Geosynthetics in tunnels and underground structures applications

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Abstract. Waterproofing systems of tunnels is of crucial importance for the long-term effectiveness of the underground works and for the possible impact on the surrounding environment. In conventional tunnelling, polymeric geomembranes are nowadays used with fluid barrier function, while nonwoven geotextiles and geonets are commonly employed with mechanical protection and drainage functions. After some descriptions of the main requirements of the geosynthetics used in tunnels and underground structures, the durability aspects of the materials forming the waterproofing systems are briefly outlined.

1 Introduction

The interaction of structures and groundwater is one of the key aspects in the design of underground works. This interaction concerns structural, durability and environmental aspects. Inflows of water in underground structures is renown as one of the main damaging phenomena for both construction and operation of tunnels ([1], [2], [3]). Indeed, water reduces durability of lining materials (e.g. by eroding concrete and corroding steel rebars), water could also damage the infrastructures and the electrical plants (i.e. power stations, lightening, ventilation fans) and be the source of hazard for the users (e.g. due to wet road surface or ice stalactites). Water inflows (or losses in hydraulic tunnels) can compromise the stability of the structure by eroding fine particles of the surrounding soil and consequently compromising the original soil-structure interaction.

In addition to these structural issues, a lack of effective waterproofing of underground structures can result in impacts on the environment, such as lowering of groundwater level and, in the most severe cases, the draining of surface water sources.

Consequently, waterproofing is of primary importance in underground infrastructures. Luciani & Peila [4] report a summary of main existing waterproofing technologies for tunnels. Dammyr et al. [5] highlight that the use of polymeric geomembranes is nowadays the best solution considering the long-term efficiency of the entire waterproofing system.

The use of geomembranes as waterproofing in underground structures has begun in the ‘70s and is nowadays recognized as the standard technology. Waterproofing geomembranes

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are the most used technology as long-term barrier systems in tunnels excavated with conventional tunnelling, both for traffic tunnels and for hydraulic tunnels.

The waterproofing system is installed between the rock or primary lining and the final lining. This technology is applicable both for umbrella approach (i.e. only waterproofing the upper tunnel to manage leakage) and for full-round waterproofing. In hydraulic tunnels it is also possible the use of an exposed system, where the waterproofing system is installed at the intrados of the tunnel without an additional concrete layer internally. This technology is used for water velocities of several metres per second and uplift pressures of several megapascals. Of course, this technology is not applied in traffic tunnels where the passage of vehicles and the need for installation of internal plants do not permit this solution.

In hydraulic tunnels the waterproofing approach can be full-round for pressure tunnels (Fig. 1) or applied only in the problematic areas for free-flow tunnels (Fig. 2).

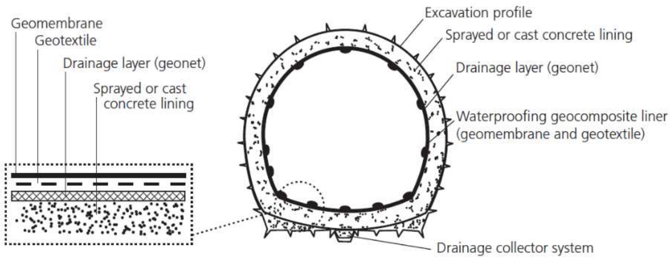

Fig 1. A typical hydraulic pressure tunnel cross-section, where the geomembrane is exposed [6].

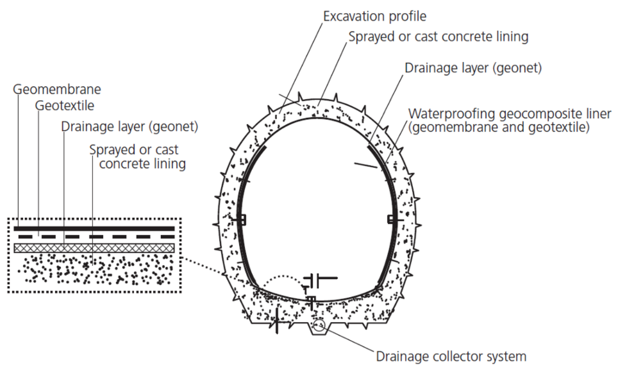

Fig 2. A typical hydraulic free-flow tunnel cross-section, where the geomembrane is placed over the walls & invert and left exposed [6].

