Development of a grout mix to be used as annular fill behind pre-cast concrete segments installed in tunnel with time dependent deformation character

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ABSTRACT
Construction of the twinning of the West Trunk Sewer Tunnel for the Region of Peel, Contract 2, in the City of Mississauga was awarded to Technicore Underground Company in June 2015. This Contract consists of approximately 3,800m (12,500ft) of 3.0m (10ft) diameter trunk sanitary sewer to be constructed by tunnelling. Technicore is using two TBM machines and is installing precast concrete segments as the final liner. Approximately 80% of the tunnel is being constructed in the Georgian Bay Shale, which is known to exhibit time dependent deformation (TDD) after excavation. The forces generated by TDD are significant and are typically dealt within tunnels by delaying the installation of the final lining to allow unrestrained swelling to occur, or by use of a compressible material outside the tunnel lining. For precast concrete segments, which are installed immediately behind the TBM, there is no delay in installation so another technique was required to deal with the TDD. Technicore proposed the use of a compressible grout to accommodate the TDD. Technicore hired Arup to design the precast concrete segments, to evaluate the forces from TDD on the precast concrete segments and to specify the requirements for the grout. Technicore then worked with BASF to design a grout mix to meet the requirements. Testing was performed at Queen’s University for physical property testing. Testing was done by a servo-controlled, electro hydraulic compression frame and the time dependent deformation of the grout was measured and used to assess the stress/strain behavior of this material. This paper discusses the development process, the role of various players in this innovative design process and the patent registration process that is underway as a result.

1 INTRODUCTION
Placing a permanent tunnel lining in ground that exhibits ongoing movement will result in large stresses and potentially damage in the lining. This paper provides an overview of these movements (referred to as Time Dependent Deformation in this paper) with a focus on the Georgian Bay Shale. Various methods are described for accommodating these movements in the tunnel lining. Contract 2 of the West Trunk Sewer is used as a case history. This project included the use of a compressible annular grout to accommodate Time Dependent Deformation. The design, development and use of the grout are described.

2 TIME DEPENDENT DEFORMATION (TDD)

2.1 General
Time Dependent Deformation (TDD) is movement that occurs after the initial ground disturbance that results from tunneling. There are two distinct mechanisms that result in TDD, swelling and squeezing, although they may occur simultaneously and one may lead to the other. Swelling is the time dependent volume increase of the ground and squeezing is the time dependent shearing of the ground. Both phenomena lead to inward movement of the tunnel perimeter.
2.2 Swelling

The swelling mechanism is a combination of physico-chemical reaction with water and stress-relief. Although the physico-chemical reaction is usually the major contributor, stress changes can have a significant effect. One can distinguish three typical mechanisms (ISRM, 1983). Mechanical swelling occurs in most clays, silty clays, clayey silts and corresponding rocks. These materials usually have a very low permeability so that loading conditions due to the excavation sequence change much more rapidly than ground water can flow into the pores, resulting in negative pore pressures. Water then flows into the pores and reduces the negative pore pressure, leading to a volume increase.

The two other forms of swelling are Osmotic swelling and Intracrystalline swelling that result in chemical reactions leading to an increase in the volume of the material (Madsen and Muller v. Moos, 1989).

The swelling stress, the pressure generated by swelling in a confined space, and swelling strain can vary based on the permeability, clay content, in-situ stresses, and confinement conditions of the ground. As Madsen and Muller v. Moos, 1989 showed, the maximum swell pressure, for osmotic swelling is about 2 MPa, the maximum swell pressure between two layers in intracrystalline clay swelling is 100 MPa and the maximum anhydrite swell pressures vary from 1 MPa to 7 MPa (Madsen and Nuesch, 1991; Madsen et al., 1989).

2.3 Squeezing

Squeezing is the reaction of ductile material against high stresses and can be related to the time-dependent shearing i.e. shear creep. In other words, squeezing acts as slow inward movements of the tunnel surface in ductile, deformable rocks such as soapstone, evaporites, clayey rocks, mudstones, clay schist, as well as in the crushed or highly jointed rocks. Two factors are mainly responsible for the occurrence of rock squeeze problems: state of high deviatoric stresses and formations like shales and shaly limestones. (Einstein, 1996).

