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Sprayed on Waterproofing in Frozen Ground Conditions: a Shaft Liner Application Case

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ABSTRACT: The authors participated in a study for a new mine shaft in Saskatchewan's Athabasca Basin where ground freezing is desired to reduce water inflows. Constraints were imposed on the design in terms of permissible water leakage (less than 10 m^3/hour) inside the shaft. Since the shaft goes through highly permeable formations, water control measures had to be incorporated into the design. Ground freezing was selected as the most reliable and proven method for the sinking and a hydrostatic liner design was implemented. While exploring various technological options available for providing a fully hydrostatic liner, the authors came up with a new design concept that offers a more cost effective solution while meeting all the design constraints. The new liner concept is a composite design using concrete and a spray applied waterproofing membrane. In the majority of cases where fully hydrostatic shaft liners are required, ground freezing is used for sinking. Although water proofing sprayed-on products for surface infrastructures, suitable for below freezing temperatures exists, their current formulation renders them unsuitable for underground applications. The currently available products, suitable for underground work, impose temperature constraints for successful applications. A new approach was developed for the membrane construction in order to resolve the issues created by the freezing conditions existing at the excavation walls. The membrane material requires a subgrade of shotcrete in order to smooth the irregular rock excavation surface. A working hypothesis was proposed by the lead author: use the shotcrete base layer, not only for creating a suitably smooth surface, but to provide the required warm temperature surface for the time duration needed for spraying and curing of the three membrane coats. The hydration heat of the shotcrete material would maintain a suitable surface temperature.

1 Introduction

The recent years saw a big push of new projects both in potash mining as well as uranium mining in the province of Saskatchewan, Canada. These mine shaft projects involved sinking through difficult ground conditions with the potential of high water inflows at depth. The most successful methods for sinking through such conditions use ground freezing technology and these applications demand waterproof liner designs. The shaft liner designs must be able to handle the high hydrostatic pressures encountered as well as being fully waterproof. Interest for waterproof liners was also very high for uranium mining projects in the Athabasca Basin. In these cases, the objective is to reduce or eliminate radon leakage in underground workings. Currently shotcrete is used, but with time cracks develop and radon emissions become an issue. Various techniques were explored to evaluate the potential of waterproofing systems for underground mining applications in shafts and in underground workings. In the mining cases concerned by this study, ground freezing technology was used, both for the shaft sinking as well the mining underground. This introduced a supplementary constraint on the eventual waterproofing technology to be used. The authors were involved in developing a new shaft design for a study on a mine project where ground freezing was required both for the sinking as well as the mining. In the case of the mine shaft, a primary requirement was to develop a water tight hydrostatic liner. Furthermore, there were interests in exploring available technologies to improve waterproofing in some of the excavations underground. To do so, established methods and technologies were reviewed as well as innovative approaches. The authors looked particularly in the most recent trends and technological developments from the tunneling industry. The technology selected had to meet mining construction harsh constraints, particularly in a conventional shaft sinking environment, as well as the low temperatures involved with the ground freezing situation. The present paper will focus primarily on the shaft sinking and design liner application.

A value engineering approach was used to compare various options which combined conventional and/or new technologies imported from the tunneling industry. This exercise aimed at coming up with a recommendation. A set of evaluation criteria was developed and six engineers involved in the project from the client side were assigned to rank these. From this ranking exercise, weighting factors were calculated and then used in scoring each option. Of the 12 assessment parameters, the top ranking ones were: cost, schedule and water containment performance of the liner design. For this project, ground freezing as a water ingress control method during sinking was required.

Obviously, conventional designs were reviewed such as the hydrostatic liners built in the past decades in Saskatchewan. The existing potash shafts in Canada were constructed more than 30 years ago.

