Transportation Tunnel Waterproofing Using Geosynthetics

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This paper describes the New Austrian Tunneling Method (NATM) tunnel waterproofing system using geosynthetics. The advantages of using a nonwoven geotextile and a plastic geomembrane sheet material for the primary drainage and waterproofing are summarized. The method of installing and inspecting the geosynthetics is described and illustrated with photographs. Example material specifications for both polyvinyl chloride and high-density polyethylene are presented based on Washington Metropolitan Area Transit Authority (WMATA) tunnel specifications.

Water infiltration can lead to deterioration and substantial damage of structural and functional components, especially in transportation tunnels. Consideration must be given to intercepting and collecting leakage before damage occurs. There are five general methods of controlling water infiltration into tunnels (*1*):

1. Drainage,
2. Grouting,
3. Water stops and gaskets,
4. Sealants, and
5. Impervious membranes.

Frequently, in conventional tunnel linings, two or more of these methods are used in the construction of the same lining. Even after construction, remedial measures, such as injection grouting, may have to be undertaken to control excessive seepage. Impervious membranes used in conjunction with conventional tunnel linings are generally very labor-intensive and require careful workmanship (*1*).

The New Austrian Tunneling Method (NATM) has been successfully applied worldwide in the construction of transportation tunnels. NATM is a method whereby the rock or soil formations surrounding the tunnel are integrated into an overall ringlike support structure, thus making the formations a part of the support system (*2*). An integral part of the NATM design is the incorporation of a highly technical sealing and drainage system composed of state-of-the-art geosynthetics. The geosynthetic system must provide watertight integrity for the life of the tunnel and must thereby withstand different kinds of stress and strain, both during installation and after construction, as well as variable and aggressive chemical environments. Plastic geomembrane sheet sealing with a protective nonwoven geotextile drainage layer has been the predominant system over conventional sealing methods such as asphalt membranes or spray-applied glass-fiber-reinforced plastic or bitumen-latex based products worldwide (*3*). The geosynthetic system developed for NATM meets the demands not only of rapid tunneling rates, but also of rough construction treatment. The requirement for absolute watertightness puts high technical demands on the system, in which the protection of the loosely laid geomembrane is of paramount importance. This paper describes the NATM waterproofing method using geosynthetics.

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NATM SYSTEM COMPONENTS

The essential components of the NATM system are the rock or shotcrete surface, the nonwoven geotextile, the fastening system, the geomembrane, and the final cast-in-place concrete lining. Detail A of Figure 1 illustrates all of these individual components in section. The minimum criteria that must be met by each of the components (*4*) are discussed in the following sections.

Rock and Shotcrete Surface

The loose laying of a geomembrane presupposes a backing of sufficient nondeformability and natural strength. A shotcrete layer with a minimum thickness of 40 mm is essential for the backing to serve as attachment for the nails of the fastening plates. The maximum size of the aggregate should not exceed 16 mm, and crushed rock generally must not be used. The surface condition of the backing is of special importance at the time of concreting. Consideration must be given to this from the time of installation of the geomembrane sheets. The sheets should lie against the shotcrete as solidly and as flush as possible without excessive stressing and damage. To achieve this, the shotcrete must be used to smooth the excavated surface and cover any metal protuberances. In addition to a smooth surface over the excavation, recent investigations show that the rock surface must be supported by shotcrete immediately after excavation so that radially acting forces can be accepted adhesively (*5*). This support is increased by the placement of rock bolts, steel arches, or reinforcing wire mats.

Nonwoven Geotextile

The nonwoven geotextile performs not only a protective function but also a drainage function, and therefore it is of decisive importance for the effectiveness of the total sealing system. The existing technical demands on the nonwovens in tunneling are a result of the various kinds of stress and strain during the construction stage as well as in service conditions. The

