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COST EFFICIENT WATERPROOF TUNNEL LININGS

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ABSTRACT

The last few years, several projects have been successfully lined by sprayed concrete with an embedded double-bonded spray-applied membrane. This composite single shell liner offers significant reduction of total project cost and construction time. Especially in drill and blast tunneling major cost savings are linked to reduced consumption of concrete materials when comparing with the traditional system with sheet membrane and cast in-situ concrete.

INTRODUCTION

Waterproofing of underground structures is a complex problem and it is not easy to successfully achieve the results specified by the designers and wanted by the owners. The problem at hand is also highly dependant on type of project and a large number of project specific variables. It is well known in the industry that waterproofing is sometimes one of the main problems of design, execution and later, operation and maintenance of the underground facility.

Sometimes the so-called *submarine* solution is needed (no water ingress permitted anywhere), while mostly some sort of *drained* solution can be used (the invert is normally not sealed off so the sealed part is sometimes called an umbrella). The choice between *submarine* and *drained* will have major impact on execution and cost and the *submarine* may attract extreme loading at high ground water head. It does also happen that the waterproofing is installed to prevent water to leak out of the structure, which poses very different problems and requires adapted solutions.

The methods used to produce waterproof structures range from ground injection and contact grouting to steel linings, watertight concrete and shotcrete and different types of sheet membranes.

Spray applied membranes offer a quite different way of ensuring a waterproof structure and as always, with some advantages and disadvantages. Until today, sprayed membrane solutions have caught just a marginal market share, but the number of successful projects is growing and this suggests a further increase in the future.

For lack of other sprayed membrane systems to present, this paper is based on technical properties and practical experience gained with Masterseal 340F and

Masterseal 345. It is known that other membrane systems exist, but if they do not offer sufficient bond against concrete, are water sensitive or without elasticity, the usage will anyway be severely limited. New and even better products may of course at any time become available and only the future will show the actual development in this interesting field.

COMPARISON OF SHEET MEMBRANE AND SPRAYED MEMBRANE

The traditional way of preventing ground water ingress through the tunnel lining is by sheet membrane installed between the primary sprayed concrete support and the permanent in situ concrete lining. Compared to sprayed membrane solutions, the following may be noted:

- Sheet joints must be welded and the quality control must be rigorous to avoid leakage.
  - Joints in sprayed membrane can be achieved by simply spraying an overlap of 200 mm, Brandenberger *et al* (1).
- Working with large and heavy sheets that has to be suspended from the roof and walls of the tunnel is labor intensive and time consuming and is hampering other tunnel activities.
  - Spray application can be executed manually or by robot, allowing easy passage of people and equipment and has little influence on other work activities.
- Undulations in the substrate must be limited to avoid over-stretching the membrane by concrete pressure during final lining concrete pouring. Smoothening shotcrete layer is often required, especially in drill and blast tunneling.
  - This is not a concern with sprayed membrane, since it completely follows the substrate undulations.
- The sheet membrane must be protected on the rock side by a geotextile layer to prevent penetration at sharp points.
  - No concern with sprayed membrane.
- Point damages to the installed membrane can occur during erection of concrete formwork and installation of reinforcement and they may be difficult to detect, even though simple to repair at this stage.
  - Such damage can be prevented by simply applying a thin layer of shotcrete (30-50 mm) onto the sprayed membrane before start of other works.
- Sprayed concrete will not stick to sheet membranes and can only be applied in combination with geotextile and reinforcement mesh used to tighten up the substrate and provide basis for sprayed concrete build-up.
  - Shotcrete can be applied against sprayed membrane without any special preparations or measures.
- There is no bond between concrete and sheet membrane on either side. This has the effect that pressurized water present on one side of the membrane will 'find' any point damage and cause leakage. Furthermore, the water leaking through the membrane can follow the other side interface and appear visually in construction joints or concrete cracks meters away from the actual leakage point. There is no way to detect the location of the problem and the repair is therefore difficult.
  - In contrast, pressurized water on the rock side will probably NOT 'find' most of the possible damage points in the sprayed membrane, due to the continuous bond. If water still penetrates a weak point, it will not migrate in the membrane/concrete interface. A humid spot or a drip from the cover

concrete will therefore show where the damage is and it can be easily sealed by point injection.