Squeezing can occur in the roof, walls, and even the floor of the tunnel. However, what makes squeezing in tunneling even more complicated is the fact that one of the triggers for this phenomenon can be the tunnel swelling. Indeed, swelling stress may bring the stress conditions close to the failure envelope and induce a shear failure. The ground ductility then provides a continuous time-dependent swelling deformation.

2.4 TDD in the Greater Toronto Area (GTA)

TDD in the GTA is as a result of swelling in the Georgian Bay Shale unit, which consists of typically moderately weathered to fresh, grey to dark grey, fine to very fine grained fissile shale interbedded with slightly weathered to fresh grey, fine grained calcareous siltstone and limestone interbeds. There are two distinctive features of the shale in the GTA. One is a high horizontal stress regime, and the second is long-term time dependent swelling behavior that develops when the following factors occur (Lo and Micic, 2010):

- Stress relief of the rock mass
- Outward salt concentration gradient from pore fluid of the rock to the ambient fluid
- Availability of fresh water

The swelling is a consequence of the reduction in confined stress in the rock that occurs upon excavation in combination with a differential gradient in salinity between the saline rock porewater and freshwater or even humid air. Osmotic and diffusive processes result in a decrease in the salinity of the rock porewater achieved by an overall increase in the water content, resulting in volumetric expansion of the shale rock over time. The development of this time dependent deformation (TDD) relative to the time of installation of the permanent lining has a direct impact on the long-term moments and forces induced on the lining.

Swelling potential is defined as the average slope of the swelling strain versus the logarithm of time and is defined for a specific direction, since behavior in the vertical and horizontal directions is typically noticeably different. The swelling potential decreases as the applied pressure is increased. The pressure where swelling potential is zero and no swell occurs is called the “Critical Stress” and is defined with the result of the no-swell test.

Hawlader, Lee, and Lo (2003) studied the impact of applied load on the swelling potential of different samples. They concluded that the applied stress in one principal stress direction reduces swelling strain not only in that direction but also in the perpendicular directions.

The swelling potential of shales tends to increase with decreasing calcite content, and an increasing outward salt concentration gradient from the pore fluid of the rock to the ambient fluid (Lee and Lo, 1993). Therefore, calcite content and salt concentrations (salinity) of pore water in the rock samples were also considered in the tests.

3 FLEXIBLE LINING METHODS

Typical options for flexible supports that are applied in rock with TDD are shown in Figure 2. Two different approaches can be used. The first is the use of a compressible layer between the extrados of a stiff lining and the excavation boundary is shown in (a), which is designed to accommodate the movements without adding significant load to the lining. The alternative is to use as lining in contact with the rock face that contains yielding elements, as shown in (b). This can either consist of lining elements that slide over each other (b1) or lining elements that compress (b2).
The design of tunnel linings to accommodate TDD has developed over many years. In 1931, Lenk reported on a patented method consisting of placing wooden elements between rock and precast concrete segments, and interlaying of wooden panels into the concrete lining (Figure 3).

Steel has been increasingly used instead of timber since the middle of the 20th century, since steel enables standardisation of support elements and prefabrication of the support. Steel support ribs are made of rolled profiles, U profiles, special mining profiles or composite sections in the form of closed arches or open at the bottom. In 1948, a sliding steel rib connection was invented by Frohlich. In 2009, a yielding support with LSC elements was invented by Barla as shown in Figure 4 (Barla and Barla, 2008).

Further progress in this field has been made recently with the introduction of compressible elements composed by of a mixture of cement, steel fibres and hollow glass particles (Kovář, 2005).

It has been typical practice in the GTA to use cellular grout, which provides some deformation under applied stress around permanent steel or concrete pipelines to avoid overstressing the final tunnel lining. For segmental linings, Hochtief Construction AG developed a compressible grouting material in 2006 to accommodate rock deformations in TBM tunneling (Billig et al. 2007).