It is important to not consider the single elements separately, but to take into account the whole waterproofing elements as a system (Fig.3). In traffic tunnels, the waterproofing system is usually composed of the superposition of various layers of geosynthetics, namely:

- Drainage layer
- Regularization layer
- Barrier layer
- Protection layer

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The first is a *drainage layer* that is connected to the rock mass or to the primary lining (usually not watertight) with the aim of permitting the water flow at the extrados of the barrier layer, and it is made of nonwoven geotextiles or geonets or drainage geocomposites. This layer avoids the uprise of unconsidered hydraulic loads on the final lining of the tunnel.

Second is the *regularization layer* which has the aim of protecting the inner geomembrane from damage due to the irregular geometry of the tunnel boundary and from punching. Usually, a polypropylene nonwoven geotextile is used, with high puncture resistance, fire resistance and elongation to failure.

The drainage layer is not always used, depending on the expected amount of water to be encountered. In fact, when a limited flow is expected, both drainage and regularization layers can be performed by a *unique layer*.

On these two layers (drainage and regularization) the barrier geomembrane is located. This is the core of the system and it is composed of a geomembrane, that can be made of plasticized polyvinyl chloride (PVC-P), polyolefins (TPO) or polymeric material joined to a bentonite layer. The most used material is PVC-P: in fact, according to the ITA - International Tunnelling Association, PVC geomembranes have been employed in over 92% of lined tunnels all over the world. In some cases, composite geomembranes - combining geotextiles and geomembranes in factory before application - are used.

Fig 3. Waterproofing geomembrane system installed in a tunnel before casting of final lining

The described layers are connected to the tunnel extrados by systematic use of fixing elements, which are disks or elements of the same material of the geomembrane, nailed to the substrate. Once the fixing elements are installed, the geomembrane is welded to them in order to keep the various layers in position, before and during casting. It is important to highlight that these fixing elements must be designed to fail before the geomembrane. In this way, it is possible to guarantee that, if the geomembrane is subjected to high shear loads during casting, the fixing element breaks, preventing any damage to the geomembrane itself. Velcro fastener fixings or strips may also be used as fixing elements if a composite geomembrane is used. In hydraulic tunnels with exposed systems the fastening system is composed of stainless-steel profiles, anchoring the composite geomembrane to the substrate. These fastenings can be tensioning profiles, flat profiles or a combination of those. When the tunnel is in operation, the composite geomembrane will be pushed against the existing surface of the concrete lining by the water pressure; when the tunnel is empty, the composite geomembrane will be subject to minimum deflections. This system eliminates wrinkles, thus improving hydraulic efficiency. For the covered protected system, the fixing elements have only to be designed in order to keep the geomembrane in position until the casting of the final lining and to avoid excessive deformation of the geomembrane during casting. Conversely, for an exposed unprotected system in hydraulic tunnels, the fastening system has to be designed considering operational conditions, suction areas and inward groundwater pressure during dewatering.

On the barrier layer constituted by geomembrane, a *protection layer* is frequently installed. This is composed of a polymeric layer with the aim of protecting the geomembrane itself against any possible job site damage before casting the final lining. This layer is not always used, but it can be very important particularly in the invert that is subject to job site traffic.

When a drained system is used, a drain that is able to collect the water flowing around the tunnel should be installed (Fig. 4). It is composed of a micro-slotted pipe installed in the lower part of the arch and connected to the drainage layer [7]. These pipes are then connected to the central drainage pipe of the tunnel, located in the invert or below the springs. The drainage system must be designed on the basis of the water inflow foreseen and of the potential deposition of fine-grained soils or salt (e.g. calcium carbonate) transported by the water.