- If any kind of penetration of the membrane is required, e.g. for bolts to suspend tunnel installations like ventilation fans, light and cables, signals or reinforcement cages for the final lining, it is difficult to ensure tightness.
  - Sprayed membrane can be applied around such bolts and will seal them off. Bolts can even be drilled for after membrane spraying, provided a simple point injection will be used.
- In a drill and blast excavated hard rock tunnel, frequently the permanent support can be accomplished by an average total shotcrete thickness of less than 250 mm. Permanent in situ concrete linings planned to be about 300 mm thick, frequently end up being double and triple that, due to overbreak during excavation. If such a lining is there just to keep up a sheet membrane, it becomes a very expensive membrane support.
  - A sprayed membrane can be integrated in a permanent lining shotcrete solution and the thickness of shotcrete need only be as required for support (independent of possible overbreak from blasting).

COST COMPARISON EXAMPLE

Cost comparisons are difficult to perform and can be done in many ways, but to keep it simple an example tunnel has been used: A 3-lane highway tunnel executed as drill and blast excavation and under North American cost conditions. Some basic data used along with some comments:

Cast in Place Concrete Lining

- Horse-shoe shape with net width of 10.5 m, maximum height 9.75 m and vertical wall height 4.5 m
- Initial shotcrete support thickness 0.2 m, fiber reinforced
- Theoretical thickness of CIP final lining 0.3 m
- Increase of excavation line cross section area due to blasting overbreak 12%
- Tunnel length (used to write off the CIP steel formwork) 1000 m
- Resulting average “thickness” of overbreak 0.46 m
- Resulting total thickness of shotcrete and concrete (including overbreak) 0.96 m
- Cost of sheet membrane installed \$25 /m^2. Numbers actually range from \$10 to \$100 /m^2
- Cost of concrete placed in the formwork \$131 /m^3

Permanent Shotcrete Lining

- Applicable data are the same as above
- Shotcrete thickness increased to 0.25 m with a 0.03 m protective cover layer on the membrane. All shotcrete fiber reinforced
- Cost of spray-on membrane applied \$25 /m^2 No major variation in this number
- Cost of fiber reinforced shotcrete placed in the structure \$375 /m^3

Results

	CIP	Shotcrete
Cost of fiber reinforced shotcrete, $/m of tunnel	2233	2909
Cost of CIP concrete lining, $/m	2694	
Cost of CIP formwork, $/m	535	
Cost of installed membrane, $/m	677	693
Total cost of permanent lining including membrane	6138	3601

The simple observation to make is that the shotcrete lining cost 59% of the traditional lining, but that is just a small part of the picture:

- If the tunnel has niches, cross cuts and other variations in cross section, the CIP and sheet membrane solution will face increased cost not applicable to the shotcrete and spray-on membrane alternative
- A pretty normal installation rate for sheet membrane of about one meter of tunnel per shift hour is just 1/3 of the spray-on membrane installation rate. To the extent this difference has influence on the overall construction time it will also significantly increase the cost of CIP with membrane. This time difference will be enhanced by the issues mentioned in above first bullet point
- The total amount of permanent shotcrete is only 43% more than the amount needed in any case for initial shotcrete in the CIP case. This means that a major part of the time necessary to install the CIP concrete lining will be added construction time. This can further increase the project cost
- Many will object that the shotcrete lining is not comparable due to problems with visual impression and driver's reactions in a traffic tunnel. However, the calculated minimum difference of $2537 /m of tunnel is more than the solution used by the Norwegian Road Authority in such cases, creating the visual quality of a CIP lining
- There are many kinds of civil tunnels where the visual quality of the lining is not important

