 0.30 and 0.40.

### B. Wet mix shotcrete

Mixture proportioning procedures for the formulation of conventional concrete for pumping applications are applicable for wet mix shotcrete. The nominal maximum aggregate size is usually 1.9 cm or smaller. The batched cement content will typically range from 300 to 420 kg per cubic meter. Rich mixtures are common for shotcrete, especially if vertical or overhead shotcrete placement is required.

The limiting factor for cement content in a mixture is often governed by the amount of cement necessary for the shotcrete to adhere to a wall or ceiling, not the specified compressive strength. It is not unusual for shotcrete used in vertical and overhead placement to have 28-day strengths in excess of 31 N/mm$^2$, due only to the amount of cement necessary to make the shotcrete adhere.

The slump for wet-mix shotcrete should be near the minimum that the pump will handle. A 7.5 cm slump should normally be considered the maximum slump to be used. If air entrainment is to be used, an air content ranging from 8 to 12 % prior to pumping is typical. The in-place shotcrete will have about one-half of the entrained air that was recorded at the pump.

Additional admixtures generally behave the same in wet mix shotcrete as they do in conventional concrete. Any admixture should be tested in the mixture proportioning studies and on the test panels prior to usage.

### C. Fiber-reinforced shotcrete

Steel fiber lengths for shotcrete are typically 2.5 cm but often range from 1.9 cm to 3.75 cm. The fiber should be at least 0.625 cm longer than the diameter of the maximum aggregate size. Shorter fibers are more easily pumped through the system, although more are required for equivalent performance. Fiber batch quantities are dependent on required shotcrete properties. Typical fiber proportions range from 0.5 to 2.0 % by volume of shotcrete. Deformed fibers and fibers with end anchorage provisions produce shotcrete with properties equivalent to straight fibers at much lower fiber loadings. Since fibers tend to rebound at a greater rate than does aggregate, the fiber batch quantity should be adjusted accordingly.

### D. Silica-fume shotcrete

Silica fume is added to a shotcrete mixture as a cement replacement or in addition to cement. Batch quantities range from 7 to 15% by mass of cement. Strength enhancement and decreased permeability is apparent at the lower dosages. Reductions in rebound and increases in cohesiveness for thick applications do not occur until silica-fume dosages exceed approximately 14%. Further mixture adjustments to wet mix shotcrete may be necessary to attain the required workability level.

### E. Polymer-modified shotcrete

Polymer emulsions are typically 50% solids and 50% water. The liquid portion of the emulsion replaces the equivalent volume of water, and the solid portion replaces the same volume of combined solids. Additional adjustments to attain desired workability levels may be required.

## V. PROPERTIES OF SHOTCRETE

The experimental tests carried out on shotcrete are not enough to perfectly describe its properties especially stress-strain relationship, tensile strength and creep behavior. The following are the mechanical properties of shotcrete.

### A. Compressive Strength

The practicality of strengths over 34.483 N/mm$^2$ should be established by laboratory or field testing prior to final use.

Early strength of shotcrete can be very high, reaching 6.896 N/mm$^2$ in 5 hours and 20.689 N/mm$^2$ in 24 hours.

### B. Flexural Strength

The relationship between the flexural and compressive strength and he found that as the compressive strength increases, the flexural strength also increases. The ratio between compressive and flexural strength appears to be the same as for conventional concrete.

### C. Bond Strength

Although few data on bond strength appear to exist, bond strength with other materials is reported to be generally higher than can be achieved with conventional concrete.

### D. Shrinkage

Drying shrinkage is most influenced by the water content of the mixture. Typical values of unrestrained shrinkage range from 600 to 1000 millionths. Shrinkage is reduced in coarse aggregate shotcrete and increased in shotcrete without coarse aggregate or shotcrete subject to high rebound. Shotcrete containing silica fume has a tendency to exhibit more shrinkage before setting than shotcrete without silica fume.