The hydrostatic liner designs used at that time were mostly based on the cast iron tubbing system (Kelland and Black, 1969); a more recent example is illustrated in Ouellet et al. 2012. The only exception is the Lannigan mine shafts which were based on the composite steel/concrete technology (Storck, 1968). The latter was very innovative for its time using welded steel sheets as the waterproof membrane component. Both of these technologies are still used today in shaft liner design where waterproof hydrostatic liners are required, as they are still very effective. The downsides are the slow sinking rates imposed on construction because of the time consuming installation and the high costs involved for labour and material. The knowledge to design, produce technical specifications, manufacture and install a tubbing liner is very limited in Canada. The composite liner employs welded steel sheets as the waterproof membrane component and has slightly cheaper per metre material cost. However the precise and high quality welding required in this liner construction is very challenging to execute in the conditions of a frozen mine shaft. Moreover, this approach requires a bottom up construction sequence with a foundation at the base which forces a wider excavation diameter at this elevation. A primary liner must be put in place as well to support the excavation frozen walls over the much longer stand up time required. Due to the time dependent nature of the wall convergence, a flexible liner is required. This adds an extra cost to the project and requires an increased excavation diameter to accommodate this extra layer in the shaft lining. This last, in turns, imposes higher requirements on the design due to this larger excavation. In terms of sinking rate with this methodology; the method is very slow as well. Moreover, these technologies are very limited in their capacities to accommodate complex geometries. Handling diameter variations or complex connections can be very complicated to handle with welded steel segments.

The authors were interested in exploring new materials and technologies to come up with a more cost effective and easier to install liner design. Through a value engineering exercise it was determined that a composite concrete design with an internal waterproofing membrane offered significant advantages in terms of preventing water migration. The sprayed-on membrane or sheet membrane was considered as a replacement for the conventional welded steel membrane. Welded steel membrane construction imposed constraints on design geometries as well as the construction sequence from the bottom up. The aim was to find a membrane technology offering more flexibility in the liner design as well as in the construction sequence. In order to maintain lower costs, a final liner design based on concrete was preferred. By putting in place a continuous barrier to the water from ever reaching the concrete liner, potential construction weaknesses in the liner, such as cold joints and or cracks, would no longer be an issue. So the new concept would add to a conventional concrete design a waterproof membrane component.

2 Selection of the membrane material for the new composite liner design

For this application, the desirable attributes of such a membrane are:

- Rapid installation minimizing the impact on the shaft sinking cycle,
- Material, equipment and installation procedures that are easily manageable in the shaft sinking environment,

- Allows for a thorough quality control and testing of membrane integrity during construction,
- Can accommodate complex geometries
- Offers excellent crack bridging capabilities,
- Forms a consistent bond with the concrete liner material,
- Can bridge cold joints without risk of failure,
- Robust and durable (mine lifespan of 50 years or more),
- Withstands hydrostatic water pressures of up to 80 bars.

In the civil engineering domain, waterproofing membranes are used extensively in shallow shafts (depths in the order of 60 metres) and tunnels. A survey of the various products showed that the technologies available could be regrouped in two categories: sheet membranes and sprayed-on membranes. Sheet membranes are delivered as rolls of a given width and length that must be tacked or pinned to the shaft wall and then glued or fused to form a continuous membrane preventing any water from reaching the inside liner. Aside from being very difficult to handle, insuring the integrity of the membrane with these products is dubious for a long and relatively deep shaft of 500 metres or more. Thousands of meters of seams need to be fused without any defects. Potential to puncture or tear the membrane during the construction is high. Moreover, handling complex geometries with these sheets is very difficult if not impossible. Actual performance in tunnels demonstrated a low rate of successfully meeting design requirements. Consequently all the conventional sheet membrane materials were eliminated in the value engineering process for shaft liner design.

The following characteristics were key driving attributes in selecting the product:

- Seamless membrane
- Effective and fast application
- Rapid curing
- High resistance to damage during construction or operational activities (no special protection required)
- An integrated quality assurance program
- Electronic testing after application providing proof of integrity
- Application in a wide range of conditions such as high humidity and cold temperatures
- A design life in excess of that of the structure it protects

The sprayed-on membranes products, from an implementation point of view in a mine shaft, seem to offer the best solution. Various products have been considered and two were initially retained: a competitor membrane product and the Integritank® HF system from Stirling Lloyd.