4 WEST TRUNK SEWER CONTRACT 2 CASE STUDY

The West Trunk Sewer tunnel project is located at in the City of Mississauga, Ontario, Canada (Figure 5). The project consists of of approximately 3,800m (12,500ft) of 3.0m (10ft) diameter trunk sanitary sewer to be constructed by tunnelling. Approximately 3,300 meter of the tunnel is being constructed in the Georgian Bay Shale, which is known to exhibit time dependent deformation (TDD) after excavation.

Geotechnical investigation of the site was carried out by Golder Associates in 2009. Based on the geotechnical investigation report, time dependent deformation (swelling) of the Georgian Bay shale is well documented and should be expected during and after excavation in the tunnel. For baseline purposes, the time dependent horizontal and vertical swell rates were defined to range from 0.05% to 0.5% and 0.1% to 2.5% per log cycle of time, respectively. These rates are based on the swell testing that was conducted as part of the geotechnical investigation and have been adjusted based on published data.
The in-situ stress were not measured in for this project, though it is known from tests in the area that the in-situ stress can be very high near the bed rock surface. Table 1 shows some published data for measured in-situ stress. For baseline purposes, the baseline maximum major and minor horizontal stresses were defined as between 6 MPa and 12 MPa and between 2 MPa and 9 MPa, respectively.

### Table 1. Summary of published in-situ horizontal stress ranges in Georgian Bay shale

<table>
<thead>
<tr>
<th>Source</th>
<th>Depth below ground surface (meters)</th>
<th>In-situ horizontal stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lo and Yuen (1988)</td>
<td>5-17</td>
<td>2.1-4.2</td>
</tr>
<tr>
<td>Morton (1975)</td>
<td>9-15</td>
<td>Up to 6.9</td>
</tr>
<tr>
<td>Lo and Morton (1976)</td>
<td>9-10</td>
<td>2-4</td>
</tr>
<tr>
<td>Lo, Devata, Yuen (1979)</td>
<td>6-16</td>
<td>1.6-9.2</td>
</tr>
<tr>
<td>Lo and Yuen (1981)</td>
<td>-</td>
<td>4.1</td>
</tr>
<tr>
<td>Trow and Lo (1989)</td>
<td>15-26</td>
<td>2.6-5.3</td>
</tr>
</tbody>
</table>

### 4.1 Design requirements

The contract documents for this project assumed that initial support would be provided in the rock sections of the tunnel, and specified a time delay of ninety (90) days before placing the final lining to allow the most significant time dependent rock deformation to occur in the shafts and tunnel.

However, given that the tunnel also passes through length of soft ground that would require immediate support, use of a precast concrete segmental lining throughout the tunnel provided many advantages compared with installing an initial support system through the soil sections that would need to be robust and was anticipated to be slow to install. After a cost/schedule analysis by Technicore, it was decided to install the precast concrete segments instead of an initial support system followed by cast in place concrete. However, with this approach, the precast concrete liners have to be placed immediately after boring of the tunnel by the TBM, which would not allow the dissipation of the TDD load.

Technicore hired Arup to design the precast concrete segmental liners and evaluate the forces resulting from time dependent deformation acting on the precast concrete segments. If the shale around the tunnel was highly restrained, which would be the case if a conventional annular grout was used, the TDD would lead to high stresses in the ground. Consequently, it was decided to use a compressible grout. Based on numerical modeling of the TDD, Arup evaluated the anticipated movements and applied pressures specified the grout requirements for this project. (Figure 6). The grout needed to have sufficient stiffness at lower stress levels to provide sufficient support to the tunnel lining, but allow sufficient deformation at higher stress levels to avoid the build-up of high loads on the segmental lining.

### 4.2 Development of the Compressible Grout

The present invention relates to a compressible grout mix for filling an annular gap between a tunnel rock wall surface and a tunnel liner of a tunnel in a rock formation subject to time dependent deformation after excavation. The invention is for resilient absorption of forces in the hardened state of the compressible grout mix exerted by the time dependent deformation of the rock wall surface into the tunnel opening. The compressible grout mix is comprised of a hydraulic binding agent, bentonite clay, foam particles, water-reducing admixture, water and air, wherein the compressible grout mix in the hardened state has a compression capacity greater than the anticipated time-dependent rock deformation.