### E. Resistance to Freezing and Thawing

Wet-mix shotcrete frost resistance is ensured by entraining a proper air-void system. Typically an air content of 8 to 12% in the mixture results in place shotcrete having a proper air void system. Although many dry-mix applications have performed well when subjected to mild freezing and thawing, dry mix shotcrete is more subject to problems from freezing and thawing than wet-mix shotcrete. This is due to the difficulty in entraining air and creating an adequate air-void system in dry-mix shotcrete.

 

### F. *Toughness*

The addition of fibers to shotcrete can result in a product displaying significant load carrying capability after the occurrence of the first crack. The relationship of post-crack load capacity to load capacity at first crack is defined as toughness. The type, size, shape, and amount of fiber determine the extent of this performance.

## VI. APPLICATION CRITERIA FOR SHOTCRETE

### A. *Safety*

Safety is very important in shotcrete construction because it combines high-powered machinery (hydraulic / pneumatic / electronic) with a method of application in which the concrete is projected through the air. Its users and people in the immediate vicinity must be protected.

### B. *Shotcrete substrate*

The bond between the sprayed concrete and the substrate depends strong keying and high adhesive strength. The substrate is generally the key factor in bonding. To optimize the operations, the surface can be cleaned with the compressed air from the spraying unit, then rinsed and wetted with running water. This job must be done immediately before spraying to prevent an insulating layer of dust forming immediately afterwards. The same applies if the sprayed concrete is built up layer by layer. If there is high water penetration, pre-sealing or discharge of the water through drainage channels is necessary.

### C. *Spraying*

Sprayed concrete and mortar are applied in layers, either in the same operation by repeatedly spraying over the same area or in a subsequent operation after a stop. After a long stop the surface must be cleaned and wetted again. The amount that can be applied in one operation depends on various factors:

1) Adhesive strength of the sprayed concrete mix (cement/max. particle size / accelerator)
2) Nature of substrate or base layer
3) Spraying process and settings
4) Spray output setting
5) Spraying direction (upward / horizontally)
6) Obstructions (reinforcement / water

### D. *Nozzle configurations*

The thorough mixing of air, concrete and setting accelerator takes place inside the nozzle. The nozzle configuration depends on the process and choice of accelerators. Alkaline accelerators are added 2-5 m behind the nozzle. Because they require a certain reaction time & better results are obtained in the early strength range. Correct feed 2-5 m behind the nozzle compensates for the pulsation and binds the accelerator. This greatly reduces the dust. The problems with caustic water vapor and aerosols are eliminated by using alkali- free accelerators. They are also extremely reactive and must be added just in front of the nozzle. The resultant short jet time of the sprayed concrete reduces the amount of dust.

High-quality nozzles are designed to take the entire conglomerate to the substrate without losses. At the same time all the particles must be distributed evenly over the cross-section of the jet.

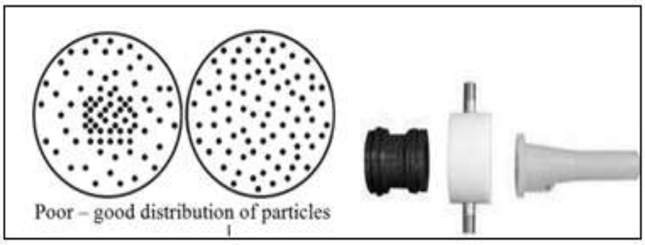


Fig. 4: Distribution of particles & Nozzle

### E. *Measurement methods*

Initial and early compressive strength development of shotcrete, i.e. up to 24 h is measured using indirect methods, namely Penetrometer and Hilti stud. Both methods correlate the impact of the compressive strength on the penetration of a needle. Results from these methods depend on the mix design, i.e. on the used aggregates (0 – 8 mm), and would not necessarily result in absolute values of the compressive strength.