The competitor membrane product is a hydrating cement polymer product that is sprayed on a shotcrete base. This is a one coat product that bonds to the cement. The product however is normally only rated to 10 bar pressure. The design life, as well as the crack bridging tests results, met the initial requirements. However, weak points were identified with this product for shaft sinking in frozen ground conditions:

- Requires at least +5°C to be installed.
- Curing at 5°C takes up to 4 days, during which time the temperature cannot fluctuate by more than 10°C, otherwise it is very soft and can be damaged easily.
- A single coat application making it more prone to missing spots thus creating pin holes that would be detrimental to the performance.
- No established quality control procedure to verify membrane integrity.
- Some instances of tunnelling applications were showing less than ideal waterproofing performance.

The sensitivity of the competitor membrane product to impact damage during curing was not favorable in a shaft sinking environment and the long curing time would seriously impact on the sinking cycle.

Moreover, in frozen ground conditions, the application surface (shotcrete preliminary liner) must be maintained at a warm temperature for the minimum 24 hours and potentially for up to 4 days. The problem with a hydrating material is that the hydration rate is very sensitive to ambient temperature. This can lead to a potentially very long curing time in a frozen shaft.

There was not a well-established procedure to insure or verify the actual membrane integrity for this product during construction, which renders the quality control aspect in this option lacking. A significant advantage of the product was the fact that little if no surface preparation was required when applied onto a shotcrete base layer.

The second option, Integritank® HF product from Stirling Lloyd, is a three coat system. The first coat is a primer which aims at limiting the detrimental effect of out-gassing from the curing shotcrete which tend to produce pinholes in sprayed-on membranes. The actual membrane is formed by two layers of a polymer material. Both coats are the same although with different color pigments. The first coat is a bright yellow and the second one is white. The principle behind the two coat system is to minimize the risk of missing spots or layers. Whatever could have been missed with the first application will be covered with the second coat. The color coding allows for an effective visual check of the quality of the coverage. The system requires only one hour per coat to reach full curing, which is a significant advantage for the sinking cycle time.

The membrane is non-toxic and provides a high flash point, which is highly desirable for work in confined areas. They developed this product specifically for underground applications such as tunnelling waterproofing. This product, being based on acrylic resin chemistry, allows for a chemical cure rather than a hydrating cure. This resulted in cure times reduced to one hour for each layer application instead of six to eight hours in other products. In addition, water pressure testing on the membrane material demonstrated water resistance for hydrostatic pressures up to 100 bars. Application time for the material is well within time limits encountered in the sinking and lining cycle. Contrary to hydrating cure material such as the competitor membrane product, the Integritank® HF product's exothermic chemical curing makes for a material much less sensitive to ambient temperature variations.

The most attractive feature of the Integritank® HF product is the quality control program. The manufacturer has a simple to operate technology to verify the membrane integrity after application, thus allowing detection of any defect before completion of the construction. It then becomes possible to detect and repair any such defects during the work. The membrane offers all the desirable characteristics of a waterproofing system, seamless, crack bridging, composite effect and rapid installation (Harper, 2011). It is very robust against shock and friction, a significant advantage when construction of the permanent concrete liner is done in front of this membrane. Crack bridging testing had been performed successfully at below freezing temperature (-10°C) which was an interesting attribute where frozen ground technology would be used. The material is compatible with concrete. It adheres to concrete and concrete bonds to it creating a true composite laminate. The concrete/membrane bond strength is comparable to the tensile strength of the concrete. The membrane material bonds very strongly to steel as well allowing detailing work around pipes or other structures. The weak points identified on this product are:

- Requires +10 °C degrees on the application surface,
- Application surface must be relatively smooth, floating of the shotcrete or use of a rendering product is recommended by the supplier.

