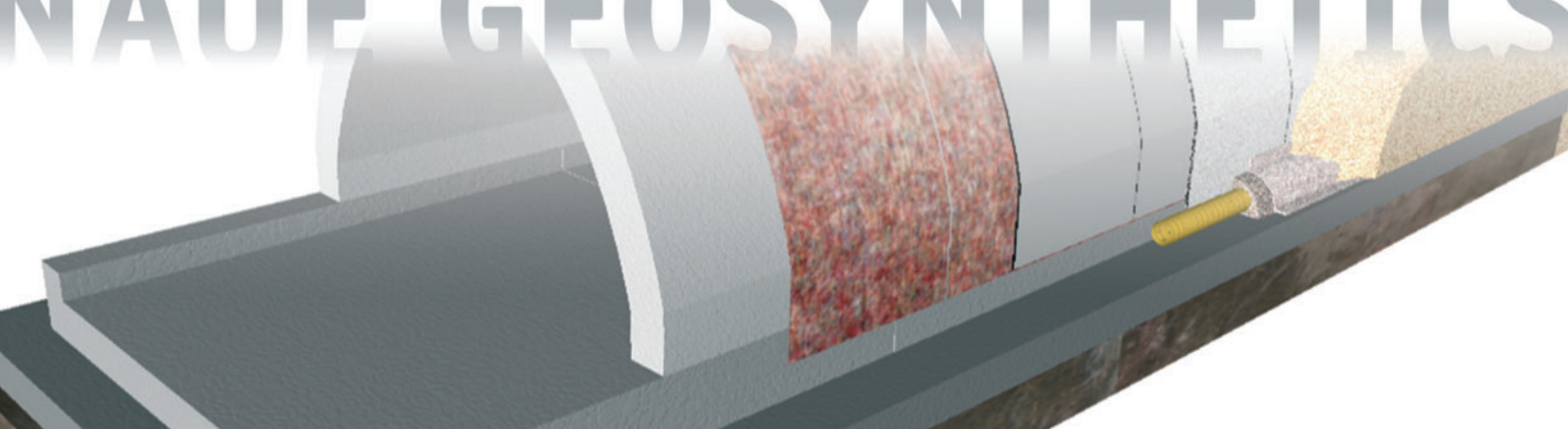


Tunnel construction

NAUE GEOSYNTHETICS



Tunnel construction

Modern traffic tunnels are increasingly planned for a functional service life of more than 100 years. For this reason they must be protected extensively against the effects of groundwater and water penetrating through rock fissures. The construction and sealing specifications are correspondingly strict, especially with respect to the required service life.

The level of hydrostatic pressure and the aggressiveness of the water determine the scope of the protection required for the construction of underground structure measures. Also, for ecological reasons, there is an increasing desire to limit the drainage of mountain water. There are a broad range of opportunities, technical as well as economic, for selecting the most suitable protection system. Each tunnel requires a specific solution; depending on construction details, such as cut and cover construction projects, varying water aggressiveness, transition sections of in-situ water under pressure and seepage water.



Fig. 1: Tunnel portal area

Sealing does more than just protect important structures against corrosion. The tunnel suitability (e. g. prevention of icing) as well as the stability itself requires a protection against moisture. In comparison to the total costs of constructing a tunnel, the costs of providing a functional waterproofing is minor – but the advantage to be gained is major. Sealing protects and safeguards the structure. It reduces maintenance costs and repairs. Therefore waterproofing is an indispensable part of any tunnel construction.

A long-term, trouble-free tunnel operation with low operating and maintenance costs can be achieved with a professionally installed sealing system. In addition, a

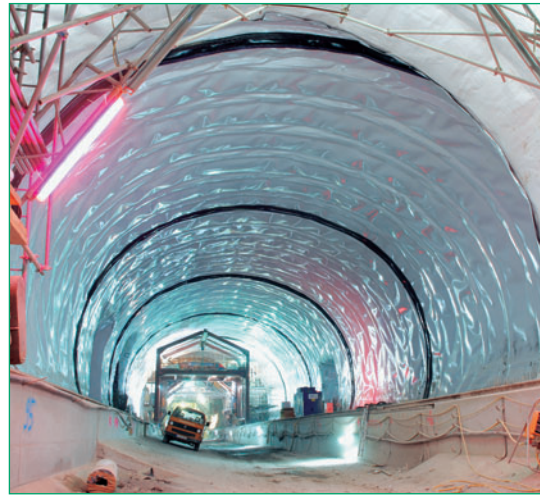


Fig. 2: Arch sealing, using Carbofol® tunnel geomembrane

tunnel's sealing system will actively contribute to environmental protection, despite the need for the construction of the tunnel, by avoiding interference with the mountain's hydrological water balance. The sealing system will also prevent environmental damage from oils or chemicals which may occur due to traffic accidents.



Fig. 3: Carbofol® tunnel geomembrane in the floor area

These important requirements are satisfied reliably and economically with the NAUE waterproof sealing system. NAUE offers complete single-source systems for tunnel construction, from manufacturing to installation including full quality assurance.

Geosynthetic functions

Sealing



Basically, sealing systems have two functions in the construction of modern traffic tunnels. They divert the mountain water away from the tunnel and they protect the supporting structure from the potentially aggressive particles in the water. This sealing and protection function must remain intact over the service life of the tunnel. To achieve this, geomembranes, particularly those manufactured from flexible polyolefins, are being used in thicknesses up to 4 mm. The type of sealing system selected will depend on factors such as geology, hydrology and stress on the sealing system. The stress will be caused by the pressure of the water or the seeping water and/or the aggressiveness of the mountain water.

Protection



Geomembranes must be protected against potential mechanical damage. Without a protection layer the geomembrane can be damaged by the rough shotcrete surface of the sealing carrier layer or by unprofessional installation of the concrete steel reinforcement layer. Nonwoven geotextiles (such as Secutex®) are used as a protection layer between the support and the geomembrane. An additional 3 mm thick Carbofol® tunnel geomembrane can also be used as protection for the installed sealing system in the floor area.