PROPERTIES OF MASTERSEAL 345 SPRAYABLE MEMBRANE

The membrane is based on an ethylene-vinyl acetate copolymer and comes in powder form. Application is done using dry mix shotcrete equipment, adding water in the nozzle, Brandenberger *et al* (1). When sprayed onto substrates like concrete or sprayed concrete in thickness of typically 3 to 4 mm, it will cure in less than an hour and change from a sticky paste to an elastic membrane. The main technical properties can be summarized as follows, BASF Technical Data Sheet (2):

- Form: Powder
- Colour: Light brown
- Bulk density (+20°C): 590 g/l ± 100 g/l
- Application thickness: 3 to 10 mm
- Application temperature: +5°C to +40°C
- Failure stress (at +20°C): 1.5 to 3.5 MPa
- Failure strain (+20 to -20 °C): 80 - 100%

- Bond strength to concrete (28 days): 1.2 ± 0.2 MPa
- Shore hardness: 80 ±5
- Flammability: Self-extinguishing (in accordance with DIN 4102-B2)

Interaction With Shotcrete

Concrete spraying against the membrane behaves as when spraying onto rock or concrete. The sprayed concrete bond strength against the membrane substrate is > 1.0 MPa. This is very well demonstrated by core drilling through such a sandwich, producing full-length cores including a membrane layer. When breaking the core, the fracture will frequently be partly in concrete. The membrane also bonds well against steel, hot dip galvanized steel, aluminum and even fresh rock.

Use of Steel Fiber Reinforcement

Practical experience and tests have demonstrated that steel fibers may be used in both the substrate concrete and in the sprayed on concrete, without any damage to the membrane.

Durability of the Membrane

The durability of the membrane is sometimes presented as a concern. This is understandable when dealing with a new product. However, there is a 40 year experience basis available with the basic chemistry of this membrane. Experience from polymer modified mortars and concrete is widespread. Hundreds of tons of such mortars are being used per year and there is no reason to expect any durability problem with this type of membrane in a concrete environment.

By submerging membrane sheets into a number of different chemicals, the results in conclusion are, BASF R&D Report (3):

- Only strong organic solvents and concentrated acids can damage or destroy the membrane.

Practical Limitation

An important practical point to be aware of is the fact that application of a non-reactive paste, which takes time to dry out (cure), cannot fight active pressurized water through the substrate, at time of application. If such active water is present it will penetrate the membrane before it can set and this will produce a leakage point. How to deal with this will be discussed below.

However, contrary to e.g. sprayable systems on polyurethane basis, there is no problem with substrate or air *humidity* at time of application. Actually, if the substrate concrete is dry, it must be pre-wetted and allowed to surface dry, before application of the membrane. Such surface humidity improves the bond strength and must be ensured before spraying.

APPLICATION OF SPRAYABLE MEMBRANE

The application of the membrane is very simple and can be executed by a dry shotcrete machine. For the thin-stream transport of powder to the nozzle, compressed air is needed. The water added in the nozzle should show a minimum of 2 bar static pressure. The product is fed into the hopper of the dry-mix machine, blown through the hose to the nozzle, where water is added. The nozzle can be easily handled manually by one man with a helper and an application capacity of more than 50 m^2/h is quite normal. With one man operating the dry-mix machine, the team is in total three men.

By attaching the nozzle to a spraying head of a sprayed concrete manipulator, the capacity can be increased to 100 m^2/h and more. This equipment set-up takes away the need of a platform, even in large tunnels and caverns. It also gives the opportunity to apply membrane directly on the fresh shotcrete just applied by the same manipulator, thus combining the effect of membrane for sealing purposes and a concrete curing membrane.

Sprayed concrete surfaces are sometimes very rough, depending on a number of practical influence factors during placement. The poorest shotcrete substrates are not suitable for the membrane (un-treated) for two reasons:

- It is more difficult to ensure a continuous membrane without pinholes
- The materials consumption could increase substantially from the normal 3 to 4 kg/m^2. It is far less costly to spray an extra fine-mortar smoothening layer first and the result will also be technically better. For this, no more than 10 mm average mortar thickness is needed.