3 Testing of shotcrete substrate on frozen surface

The low temperature condition is an issue since most instances where high strength hydrostatic shaft liners are required, ground freezing is also used. For instance, the potash mines in Saskatchewan are good examples. A working hypothesis was proposed by the lead author: use the shotcrete base layer, not only for creating a suitably smooth surface, but to provide the required warm temperature surface for the time duration needed for spraying and curing of the three membrane coats. The hydration heat of the shotcrete material would maintain a suitable surface temperature. Although some frozen ground shotcreting experiments were documented in the literature, no information was found providing temperature curves over time for such conditions. Consequently, the low temperature issue was studied by the author through a pilot scale proof of concept test program completed in 2011 (Ouellet, 2011). The test results demonstrate that the membrane system, combined with the appropriate shotcrete mix, can be used in frozen shaft conditions. Using shotcrete as a substrate on frozen surface was done successfully, demonstrating the effectiveness of the approach. The following Figure 2 illustrates a data sample of temperature profiles over time that was obtained during this proof of concept testing in 2010. These temperature profiles were obtained for shotcrete without the application of the membrane (Phase I). Laboratory testing was conducted on core samples of the shotcrete to determine its compressive strength. The compressive strength of the samples ranged from 40 to 75 MPa. These tests showed that the quality of the cured shotcrete, even after being applied and curing on a frozen surface was excellent.

The time to construct and test the waterproofing membrane had to be carefully studied. In order to do so we had to rely on the practical experience of the supplier. For the scenario under consideration, we studied the time and sequence for each operation involved in the membrane construction. The case considered was for a shaft with a finished inside diameter of 7.5 m using jump forms every 6 m. Each cycle then involved waterproofing a 6 m section of shaft. The results of this cycle time study showed that application and testing of the complete membrane system was achievable well within a six hour window. The test objective was to prove that a surface with a temperature above +10 ºC for duration of at least 6 hours could be maintained.

A special testing system had to be designed and built to produce shotcrete testing on frozen surface. Then the test program was executed to demonstrate the concept. Due to time and budget constraints, the testing matrix had to be limited to a few options. Tests were conducted on two shotcrete mixes over three different panel thicknesses (75 mm, 100 mm and 150 mm). The first phase of the testing was aimed exclusively at obtaining temperature profiles of the various shotcrete combinations (mix/thickness) without any membrane application.

The test program included various shotcrete mixes, three different thicknesses and various dosages of accelerators. For this testing program, different ratios of cement to fly ash were used. To simulate conditions typically used in shaft sinking, a wet shotcrete mix system was selected rather than the dry mix method. For these experiments the various custom mix recipes were prepared at the plant and delivered by truck. The transit time in the truck, prior to shotcreting, could vary from 20 to 40 minutes. In order to stabilize the mix, 122R/RHEOTEZ Z-60 was added to the mix at the concrete plant. Once at the test site, the concrete was fed from the concrete truck to a cement pump which in turn was feeding the shotcrete nuzzle. For this experimental program, the accelerator was added at the nozzle in concentrations varying from 2 to 8%. The shotcrete which produced the best results (illustrated in **Figures 1 & 2**) had a cement/fly-ash mix of 600 kg/m^3 and used a concentration of 8% MEYCO SA160.

Figure 1 illustrates a few test results of this first phase. It can be seen that the minimal 6 hours' time window was achieved with the 150 mm samples. Without membrane, tests results showed that the target surface temperature (+10ºC) could be maintained for: 75 mm produced 3 hours, 100 mm produced 5 hours and 150 mm produced 6 1/2 hours.

The second phase of testing repeated the experiments on the 150 mm thick panels which had been identified as the thickness providing the minimum 6 hours required for the surface temperature. But this time, the waterproofing membrane was applied over the panels, which seems to reduce heat loss from the substrate, probably due to an insulating effect. When the first membrane coat was applied (yellow layer) a sharp temperature increase was observed in the shotcrete. Experimental results, such as the sample illustrated in **Figure 2**, demonstrate that a suitable surface temperature can be achieved for duration of up to 20 hours in frozen shaft conditions. Considering this result, the minimum 6 hour requirement derived from the concrete alone is probably too stringent a requirement as the Integritank HF appears to enhance and maintain the heat from exotherm within the substrate. Therefore it is likely the 3 hours achieved for the 75mm panel could be extended in the same way to achieve longer than the minimum 3 hour window; the minimum time within which primer and first coat can be applied. This suggests that the shotcrete thickness required could be reduced to as little as 75 mm. But further testing would be needed to demonstrate this conclusion.