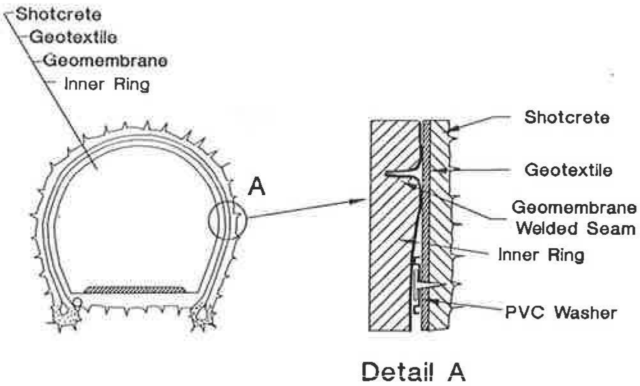

FIGURE 1 Section through a typical NATM design showing the various components of the structural and waterproofing system.

types of stress include those caused mechanically, chemically, and hydraulically; functional correlations can occur between them. It is therefore only possible to claim a permanent mechanical protection function of the nonwoven when it is permanently inert to acid and alkali attack. The following technical requirements for nonwoven fabrics used in underground construction in rock and soil correspond to state-of-the-art geotextile research (*4*):

- Chemical resistance—pH range of 2 to 13,
- Mechanical resistance,
- Hydraulic transmissivity, and
- Decay resistance.

Chemical Resistance

So that the nonwoven fabric can perform a lasting protective function, it is of paramount importance that it have a chemical resistance to all types of groundwater, especially to calcium hydroxide, $Ca(OH)_2$ (hydrated lime), and other aggressive compounds found in hydraulic binders (e.g., concrete and grout). Importantly, the requirement on a nonwoven can only be met (assuming that there is no doubt about the chemical compound of the base polymer material) by the inert nature of the final product. Polypropylene and polyethylene are resistant to the required pH range of 2 to 13, whereas polyester has only a limited resistance. Geotextiles made from more than one type of polymeric filament and nonwovens made from unknown regenerated materials should be avoided in tunnel construction. The importance of chemical stability cannot be overstated. Long after construction, stress redistribution within the surrounding rock or soil mass may lead to convergent movements of the tunnel. It is essential, therefore, that the nonwoven be still intact to protect the waterproof membrane and provide the necessary planar drainage.

Mechanical Resistance

Protective nonwoven geotextiles must have certain minimum values for mechanical strength and elasticity to absorb stresses resulting from mounting and concreting pressures and deformation of the tunnel lining due to load redistribution and temperature variation. It is also important that the nonwoven fabric structure resist the potentially damaging effects of high hydrostatic pressure, which can occur on a localized basis at fissures during final concreting of the inner ring. The fabric must absorb high-tensile elongation and tearing stress when being placed and when in contact with the partially sharp-edged shotcrete.

Hydraulic Transmissivity

Local entry of water is collected in the course of shotcrete lining by means of polyvinyl chloride (PVC) drain pipes or central, slotted pipes and conducted to the drain at the bottom. The residual water, which includes seepage water and other smaller types of water entry, can dissipate in the plane of the nonwoven geotextile. It is then conducted in longitudinal collection drains to the tunnel exit. The three-dimensional spatial structure and the void reduction of the nonwoven under pressure are important when designing for planar (transmissivity) permeability. Minimum values for the permeability in the geotextile plane under normal compressive loading are as follows (*4*): k-value under 2 kPa, 8×10^{-1} cm/sec; k-value under 200 kPa, 8×10^{-2} cm/sec.

These coefficients of permeability are based on the assumption that the nonwoven is pressed solidly against the shotcrete surface and that the dewatering takes place exclusively in its plane. However, this assumption does not very often occur in practice, because additional voids exist between the nonwoven fabric and the shotcrete lining into which seepage water can also drain. The values stated above are to be regarded as absolute minimum values; the real permeability in the plane generally will be about 10 times higher.

Decay Resistance

The geotextile could be in contact with soil or certainly with water, which may contain aggressive microorganisms. All nonwovens produced from 100 percent synthetic fibers are resistant to decay. The requirements for decay resistance are the same as those set out in the section Chemical Resistance and relate to all nonwovens including those made from regenerated material, those not produced from 100 percent synthetic fibers, and those that are produced from viscose (regenerated cellulose) fibers.

