The use of geomembranes in tunnel construction

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Summary

The sealing of tunnel walls involves the use of membranes which, depending on the situation, are constantly exposed to the leaching action of groundwater, or of water emanating from the surrounding rock. In terms of ecological product compatibility, the question arises as to whether pollutants may be released in the process. Various geomembranes are examined in more detail and subjected to an evaluation system. It emerges that in particular geomembranes with especially worrying components such as phthalates should generally be kept away from the environment for precautionary reasons, even though some phthalate plasticisers have not yet been evaluated by the EU. Phthalates are characterised by the fact that they are released from the membranes in considerable quantities.

Keywords: Geomembranes, tunnel construction, pollutant release, groundwater

1 Definition of task

In contrast to the manner in which substances hazardous to water are dealt with in production plants, i.e. in plants for storing, filling, handling, manufacturing, treating and using, the requirements for the manner in which these hazardous substances/products are dealt with in applications, i.e. when the substances or products are introduced into the open system 'environment', must be

- technically appropriate and
- environmentally sound.

It is assumed that the first requirement is met for all products under consideration for the sealing of tunnel walls. The second requirement requires ecological product compatibility for geomembranes used in tunnel construction.

For products in the open system 'environment', the issues to be questioned are:

1. Are substances released from the product by gas release or by environmental conditions?

2. How dangerous are the released substances for water and soil?

For the engineering measures to be considered here – tunnel-wall sealing with geomembranes – many square metres of this material are normally used, so that if hazardous substances are released, critical quantities of these substances may find their way into the environment via the surface and/or groundwater pathway.

2 Legal framework

Considering the various paths of potential negative environmental impact, then in the present application case of geomembranes in tunnel construction, soil can be neglected as a material to be protected because the tunnel location is solid rock. The air pathway, which is causally related to health protection, is only relevant if people are in the tunnel during maintenance and construction measures, and this is only temporary. The water pathway is therefore relevant, since the water in the fissured rock can leach hazardous substances from the geomembranes and release these into the groundwater and, under certain conditions, surface water along this path.

Thus, in this paper, the instrumentarium of water law will be used as the basis for the assessment grid. The basis here is the Wasserhaushaltsgesetz (Water Resources Act, WRA) [1].

§ 5 WRA - General duties of care

(1) For measures which may have impacts on a body of water, every person shall be required to take the care appropriate to the circumstances in order to

1. *avoid any pollution or adverse change in the properties of the water,*
2. *bring about economical use of the water in order to maintain the efficiency of the water reserves,*
3. *maintain the efficiency of the water reserves and to avoid an increase and acceleration of water run-off.*

§ Article 47 WRA - Management objectives for groundwater

(1) Groundwater shall be managed in such a way that

1. *a deterioration in its quantity and chemical state is avoided,*
2. *any significant and sustained upward trend in the concentration of any pollutant resulting from the impact of human activity is reversed,*
3. *a good quantitative status and a good chemical status are maintained or achieved; good quantitative status implies in particular a balance between groundwater removal and regeneration.*

§ Section 48 WRA - Control of groundwater pollution

(1) A permit for the introduction and discharge of substances into groundwater may only be granted if there is no reason to fear an adverse change in the quality of the water.

The principle of concern underlying Article 48 is the decisive benchmark for precautionary groundwater protection. The principle of concern is defined as extremely stringent by several court rulings of the Federal Administrative Court. The following are some citations.

1966 Human experience must show that the occurrence of contamination of water or any other adverse change in its properties is highly unlikely.

The greater and more serious the potential damage, the more stringent the requirements for the unlikelihood of the damage occurring must be.

In individual cases, this can lead to a degree of improbability of an incidence of damage that is, or is close to, impossible.

1971 There must be no cause for concern for those responsible for water management.

1981 Any possibility, however remote, of contamination of the groundwater, which is particularly worthy and in need of protection, must be prevented.

A negative impact on the groundwater must always be feared if its possibility cannot be dismissed within the framework of an objectively justifiable forecast.

Furthermore, the Groundwater Ordinance (GwO) [2] must be observed; this prescribes threshold values to be observed with regard to groundwater quality.

§ 5 GwO - Criteria for the assessment of the chemical status of groundwater

(1) The basis for assessing chemical groundwater status are the threshold values listed in Annex 2.

Annex 2
Threshold values

Substance name	***CAS No. 1***	***Threshold value***
Nitrate (NO_3^-)	-	*50 mg/l*
Active substances in plant-protection and biocidal products including relevant metabolic, degradation and reaction products	-	*0.1 µg/l each, in total 0.5*
Arsenic (As)	*7440-38-2*	*10 µg/l*
Cadmium (Cd)	*7440-43-9*	*0.5 µg/l*
Lead (Pb)	*7439-92-1*	*10 µg/l*
Mercury (Hg)	*7439-97-6*	*0.2 µg/l*
Ammonium (NH_4^+)	*7664-41-7*	*0.5 mg/l*
Chloride (Cl-)	*168876-00-6*	*250 mg/l*
Sulphate (SO_4^{2-})	*14808-79-8*	*240 mg/l*
Sum of tri- and tetrachloroethene	*79-01-6* *127-18-4*	*10 µg/l*

For the nationwide uniform assessment of changes in groundwater quality that must be prevented, the Federal/State Working Group on Water Resources (LAWA) has developed transparent, uniform assessment criteria [3] for determining the concentrations of substances up to which anthropogenic, spatially limited changes in the chemical quality of groundwater are to be classified as minor, and the concentration above which there is an adverse change in the water quality of the groundwater (groundwater contamination). This benchmark is the 'de minimis threshold' (DMT) [4].