USE OF GEOTEXTILE DRAINAGE LAYER

Purpose of the Geotextile Sheets

In cases where part surface (or full surface) drainage is required, and/or where active water is penetrating the substrate at time of membrane application thus disturbing setting of the sprayed membrane, a specially designed geotextile can be used.

Geotextile Product Features and Installation

This product consists of polypropylene fleece geotextile in two layers (each 150 g/m^2) with a 0.2 mm PE membrane laminated between them. The thickness of this 3-layer product is about 4 mm and it comes in rolls of 1.95 x 50 m. A special feature is that the fleece side facing the rock side (the wet side) is hydrophobic, while the other fleece layer is hydrophilic, BASF Technical Data Sheet (4).

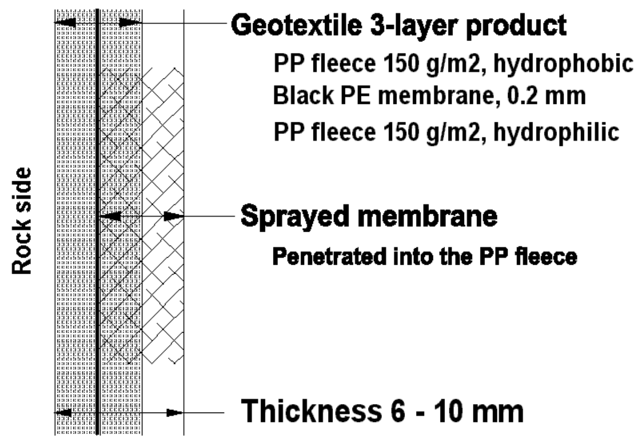

Figure 1. Geotextile sheet for drainage and control of active water flow from substrate

When shooting nails through the fleece into the concrete substrate for fixation, the pressure from the rubber washer compresses the fleece and helps preventing water drip at the penetration. The tunnel side will easily be saturated by the membrane when spraying it on, thus ensuring a good bond and membrane continuity.

The purpose of the thin layer of PE membrane in the middle of the sheet is to drain away water migration from the substrate while the spray membrane gets time to dry out. Also, it prevents the spray membrane from destroying the drainage capability of the rock side geotextile. The nails used can be of any type designed for penetration into concrete and should be combined with a stiff rubber washer. There are pneumatic guns available for such works. The fleece sheets must be overlapping by about 5 cm in the joints. To ensure continuity of the sprayed membrane across joints double sided Velcro strips are used to tie down the sheet edges.

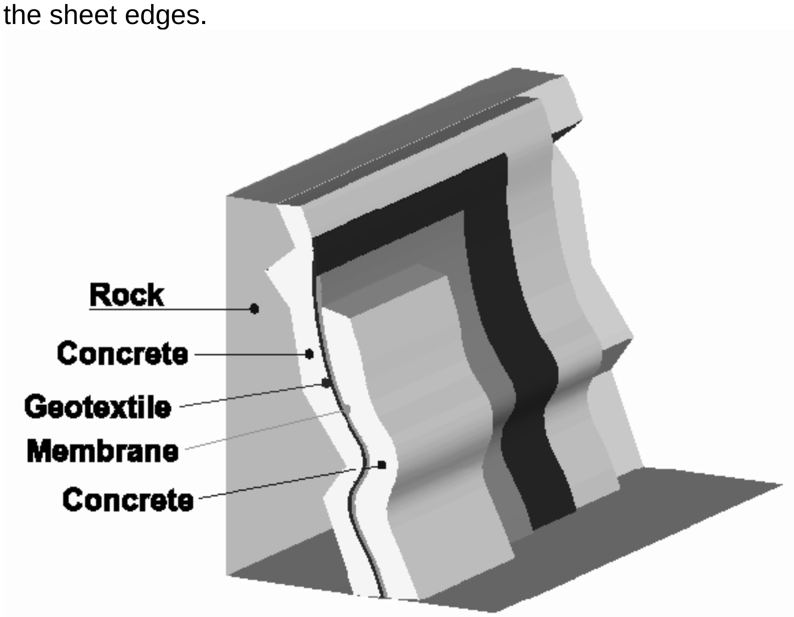

Figure 2. Composite system. Drainage can be installed part- or full surface as needed

FULL SCALE TESTING, HAGERBACH TEST GALLERY, SWITZERLAND

Test Set-Up

A tunnel section of about 10 m length was equipped with Fuko injection hoses placed longitudinally along the tunnel contour with a spacing of about one meter. These hoses were covered by sprayed concrete, membrane was sprayed onto the concrete and a cover layer of sprayed concrete was placed as the last step. This monolithic sandwich was then subjected to external water pressure, by feeding the Fuko hoses with pressurized water.