The advantage that the Carbofol® protection geomembrane has compared to concrete is that it can be installed economically and systematically as the water-proofing progresses. There is also the potential for full-area damage quality assurance with a light-coloured signal layer of Carbofol®. Reinforced concrete, however, must be used if the floor area will support traffic.

Drainage



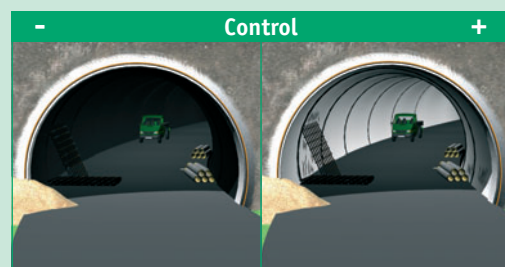
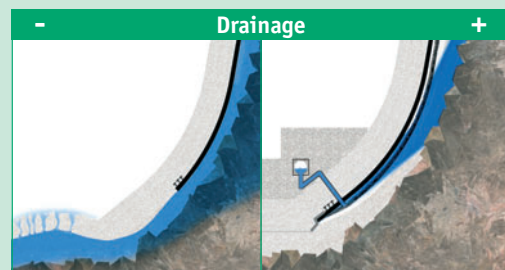
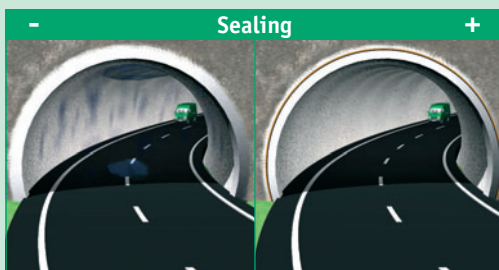
For tunnel structures that are designed for drainage, the drainage element (such as Secudrain®) must survive the tunnel service life.

Geosynthetic tunnel drainage mats that are installed over the entire area will divert mountain water flowing towards the tunnel in such a way that the operation of the tunnel is neither disturbed nor impeded. The collection and drainage of the water must remain intact over the service life of the tunnel. Nonwoven geotextiles with a drainage function, drainage nets and mats are most suitable for this requirement as they also provide the protection as well as the drainage function.

Control



In order to ensure that accidental damage to the geomembranes becomes visible during construction, the geomembranes are provided with a top-sided signal layer that is approximately 0.1 mm thick. This signal layer provides a full-area control of the sealing geomembrane and, at the same time, provides a clear improvement of the lighting conditions in the tunnel.



Sealing materials and their production

To refurbish a tunnel seal requires a great deal of technical effort and massive financial investment. To prevent this occurring, it is sensible to select products and sealing systems that will ensure long-term effectiveness.

Carbofol® geomembranes for tunnel construction

Geosynthetic materials manufactured from polyethylene (PE), which is highly resistant to chemicals and ecologically safe to the environment, meet highest requirements. Carbofol® tunnel geomembranes consist of PE-VLD (polyethylene - very low density) or PE-LLD (polyethylene - linear low density). Due to the careful resin selection, Carbofol® tunnel geomembranes are highly flexible and free from plasticizer.

The selection of materials depends mainly on the expected service life of the tunnel and the composition of the surrounding mountain water and ground water. The sealing elements should be flexible enough that when the concrete inner shell is being poured, it adjusts over the entire surface of the sealing carrier layer. The stresses resulting from the construction process and operation must be absorbed without any exceptions. National requirements for the geomembrane must be taken into account and it should be possible to process the material in a safe and sensible manner.

For this reason, Carbofol® tunnel geomembrane by NAUE meet the following criteria:

- good mechanical behaviour with high flexibility
- dimensional stability
- extraordinarily good performance against high temperatures and aggressive liquids
- bridges spontaneous fissure formation in the concrete without losing its functionality
- root resistance
- resistance against rodents
- ecologically safe and thus environmentally sound
- good aging behaviour/very good durability (> 100 years expected service life)
- fire classification E per EN ISO 11925-2 and/or EN 13501-1
- in case of fire, emits no chlorine or hydrochloric acid. When PE burns, it produces non-toxic carbon dioxide and water
- free of solvents and plasticizer
- free of chlorine compounds
- suitable for potable water
- optimum welding characteristics
- white, reflecting signal layer
- Certified according to the German guideline RIL 853 and ZTV tunnel

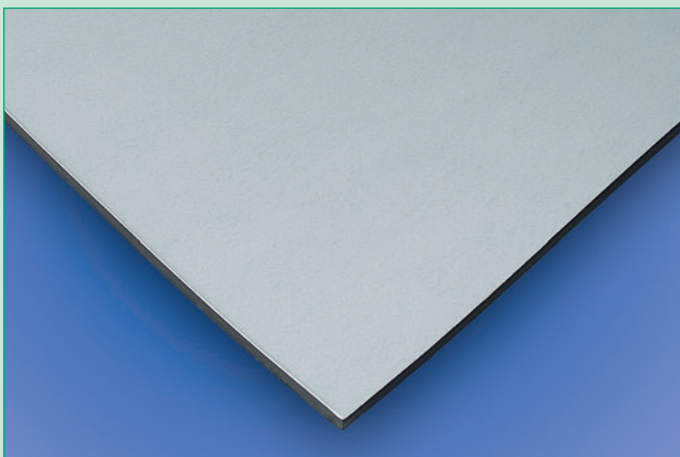


Fig. 4: Carbofol® tunnel geomembrane

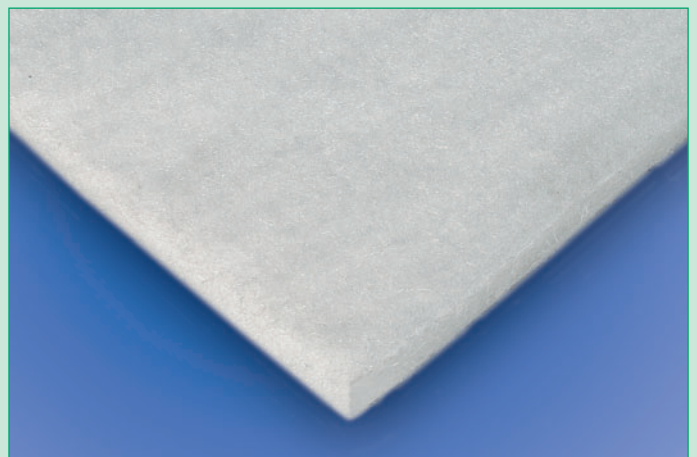


Fig. 5: Secutex® nonwoven geotextile

Production

All raw materials for the production of geosynthetics used in tunnel construction are subject to an intense and strict incoming quality assurance. The specifications agreed with the suppliers are checked at the plant and only after release by quality assurance will the raw material be accepted for production.