The de minimis threshold (DMT) is defined as the concentration at which no relevant ecotoxic effects can occur despite an increase in the substance content opposite regional background values, and at which the requirements of the Drinking Water Ordinance or values derived in like manner are met.

For the purposes of precautionary water protection, any use of a water body requires a permit in accordance with § 9 WRA. Uses which can lead to changes in substance concentrations in groundwater are, in particular, the introduction and discharge of substances into the groundwater (§ 9 Para. 1 No. 4 WRA).

A change in water quality is disadvantageous if it represents a more than minor impairment in comparison with the natural groundwater quality. The DMT values are used to assess whether the predicted or measured substance concentrations are likely to cause adverse changes in groundwater quality as a result of an intended action or a specific application for groundwater use.

The Groundwater Ordinance (GwO) defines "threshold values" as the concentration of a pollutant or group of pollutants determined for the protection of human health and the environment (Article 1 No. 1 GwO). The threshold values are the basis for assessing the chemical status of groundwater.

The German thresholds in the GwO were developed on the basis of the derivation system for the DMT values, but currently contain only a small parameter spectrum. The DMT values may be used for the establishment of further threshold values by the competent authority where the chemical status of a body of groundwater is at risk from a substance or group of substances not listed in Annex 2 to the GwO. If the regional or local geogenic background values in groundwater exceed the DMT values, different threshold values may be set by the competent authorities in accordance with the provisions of the Groundwater Ordinance.

The de minimis threshold is the central assessment standard for all applications related to groundwater **(Fig. 1**). No de minimis thresholds have yet been derived for the substances (plasticisers) relevant to the problem considered here.

The water endangerment class (WEC) is not a direct yardstick for the issue at hand here, as the WEC is an "installation reference number". In accordance with the Ordinance on Installations [5], it serves to protect water bodies from adverse changes in their properties due to the release of substances hazardous to water from installations for handling these substances. It also describes the requirements for a safe installation so that no substances hazardous to water are released uncontrolled into the open system environment during intended and non-intended operation. Nonetheless, the WEC can be used to characterise substances with regard to the hazards they pose to the water bodies.

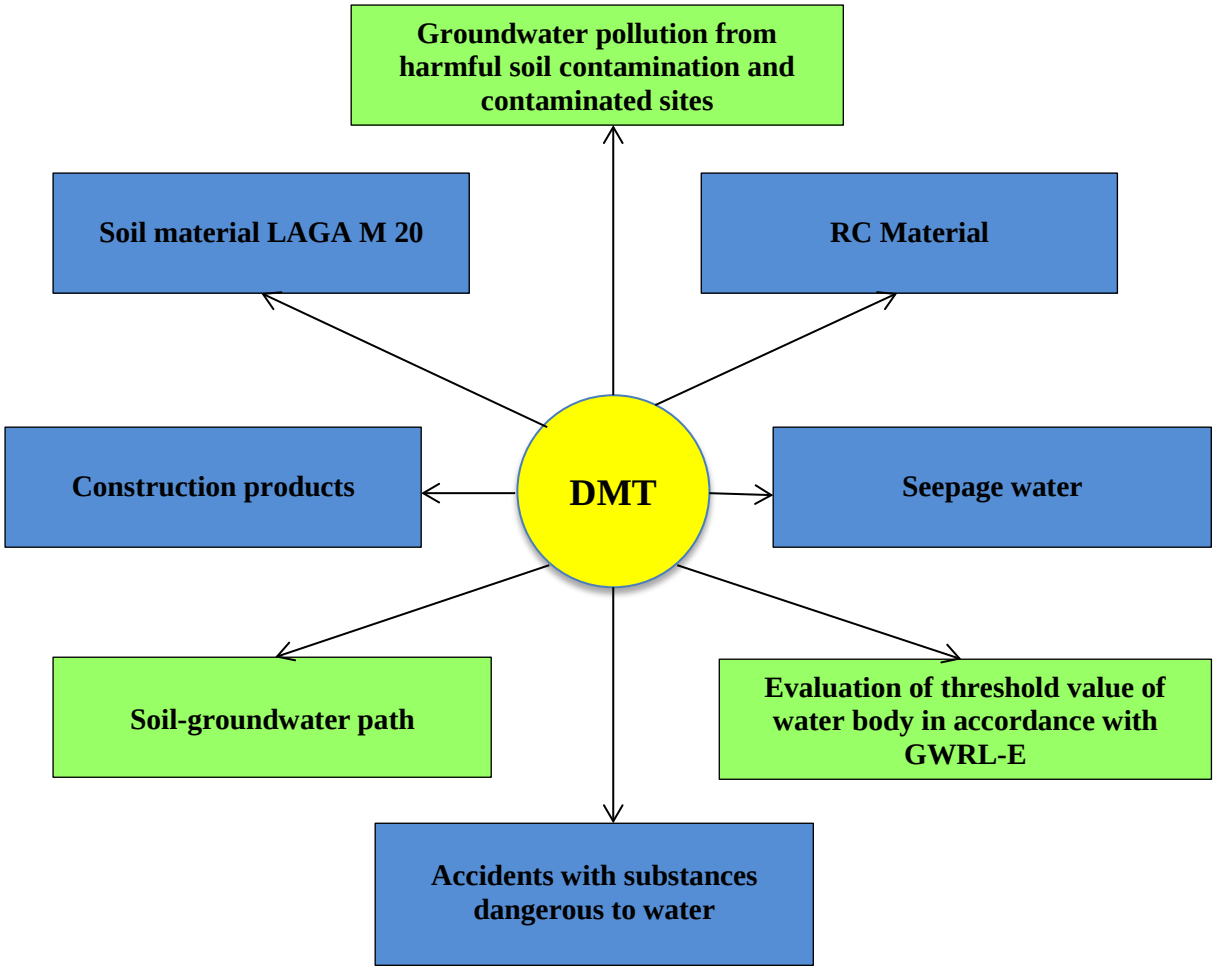


Fig. 1: Areas of application of the de minimis threshold

The Deutsches Institut für Bautechnik (DIBt) has developed principles [6] for the assessment of construction products which can be used as rules of technology. They are used to assess the effects of construction products on soil and groundwater when the DIBt issues general construction Approval Certificates.

