INTRODUCTION

Shotcrete is a robust design strategy. Several advantages such as ease of application, compatibility and quick application make this method a suitable procedure for tunnel works. Historically, this method has evolved a successful strategy out of 40 years of experience which may be adopted in supporting tunnels in widely different rock conditions. A tunneling revolution has occurred in the last 40 years with advent of wet-process shotcrete and structural fiber reinforced shotcrete (SFRS). Since steel fibers are not continuous, they do not experience corrosion like mesh and RCC. Synthetic polymer fibers such as Polyolephyne and Polypropylene totally remove the corrosion problem. As far as life of these “light” support systems is concerned, they are stable for last 40 years. Their cost is only a fraction of the concrete lining.

Shotcrete is mainly used as preliminary support in soft grounds or jointed rocks but there is a potential of being used as permanent lining as it has all the specifications of in-situ concrete lining. In this paper an improved method of using shotcrete in tunnel lining construction is proposed. This system is a combination of current technologies in this field and uses their advantages to obtain a quick, durable, effective, economic and reliable support.

Sprayed concrete lined tunnels are rapidly growing in popularity due to their versatility. The design and construction of both hard rock and soft ground tunnels has been revolutionized by the advent of this method and now the use of permanent sprayed concrete linings has unlocked the true potential of the method to minimize construction costs and
times. Yet the complex early-age behavior of the sprayed concrete makes the design difficult and requires a robust management system during construction.

Consequently the great advantages of the method must be balanced against the large risks, as illustrated by recent high-profile tunnel collapses.

2. SINGLE AND DOUBLE SHELL LINING

Secondary linings are normally formed of cast in situ concrete, although sprayed concrete is increasingly used, especially where the cost of formwork is high e.g. at junctions or tunnels of varying shape. Since the secondary lining is placed inside a waterproof membrane, it is typically designed to carry the water loading plus most or all of the ground loads.

Cast concrete linings are placed within formwork and normal concrete technology is applied. The type of formwork depends on the specific requirements of each tunnel. Mobile steel formworks are used for longer tunnels with a constant cross-section. Timber formwork is cheaper in terms of materials but more labor intensive. Hence it is used in countries where wage costs are low or for special cases, such as junctions, where it is not cost-effective to buy steel formwork.

Ideally inner linings are designed to be unreinforced concrete. The shape of the tunnel can be chosen to minimize bending moments and, depending on the compressive hoop load in the tunnel, they may be low enough to be safely within the capacity of plain concrete. The risks of cracking due to thermal or shrinkage effects can be reduced by good mix design e.g. using cement replacements like pulverized fly ash to slow the hydration process and casting the lining in short lengths e.g. less than 10 m long bays. If there is no waterproofing membrane, it is sometimes advisable to install a plastic separation sheet to reduce friction on the contact with the primary lining and reduces the risk of cracking in the final lining. For high lining loads, reinforcement is added to the secondary lining.

The inner lining can be formed of sprayed concrete. Sprayed concrete can be produced with acceptable durability characteristics equal to that of in situ concrete, as indicated by its permeability and porosity values, although this increases the unit cost of the material. To be permanent, this sprayed concrete must be durable enough to last for the design life of the tunnel.

The strength should not degrade over time and the concrete should be dense and have a low permeability for water. The latter criteria are aimed to reduce the potential for water ingress through the body of the lining and corrosion of reinforcement within the lining. To achieve those basic criteria a minimum reinforcement like mesh or fibers will be necessary. There has been some concern that the loading experienced by the sprayed concrete at an early age may damage its long term strength. In any case the normal compressive strength testing of the in situ sprayed concrete should detect any significant damage. Hence a higher specification is required than for sprayed concrete used in temporary works.

Higher standards of workmanship hand in hand with greater quality control are necessary. Occasionally curing is applied but this introduces an additional activity in the tunnel which the construction team prefers to avoid.

Clearly installing a secondary lining and ignoring the primary lining costs more, both in time and money, than a lining which uses all the concrete sprayed as part of the permanent lining. Hence attempts have been made to improve upon this simple approach.