The tunnel geomembranes are produced with a flat extruder machine in a standard width up to 2.08 m. The

each product having its own specific plan. The results of the quality controls are documented in a final inspection certificate according to EN ISO 10204.

These quality control measures which are performed for all products meet the respective requirements of the current standards and regulations for tunnel construction. In addition, twice a year the products are audited by an external quality assurance. For Carbofol®

tunnel geomembranes and Secutex® protection geotextiles, the review by an outside agency takes place at a Federal Material Testing Institute. The external auditors take samples of the products from the current production and test them according to the guidelines currently in effect and compares them with the data sheet values. They also inspect the production processes and the internal-plant production auditing.

Since December 1994, the geosynthetics development, production, sales and geotechnical engineering divisions of NAUE GmbH & Co. KG have been certified according to EN ISO 9001 : 2000. This certification

is regularly validated by scheduled audits.

Customer requirements are fully implemented within the company due to the integrated quality management system.



Fig. 6:
Carbofol® tunnel
geomembrane
production

Carbofol® tunnel geomembrane is generally produced with a signal layer. This signal layer is intended to show immediately any damage that may occur during the course of construction. Additional quality control measures are performed during production with



Fig. 7: Tensile test on Carbofol® geomembranes (ISO 527)



Fig. 8: Burst test of a Carbofol® according to EN 14151

Carbofol® sealing systems

In principle, there are distinctions made in tunnel construction between a sealing against water pressure and against seepage water. For seeping water, a Carbofol® tunnel geomembrane that is 2 mm thick can be used as an umbrella seal. For occurring hydrostatic water the use of an all-around sealing (360°) with a separation system is the required solution.

This results in the following sealing systems:

1. Seepage water sealing system (SWA)

“Drained tunnel”

The structure is protected against water by a Carbofol® tunnel geomembrane with an umbrella sealing system (Fig. 9). This system discharges the incoming seepage water without pressure over the longitudinal drainage at the foot of the structure. If the seepage water corresponds to class XA3 (“highly aggressive”), 360° single-layer geomembrane must be installed for corrosion protection reasons.

2. Hydrostatic pressure sealing system (DWA)

“360° sealing with segmental waterstops”

When hydrostatic water pressure is present, it is recommended to use a water-impermeable concrete that is protected with a Carbofol® tunnel geomembrane (Fig. 10), especially if the classification of the seepage water corresponds to exposition class XA3 (“highly aggressive”).

In order to limit potential damage and to confine the damaged area, the concrete segments are additionally sealed with external waterstops.

3. Hydrostatic pressure sealing system with integrated injection system (DWA-I)

“360° sealing with segmental separation including injection devices for injection after hydrostatic pressure stress”

For hydrostatic pressures in excess of a 10 m water column, an integrated injection system for targeted repair options is planned (Fig. 11). The sealing system otherwise corresponds to the construction of the hydrostatic pressure system (DWA).

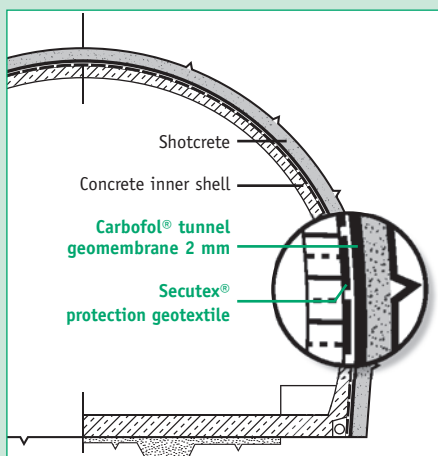


Fig. 9: Sealing against seepage water (umbrella sealing)

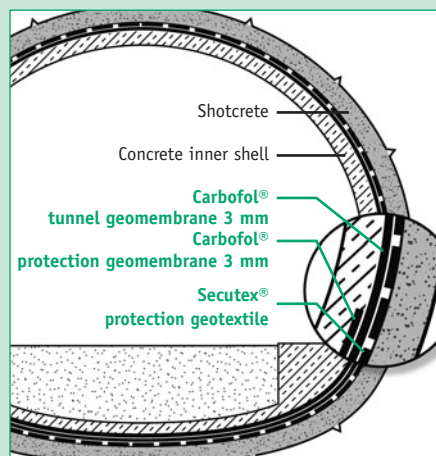


Fig. 10: Sealing against hydrostatic water pressure without an injection system

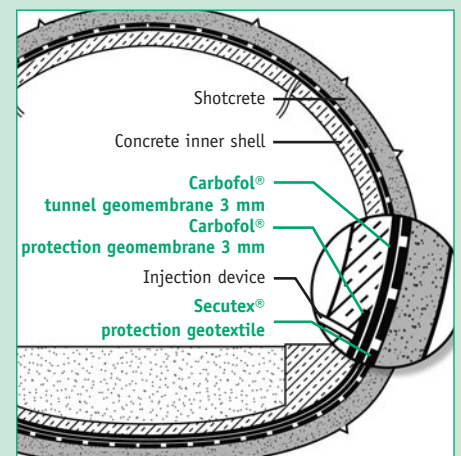


Fig. 11: Sealing against hydrostatic water pressure with an injection system

Carbofol® seepage water sealing system (SWA)

Drained tunnel

The Carbofol® sealing system is carried out with a 2 mm thick Carbofol® tunnel geomembrane according to the cross-section in fig. 12 (from the inside out):

- Interior shell
- Carbofol® tunnel geomembrane 2 mm with signal layer
- Secutex® R 551-B2 ($\geq 500 \text{ g/m}^2$ or $\geq 900 \text{ g/m}^2$) fulfilling fire classification (E)
- Shotcrete

For the connection of the sealing to the drainage area the following is a solution:

Drainage systems are intended to collect any water and

to discharge it away from the tunnel structure. Drained tunnel structures are constructed using either cut and cover or mined technique. Water built-up is not expected to occur when the drainage system has been planned and constructed carefully.