The assessment is based on an assessment concept comprising two stages:

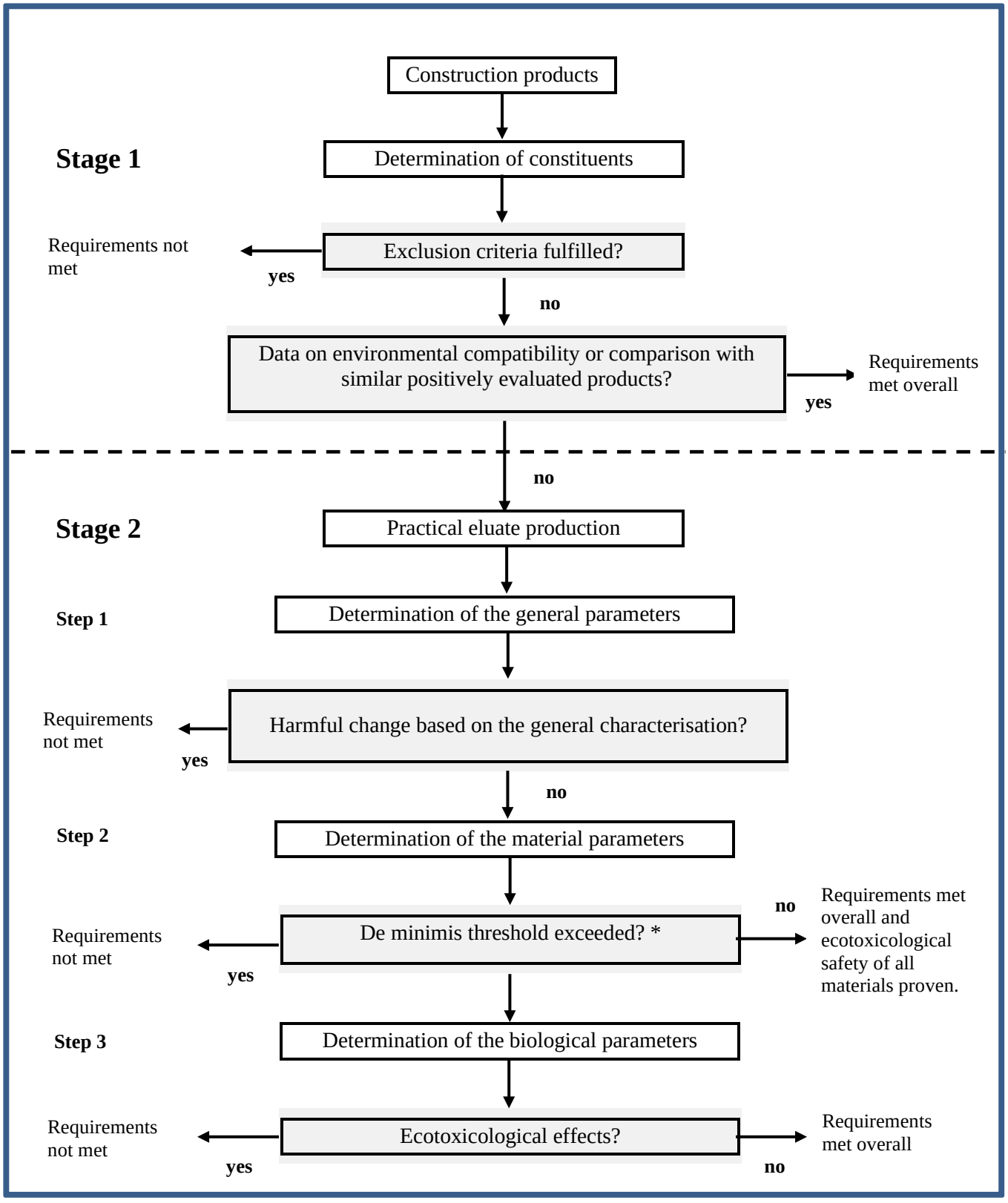
Stage 1: Identification and assessment of all substance in the construction product to be assessed

Stage 2: Identification and assessment of the mobilizable substances in the construction product to be assessed.

The second stage comprises the identification and assessment

- *of the general parameters in a first step,*
- *of the material-chemical parameters in a second step and*
- *of the biological parameters in a third step.*

The flow chart for this step-by-step assessment of the ecological product compatibility is shown in **Fig. 2**.