Fastening System

The nonwoven geotextile and the geomembrane sheets are installed with the help of a special scaffold. As a first step, the nonwoven fabric layer is fastened to the shotcrete (gunite) by means of plastic disks (plates) and fasteners (nails). As a second step the actual sheeting that will seal the tunnel is then secured to these disks by means of high-frequency ring welding or hot-air welding. On average, three fastening points per square meter are required to attach the protective geotextile layer to the tunnel wall (*6*). The fastening disk is designed in such a way that if the geomembrane sheet is overstressed and deformed at a weld, the failure will always occur in a certain plane of weakness inside the fastening disk, never in the geo-

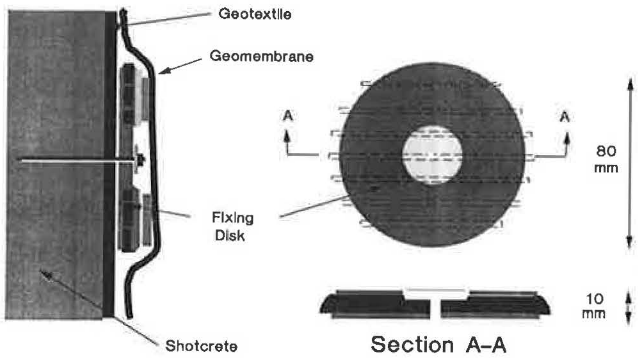

FIGURE 2 Support disk fastening system. (*6*)

membrane sheet itself (*3*). Thus it is possible to avoid excessive stress and distress of the geomembrane sheet during installation or when excessive deformation occurs when the internal tunnel ring is concreted. Figure 2 shows a support disk and fixing nail in detail both in isolation and in place on the tunnel wall.

Geomembrane Waterproofing System

The geomembrane is the integral part of the waterproofing function for the geosynthetic system. As such, the membrane must meet certain minimum criteria, as follows:

- Provide continuous enclosure, especially in critical areas of the construction;
- Provide permanent or tunnel design life imperviousness;
- Be adaptable to surface discontinuities;
- Not lose its waterproofing effect in spite of structural movements caused by shrinking, creep, temperature variation, settlements, or vibration;
- Be able to absorb stress over long discontinuities without being damaged (in this respect, the biaxial elongation of the geomembrane should be known and specified, because the material is actually subjected to two-dimensional strain);
- Be able to absorb tensile stress both during placement and during service;
- Be able to bridge cracks and discontinuities in the construction surface;
- Be chemically resistant to all types of aggressive water, whether from natural origin or leached from concrete, grouts, or other materials (pH range should be 2 to 13);
- Be resistant to biological attack;
- Be suitable for installation in wet areas also;
- Be easy to handle and install in large quantities;
- Be quickly and easily thermally welded with a reliable, mechanized welding method;
- Have welded seams constructed so that they are easily checked for watertightness;
- Be produced of material that is easily repaired when damaged;
- Be produced of a material compatible with the plastic fastening disks so that the geomembrane can be fused to the disks;
- Be fire resistant or at least self-extinguishing; and
- Have a low coefficient of friction to allow for gliding of the final concrete lining, thus reducing shrinkage and cracking and permitting larger lining segments to be cast monolithically.

Tunnel specifications for geomembrane material often call for a "high polymer," referring to a pure polymer as opposed to polymer-blended materials. Generally, three geomembrane materials have proven themselves as base materials for tunnel lining. These are plasticized PVC (PVC-soft), high-density polyethylene (HDPE), and ethylene copolymer bitumen (ECB). The most commonly specified material in the past, primarily from the experience of installing contractors and the know-how of the manufacturers producing PVC for tunnel lining, has been PVC-soft (*7*). PVC is also very flexible, workable, and easily welded even in the commonly specified thickness of 1.5 mm. PVC geomembrane sheets are generally from 1.6 to 1.8 m wide. Table 1 gives some recommended minimum properties for the PVC geomembrane. HDPE has also been specified in numerous tunnels worldwide and is also easily welded, generally by extrusion welding. HDPE sheets are usually 7 to 10 m wide and 2.0 to 2.5 mm thick.

INSTALLATION OF TUNNEL GEOSYNTHETICS

Once it has been decided to use a complete waterproofing system in the NATM design, a highly specialized, experienced subcontractor in such installations will work very closely with the prime contractor so as to effect a continuous rapid, sequential installation with minimal disruptions for the overall tunneling operation. The following methodology will include PVC and HDPE geomembranes as typical examples.