The criteria listed below are required for planning a drainage system:

- Minimize the alkaline content in the shotcrete and drainage gravel
- HDPE drainage pipes with a diameter $\geq \text{DN } 200$, smooth interior surface, sufficient hydraulic discharge capacity
- The drainage pipe must be designed for the pressure resulting from the entire system
- Slot widths in the drainage pipe of 5-6 mm
- Drainage gravel and installation process must be adjusted to the size of the drainage slots
- Revision shafts and drainage pipe system to be acceptable for monitoring by mobile cameras and flushing

It must be mentioned that constructing a tunnel with a sealing against seepage water constitutes an interference with the surrounding water supply and thus must be authorized by the appropriate authorities.

Tunnel structures built according to the mined method with an impermeable concrete sealing system but without geomembrane do not achieve the sealing class I according to Ril 853 and ZTV-Ing.

Fig. 12:
Follow-up detail:
drainage sealing

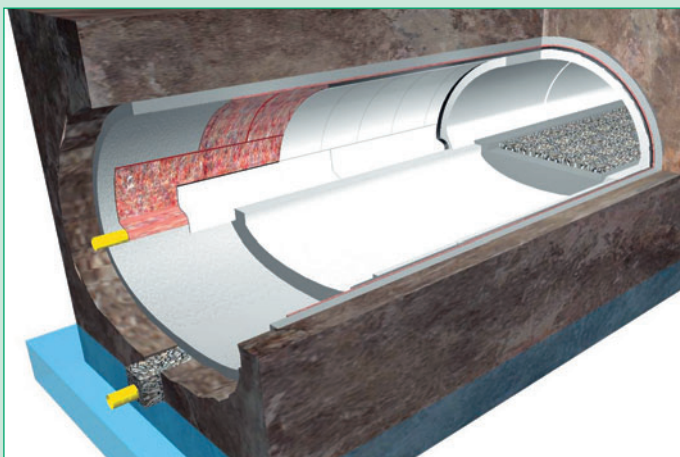
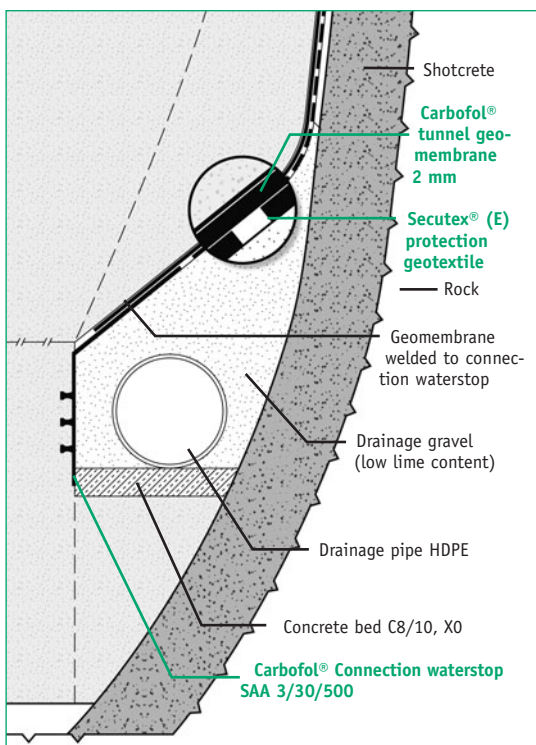


Fig. 13: Sealing against seepage water using the mining technique

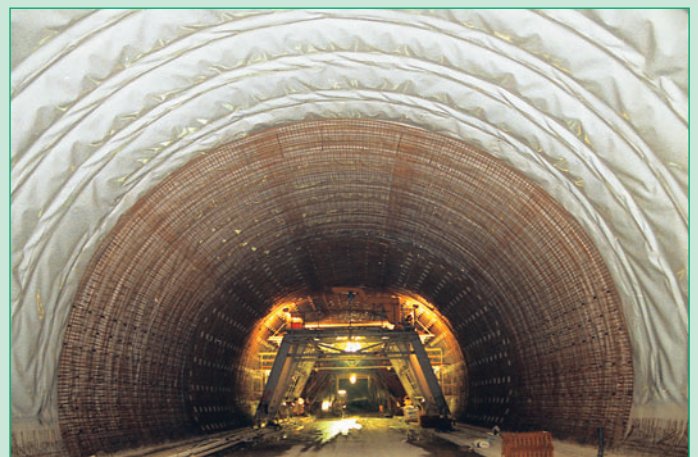


Fig. 14: Installing Carbofol® tunnel geomembrane between the concrete reinforcement, the inner shell and the shotcrete

Carbofol® hydrostatic water pressure with segmental waterstops (DWA)

Water column

The main component of the sealing system comprises of a 3 mm thick Carbofol® tunnel geomembrane, which is installed as a single circumferential layer to resist hydrostatic water pressure. An effective visual, quality assurance of the entire sheet is created by a light-reflecting signal layer on the Carbofol® tunnel geomembrane side that is faced to the inside of the tunnel.

To protect against mechanical damage, Secutex® geotextiles are installed towards the mountain. Needle-punched, nonwoven geotextiles are necessary for protection particularly for high-quality, single-layer sealing systems. Depending on the condition of the surface and the water pressure it might also be necessary to install nonwoven Secutex® geotextiles that have a higher mass per unit area than recommended in the standards and guidelines.

Construction guidelines recommend the following (from the inside out):

- Concrete inner shell
- 3 mm Carbofol® tunnel geomembrane
- Secutex® R 551-B2 (500 g/m²) or Secutex® R 1001-B2 (≥ 900 g/m²) with fire classification E
- Shotcrete

The concrete segment blocks are sealed with six stud Carbofol® waterstops. These will restrict the movement of water to other segments should damage occur in a segment.