| Development of | Method | Instrument | Strength | Time |
|---|---|---|---|---|
| 1 Initial strength | needle penetration | Penetrometer | up to 1.5 MPa | 0 – 3 h |
| 2 Early strength | stud driving | Hilti DX 450-SCT | 3 – 20 MPa | 3 – 24 h |
| 3 Final strength | coring | Compression testing machine | 5 – 100 MPa | 1 – 28 d |

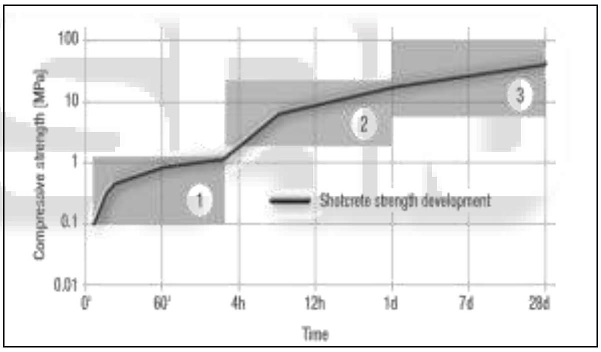


Fig. 6: Development of strength & method of measurement

#### 1) *Needle Penetration Method*

Results from this method are calculated from the force which is required to penetrate 15 mm of the specimen's surface using a 3 mm needle. The tip of the needle has an angle of 60°. Using this method one can manually determine the strength up to approx. 1.5 MPa.

Fig. 7: Digital Penetrometer

#### 2) *Stud Driving Method (Hilti)*

Compressive strengths between 3 and 20 MPa are determined by threaded studs, which are driven into the shotcrete surface. The depth of penetration results in the compressive strength according to a calibration curve.

 

Fig. 8: Stud driving method: Penetration & measurement

#### 3) Drill Core Method

The final compressive strength is determined using concrete drill cores according EN 12504-1 “Testing concrete in structures”

Fig. 9: Drilling of core sample & Compressive strength measurement

### F. Rebound

The rebound changes during the spraying process. In the first few minutes it is mainly the larger aggregates that rebound because a fine adherend surface layer has first to be built up on the substrate, then, all the components in the mix rebound, during the spraying operation. The rebound quantity can be well controlled through the adhesive strength of the sprayed concrete. Without separate measurements of the rebound under the conditions prevailing on site, the quantity can only be roughly estimated: Rebound with dry sprayed concrete 20 % to 30 % for application vertically upward & Rebound with wet sprayed concrete 5 % to 15 % for application vertically upward. As with structural concrete, a small proportion of 10 % to 20 % maximum of correctly treated sprayed concrete rebound can be reused without any problem.

### G. Dust development

Dust occurs with any type of sprayed concrete application, but the dust quantities and types differ very considerably. There is a major problem with dry sprayed concrete because the components have a natural tendency to generate dust. Despite all these measures, two to four times more dust is generated by dry sprayed concrete than by the wet method. To further improve safety, only alkali-free setting accelerators should be used.

## VII. ADVANCEMENT IN SHOTCRETE SPREYING SYSTEM

### A. Concrete Spraying Systems

The product range of shotcreting equipment includes mobile spraying robots as well as trailer-mounted units, with spraying reaches of up to 17 m and concrete conveying performances of up to 30 $m^3$/ h

Track-mounted mobile spraying unit designed for automatic application of shotcrete in underground work (wet and dry process). Ideal for smaller tunnel sections and slope protection:

Fig. 10: Track-mounted mobile spraying units

### B. TBM Spraying Robots

During the stabilization phase, either precast tunnel segments (prefabricated concrete units) can be installed, and/or sprayed concrete can be applied over steel reinforcement.

For stabilization by applying sprayed concrete, robotic sprayed concrete equipment is designed and produced to be mounted on and incorporated into the TBM.