Pneumatically applied concrete (shotcrete)

The initial shotcreted outer lining is placed over all excavated rock or soil surfaces so as to form a relatively smooth surface with minimum depressions. Generally, the depth of depressions are not allowed to exceed 30 percent of the depression span. Any protruding steel wire or other construction/reinforcement related objects must be cut off flush with the surface of the shotcrete. All steel ribs, lattice or plates must be covered by additional shotcrete to provide a smooth surface of at least 40 mm using a grain size in the shotcrete not to exceed 16 mm (*4*). A minimum of 40 mm thickness is needed to facilitate nailing of the geotextile. Once the initial shotcrete has cured, the geotextile protective/drainage layer is applied to the shotcrete surface.

Geotextile and Fixing Disks

To facilitate rapid installation of both geotextile and geomembrane over the entire intrados of the tunnel, a special mobile rail-mounted scaffolding is used, as shown in Figure 3. The geotextile is unrolled in one continuous length radially and then fixed to the shotcrete of the tunnel sides and crown with a minimum of three fixing disks per square meter of surface (*6*). As shown in Figure 4, the plastic fixing disk is designed to be nailed against the geotextile and into the shotcrete with 40-mm-long nails and a pneumatic or explosive cartridge gun. The disk design is such that the yield point of the disk will cause it to fail under stress rather than the geomembrane that is eventually welded to it, thus preventing

TABLE 1 MINIMUM RECOMMENDED PROPERTIES FOR A PVC GEOMEMBRANE IN TUNNELING (6)

Property	Standard	Unit	Value
Ultimate Tensile Strength	DIN 53455 ASTM D638	kPa	17000
Ultimate Tensile Elongation	DIN 53455 ASTM D638	%	300
Tear Resistance	DIN 53363 ASTM D1004	N/mm	80

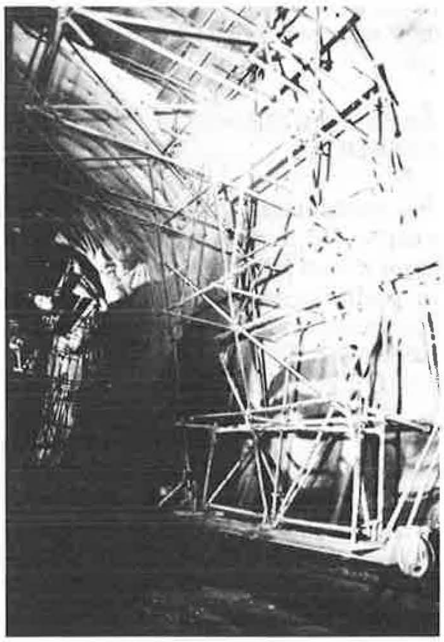

FIGURE 3 Mobile installation scaffolding.

damage to the geomembrane system. Once the geotextile strips have been nailed in place and overlapped a minimum of 100 mm, the geotextile is then heat-bonded at the seams as shown in Figure 5.

Geomembrane System

The geomembrane is unrolled and positioned from the mobile scaffold, also in a radial manner. As it is supported below the crown, it is manually hot-air-welded to the fixing disks, thus providing the required support for each strip, as shown in Figure 6. As the geomembrane strips are supported in place, they are positioned with a minimum 70-mm-wide overlap to facilitate thermal welding. Placement of the geomembrane strips is such that seam lengths are always radial within the tunnel.

At large crossovers or stations, there will also be a need for various other joints to effect a 100 percent waterproof coverage of the shotcrete surface. At these locations, HDPE sheeting may be more desirable due to its extrusion welding capability and its resistance to the mechanical damage that can occur in and around the reinforcing steel rebar. Figure 7 shows an installation of HDPE behind rebars in an underground station wall.