A 3 mm thick Carbofol® protection geomembrane is installed in the floor area to protect the floorsealing (see Fig. 19).

Block joints

The circumferential segmental block waterstops between segments have, essentially, the following functions:

- a) Restricting the flow of seepage in the event of leakage
- b) Protection of the Carbofol® tunnel geomembranes from the front casing and from pressure from the concrete edges
- c) Limiting the leakage

These functions are fulfilled safely and reliably by the six stud Carbofol® waterstops. A homogeneous stud welding of the Carbofol® tunnel geomembranes with the waterstops is possible by using the same raw material for both products.

The waterstops are provided with an additional injection system for the removal of air during the pouring of the concrete or for retroactive injection possibilities.

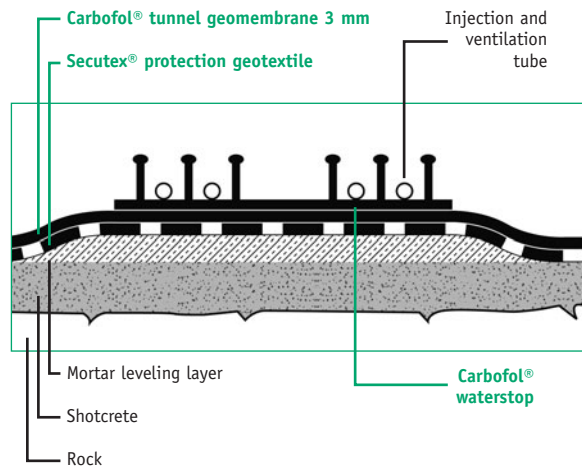


Fig. 15: Carbofol® waterstop with injection tubes

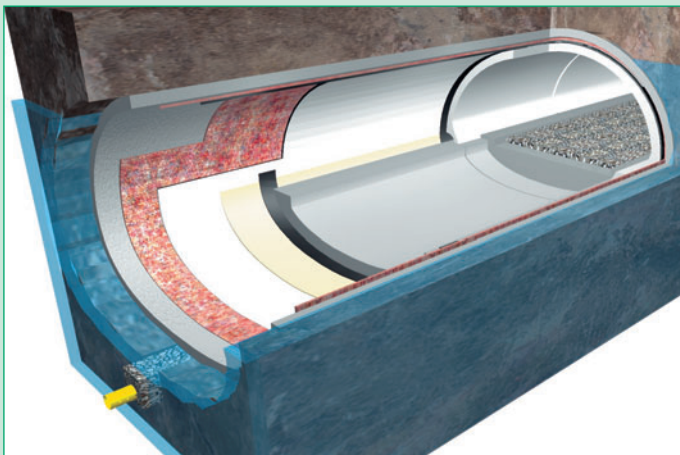


Fig. 16: "360° sealing with segmental waterstops"



Fig. 17: Segmental Water stops in the segmental joint section

Carbofol® sealing system against hydrostatic water pressure with integrated injection system (DWA-I)

For the Carbofol® DWA-I system, the basic design is identical to that of the DWA system (page 8). Additionally, an injection system is integrated, which permits retroactive sealing.

The integrated injection connections allow for sealing of:

- potential damage caused by subsequent construction (e.g., installation of steel reinforcement)
- exposed steel reinforcement due to poor pouring of the concrete (concrete nests)