Providing the shotcrete surface is relatively smooth, through the use of fine aggregates within the mix, the testing showed that the membrane could be successfully sprayed on without floating the shotcrete surface. This reduced the cost of an added layer to the normally sprayed on two coat (yellow and white) system. The supplier of the membrane product is considering development of a filler/sealer product that could avoid the floating requirement. Such a development would make the technology much more effective for the considered application. They also have developed an alternate product as primer that can be used at lower temperatures than the +10 ºC. For dry conditions the new product can be applied at temperature as low as 0 ºC and +5 ºC in wet conditions. This resolves the main issue identified during the testing program with the original primer component being water based. Although Stirling Lloyd has a membrane product that can be used in below freezing temperatures, its characteristics (flash point, fumes) are not suitable for underground work. By developing a variant product, meeting underground requirements, better able to withstand cold temperature, the flexibility of the membrane system for frozen ground conditions could be further improved.

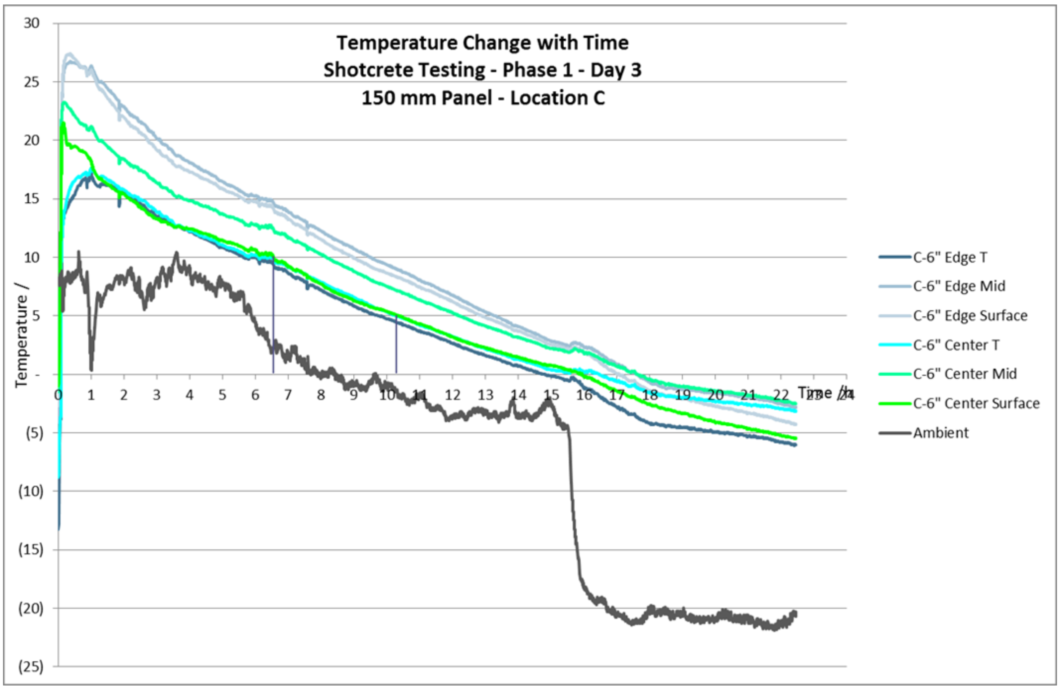

Figure 1: Temperature profiles of shotcrete on frozen rock, (Ouellet, 2011).