PVC seams are welded using an automatic, double-wedge, thermal self-tracking welder, as shown in Figure 8. The double-wedge weld produces a seam that contains a con-

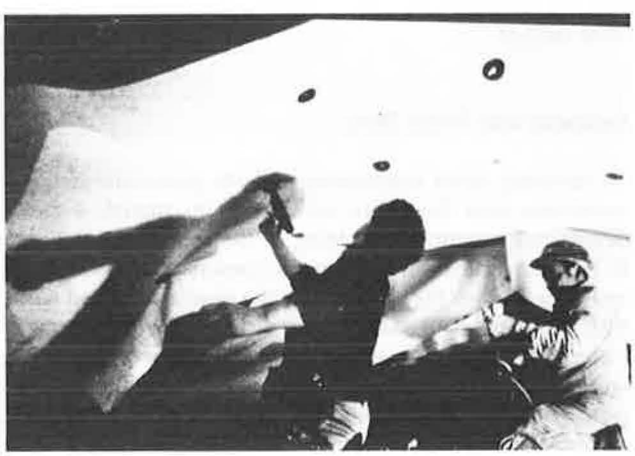

FIGURE 4 Nailing the geotextile with a fixing disk.

FIGURE 5 Heat seaming the geotextile.

FIGURE 6 Welding the PVC geomembrane to fixing disks.

FIGURE 8 Welding a PVC geomembrane panel.

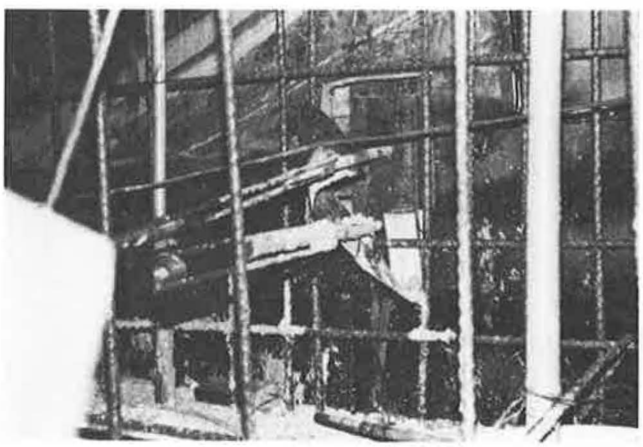

FIGURE 7 HDPE installation behind rebar.

tinuous channel between welded tracks. The channel is then used to test the continuity of the seam with air pressurization as a quality control procedure. The channel is generally subjected to a pressure of 2 Pa for approximately 10 min with a requirement for not more than 10 percent pressure loss (*6*). HDPE sheet material is generally welded by the extrusion welding process, as shown in Figure 9. This type of weld allows joining of the geomembrane panels in limited access areas. The seams can be inspected using the vacuum-box technique similar to steel weld testing.

The geotextile and geomembrane as a system are connected on each side of the tunnel to a drainage system that may be composed of a perforated drain line embedded in porous concrete. The lower ends of the geomembrane-geotextile cover the side drains. The geotextile directs all groundwater from the sides and crown down the geomembrane surface to the porous drainage system, and the drainage system directs the groundwater out of the tunnel. It is important to note that the drainage system should be designed so as to limit the exposure of groundwater to free air. This will help eliminate problems associated with calcification in the drainage system, as was found in the investigations for the Washington, D.C., Metro B-10a tunnels (*8*).

FIGURE 9 Extrusion welding of HDPE sheets.

U.S. NATM INSTALLATIONS AND TYPICAL MATERIAL SPECIFICATIONS

The first use of the NATM method in the United States was in a rail tunnel in Mt. Lebanon, Pennsylvania, built by ILBAU America under subcontract to an American firm. This project was largely paid for by a demonstration project grant from the Urban Mass Transportation Administration (UMTA) and did not receive great publicity (*9*).

The second and most notable use of NATM in the United States was on the Washington, D.C., Metro contract B-10a, which is an extension of the Washington Metropolitan Area Transit Authority (WMATA) Red Line in Wheaton, Maryland. The twin Wheaton tunnels and station were constructed using NATM and a geosynthetic waterproofing system as a result of a value engineering proposal submitted by the contractor, ILBAU America. The station was 183 m long and 36 m below the surface, and the two single-track tunnels were 4400 m long and as deep as 60 m below street level. Contract B-10c on the WMATA Project also calls for NATM for rock excavation and geosynthetics for waterproofing.

In addition to specified construction procedures, the minimum physical properties for the geosynthetic must be specified. An example of minimum values for a PVC geomembrane and polypropylene geotextile taken from the WMATA B-10a specifications is shown in Table 2. Table 3 gives minimum values for an HDPE geomembrane as extracted from the WMATA specifications for the Greenbelt route (Shaw Station) and tunnels.