Test Execution

The whole test was running for 56 days altogether and started at low water pressure, but with a stepwise increase up to a maximum of 15 bar, or 150 m water head. The membrane-protected area was bone dry during the whole test period. In the tunnel wall there was a window in the cover concrete the size of 1 x 1 m, exposing the sprayed membrane. The membrane did not debond and also this area was completely dry. It must be mentioned (to demonstrate that the water pressure system did work) that a different area sprayed with a polyurethane membrane with the same kind of window in the cover concrete, produced a debonded membrane "pillow" inflating like a balloon into the tunnel.

Test of Drainage Geotextile

Tests have been carried out with fixation of the geotextile drainage in the roof while water was running. A drip free geotextile surface was achieved, draining the water down to the floor on the rock side. Spraying of membrane could be carried out without any damage from the running water. It was furthermore demonstrated that sprayed concrete placement onto the geotextile in the roof could be carried out without problems. Contrary to expectations, it was even a very hard job to remove the cover concrete and membrane, after the testing had been finalized.

THE MACHADINHO HYDRO POWER PROJECT, BRAZIL

Some Relevant Project Details

This 1150 MW project is located in the SW of Brazil, close to the town of Piratuba. Owner: Gerasul. Contractor: Camargo Correa. Designer: CNEC (Brazil). Upstream of the powerhouse there are three inclined pressure shafts with an excavated diameter of 11 m. With an inclination of 55° and a length of about 100 m, the maximum internal water head in the shafts is about 10 bar. At this project the Masterseal 340F was used. Two of the shafts were treated.

The shafts are located in highly fractured basalt and the rock cover is partly just a few meters. The risk of water leaking out from the shafts into this jointed and minimal rock cover, with the possibility of hydraulic fracturing, was the main reason for requiring water tight shaft linings.

Construction Method Used

The shafts were excavated by drill and blast and they were supported by sprayed concrete. Because of the rough concrete surface, it was decided to apply a smoothening layer of pre-bagged fine mortar followed by the membrane spraying. When the membrane had dried out it was protected by a cover layer of sprayed concrete.

It should be noted, that the membrane was sprayed around a large number of steel dowels installed for later fixation of the heavy reinforcement for the in situ concrete lining of the shafts (about 300 tons per shaft). It is pretty obvious that the sprayed membrane under these conditions represented a major advantage compared to a sheet membrane system. In addition, there were also a large number of penetrations by pipes for later drilling and grouting of the rock and for temporary drainage of active water during membrane application.

If a limited number of humid spots or even drip points are observed after works execution, these spots can be treated by drilling for spot drainages and by a local membrane brush-application, or by spot injection. The result could be visually verified as satisfactory before continuing with the concrete lining.

Results

The total area sealed was 6200 m^2 and the membrane consumption was in average 6 to 7 kg/m^2. Application was executed in two steps, by first visually applying a full cover with one color and then another layer using a contrast color. Quality control was carried out by drilling a pattern of "core" holes to take out round membrane disks for thickness control. The holes created could be easily repaired by manually patching the spots with the membrane paste.

Both the Client and the Contractor at the Machadinho powerplant project have expressed their satisfaction with the solution and the fact that the project saved important and valuable construction time. An inspection after 3 years of operation has confirmed the good results.

ITA DAM, BRAZIL

Problem Description

The Ita hydropower project is located downstream in the same river as Machadinho and the plant is now in operation. When test-filling the outlet water channel downstream of the powerhouse, water ingress back into the powerhouse was detected. The ingress was in total 120 m^3/h. The water penetrated both sides of the concrete/rock interface at the sides of the excavated outlet channel, with about 70% in one side and 30% in the other.