Considerable cost savings are possible if the concrete, sprayed as the initial ground support, can be included in the permanent lining. Permanent sprayed concrete linings may be formed in several ways and in actual fact the ‘single shell’ may consist of several layers of sprayed concrete, placed at different times. However, the underlying principle is that all the sprayed concrete carries load over the life of the tunnel and the different layers normally act together as a composite structure. This approach is common in certain sectors, notably on hydroelectric power projects and in certain ground conditions such as dry hard rock. More recently it has been extended to water-bearing soft ground situations and transport tunnels. A comprehensive listing of more than 150 tunnels of all types and from all parts of the world can be found in Franzen et al. (2001).

3. PERFORMANCE GOALS OF SINGLE SHELL LINING

There are normally two questions that must be answered before a project accepts the use of a single shell lining. Is the sprayed concrete durable? and is the lining sufficiently watertight?

Modern good quality sprayed concrete is a durable material. Poor workmanship, water inflow during construction or excessive loading at an early age is the only real risks to durability of the concrete. Corrosion of reinforcement steel embedded in the sprayed concrete presents the main residual risk. One way to remove this is to use fiber reinforcement. However, there may still be cases such as junctions where heavier, steel bar reinforcement is required. In those cases good workmanship should ensure that the steel is safely encased in dense concrete with a low permeability just as in cast concrete.

Sprayed concrete is a material well suited to tunneling for the reasons below:

- Sprayed concrete is a structural material that can be used as a permanent lining.

- The material behavior of sprayed concrete which is initially soft and creeps under load but can withstand large strains at an early age is compatible with the goal of a lining which permits ground deformation and therefore stress redistribution in the ground.

- The material behavior, specifically the increase in stiffness and strength with age, is also compatible with the need to control this deformation so that strain softening in the ground does not lead to failure.

- Sprayed concrete linings can be formed as and when required and in whatever shape is required. Hence the
geometry of the tunnel and timing of placement of the lining can be tailored to suit a wide range of ground conditions. Sprayed concrete can also be combined with other forms of support such as rock bolts and steel arches.

Single shell lining design and performance goals are:
- Stability and Strength
- Durability
- Deformability and Energy Absorption
- Facilitated and Fast Construction
- Easy/Low Cost Maintenance/Repair
- Economy

From construction point of view for accelerated construction there are some issues to be discussed:
- Heavy Reinforcement
- Concreting and Related Activities
- Concrete Setting Time
- Form Work
- Water Tightening and Joints
- Contact Grouting

Available methods for accelerating construction of tunnel lining can be summarized as following:
- Fiber Reinforced Concrete
- Fiber Reinforced Shotcrete
- Rib/3D Panel Reinforced Shotcrete
- Partial Reinforced FRC/FRS
- External Water Tightening/No Joints
- Other Single Shell Lining Systems

A combination of the above systems can also be implemented for obtaining a cost effective lining system. The selected system is called Composite Macro Synthetic Fiber Reinforced Shotcrete in 3D Panel.

4. PANEL-SHOTCRETE COMPOSITE

The proposed system is composed of 3 major elements:
- Special 3D panel
- Macro-synthetic fiber reinforced shotcrete
- Reinforcing bars

Special 3D Panel is a prefabricated panel consists of a three-dimensional welded wire truss with or without a polystyrene core sheet placed between two layers of welded wire fabric. Each surface of the 3D wire truss has a 10 cm square welded mesh pattern of longitudinal and transverse wires of 3mm diameter, and is made of galvanized steel with low carbon content. Squared welded mesh at each side is connected to the other side’s mesh using inclined transverse bars. At each 1 m² of panel there are 200 joints each joint were connected to each other by electronically controlled welding. The welding is perfect and no any separation in the connection points. Panels are available in 10 and 15 centimeter thicknesses. Fig.1 illustrates 3D panel’s schematic and real view.

The 3mm diameter St52 bars are used in panels with yield strength of 500 MPa. In case of using them as in-situ formwork, the type with polystyrene can be used and after shotcrete application on the outside it can be used as a formwork with high bearing capacity. Panels are completely corrosion resistant having high capability in crack control and energy absorption because of 3D structure. Higher bending and shear strength can also be obtained by adding additional reinforcing bars to the panel sides.