*taking the relevant transfer function into account

Fig. 2: Flowchart from [6]

Stage 1

The following criteria are used to assess the relevant substances:

- *Application of exclusion criteria for individual substances,*
- *well-founded knowledge of the harmlessness of all substances with regard to concerns about any occurrence of detrimental changes to the soil, and of groundwater contamination,*
- *Comparison with construction products of similar composition already evaluated on the basis of these principles.*

The following exclusion criteria apply:

- *Existing legal prohibitions and restrictions on the use of special substances must be observed (e.g. Ordinance on the Prohibition of Chemicals).*
- *The use of substances which, according to EU Directive 67/548/EEC in its current version must be labelled with "N", "T+" and "T", should be avoided; if such substances are technically unavoidable, an evaluation according to stage 2 must be carried out. Stage 2 evaluation may be omitted if the safety of these substances in the product can be demonstrated by other evidence.*
- *Persistent Organic Pollutants (POPs) from the respective current ICCA list and the following may not be actively used.*
- *If carcinogenic (R 45), mutagenic (R 46) or reprotoxic substances (R 60, R 61) are used in the manufacture of the construction product in accordance with EU Directive 67/548/EEC, it must first be examined whether they may pose a risk to soil and groundwater. If this is the case, they may not be actively used. These regulations do not apply to substances whose dangerous effects are caused solely by exposure to inhalation.*

Stage 2

These principles for the assessment of construction products require that the de minimis thresholds are not exceeded at the places where they are to be met and that therefore no relevant ecotoxicological effects occur there.

3 Construction methods in tunnel construction

Tunnel constructions are always exposed to the influence of water in the surrounding rock body. The design of a tunnel cross-section is determined to a large extent by its position in relation to the groundwater, and here it must be decided in principle whether the cross-section is to be designed to be **relieved of water under pressure** or **subjected to water under pressure**. This far-reaching decision also has a decisive influence on the choice of the sealing system and the sealing geometry. The decision depends on the following aspects, among others:

- If the tunnel is above the groundwater table, the tunnel only comes into contact with seepage water and can normally be designed as **relieved of water under pressure**.
- If the tunnel is below groundwater level, the water pressure must be reduced by means of basal drainage. The tunnel can be designed as being **relieved of water under pressure**. As a rule, a sealing system (umbrella sealing) is only provided in the vault and drainage is foreseen to remove the groundwater at the base.
- In case of continuous water pressure on the tunnel cross-section, it shall be designed as being **subjected to water under pressure**. The sealing system must be provided over the entire cross-section (all-round sealing).

Sections not subjected to water under pressure require safe and permanent drainage of the groundwater and seepage water (connection to a recipient water body). This can lead to interactions between the components of the waterproofing system and the led-off water, to resulting in damage to the overall structure, but also to adverse changes in the properties of the water body.

An essential element of the waterproofing systems are geomembranes (GMB), which can be used to control all types of water loading for the tunnel structure. For example, according to the regulations of Deutsche Bahn, sealing using geomembranes is approved as follows:

1. as loosely laid geomembranes in double-layer tunnel construction in wet soil, water under pressure (diaphragm waterproofing), and water not under pressure,

2. as loosely laid geomembranes for umbrella waterproofing in tunnel construction in damp soil and water not under pressure,

3. as loosely laid geomembranes in combination with a waterproof reinforced-concrete construction (WUBKO) in the presence of water under pressure.

4 Negative impacts on water bodies

When selecting the construction materials for the lining of tunnels with sealing **relieved of water under pressure**, it is particularly important to ensure that no groundwater-endangering substances are leached out, which are then fed into the recipient water body via the drains. However, at least that part of the groundwater being led off which comes into contact with the substances may also directly enter the groundwater and thus pollute the surrounding groundwater with the released substances and also endanger medicinal springs.

5 Sealing membranes made of synthetic materials

For the assessment and selection of building products in the design, construction and operation of structures, the WECOBIS [7] database system can be consulted. It provides information on environmental and health aspects of important building-product groups in the context of sustainable construction. The information in WECOBIS refers to the basic "average" material properties.

5.1 Structure of the geomembranes

Basically, a distinction can be made between multi-layered membranes and homogeneous membranes. While the homogeneous geomembranes consist of a single layer, the multi-layer geomembranes have an inner carrier layer (insert), which is covered on both sides by functional layers. The material of the functional layers determines the designation of the geomembrane. For example, a membrane with functional layers of flexible polyolefins (FPO) is called an FPO geomembrane.

The frequency of use of geomembranes of different material groups varies greatly. PVC-P membranes are the most frequently used.

5.2 Characteristics

Flexible polyolefins (FPO), very low-density polyethylene (VLDPE), polyethylene modified with ethylene vinyl acetate (EVA) or plasticized PVC (PVC-P) are used for sealing tunnel structures with geomembranes.

Multi-layer membranes consist of a carrier layer of glass-fibre or polyester nonwoven and surface layers of polyvinyl chloride (PVC-P), polyolefins (FPO), ethylene-propylene-diene terpolymer (EPDM), ethylene-vinyl acetate terpolymer (EVA, VAE), ethylene copolymer bitumen (ECB), chlorinated polyethylene (PE-C) or polyisobutylene (PIB). Current FPO and PVC geomembranes are multilayer. EPDM and EVA membranes are also offered with inserts.

Homogeneous membranes are offered in EPDM for area sealing.