A number of alternatives were discussed, including contact injection, but it was decided to try the sprayable membrane.

Problem Solution

From the bottom of the water channel to normal water level is about 40 m height. The corners on both sides, between concrete and rock, were sprayed with concrete. The purpose was to produce a smooth curve rather than a sharp 90º angle, by spraying some decimeters on both sides of the corner as a fillet.

This area was then sprayed by membrane at about 60 x 60 cm over the full height. For treatment of both sides of the channel, about 600 kg of membrane was consumed. Finally, a cover layer of about 50 mm of protective concrete was sprayed over the membrane.

The result was excellent, since both sides were reported practically dry. It is obvious that this solution was much quicker and less costly than any of the other alternatives discussed.

ZAPATA AND LO PRADO ROAD TUNNELS, SANTIAGO, CHILE

Both the tunnels were planned with sheet membrane according to specification. However, the contractor ACS-Sacyr JV decided to use spray-on membrane with a cover layer of steel fiber shotcrete. A major part of the executed waterproofing was done by shotcrete sandwich, partly with the geotextile drainage layer and sprayed membrane.

One of the experiences made was that spot leakages that were found after the end of waterproofing could be easily sealed. Most of these leakage points were created by the need for drilling of installation anchorage bolts through the executed waterproofing, while some where in conjunction with the edges of sheets of drainage. All of them were treated with spot injection of foaming polyurethane (like a coffee cup volume per point) and were quickly sealed off.

GISWIL TUNNEL, SWITZERLAND

An escape tunnel in Giswil, Switzerland (2003) required the construction of a 4m diameter tunnel using a TBM (for the entire 1966m length) with Drill and Blast methods used for the portal areas (approximately 10m tunnel length). The tunnel was bored through schist and hard rock utilizing a single shell sprayed concrete lining. In the region of 1900m^2 of tunnel was waterproofed using Masterseal 345 (130m of bored tunnel and 10m of blasted tunnel).

This is one of the few examples of a *submarine* solution. The theoretical maximum water head may rise to 15 bar and is locally monitored by piezometers. At reached 5 bar pressure there was still no leakage detected.

MTRC DISNEY TUNNELS, HONG KONG

The tunnel to the new Disney Theme Park in Hong Kong, built in 2003, is 710 m long and goes through massive granite with occasional water seepage observed. The running tunnels were 6.2 m in diameter and utilized a PVC membrane on a sprayed concrete primary lining, as the waterproofing method. MASTERSEAL®345 and MASTERSEAL® DR1 was used on two inner concrete lining vent fan enlargements, both 16m in diameter (one is 39 m long, the second is 43 m long). A 150mm thick, Steel Fibre Reinforced Shotcrete (SFRS) lining was used with drainage geotextile installed due to the requirements for a drained tunnel. The final coat included a 200mm SFRS layer with a 50mm smoothing coat.

MTRC TSEUN WAN LINE, HONG KONG

The MTRC Tseun Wan Line in Hong Kong is 1.75 km in length and has 19 cross passages. The Contract specification required a 100% “dry” tunnel and, with the complicated intersections between the running tunnel segmental lining and the cross passages, the contractor needed a waterproofing solution that would be cost effective and could be applied into the most extreme, adverse geometry.

Additionally a bond strength of 1.0 N/mm^2 to the segmental lining of the main tunnel was required. Double sided geotextile fleece was installed in conjunction with sprayable membrane where local water inflow was present, using Hilti bolts, to channel ground water inflow to a temporary drainage channel at invert level. Due to the ease of application the contractor was able to carry out the membrane spraying without the need for a specialist contractor, therefore, making savings not only in costs but also in production time. Further advantages included fast application times and ease of permanent lining application due to high bond strengths between the membrane and the shotcrete.