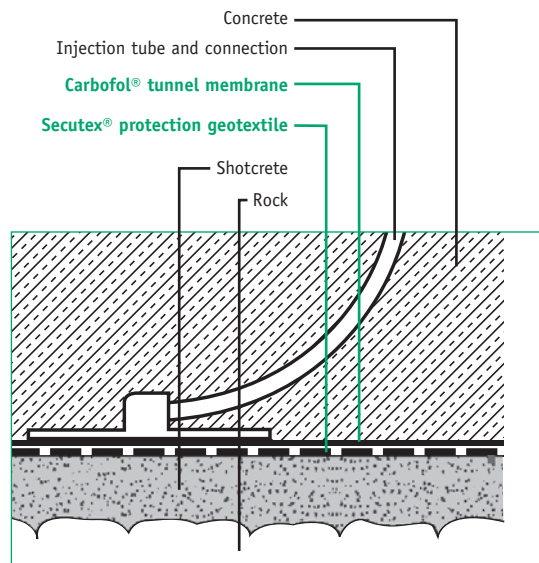


Fig. 18:
Injection connection with tube on Carbofol® tunnel geomembrane

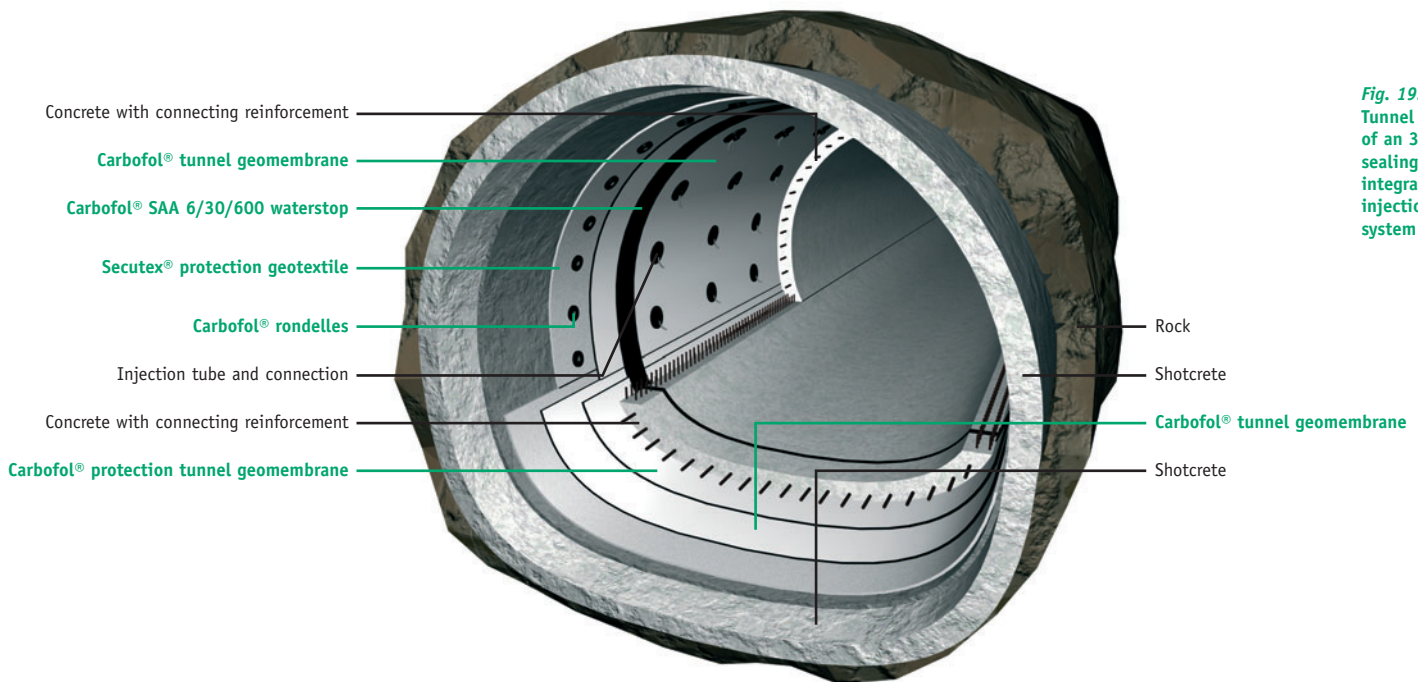


Fig. 19:
Tunnel design of an 360° sealing with integrated injection system

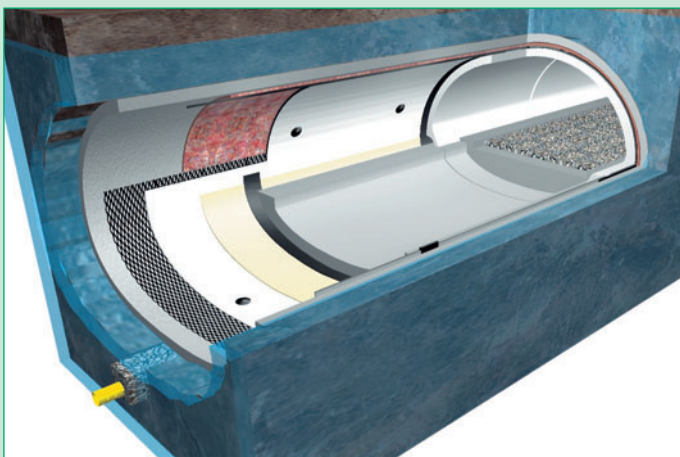


Fig. 20: 360° sealing with integrated injection system



Fig. 21: 360° sealing in a connection tube

Carbofol® system and drainage system – cut and cover construction, including portal sealing

In contrast to the mining technique of a tunnel, the cut-and-cover method takes place in the open. The Carbofol® tunnel geomembrane is placed loosely on the protection Secutex® geotextile, which is installed first onto the sealing carrier layer (construction concrete) and which must be smooth and free of cavities and ridges. A second protection Secutex® geotextile is placed (also loosely) on top of the Carbofol® tunnel geomembrane.

In a cut and cover construction regulations require that the sealing system is installed on the tunnel outside surface as follows:

- Concrete shell (sealing carrier system)
- Secutex® protection layer (geotextile)
- Carbofol® tunnel geomembrane
- On the floor, protection Secutex® layer, if required, Secudrain® geosynthetic drainage system
- Fill material

Sealing against seepage water (SWA), single layer

A Secutex® geotextile is installed as a protection layer below the Carbofol® tunnel geomembrane. This avoids any possible damage from the concrete shell. The Carbofol® tunnel geomembrane is a single layer, at least 2 mm thick and is fixed longitudinally to the tunnel structure, using connection profiles. NAUE recommends a 3 mm thick Carbofol® tunnel geomembrane with signal layer, so that possible damage to the surface of the Carbofol® tunnel geomembrane, such as that might be caused by backfilling operations, can be detected.

Backfill work can cause unintended damage to the Carbofol® tunnel geomembrane. For this reason, a 3 mm thick protection Carbofol® tunnel geomembrane will provide excellent protection against the high stresses during backfill operations. The Carbofol® reflective layer is beneficial, so that visual inspections for damaged areas can be carried out immediately. Generally, due to the backfilling, the protection layers should be dimensioned thicker in a cut and cover construction than in a the mining technique construction. Alternative systems can be used, such as Secutex® protection geotextiles, Secudrain® geosynthetic drainage systems or others.

Sealing against water pressure (DWA)

In this case, the Carbofol® tunnel geomembrane has a thickness of 3 mm. The floor Carbofol® and the arch Carbofol® are welded together and an expansion joint is welded to both of the geomembranes horizontally.

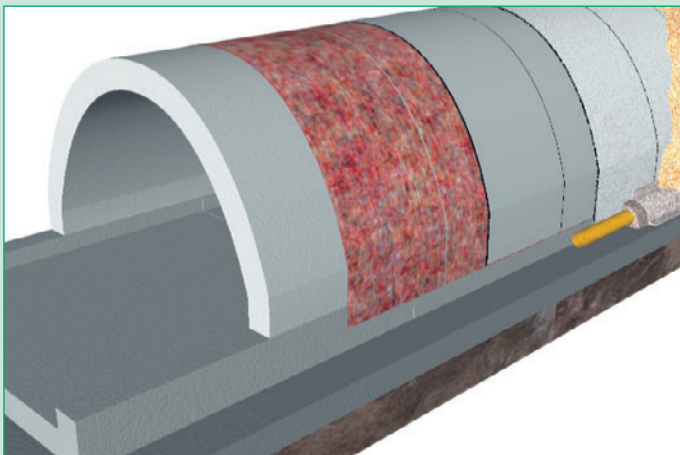


Fig. 22: Sealing against seepage water in cut and cover construction



Fig. 23: Portal area with Carbofol® tunnel geomembrane

Requirements for the sealing carrier system

The shotcrete formation layer, which simultaneously serves as the backing and the fixing support for the sealing system, is an important criterion for the functioning of the sealing geomembrane in mining technique tunnel construction. The sealing carrier system is to be constructed such that a full-plane interface connection of protection layer and geomembrane is ensured without the geomembrane being overstressed or being folded.