SUMMARY

Although NATM has been in existence for almost two decades, the method obviously will be used to a greater extent with the completion and publicizing of projects such as the Washington, D.C., Metro. The use of geosynthetics in NATM is also not new but will certainly gain rapid acceptance in the United States, where the geosynthetics manufacturing industry and standardization are far ahead of the European community. The benefits of a geosynthetic waterproofing system in transportation tunnel construction include the following (*11*):

- Continuous waterproofing element,
- Continuous sidewall drainage,

TABLE 2 GEOSYNTHETIC PROPERTIES ACCORDING TO WMATA SPECIFICATIONS (*10*)

Property	Minimum Specifications	DIN	ASTM
A. GEOTEXTILE (non-woven polyproplyene)			
Thickness (mm)	4.0	53855/3	D1777
Unit Weight (g/m^2)	500	------	-----
Grab Strength (N)	1150	53858	D1682
Elongation (%)	80	53857	D1682
Trapezoid Tear Strength(N)	440	53363	D2263
Burst Strength (kPa)	2760	N/A[a]	D751
Chemical Resistance: (pH value)	2 to 13	E16726	N/A[a]
Flammability	Self Extinguishing	4102/1	D568
B. GEOMEMBRANE (PVC-soft)			
Thickness (mm)	1.5	53370	D374
Ultimate Tensile Strength (kPa)	7600	53455	D638
Ultimate Elongation (percent)	300	53455	D638
Brittleness Temperature	±7°C	53361 53372	D1790
Flammability	Self Extinguishing	4102/1	D568
Dimensional Stability 6 hr @ 80°C (percent)	2	53377	D1204
Welded Lap Shear Strength	Pass	E16726 53455	D3163
Tear Resistance (N/mm)	40	53515	D1004
Chemical Resistance: (pH value)	2 to 13	E16726	N/A[a]

[a]N/A = not available

TABLE 3 HDPE MINIMUM PROPERTIES ACCORDING TO WMATA SPECIFICATIONS (*10*)

PHYSICAL PROPERTIES Property	Test Method	Value	Unit
Density, (minimum)	ASTM D1505	0.949±.003	g/cm^3
Melt flow rate	ASTM D1238, Condition E	0.20±.04	g/10minutes.
Average molecular weight	ASTM D2857	1.5×10^5	---
Coefficient of linear thermal expansion	ASTM D696	1.2×10^{-4}	Degree C^{-1}
Water absorption, (maximum)	ASTM D570	0.085	percent/ 4 days
Shore D hardness	ASTM D2240	65	Shore D
Impact resistance, (notched)	ASTM D256 Method B	No break	ft. lb/inch of notch
Elongation at yield	ASTM D638	15±3	percent
Elongation at break	Test Specimen	>800	percent
Tensile stress at yield	Type IV	2800±200	psi
Tensile stress at break		3800±300	psi
Stress cracking resistance	ASTM D1693, Condition C, w/notch depth for Condition A, Igapal Reagent	min. 500	hour
Thickness (nominal)	ASTM D374	0.100	inch

Waterproofing Sheet: High density polyethylene (HDPE) containing no additives, fillers, or extenders. Carbon black, 2 ± 0.5 percent, ASTM D1603, added to resin.

- Independence from concrete lining cracking,
- Rapid installation,
- Cost savings over conventional methods, and
- Cost savings in long-term maintenance.

With the technical advantages, reduced costs are also an added benefit—not only cost reduction during construction, which can be as much as 30 percent for NATM versus conventional tunnel construction, but also the long-term reduced maintenance costs provided by the geosynthetic waterproofing system.

Because of the highly technical requirements imposed on the geosynthetics used in tunnel construction, these materials must perform their function for the intended life of the tunnel. Once the final cast-in-place concrete lining is constructed, the geosynthetic system cannot be reached for repair. It is important to point out, however, that the individual geosynthetic components must be strictly specified as to material (polymer) type as well as minimum survivability properties. In addition, a sound quality control program must be established and adhered to, from initial manufacture of the geosynthetics through final installation.

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