COLLOMBEY ROAD TUNNEL, SWITZERLAND

The Collombey Road Tunnel in Switzerland is an 850 m long tunnel constructed using cut-and-cover techniques in alluvial deposits below the ground water table and drill-and-blast (D&B) techniques in rock. Sprayed concrete was used for temporary support and a cast in-situ concrete lining for the permanent works. The first 100 m of the D&B tunnel were partially below groundwater level.

A PVC membrane was chosen as the waterproofing method above the water table. Below the water table, the solution needed to be compatible with the PVC sheet membrane and to enable reliable waterproofing at the interface between the cut-and-cover tunnel and the rock tunnel. The sprayable membrane system provided a barrier to prevent the migration of water along the membrane/substrate contact, allowed ease of repair and provided a good bond to the PVC sheet membrane.

Spraying capacities of 50 m^2/hour were achieved using Masterseal 340F. A smoothing layer of sprayed concrete with maximum aggregate size of 4 mm was applied prior to the spraying of the membrane. In local areas with drips, the drainage fleece was applied in order to manage the water inflow and provide dry conditions for the membrane spraying.

REPORT BY MOTT MACDONALD ON MASTERSEAL 345

The extensive evaluation of the sprayable membrane Masterseal 345 carried out by Mott MacDonald gives the following statement in the Conclusions, Mott MacDonald, March 2004 (5):

“The principle conclusion of this report is that the product, MASTERSEAL® 345, essentially meets the stated claims that MASTERSEAL® 345 is suitable as a spray applied waterproofing membrane for use in sandwich construction in underground structures.”

MASTERSEAL® 345 has been proven to have an excellent resistance to water ingress in laboratory tests, tested up to 20 bar for a period of 1 year, Trindler (6). As with any material constructed in-situ, there remain residual concerns about quality control and workmanship. A generic specification has been produced as a guide for specifying this product. Each project must complete and amend the specification to suit the particular application. Recommendations for quality control test methods have been made and it is considered that a robust quality control system can be implemented on site. Preconstruction trials and training of operatives are vital for a successful application."

SOME THOUGHTS ABOUT EXPERIENCES MADE

As found by Mott MacDonald, the system works for waterproofing in underground structures. However, as with most technical solutions and products, there are strong sides and weaker sides and these must be evaluated for each individual application.

Favorable Aspects of Sprayable Membrane Waterproofing

First of all, it is a very flexible system from a practical viewpoint. When excavation takes place in several stages, the membrane can be installed in stages as well and quality joints are created by simply overlapping previous application by 200 mm. Metro stations and other openings with variable cross section and many intersections, may easily be covered by membrane regardless of shape.

The membrane can be installed anywhere in the cross section of the concrete support, as decided by the designer. There is some discussion about how monolithic the overall shotcrete structure is, with a layer of membrane included. If the designers do not want to deal with this question mark, the membrane can be installed on the rock side or on the tunnel side, leaving all the structural design shotcrete (or concrete) thickness uninfluenced by the membrane.

This author's view is that a layer of sprayed membrane integrated into a given structural support shotcrete will work as if without the membrane. After all, the bond on both sides of the membrane is typically equal to shotcrete against shotcrete bond of 1.0 MPa. Mostly, a structural support shotcrete is placed in two or more steps anyway, so there will typically be at least one bonded interface with about the same bond strength. Then the objection may be that the membrane is elastic and with a much lower E-modulus than the shotcrete. This is correct, but is it necessarily negative?

A shotcrete structure may be loaded in many different ways and a shear load along the membrane interface is one of the concerns raised. When we consider the detailed roughness on both sides of the membrane, it is pretty obvious that an initial minor shear displacement will cause a mechanical interlocking concrete/concrete. So what happens is a marginal shear displacement (and positive stress relief), before the shotcrete can be fully loaded. Chances are that the initial shear movement is favorable and after that, the structure behaves as if there is no membrane at all. The argumentation sometimes goes as if we normally subject permanent structural shotcrete linings to loads causing large deformations and failure. In permanent linings this is fortunately a very rare scenario and is not decisive.