The 5 to 15 cm thick shotcrete shell, which can be far thicker, depending on the geological conditions, ensures that:

- a) The stability of the mined mountain can be ensured on a temporary basis
- b) Edges, ridges, burstings, protruding anchor bodies, support arches and suspensions can be covered.

Therefore the following conditions must be met by the shotcrete shell:

- thickness ≥ 5 cm
- max. particle size 8 mm, if possible, gradiated in a base layer (0 - 16 mm) and cover layer (0 - 8 mm)
- Rise difference $a \leq 20$ cm
- Sufficient dimensional stability
- rounding radius $N a \geq 5a$
- distance low and high point $L \geq 10a$

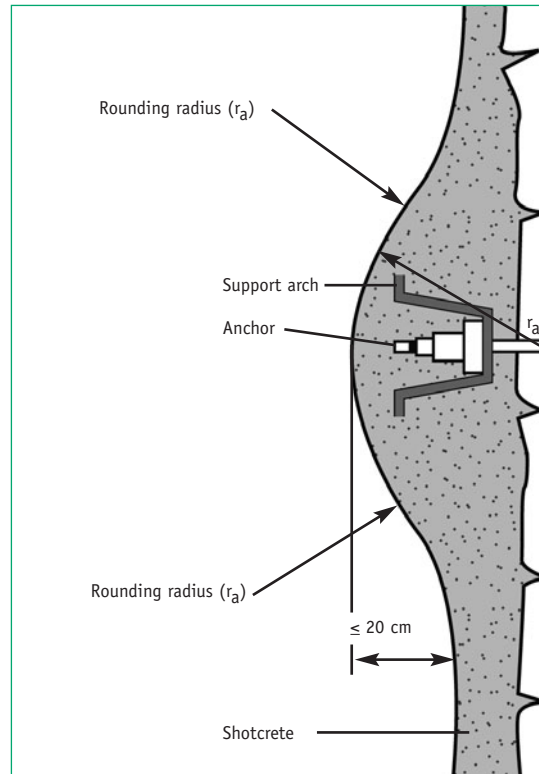


Fig. 24: Construction of the shotcrete backing

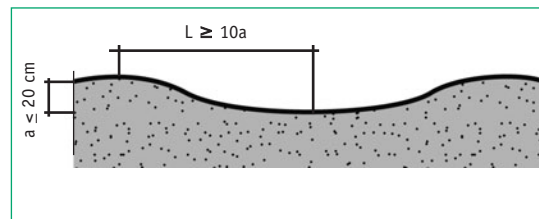


Fig. 25: Attaching Secutex® protection geotextile on the sealing carrier layer side wall



Fig. 26: Securing the Secutex® protection geotextile (arch area)

Installation of Carbofol® tunnel systems

Sealing the floor

When using Carbofol® as the floor sealing system (e.g. in hydrostatic water pressure applications), a Secutex® protection nonwoven is installed as protection layer to prevent mechanical stress. Secutex® is attached to the carrier construction, using Carbofol® rondelles, to prevent movement and slippage.

The Carbofol® tunnel geomembrane is then installed in the slightly curved floor. In order to prevent the Carbofol® tunnel geomembrane from slipping, it is welded against to the Carbofol® rondelles.

It is recommend that the Carbofol® tunnel geomembranes laid in the floor area are installed to approximately 1 m above the top edge of the floor concrete reinforcement bars. This makes it possible to correctly

Fig. 27:
Attaching the
protection
geotextiles using
Carbofol® rondelles
and a bolt gun



weld the floor sealing to the sealing system of the arch. A further welding of the Carbofol® tunnel geomembrane is carried out between Carbofol® and the waterstops at the segmental block joints.

After the quality inspection and acceptance of all welding work, a 3 mm thick Carbofol® protection geomembrane with signal layer is installed and welded. The edge of the Carbofol® floor tunnel geomembrane must also be welded to the Carbofol® protection geomembrane to prevent any cement suspension protruding between the layers.

Sealing arches

The Carbofol® tunnel geomembrane for sealing arches and tunnel side walls is installed radially to the structure's axis using movable scaffolding and welded to the drainage connection joint or the floor sealing system.

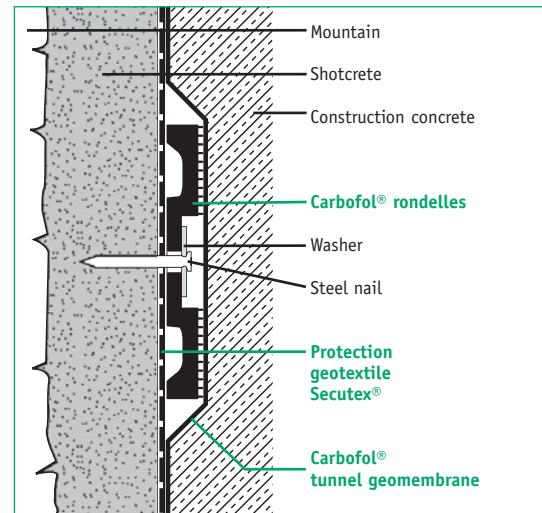


Fig. 28:
Attaching the
geomembrane
(final state)

During the first working step, the Secutex® protection or Secudrain® geosynthetic drainage mats are attached to the shotcrete sealing carrier system with a bolt gun, using steel nails and Carbofol® rondelles. On average, the number of anchoring points (rondelles) that are



Fig. 29: Installing Carbofol® tunnel geomembrane in the arch



Fig. 30: Welding of Carbofol® tunnel geomembrane
using a hot-wedge welding machine

fastened to the shotcrete supports/Secutex® geotextiles with bolt-driven steel nails are approximately 1 to 2 pieces/m². Carbofol® tunnel geomembranes are installed with sufficient lateral overlapping at the edges. This makes for an easy welding of the next geomembrane of Carbofol® tunnel geomembranes.