Use of 3D panels with local reinforcing will result in faster and high quality construction along with improvements in shear and tension behavior and higher energy absorption capabilities.

3 Dimensional structure, flexibility, integration and no need to special connections, make this system more effective than usual frame-rib systems. Capability to be bent by hand, easy handling and quick installation due to lightweight are unique advantages of this system.

One of the most important factors which limit the use of shotcrete instead of in-situ concrete is the durability problem. In order to obtain a durable shotcrete in structure’s lifetime some points should be considered:
1- Reinforcements durability and corrosion resistance
2- Crack prevention and control in sprayed concrete
3- Increase in bond strength and reducing concretes porosity
4- Increase in electric conductivity of final product
5- Water tightness

To achieve these parameters, following solutions can be taken into account:
1- Introducing MCI corrosion inhibitor
2- Adding macro-synthetic fibers with 1 to 3 kg/m³ dosage to reduce cracks and eliminating joints and longitudinal reinforcing
3- Waterproofing layer application
4- Using of corrosion resistant panel which improves the shear strength up to 80 percent and energy absorption capacity up to 200 percent of normal shotcrete

Figure 1: 3D-Panel with polystyrene
Introducing such modifications results in durable shotcrete and electrical resistance of mix reaches the acceptable limits for durable concrete (12 to 20 kΩ.cm). This resistivity can be measured in 3 to 5 years period using NDT tests.

Macro Synthetic Fiber Reinforced Shotcrete shows better mechanical characteristics compared to conventional concrete and shotcrete as follows:

- Energy Absorption Ratio: ~5 times
- Fracture Toughness Ratio: ~7 times
- Flexural Fracture Modulus Ratio: ~1.3–1.6 times
- Shear Strength Ratio: ~1.4–2.0 times
- Elasticity Modulus Ratio: ~1.0 times
- Compressive Strength Ratio: ~1.0 times

This material can be used independently for final lining of the tunnels as mentioned before. A sample successful project has been shown in figure 2. The 2 Km Khomari tunnel is a railway tunnel in Iran which has been executed using shotcrete Robots.

By attaining such durable shotcrete and having the ability to determine the amount of reinforcement in this system, the design process becomes mainly the same as reinforced concrete lining. Even though, some advantages of shotcrete such as integration with rock surface, well bond strength, quick application and multilayer application capability makes this method a good replacement for conventional in-situ reinforced concrete. Different combinations of this system with preliminary lining or rock support are possible which result in fast, economic, effective and less construction works.

In regions with high over breaks panel with polystyrene inside can be used. In this method, the front side of panel is reinforced as required and shotcrete will be applied on it. Then, the back side of panel is filled with lightweight concrete. Fig. 3 shows some of different design patterns in part of Isfahan-Shiraz Railway tunnel near Shiraz.

Another sample of such projects has been shown in figure 4. This road tunnel is located on Jolfa road in north west of Iran. This sample does not use structural fibres and the were...
fibres only used for shrinkage control of the wet shotcrete. In this case no longitudinal and thermal reinforcements will be necessary and they can totally be omitted. For such cases the filling concrete is self compacting which does not require vibration.

Figure 4: Jolfa road tunnel in north western Iran

Next sample project is a road tunnel near Isfahan. The Talkhab tunnel also utilizes this system. For such short tunnels preparation of form work is very costly and time consuming and the presented system will be very effective.

5. DESIGN PROCEDURE FOR A CASE STUDY: PARCHIN ROAD TUNNEL

This system has been used successfully in several projects around the country in different geological, geotechnical and operational conditions ranging from road to railway to water transmission tunnels. Among different projects is the Parchin road tunnel which is a very new project under construction.

Parchin road tunnel is located in Tehran province in Tehran-Parchin route near Mamlou dam. This road is an alternative for current road which is going to be submerged after filling dam’s reservoir. This 1km long tunnel has been excavated in different rock profiles from strong Andesite rock to weak shale layers. So, as the excavation section is unstable in some regions, a double-shell lining is proposed for this tunnel providing the stability in excavation phase by combining of steel ribs or lattices along with dry mix shotcrete application. The plan for final lining was conventional reinforced concrete but In order to accelerate the construction the panel-shotcrete system was used for final lining. Fig. 3 shows the excavation section of tunnel.