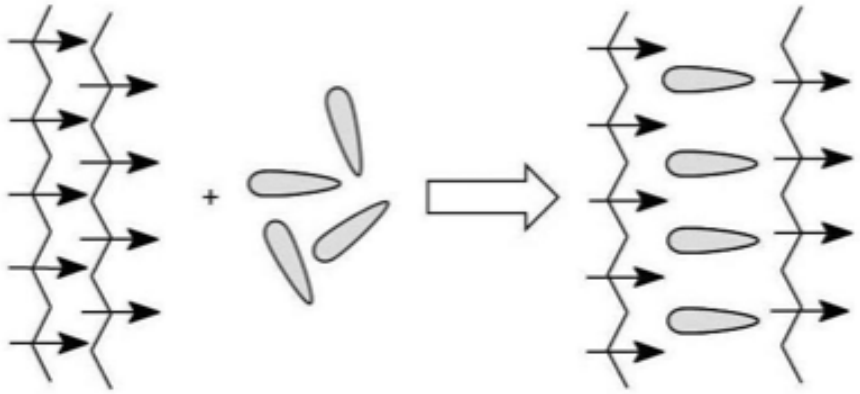
As a rule, membranes of polyvinyl chloride (PVC-P), ethylene-vinyl acetate terpolymer (EVA, VAE), ethylene copolymer bitumen (ECB) or polyisobutylene (PIB) for area sealing are now only used for sealing at the edges.

PVC geomembranes

PVC geomembranes are among the oldest synthetic waterproofing systems. They consist essentially of plasticized polyvinyl chloride, so-called PVC-P. Pure PVC is hard and relatively brittle and only becomes pliable when up to 50% of the plasticiser-additives are added to the polymer **(Fig. 4**). As plasticisers phthalates (phthalic acid esters) are predominantly is used. Plasticisers are toxicologically important because they can generally be released throughout the life of a product.

PVC becomes resistant to light and weathering through the addition of stabilizers. During degradation of the plastic, which can be recognized by discolouration and embrittlement, pollutants can be released [7]. The most important stabilizer is lead.

Polymer + Plasticizer + Energy = Soft Polymer



Source: M. Bonnet, 2., revised and extended edition 2014, XIII, Publisher: Springer Verlag

Fig. 4: Structure of PVC-P

A distinction is made between PVC geomembranes:

PVC type	**Short description**
Hard polyvinyl chloride	PVC-U for "PVC unplasticized"
Soft polyvinyl chloride	PVC-P for "PVC plasticized"
Chlorinated polyvinyl chloride	PVC-C
Polyvinylidene chloride (copolymerization with vinylidene chloride)	PVDC

PVDC and PVC-C are modifications with a higher chlorine content than PVC.

Polyolefin geomembranes

Polyolefins (PO) are a group of plastics to which such well-known representatives as polyethylene, polypropylene and polybutylene belong. The backbone of these synthetic materials consists only of carbon and hydrogen. The polyolefins consist of alloys of these individual plastics and are often also referred to as flexible polyolefins (FPO-A, A = Alloy), because they are significantly less rigid than polyethylene, for example. Since the early nineties, FPO has been used more widely in technologies for the waterproofing of structures. Additives are added to improve flexibility and resistance to ageing.

EPDM geomembranes

EPDM is the abbreviation for ethylene-propylene-diene terpolymer. The plastic consists of a combination of the three polymers ethylene, propylene and diene, which are linked to form a larger polymer. In addition to EPDM, polypropylene or other unspecified thermoplastic elastomers are used for the production of EPDM sealing membranes. EPDM membranes have a glass

transition temperature below 0 °C, which means they remain flexible even at low temperatures. In accordance with DIN standards that are no longer current, they are also referred to as "elastomeric sheets".

EVA geomembranes

EVA stands for ethylene vinyl acetate and refers to copolymers of ethylene and polyvinyl acetate. The plastic polymer consists of polymers of different plastics. In EVA geomembranes, EVA with a share of ≥ 25% and PVC with a share of ≤ 50% are used. Ethylene-butyl acrylate can be added as a further type of plastic. These geomembranes may also contain phthalate-based plasticizers.

In order to be able to detect damage during construction, the geomembranes always have a light-coloured signal layer on one side. This also improves the working conditions in the tunnel and thus increases safety at work. For cut-and-cover tunnels, a light-coloured signal layer is useful to prevent wrinkling due to the sun's rays.

The different materials mean that all aspects of environmental protection, material resistance (e.g. during freight transport), mechanical durability and fire behaviour (formation of toxic gases and release of chlorides that attack metals) must be taken into account when selecting materials.

6 Assessment

The relevant pollutants and their release potential must be considered for the geomembranes used in tunnel construction.

6.1 PVC geomembranes

The critical point in connection with the potential environmental and health risks posed by geomembranes are the phthalates that are added to the PVC as plasticizers. Phthalates can be released by gas emission or by leaching from the product "geomembrane", as they are generally not chemically bound in PVC. **When geomembranes are used in tunnel construction, the leaching process is assured by the constant contact with groundwater flowing over the membrane.** The plasticizers are classed as low-volatility compounds and can therefore slowly and permanently evaporate from products or dissolve on contact with liquids or fats. Due to the low vapour pressure, however, their release into the air is of secondary importance. Furthermore, phthalates tend to attach themselves to particles.

If they get into wastewater, they accumulate in the wastewater treatment plants mainly on the sewage sludge and can be spread on fields and contaminate the soil.

Most phthalates are harmful to aquatic organisms, such as small crustaceans, and are classified as water hazard class 1 "slightly hazardous to water" and should nevertheless not be released into the groundwater, water bodies or drains.

Phthalates are divided into low-molecular phthalates (low molecular weight = **LMW**) and high-molecular phthalates (high molecular weight = **HMW**) [7].

LMWs include di-(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), benzyl butyl phthalate (BBP) and di-isobutyl phthalate (DIBP). These four low-molecular phthalates are classified as reprotoxic (toxic for reproduction), for which from 21 January 2015 the placing on the market and use (**Tab**. **1**) of the substance are prohibited without certification [8].