Fig 4. Drainage pipe installed at the base of the spring, surrounded by the drainage layer and the barrier layer, i.e. geomembrane

2 Installation schemes and quality control

The elements and various layers of the waterproofing system described above are particularly important to guarantee the quality of the overall application: in fact, the correct choice of the waterproofing system as a whole could guarantee the efficiency of the long-term protection against water inflows.

The easiest installation scheme is the single layer system. It is made of a single layer of geomembrane installed above the drainage/regularization layer and welded to the fixing

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elements. The main disadvantage of this solution is that - if there is a damage - water is no longer controlled and it can run along the extrados of the lining till it finds a way to enter the tunnel. Since it creates a continuum layer, it is not possible to detect the damaged area and therefore repair works cannot be carried out and only remedial actions can be done.

This system can be improved with the compartmentalization: one single layer of geomembrane is used, but it is divided by transversal water-stops bonded in the cast concrete. In this way it is possible to create sectors of waterproofing systems of about 100—200 m^2. Compartmentalization is not always used, but its application is increasing all around the world and it is becoming compulsory in some countries ([8], [9]).

This technology permits an easy identification of the damage. Consequently, resin injection for the repair of the leakage can be performed in the exact position where is the damage. Injections are done through injection pipes usually installed before casting of the final lining and connected to an external control box. These injections have to be carried out in the layer between the geomembrane and the cast concrete, that is often irregular and therefore the volume of resin to be injected is not known *a priori*. This scheme has been widely used, e.g. in Milano Metro Line (Italy) or in Farringdon Station of Crossrail in London (UK) [10].

In any case, the most complete and upgraded scheme is the double layer system. In this case, two layers of geomembranes are welded together and divided into sectors using water-stops (Fig. 5). Water-stops are used to create separate sectors of about separate 60—80 m^2. The first self-evident advantage is of having a double barrier against water inflow. But, in addition to that, this scheme allows injection for repair to be made exactly between the two layers, with a high efficiency of the injection and with no waste of resin.

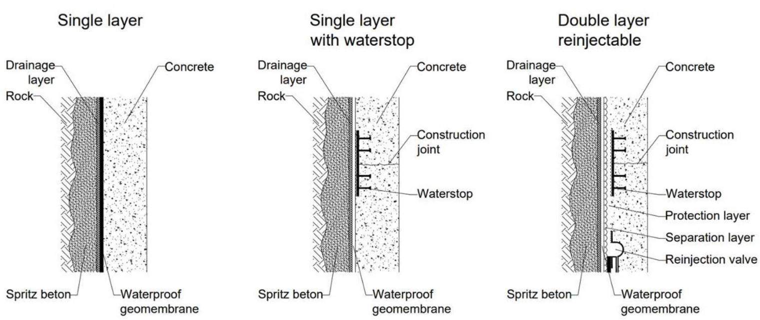

Fig 5. Installation schemes of waterproofing systems including geomembranes

Since geomembrane is a factory manufactured product, its quality is directly controlled during the manufacturing and certified by the supplier.

The first check to be done on site is the quality and smoothness of the substrate that has to comply with the required geometric constraints to avoid damage to the geomembrane itself.

Another crucial aspect of the watertight system is the quality of welds. The first level of control is the visual inspection in order to check the correct penetration and continuity of welds and the absence of burnt material. A manual hook or a screwdriver can be used to verify the continuity. Long welds are usually done with a double welding machine that creates two parallel welds with a channel in between. The aim of the channel is to allow for testing: the extremes of the channel are closed with clumps and pressured air is pumped in the channel through a needle with a pressure of 2 bar. The test is considered passed if after

10 minutes the pressure lowers less than 10% of the original value. Otherwise, the leakage point has to be precisely identified and reparation of welding has to be done (Fig. 6).

Fig 6. Geomembrane welding control with pressured air in the channel between the double welding.

For specific joints and patches, where double welded seams are usually not possible, the welding can be checked with a vacuum bell: soap solution is applied over the weld, the bell is put on the weld to be tested and vacuum is created (about 0.2 bars). The presence of holes will avoid the vacuum build-up and therefore bubbles will show their location.

The parameters of the welding tools (i.e. temperature, pressure, speed) have to be checked daily to be adapted to the environmental conditions of the jobsite (temperature, humidity).