Figure 5: Talkhab road tunnel near Isfahan

Figure 6: Excavation section
Stress analyzes for determination of lining forces were performed using Phase2 v.6 software. Due to different rock properties along the tunnel, two types of strength parameters considered for design purpose. These parameters are shown in table 1.

<table>
<thead>
<tr>
<th>Type1 (Weak Rock)</th>
<th>Internal Friction Angle</th>
<th>$\phi = 20^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesion</td>
<td>$c = 1.5 , kg/cm^2$</td>
<td></td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>$\nu = 0.25$</td>
<td></td>
</tr>
<tr>
<td>Elasticity Modulus</td>
<td>$E_s = 4 , GPa$</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>$\gamma_d = 2.4, , \gamma/, cm^3$</td>
<td></td>
</tr>
</tbody>
</table>

Low strength parameters of rock had been made the excavation difficult and quick stabilization of excavation face was necessary. So, 16 cm of dry shotcrete along with IPE16 frames with 1m spacing were used as temporary rock support. For final lining, with respect to analysis results, 30 cm of wet shotcrete reinforced with two layers of rib panels and reinforcement bars was adequate to carry loads. Also, for sections with high over breaks panel with polystyrene inside and lightweight fill concrete proposed. Fig.7 illustrates designed section of tunnel.

![Figure 7: Preliminary and permanent support](image1)

Figure 7: Preliminary and permanent support

It should be considered that the load bearing capacity of preliminary lining has not been considered in final lining design, and all the long term and seismic loads are carried by final lining. Fig.8 to Fig.11 present some sample results of analyses.

![Figure 8: Maximum principal stress contours](image2)

Figure 8: Maximum principal stress contours

![Figure 9: Total displacement trajectories](image3)

Figure 9: Total displacement trajectories

![Figure 10: Final lining’s axial force distribution](image4)

Figure 10: Final lining’s axial force distribution
Also, macro-synthetic fiber used in the mix which has the following advantages:

- reduces shrinkage cracking
- reduces rebound
- Improves toughness, flexural resistance, increase tensile strength and shear resistance
- Optimizes sprayed lining thickness
- Reduces permeability
- Increase fire resistance of the lining which is very important for road tunnels

Figures 12 and 15 show construction works in Parchin tunnel. From construction point of view the rebound of shotcrete in this system reduced to about 8 percents which is around one third of conventional shotcrete systems. The use of appropriate additives in the mix design will result in such capability and effectiveness.
6. CONCLUDING REMARKS

An innovative scheme for final lining construction was presented in this paper. Although, design procedure and analysis results were presented, it should be noted that design process is completely depends on designer’s idea and any design philosophy can be taken into account. What is important here is that, this system is an alternative to conventional reinforced concrete lining having all the advantages of shotcrete and in-situ concrete with some extra features and capabilities as follows:

- Accelerated construction, 3 to 4 times faster than conventional methods by omitting formworks, reinforcement placing and time needed for concrete setting.
- Optimizing the lining thickness by taking into account the preliminary lining’s capacity with regard to its durability and integration with final lining.
- Reduction in steel consumption by utilizing the adequate amounts of fiber in sprayed concrete mix.
- Ease of construction in tunnel sections with high over breaks and non-uniform shapes.

7. ACKNOWLEDGMENT

Technical and financial supports by the UK Construction Technologies Company and Betonpash EPC Contractor are gratefully appreciated.

8. REFERENCES

Austrian Concrete Society (1999), Sprayed Concrete Guideline, Karlsgasse Österreichischer Betonverein.


British Tunneling Society (BTS) and Institution of Civil Engineers (ICE), (2004), Tunnel Lining Design Guide, Thomas Telford, London, UK.


Franzen, T., Celestino T.B. (2002), Lining of Tunnels under Groundwater Pressure, Shotcrete Use, International Tunneling Association ITA.


Sprayed Concrete for Rock Support (1993), Technical Specification and Guidelines, Publication No. 7, Norwegian Concrete Association, Committee on Sprayed Concrete.

Thomas A. (2009), Sprayed Concrete Lined Tunnels, Taylor & Francis, New York, USA.