The Carbofol® tunnel geomembranes are positioned by working from the installation scaffolding and are hot-air welded to the rondelles. The rondelles have a pre-determined breaking point, so that in the case of excessive stress the tear will not be within the geomembrane. The thickness of the tunnel geomembrane must not be minimized by such an occurrence.



Fig. 31:
Carbofol® tunnel
geomembranes
over an arch
scaffold

Welding and testing methods

Welding can be done independent of the state (roughness, waviness) of the sealing carrier system. However, basic requirements are an ambient temperature of at least 5°C and a relative humidity of less than 80 %.

Fig. 32:
Carbofol® tunnel
geomembranes in
the niche area



One of the installation personnel positions the light-weight welding device between the overlapping Carbofol® tunnel geomembranes to be welded and continuously monitors the required overlap width of the geomembranes. The homogeneous welding of the Carbofol® tunnel geomembrane is carried out with hot-wedge welding machines that create a testing channel between two parallel-running welded seams. The double seam thus created is tested with compressed air. Additional tests for the mechanical strength of the seam are also performed.

The testing of all the seams is usually done at the end of the working day.



Fig. 33: Air pressure testing of a double wedge weld seam



Fig. 34: Welding a waterstop to the Carbofol® tunnel geomembrane

CE-marking

Compulsory CE-marking

From 1st October 2002, CE-marking for geosynthetics was made compulsory (except for erosion control mats). The CE-marking certifies that a product corresponds to the product-specific European guidelines for specific applications and functions (separation,

filtration, reinforcement, sealing, protection and drainage). NAUE has taken all necessary steps to put into effect the compulsory CE-marking.



Carbofol® waterstops

Carbofol® waterstops are used in tunnel construction to seal block joints, create segmental sections and allow connections between geomembranes. Carbofol® tunnel geomembranes and Carbofol® waterstops are made of similar materials, so that a problem-free and permanent weld is possible between waterstops and a Carbofol® geomembrane.

Waterstops - installation and embedding in concrete

In order to achieve the flawless encasing of waterstops in concrete, in particular in the arch area, it is absolutely necessary that the use of injection de-airing tubes is allowed for.

De-aeration and injection tubes fulfil the following tasks:

- Ventilation of the areas between the waterstops to ensure that they are completely encased in concrete and to avoid seepage
- Injection of fine cement and resins through the injection tubes to be able to safely seal potential water flows in the event damage might have occurred.

A sealing-off of the blocks is possible only if the waterstops have been completely encased in concrete.



Fig. 35:
Waterstop system
in the shaft area

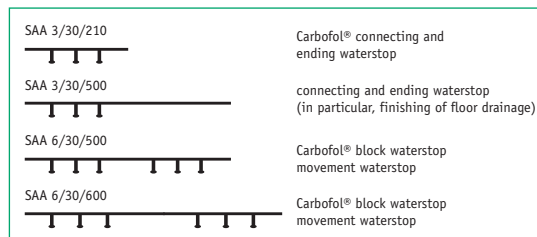
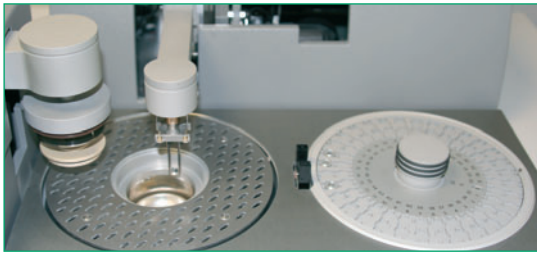


Fig. 36:
Carbofol®
waterstop
versions



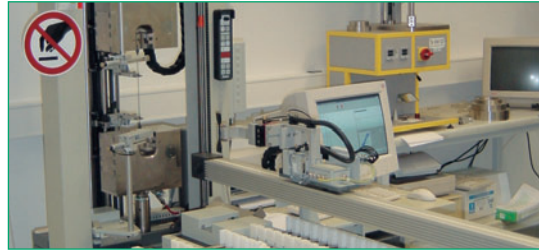
Raw material identification according to the DSC method



Determination of the carbon black content



Melt Flow Index via ISO 1133



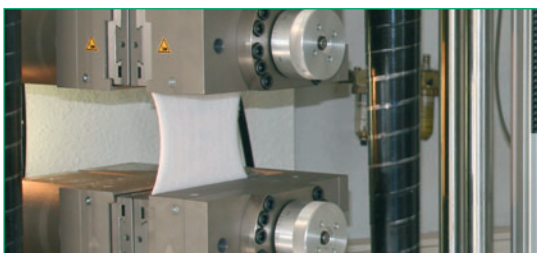
Tensile test on Carbofol® geomembranes ISO 527-3 or ASTM D 6693



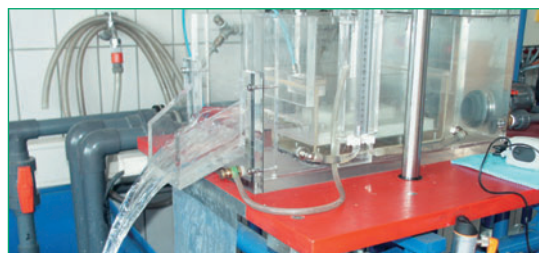
Burst test of a Carbofol® geomembrane according to EN 14151



Determination of the strength and elongation properties of single fibres



Tensile strength test on wide-width strips according to ISO 10319



Determination of water flow capacity in their plane ISO 12958



Load plate-bearing test for the qualification of geotextile protection layers EN 13719



Flame test to determine fire classification E according to ISO 11925-2

Further information on the subject **geosynthetics** are available through our website or from our:

- **Corporate brochure**
- **Application-related brochures:**
 - Civil engineering
 - Groundwater protection
 - Hydraulic engineering
 - Landfill engineering
 - Tunnel construction
 - Waterproofing manual
- **Application-related flyers and technical flyers with project-specific solutions**



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