3 Waterproofing system materials

3.1 Geotextiles

Geotextiles usually cover many functions (e.g. separation, reinforcement, filtration, drainage) and - in the case of waterproofing systems of tunnels - are used with two main functions: mechanical protection of the geomembrane from uneven substrate (*regularization layer*) and drainage of groundwater (*drainage layer*).

For the regularization layer, the main required property is puncture resistance particularly during the installation phase but also during operation. For the drainage layer, the main property is the in-plane permeability. The incorrect design of the drainage layer result in the upraising of unwanted and unforeseen hydraulic pressures on the final lining that can impact on the stability of the overall waterproofing system [11].

The polymers used are mainly polypropylene (about 95% of the market) and in some cases polyester (about 2%) and polyethylene (about 2%) [12]. The manufacturing can be woven or nonwoven, the latter being widely the most used for underground applications.

In such underground applications, nonwoven geotextiles are usually applied with a mass per unit area of more than 500 g/m^2.

However, geotextiles are inadequate for drainage in case of high flows. Furthermore, this kind of product may suffer important clogging due to the solid part contained into the water.

3.2 Geonets and geocomposites for drainage

In the case of high flows to be drained, the drainage layer can be a geonet, possibly used in a composite system forming a so-called "geocomposite for drainage". The most of geocomposite for drainage products fully answer the requirements of being flexible, able to guarantee a very high draining capacity, even under very important compressive stresses, having a very high compressive resistance and also an excellent puncture resistance.

Geocomposites for drainage (formed by geotextiles and geonets) can be used as enhanced drainage and filter layer in case of relevant design water flow and external pressure, avoiding the issues related to the reduction of permeability with external load that exists for geotextiles [13].

3.3 Geomembranes

The aim of geomembranes is to create a water barrier. This layer does not have any structural function during the operational life of the tunnel. Therefore, the required properties are mainly watertightness and continuity. While watertightness is guaranteed by the choice of the correct material (type of polymer, eventually type of bentonite composites), continuity has to be created through correct junctions (e.g. welding) and conserved during all phases of installation, casting and operation.

The required mechanical properties of the geomembrane aim to preserve the continuity of the geomembrane itself during storage, transportation, installation and casting, to avoid puncture damage during the design life and to assure the geomembrane to withstand the tensile loads that may act on it.

Geomembranes are often used also as a protection layer. In this case the same material used as the barrier layer is used but with different thickness (1.9 mm according to AFTES and 3 mm according to ÖBV [14]).

Polymeric geosynthetic barriers are the most used in waterproofing systems for underground structures. The polymers commonly used are PVC and TPO, only few examples as polyethylene (HDPE, LLDPE) and flexible polypropylene (fPP). The permeability of polymeric geosynthetic barriers ranges between $1\ 10^{-11}$ m/s and $1\ 10^{-14}$ m/s [12].

Bituminous geosynthetic barriers are sometimes used for cut-and-cover waterproofing and are obtained dipping geotextiles in bitumen or polymer modified bitumen (e.g. styrene-butadiene-styrene bitumen, SBS).

Clay geosynthetic barriers are seldom used in underground waterproofing systems, while they are more used in foundations and retaining walls related structures annexed to the tunnelling constructions. Their permeability is about $1\ 10^{-9}$ m/s [12].

As already mentioned, the most frequently and traditionally used material is PVC-P. Two types of PVC-P geomembrane are usually adopted in tunnels: translucent membranes and coloured ones. The former has the advantage of guaranteeing the purity of the material (absence of pigments and fillers) and allowing the visual checks of weldings and of any unwanted presence of burnt material on the weldings themselves ([9], [15]). The coloured geomembranes have the advantage of facilitating the identification of any damage to the geomembrane itself thanks to the signal layer. This consists of a two-colour geomembrane: the intrados layer of the geomembrane is made of a different coloured material with small thickness, usually only about 20% of the whole geomembrane thickness. If damage occurs to the surface of the geomembrane during installation works, the colour of the extrados layer appears and allows the damage and its position to be identified. This type of geomembrane is used in a growing number of applications and today it is required in many projects.