HMWs include di-isodecyl-phthalate (DIDP), di-isononyl-phthalate (DINP) and di-2-propyl-heptyl-phthalate (DPHP). The phthalates DIDP, DINP and DPHP, which are increasingly used today (more than 70% of all plasticisers in Europe [9]), have not yet been found to have any significant environmental impact. Nevertheless, the phthalates DIDP, DINP and DPHP have been registered by manufacturers under REACH. This means that manufacturers have provided data for DIDP, DINP and DPHP to demonstrate their safe production and use.

A striking criterion is their reproductive toxicity.

Definition of reproductive toxicity:

Impairment of male and female reproductive functions or ability (fertility) and damage to development (prenatal non-heritable health damage and fruit damage).

These include damage to all stages of reproduction: from impairment of female and male sexual functions and fertility, to damage during pregnancy and lactation, to effects that are triggered prenatally and only manifest themselves in the succeeding generation.

This also includes the effect on lactation, i.e. the milk supply of breast-feeding women.

In accordance with the GHS Regulation these phthalates are labelled with the hazard statements

H360F: May affect fertility

H360D: May cause harm to the unborn child

H360D: May cause harm to the unborn child

H361f: Suspected of impairing fertility,

H361d: Suspected of causing damage to the unborn child

H362: May cause harm to breast-fed babies

and are marked with the pictogram GHS 08.

DEHP, DBP and BBP are very toxic to aquatic organisms and can cause long-term damage to water bodies. They are classified as environmentally hazardous in the EU.

The low molecular weight phthalates **(LMWs**) DEHP, DBP and BBP have been identified as substances of very high concern (SVHC) due to their classification as toxic to reproduction and are listed in Annex XIV of the EC Regulation No. 1907/2006 concerning the Registration, Evaluation, Certification and Restriction of Chemicals (REACH). They are therefore subject to the approval procedure laid down in the chemicals legislation. The medium-term aim is to remove the substances concerned from the market. This would protect human health or the environment from the undesirable effects of the substances concerned.

Low molecular weight phthalate DIBP has not yet been evaluated at EU level and is therefore not subject to an EU ban.

For substances subject to certification, a general ban on manufacture and use applies from the so-called "expiry date" **(Tab. 1**), which is also tabulated in the REACH Annex. For the three phthalates mentioned, the expiry date is 21 February 2015 [8].

Tab. 1: Annex XIV to Regulation (EC) No 1907/2006

Substance	**Inherent characteristic(s) referred to in Article 57**	**Transitional arrangements**		**Excluded uses or categories of uses**
		Closing date for applications	**Expiry date**	
Bis (2-ethylhexyl) phthalate **(DEHP**) EC No.: 204-211-0 CAS No.: 117-81-7	toxic for reproduction (Category 1B)	21 July 2013	21 January 2015	Uses in the primary packaging of medicinal products covered by Regulation (EC) No. 726/2004, Directive 2001/82/EC and/or Directive 2001/83/EC
Benzyl butyl phthalate **(BBP**) EC No.: 201-622-7 CAS No.: 85-68-7	toxic for reproduction (Category 1B)	21 July 2013	21 January 2015	
Dibutylphthalate **(DBP**) EC No: 201-557-4 CAS No: 84-74-2	toxic for reproduction (Category 1B)	21 July 2013	21 January 2015	

DEHP is listed as a priority substance in the EU Water Framework Directive 2000/60/EC [10].

Under the new CLP Regulation [11], phthalate DBP is classified as "very toxic to aquatic organisms" and phthalate BBP as "very toxic to aquatic organisms with long-term effects".

The EU Commission issued a ban on the use of the phthalates DEHP, DBP and BBP in baby articles and children's toys if they are present in concentrations of more than 0.1 % by weight of the material containing the plasticizer (Regulation (EU) No. 1907/2006, Annex XVII; 51). And these three substances may also not be used in the manufacture of cosmetic products, or in mixtures such as varnishes and paints, which are sold to private consumers.

After the expiry date, a substance subject to authorisation may only be used or manufactured for a limited period with an exemption ("certification"). The competent European Commission will grant such approvals only if the applicant can demonstrate that the risks associated with the specific use of the substance are adequately controlled, or if the total benefits to society outweigh these risks. DEHP, DBP and BBP are exempt from the authorisation requirement for use in packaging for medicinal products.

The Umweltbundesamt (German Environment Agency) [12] advocates that, as a precaution, substances with properties of very high concern, in this case phthalates, should generally not be released into the environment.

Estimation of the amount released

On the assumption that PVC is only suitable for use as a geomembrane in tunnel construction after 40 to 50 % plasticizers have been added, then a geomembrane with a thickness of 3 mm at an average density of PVC of 1.30 g/cm³ will produce a quantity of phthalates of

$$10^4 \text{ cm}^2 \times 0.3 \text{ cm} \times 1.30 \text{ g/cm}^3 \times 0.4 = 1{,}560 \text{ g/m2}$$

If it is further assumed that phthalates will be released at only 10 % (an optimistic view), then 156 g/m² will be released into the open system environment, into the groundwater or surface water over the years.

For a tunnel construction project, based on 10,000 m^2 of geomembranes of this type of material, for example, 1,560 kg would be released, in order to give a feeling for the scale.

6.2 Polyolefin geomembranes

Polyolefins (polyethylene = PE, polypropylene = PP) are mainly used as an alternative to soft PVC.

This group of plastics includes representatives such as polyethylene, polypropylene and polybutylene. The backbone of these plastics consists only of carbon and hydrogen. The polyolefins consist of alloys of these individual plastics and are often referred to as flexible polyolefins (FPO-A, A for Alloy) because they are significantly less rigid than polyethylene, for example.