When a full surface area is drained by installed drainage fleece, the system behavior will be just like with sheet membrane, with very limited interaction between concrete on both sides of the membrane. With sprayable membrane and the built in flexibility, the designer may still create a basically monolithic structure, even when drainage is installed. As an example of such a solution, strips of 0.3 m wide geotextile fleece could be placed every 2 m in a systematic pattern, thus achieving both targets.

Unfavorable Aspects of the Sprayable Membrane System

The sprayed product hits the substrate as a paste. It will take about an hour before this paste can be considered a membrane. Before a proper curing and polymer cross-linking, the strength is low and the bond strength to substrate is limited. Because of this, the shotcrete coverage layer can not be placed immediately and active water on the substrate will penetrate before the membrane has been formed.

In some situations these are serious drawbacks, in others they can be handled quite easily. It is clear that the creation of a monolithic solution (no geotextile drainage) in a case where the shotcrete is generally penetrated by water everywhere, creating “rainy” conditions, is not a good case for sprayable membrane.

On the other hand, some point leakages with a reasonable frequency and distance, can be handled in many different ways. The best way is probably to drill short holes through the shotcrete layer into the rock, where the wet spots are. Into these holes, place short pipes or hoses fixed by quick setting mortar. The water will be drained through these pipes, water pressure will be released and the substrate should normally dry up. After application and curing of the membrane and application of cover shotcrete, the pipes may be conducted to the invert, or blocked by point injection.

As pointed out by Mott MacDonald, the membrane is not a manufactured product, but is actually “manufactured” in place under quite variable conditions. This prevents industrial manufacturing quality control. Training, pre-construction testing, quality control in place and other measures to ensure satisfactory in place properties are therefore important. This must be consciously enforced to balance the flexibility in usage and the speed of application, to maintain control over the process. If done properly, it can be managed and it is not a problem, but otherwise could lead to poor results.

Substrate roughness is sometimes seen as a major problem due to increased material consumption and increased tendency of pinholes in the membrane (shadow effects causing discontinuous membrane). Shotcrete substrates can be found with widely variable detailed roughness. Sometimes they are so poor that application of sprayable membrane is ruled out, unless smoothening layer is sprayed on.

The important fact here is that a 5-10 mm layer of fine shotcrete, can easily solve the problem. Using sand with particle size 0-4 mm and a small quantity of accelerator, the resulting substrate can be optimal, even if it was in terrible condition before. The cost of this step and the time needed is quite marginal, but it can have a substantial effect on the final result. The recommendation will therefore be to apply such smoothening if there is any doubt about the roughness of the substrate.

May be it should be pointed out that this is a smoothening of detailed roughness where 1 m^3 of material will cover 100 to 200 m^2 of surface. This has nothing to do with the smoothening required for sheet membrane installation, where macro undulations must be filled out and average “thickness” could be 0.2 to 0.5 m. One m^3 will then yield only 2-5 m^2 of surface coverage.

CONCLUSIONS

The sprayable water proofing membrane offers technical solutions not previously available in underground construction. The main advantages are:

- Full flexibility to adapt to difficult geometry and stepwise excavation procedures, since joints are created by simply spraying an overlap and the spray-application can follow any geometry without added complexity.
- The excellent bond to concrete substrate and equally good bond of sprayed concrete against the membrane prevents water migration along the membrane interfaces. The probability of actually having a leakage through a membrane damage point is therefore small and if it happens, the damage location is known and can easily be repaired by point injection.
- Practical, easy to execute without blocking access for other activities in the tunnel. Manually, more than 50 m^2/h may be covered. With robotic equipment, 100 m^2/h and more can be placed.
- Penetrations necessary for anchoring of suspended structures can easily be accommodated, since spraying around bolts provides sufficient bond on steel, hot dip protected steel and aluminum to create a watertight contact.
- Offers major savings potential in drill and blast hard rock cases, if in situ concrete lining can be omitted. Cost of permanent shotcrete lining with spray-on membrane may be 40% less than normal concrete lining with sheet membrane.
- The spray-on membrane may also offer project time savings that can additionally reduce the overall project cost.

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