The proportions of the ingredients are selected based upon the desired compressibility of the compressible grout mix in the hardened state that is in turn based on the expected time dependent deformation of the rock through which the tunnel is excavated. Preferably, the formulation provides a compression capacity up to twice the anticipated time-dependent rock deformation, which was a strain level of around 8% in the annular grout in this case. Consequently, a compressible grout mix capable of supporting up to 16% compression as measured by ASTM standard testing protocol ASTM...
4.3 Preparation of compressible grout and testing procedure

Technicore hired BASF to prepare a design mix, using materials supplied by Technicore. The design mix ratio was determined by BASF. Six grout specimens were prepared and shipped to the Queen’s University laboratory for physical testing.

Two samples at a 7-day cure interval were tested using the standard ASTM testing protocol (ASTM D7012-14) for unconfined compression strength analysis. Subsequently a nonstandard European test for semi-confined compression strength testing was conducted utilizing 14 and 28-day cure specimens to more accurately represent the actual configuration of the grout as placed behind the tunnel lining. One specimen was tested at 14 days cure and two additional specimens were tested at 28 days cure for modified compressive strengths determination (European test).

For all of the above testing, each sample was cut to prepare cylindrical samples having nearly parallel end faces. The samples were subjected to failure within a servo-controlled compression frame.

All tests were performed under axial strain control at rates approximating $2 \times 10^{-4}$ s$^{-1}$ (equivalent to an axial deformation rate of 0.033 mm/s) and, for these tests, simultaneous recording of axial force and axial deformation was performed from which determination of standard failure parameters (Young's modulus and peak compressive strength) were made. Each unconfined compression test was permitted to undergo axial deformation equivalent to 20% axial strain prior to completion of testing.

The pre- and post-test views of a confined compression test of a 28 day cured specimen of compressible grout of the present invention is illustrated in Figure 7. The strain-stress chart is shown in Figure 8.

4.4 Placing the Compressible Grout in the Tunnel

The compressible grout is being made by batching plant at the job site and transport into tunnel by grout machine. The grout machine is equipped with an agitator and pump.

The compressible grout injection behind the precast concrete segments through the grout sockets. The pressure of the grout is monitored by a pressure gauge and is limited so as to not exceed of ground water pressure plus half a bar.

The compressible grout could also be injected directly from the TBM tail shield.

The precast concrete segments and grout sockets are demonstrated in Figure 9.
5 CONCLUSION

Placement of a final tunnel lining in rock with TDD requires either a time delay to allow movements to dissipate, a flexible grout or a yielding lining. In a situation where a segmental lining is to be used, using a compressible grout between the extrados of a stiff lining and the excavation boundary is a feasible and economical option to offset problems resulting from potential TDD effects. For large diameter tunnels, the over excavation dimension by TBM should be evaluated during the design stage because there is a limit for compressible grout (deformation capacity?).

Briefly, the roles of compressible grouting behind precast concrete segments in rock with TDD are as follows:

- Providing a stable backfill for the concrete segments
- Accommodating the deformation up to 16% of the annular space (the percentage of compressibility could be increased by changing the ratio of particles in the mix design)
- Avoiding overstress on the liners due to TDD
- Minimizing water leakage into the tunnel (as a backup to the gasket)
- Minimizing penetration of gases to into the tunnel (methane etc., if present, as a backup to the gasket)

Some concerns during preparation and installation of grout in a tunnel include:

- Some percentage of the foam particles may float to the top of the grout, and for this reason mixing the elements should be done by an automated system
- A special grouting pump is required to pump out the grout to avoid clogging of the pump
- The filter of regular pumps should be cleaned frequently
- The density and viscosity of the grout should be checked at each pour

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7 REFERENCES


Diederichs, M. 2011. Sharing geological research during cross-Canada trek, Queen's University, Ontario, Canada.


Hoek, E. and Marinós, P. 2000. Predicting tunnel squeezing problems in weak heterogeneous rock masses. Tunnels and Tunnelling International


Hoek, E. 2012 Alternative ground control strategies in underground construction, International symposium on tunnel contract. Athens, Greece


Maidi, B, Thewes, M and Maidi, U. 2013. Handbook of Tunnel Engineering, Structures and Methods, WILEY