Due to the composition, no relevant emissions are to be expected.

6.3 EPDM geomembranes

EPDM is the abbreviation for ethylene-propylene-diene terpolymer. The plastic consists of a combination of the three polymers ethylene, propylene and diene, which are linked to form a larger polymer. EPDM geomembranes are flexible particularly at low temperatures. Due to the composition, no relevant emissions are to be expected.

6.4 EVA geomembranes

Ethylene vinyl acetate (EVA) is also used as a further alternative to soft PVC. The plastic polymer is in turn composed of copolymers. The ethylene vinyl acetate copolymers are non-toxic. They contain no plasticizers or other additives. Vinyl acetate (VA) with a share ≥ 25 % is used in EVA geomembranes.

6.5 Pigments and stabilizers

Heavy metals are used as pigments. As a rule, they are embedded in a stable plastic matrix in the end products and are therefore only accessible to release in the use phase if these products are subject to severe abrasion. This is not the case for the application in tunnel lining considered here.

The heavy metals lead and cadmium are added in various compounds as stabilizers to plastics to prevent their decomposition by temperature, oxygen and light. Due to different chemical mechanisms, they ensure that the defects in the polymerization of the vinyl chloride (e.g. unsaturated end groups, double bonds) do not become the starting point for the splitting off of hydrogen chloride and thus a chain-like decomposition of the polymer. Sulphur-free and sulphur-containing tin stabilisers and various organic compounds also play an important role as stabilisers.

If geomembranes made of polyethylene (PE) are not stabilized, then depending on the properties of the individual materials [13] they will age under normal conditions within a few years to a few decades due to oxidative degradation.

Antioxidants are therefore added to polyethylenes for long-term stabilisation (e.g. high-molecular weight phenolic antioxidant). In addition, stabilizers for processing (e.g. phosphite for processing stabilization) and for extended storage are added. Typically, the sum of antioxidants and stabilizers is between 0.1 and 0.5 % by weight.

The situation of stabilisers has changed markedly in recent years. For example, the sale of cadmium stabilisers in the EU was stopped at the end of 2007. The use of lead-based stabilisers in PVC was reduced by more than 70 % in the EU by 2010.

By 2015, European PVC producers have committed themselves to a complete phase-out of stabilisers containing lead [9]. However, even after this date, it cannot be ruled out that PVC products containing lead stabilisers may be imported from non-EU countries (e.g. China). Lead-based stabilisers are mainly replaced by calcium-based stabilisers.

According to [9], tin stabilizers are only used in rigid PVC applications. According to [14], the higher costs are an additional reason why tin stabilisers are not an alternative to lead stabilisers.

As the stabilizers are firmly embedded in the stable plastic matrix, practically no heavy metals are released during usage, except for products whose use subjects them to severe abrasion. This is not the case for the use in tunnel lining considered here.

6.6 Summary assessment

In water law, the principle of cause for concern is the main pillar of consideration. And if certain plasticisers are officially discredited or a reasonable suspicion of danger exists, then there is cause for concern, even if the substances are not explicitly regulated by law or a regulation. The so-called Everyman's Clause (§ 5 WRA) always applies and is independent of the quantity.

The ecological product compatibility of geomembranes should be based on the basic procedure of the DIBt for the assessment of construction products [6], as shown in **Fig. 2** , or as provided for in the "Sustainable Construction (BNB)" rating system [15] of the Federal Ministry for the Environment, Nature Conservation, Construction and Reactor Safety **(Tab**. **2**).

According to the **DIBt approach** (**Fig. 2**), PVC geomembranes containing low molecular-weight phthalates (DEHP), (DBP), (BBP) and (DIBP) do not meet the requirements for soil and groundwater protection. This is already the case after stage 1 of the rating, as the main substances used are classified as environmentally hazardous due to their toxicity for reproduction in accordance with

EC Regulations, and there is a general ban on their manufacture and use. The decisive factor, however, is their very high release potential, so that the substances are released uncontrolled into the open system environment (in this case groundwater).

Although some high molecular-weight phthalates (DIDP), (DINP) and (DPHP) have not yet been evaluated at EU level and are therefore not subject to an EU ban, as a precautionary measure, PVC geomembranes containing these substances should not be used [12].

Based on the **"Sustainable Construction" rating system (BNB)"** [15], three potential pollutant groups must be considered in the evaluation of geomembranes.

1. Hazardous substances and Substances of Very High Concern (SVHC),
2. Hazardous substances which can be leached out,
3. Heavy metals (for geomembranes as plastic stabilisers).

Tab. 2: Requirements for the use of geomembranes

Quality level (QN)	**Requirements**
QN 1 Minimum requirements	Product documentation including declaration of SVHC > 0.1 % by weight in the candidate list
QN 2 (in addition to QN 1)	Exclusion of phthalates toxic to reproduction
QN 3 (in addition to QN 2)	no cadmium and lead stabilisers
QN 4 (in addition to QN 3)	Exclusion of phthalates toxic to reproduction, no cadmium, lead and tin stabilisers
QN 5 (additional to QN 3+4)	Exclusion of phthalates toxic to reproduction, no cadmium, lead and tin stabilisers, The following applies to PVC geomembranes in contact with soil and groundwater: documentation of the eluate values

After this, the evaluation comes to the same result as before. All geomembranes with reproduction-toxic phthalates as plasticizers are therefore not suitable for use as sealing in tunnel construction, even if there is only an indirect requirement at quality level QN 5 in the shape of a documentation of the eluate values.