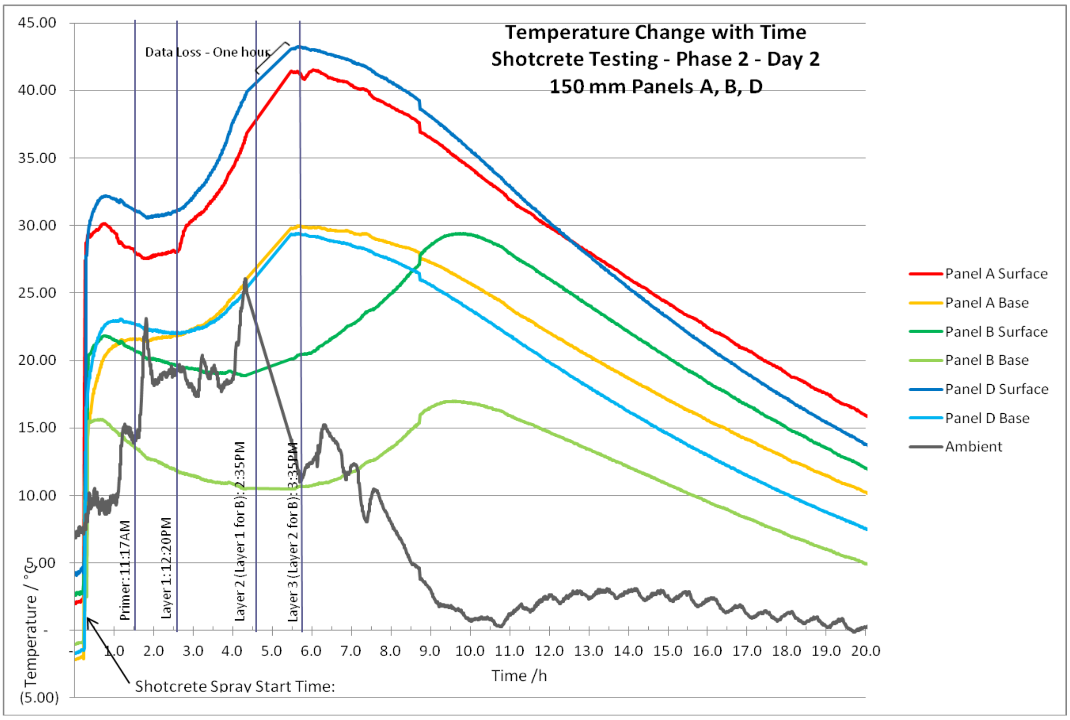

Figure 2: Temperature profiles of shotcrete on frozen rock with membrane, (Ouellet, 2011).

Considering the technical advantages and disadvantages of the two products considered we came to the conclusion that the Integritank® HF product offers the best potential for this application. The integrated quality assurance program including integrity membrane testing at application time was paramount in our final selection. The high durability of the material made it an interesting product able to better withstand the harsh conditions of shaft sinking.

4 New composite membrane design

The membrane material requires a subgrade of shotcrete in order to smooth the irregular rock excavation surface. In the case of a frozen ground situation the shotcrete must serve two functions. The first function is to produce an application surface suitable for the membrane. The second one is to generate a sufficient amount of heat to counterbalance the freezing conditions of the rock wall and maintain a suitable surface temperature for the duration required to construct the membrane.

The sprayed-on membrane creates the water barrier in the same way as the welded steel membrane in the classic composite liner design. For design, the load acting on the liner must be considered. The shotcrete primary liner was not considered to be a contributing structural component for resisting the hydrostatic pressure. The designer must assume that water can reach through the shotcrete layer and act directly on the membrane. Consequently the inner concrete liner must be designed to sustain the full hydrostatic loading. The total load acting on the liner includes a ground load component. For this component of the load, the primary shotcrete liner could be considered in the calculation. But, depending on ground conditions, the major load component is usually the hydrostatic head.