Fig. 12: Robotic Sprayed Concrete Equipment for a TBM

## VIII. CASE STUDY OF HONGKONG TUNNEL WORKS

### A. Introduction

At present, there are over 380km of bored tunnels in Hong Kong, 59km in the next seven years and at least another 50km has been planned by 2015. Traditionally tunnels are constructed in hard rock but there is an increasing demand for large diameter soft ground tunneling. Application of shotcrete is directly onto water proofing membranes and drainage relining works. Both dry and wet mix shotcrete are used in permanent Shotcrete applications in: Caverns, Tunnels, Shafts and other applications.

### B. Mix design

#### 1) Dry Mix

OPCement… ……….......................….480kg
10mm Aggregate...........................…...600kg
Crushed rock...1200kg
Accelerator....15kg
Water (added at nozzle)

#### 2) High Performance Wet Mix

OPCement…..................400kg
PFA…………………….................……60kg
Silica fume…..................40kg
10mm Aggregate……................……450kg
Crushed rock...1230kg
Water….................200ltrs
RB561 (Super plasticizer)…....................6ltrs
Steel fibers RL45/35……...................…30kg

Fiber mesh 150…………..................…0.9kg

### *C. Permanent Shotcrete Applications*

*1) Caverns – Island West Transfer Station*

a) Waste transfer station on HK Island located within a Hill side waterfront cavern
b) Excavation in rock
c) Primary shotcrete and permanent rock dowels
d) Concrete lining only at portals
e) Engineer's design 175,000m$^3$
f) Shotcrete Final design 30,000m$^3$
g) HK$ 200 million saving

*2) Caverns – Pak Shing Kok Crossover*

a) 6.1km of running tunnels
b) Standard tunnel lining by moving form
c) Unreinforced cast in-situ concrete
d) Not suitable for Crossings, Junctions, Fan Niches.

*3) Caverns – Pak Shing Kok Crossover*

a) One 24m wide crossover Cavern
b) Seven 12m wide fan niches & five bifurcations
c) Two 'T' junctions & all permanent shotcrete lined

*4) Caverns – Queensway Subway*

a) 300m long pedestrian subway
b) Cavern enlargement for escalator connection
c) Excavated in rock with low cover below major road
d) 15m wide x 33m long rock cavern
e) Constantly varying section &constant access required
f) Fully tanked Sprayed membrane (Master seal 345)
g) Steel and polymer fibres & primary sprayed concrete
h) Gunite smoothing layer Reinforced concrete invert
i) Main tunnel unreinforced cast in-situ
j) 5-6mm thick Sprayed over sheet membrane at inter Sections
k) Permanent sprayed concrete applied directly onto Master Seal 600mm thick applied in 2-3 layers
l) Minimal rebound (<10%)
m) Survey check then final layer, no fibres
n) Escalator adit fully reinforced sprayed concrete

*5) Shafts – Kai Tak Transfer Drainage Scheme*
(Drainage Services Department)

a) 1.9km long storm water transfer tunnel with six shafts
b) Four shafts by the one-pass shotcrete method
c) Circular: 7.0-8.5m I.D. & depth: Max. 21.0m
d) Shotcrete One Pass Temporary and Permanent lining
e) Foam Concrete Backfill for TBM Entry
f) R.C. Base Slab & Roof Slab & Pipe piles installed
g) Excavate 2.0m & Steel ring beam installed
h) Excavate 2.0m & shotcrete Primary layer 200mm x 1.5m
i) Shotcrete Permanent layer 100mm x 1.0m
j) Early Strength 16MPa at 12 hours
k) Excavate 1.5m &Fix hydrophilic and grout tube strips
l) Shotcrete primary layer 200mm x 1.5m
m) Shotcrete permanent layer 100mm x 1.5m
n) Float finish permanent layer
o) Repeat three-day cycle
p) Construction joint 1.3m long
q) No membrane, no leaks
r) Float finish as good as cast in-situ lining form

## IX. CONCLUSION

Shotcrete technology is suitable for safe tunnel construction as it is used for stabilization & inner lining work and it improves the performance of tunnel structure. This method is suitable for safety control and observational design of underground tunnels with shotcrete lining. Also there is need of technology which controls the dust generating due to shotcrete process.

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