The issue of heavy-metal stabilizers does not play any role in the use of geomembranes in tunnel construction dealt with here, since abrasion and disposal are not relevant in the specific area of application.

7 Conclusions

In assessing geomembranes in the specific application of tunnel construction, from the point of view of environmental protection only the groundwater path needs to be considered. Activities when in use, such as abrasion and disposal, are not taken into consideration because of the nature of the products' installation in the tunnel-lining construction. Occupational health and safety aspects and constructional requirements were not subject to evaluation here.

According to the assessment in Chapter 6, all geomembranes containing phthalate plasticisers should be excluded from use in tunnel construction, even if some phthalate plasticisers have not yet been assessed by the EU.

No substances may be added to the geomembranes which are classified as

- carcinogenic in category 1 or 2 or categories 1A and 1B according to Annex VI of EC Regulation 1272/2008,
- mutagenic in category 1 or 2 or categories 1A and 1B according to Annex VI of EC Regulation 1272/2008,
- toxic for reproduction in categories 1 or 2 or categories 1A and 1B according to Annex VI of EC Regulation 1272/2008,
- of very high concern for other reasons according to the criteria set out in Annex XIII of REACH, to the extent that they have been included in the list established under REACH Article 59(1) (so-called candidate list).

Heavy-metal stabilizers and heavy-metal pigments do not play a role in this consideration as they have no release potential.

Alternative products such as polyolefine geomembranes, EPDM geomembranes and EVA geomembranes, which do not pose a risk to groundwater, are available for the application under consideration here.

In any case, when selecting a product, care must be taken to ensure that the release potential of substances in the product matrix under the respective conditions of use and the ambient conditions is checked in advance and assessed for environmental relevance. In each individual case it must be checked whether plasticizers such as DEHP (di(ethylhexyl)phthalate), which are no longer permitted under EC Regulation, are contained.

The German Federal Environment Agency's 2007 [12] view that substances with properties of particular concern, such as phthalates, should generally be kept out of the environment for precautionary reasons can only be emphasized here, especially since other geomembranes are available. It is irrelevant here whether 20 % or only 2 % of hazardous substances are released into the environment.

8 Documents

[1] "Gesetz zur Ordnung des Wasserhaushalts (WHG - Water Resources Act)"

of 31 July 2009, (BGBl. I No. 51 p 2585), last amended on 04.12.2018

[2] "Verordnung zum Schutz des Grundwassers (GrwV – Grundwasserverordnung)" (Ordinance on the Protection of Groundwater (GrwV - Groundwater Ordinance) of 9 November 2010, (Federal Law Gazette No 59, p. 1513)

[3] "Ableitung von Geringfügigkeitsschwellenwerten für das Grundwasser" (Derivation of negligibility thresholds for groundwater) Länderarbeitsgemeinschaft Wasser (LAWA), status 15.07.2015

[4] Lühr, H.-P. "Die Geringfügigkeitsschwelle – Dreh- und Angelpunkt im Boden- und Grundwasserschutz" (The negligibility threshold - the linchpin of soil and groundwater protection) TerraTech 10/2004

[5] "AwSV - Verordnung über Anlagen zum Umgang mit wassergefährdendenden Stoffen" of 18 April 2017, (BGBl. I No. 22 p. 905)

[6] "Grundsätze zur Bewertung der Auswirkungen von Bauprodukten auf Boden und Grundwasser" (Principles for the assessment of the effects of construction products on soil and groundwater) Deutsches Institut für Bautechnik -DIBt, 2011

[7] "WECOBIS - Ökologisches Baustoffinformationssystem" (WECOBIS - Ecological Building Material Information System) Federal Ministry for the Environment, Nature Conservation, Building and Reactor Safety + Bavarian Chamber of Architects

[8] Commission Regulation (EU) 2018/2005 of 17 December 2018 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) as regards bis(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), benzyl butyl phthalate (BBP) and diisobutyl phthalate (DIBP) (OJ No L 322, 18.12.2018, p. 14)

[9] Sustainability initiative of the European PVC industry (Vinyl 2010)

[10] DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for Community activities in the field of water policy of 23 October 2000 (OJ L 327, 22.12.2000, p. 1)

[11] Regulation (EC) No 1272/2008 on classification, labelling and packaging of substan and mixtures (CLP or GHS Regulation) of 13 December 2008, (OJ 2008 L 353, p. 1)

[12] "Phtalate – Die nützlichen Weichmacher mit den unerwünschten Eigenschaften" (Phthalates - the useful plasticisers with the undesirable properties) Federal Environment Agency, February 2007

[13] Müller, W. "Handbuch der PE-HD-Dichtungsbahnen in der Geotechnik"

(Handbook of PE-HD geomembranes in geotechnics)
Birkhäuser, 2001

[14] "Leitfaden zur Anwendung umweltverträglicher Stoffe für die Hersteller und gewerblichen Anwender gewässerrelevanter Chemischer Produkte" (Guideline for the use of environmentally sound substances for manufacturers and professional users of water-relevant chemical products)
Part 5 "Hinweise zur Substitution gefährlicher Stoffe - 5.3 Funktion: Pigmente und Stabilisatoren" (Guidance on substitution of hazardous substances - 5.3 Functi Pigments and stabilizers)
Publisher: Federal Environment Agency Berlin, February 2003

[15] "Bewertungssystem Nachhaltiges Bauen (BNB)" (Rating System for Sustainable Building (BNB))
Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2019

[16] Database - ÖKOBAUDAT
Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2019

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