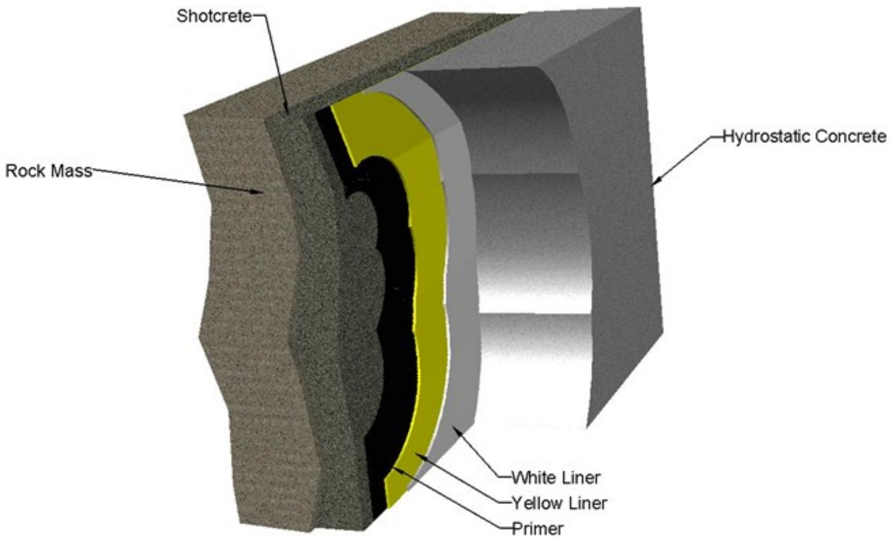

Figure 3: Composite liner concept with sprayed on membrane.

Figure 3 illustrates a schematic view of the proposed composite liner design. In this example, a simple hydrostatic concrete liner design is considered. Actually the final hydrostatic liner does not need to be simply concrete. Various combinations could be considered where high stresses are expected. An inner bolted steel component could be added to keep the overall thickness of the liner smaller. The new membrane could be combined with any style of composite design. The extreme flexibility a sprayed-on membrane provides to the construction process allows accommodating diameter and liner thickness changes very easily.

Through the value engineering exercise that was conducted, for the mine shaft project under study, the cost for constructing a hydrostatic liner with tubbing liner, a conventional composite steel/concrete liner and the new design proposed here were compared. This exercise showed that, for the same shaft, the new liner concept was saving up to 45% of total cost compared to a tubbing construction. The proposed new liner design produced a total shaft sinking schedule three months shorter than the conventional tubbing liner or composite steel construction. This was for a 7.5 m finished diameter and a total depth of 721 m. But only the top 491 m of the liner was required to be hydrostatic.

5 Conclusion

The authors developed a new composite liner concept incorporating the most recent technologies developed in the civil engineering tunnelling industry. Supplementary testing demonstrated that the sprayed-on membrane developed in tunnelling can meet deep shaft lining requirements in terms of hydrostatic pressure, design life and crack bridging capabilities. The proposed new concept provides a much more advantageous alternative to the previous technologies relying on cast iron or welded steel components. In the majority of cases where fully hydrostatic shaft liners are required, ground freezing is used for sinking. Although water proofing sprayed-on products for surface infrastructures, suitable for below freezing temperatures exists, their current formulation renders them unsuitable for underground applications. The currently available products, suitable for underground work, impose temperature constraints for successful applications.

The authors, through the experimental work described in this paper, developed a system that makes possible the use of the existing membrane products in frozen ground conditions. It was shown that suitable temperature conditions could be provided through the application of a shotcrete layer over the frozen excavation walls. The hydration phase of the specially formulated shotcrete produced enough heat to sustain the required application temperature for a time window well in excess of the minimum time requirements. It was observed that the application of the first Integritank® HF layer provided an insulation effect to the concrete maintaining the required substrate temperature for more than 20 hours.

The most important conclusion is the cost effectiveness of the proposed liner design (Eddie et al., 2010). When comparing to a conventional welded steel composite design or a cast iron tubbing design we could expect a sinking rate more than twice as fast with the sprayed-on membrane. When costing a shaft using the design proposed in this paper we see a huge difference. The sprayed-on membrane system is much less expensive than the tubbing liner system or the conventional steel composite liner. Comparing them on a material basis, the sprayed membrane is one order of magnitude cheaper.

Stirling Lloyd has now developed a new primer that can be used down to 0 ºC and are working on lowering the Integritank® HF application temperature range. Further work that should be undertaken is combining a filler material to the primer formulation that would reduce the amount of material required as well as the application time of the membrane. Presently, recommended practice in tunnelling applications is to float the surface of the shotcrete or apply a rendering layer on top of it. This insures a smooth surface ideal for sprayed-on membranes. Combining the primer with rendering filler would improve cycle time in the sinking process.

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