The success of PVC-P geomembranes is due to the fact that they are flexible and easy to install, even when the substrate geometry is irregular. Moreover, they exhibit good workability and weldability and they are self-extinguishing. TPO geomembranes are more increasingly used in Germany and Switzerland. Polyolefins have a relatively lower weldability and are stiffer than PVC-P. This results in some difficulties during installation in irregular geometries. On the other hand, polyolefins have better resistance to aggressive underground environment, especially where aromatic hydrocarbons are present.

Finally, sometimes a polymeric membrane joined with a bentonite layer is used. This technology advantages the swelling properties of bentonite: if leakage occurs, the bentonite is self-repairing. This kind of solution is frequently used in cut-and-cover tunnels and below the invert of the tunnel, but is not usually applied in bored tunnels and in hydraulic tunnels with water pressures [16].

3.4 Standard requirements

In the following Tables the requirements on waterproofing systems from different national authorities are summarized. In particular, Table 1 illustrates the requirements for geotextiles, in which there is a remarkable variety in the prescribed values. On the contrary, in Table 2 referred to geomembrane requirements, some properties are common to almost all technical documents and their values are quite constant: thickness at least 2 mm, tensile strength greater than 12 N/mm^2 for PVC-P and 15 N/mm^2 for TPO and strain at failure greater than 250% for PVC-P and 500% for TPO.

Table 1. Required properties for geotextiles for the different authorities in Europe

		OBV [14]		**SIA [17]**	**DB [18]**	**RFI**	**BBT**	
Properties	Unit	PP (max 10% internal reworked)		-	PP or HDPE	-	PP (max 5% internal reworked)	
Mass per unit area	(g/m^2)	≥500 (crown and springs)	≥900 (invert and cut &cover)	500-1500	500-1200	≥500	≥500	≥900
Thickness at 200 kPa	(mm)	≥1.7	≥3.4	-	≥4	≥1.9	≥1.7	≥3.4
Tensile strength	(kN/m)	≥30	≥50	≥15	≥25-30	≥30	≥30	≥50
Tensile strain at failure	(%)	≥50		≥20	≥50 (nonwoven) ≤30 (woven)	-	≥50	-
CBR puncture resistance	(kN)	≥3	≥7	≥2.5	≥5.5 and < 20	≥5	≥3	≥7
Dynamic perforation (cone drop test)	(mm)	≤13	≤7	≤10	-	-	≤13	≤7
In plane permeability	(m^2/s)	≥2 10^{-6} (@200 kPa)		≥ 10^{-5} (@200 kPa)	≥ 10^{-3} (@20 kPa)	≥1.5 10^{-6} (@100 kPa)	≥2 10^{-6} (@200 kPa)	
Fire resistance	(-)	Class E		-	B2	-	Class E	

***OBV:** Österreichische Bautechnik Vereinigung (Austrian Tunnelling Association); **SIA**: Schweizerischer Ingenieur- und Architektenverein (Swiss Society of Engineers and Architects); **DB:** Deutsche Bahn AG (German Railways); **RFI:** Rete Ferroviaria Italiana (Italian Railways Infrastructures); **BBT:** Brenner Basistunnel (Brenner Base Tunnel).

Table 2. Required properties for geomembranes for the different authorities in Europe

		OBV [14]		**SIA [17]**	**DB [18]**		**RFI**		**BBT**	**MEF [9]**
Properties	Unit	PVC-P	TPO	-	PVC-P	PE	PVC-P	TPO	PVC-P	PVC-P
Thickness	(mm)	≥2	≥2	≥2	≥2		≥2		≥2	≥2
Tensile strength	(N/mm^2)	≥12	≥15	-	≥12	≥15	≥15		≥12	≥12
Tensile strain at failure	(%)	≥250	≥500	≥200	≥300	≥500	≥250	≥500	≥250	≥270
Elastic modulus 1-2%	(N/mm^2)	≤20	≤65	≤80 (TPO) ≤20 (other)	<20	<100	-		≤20	-
CBR puncture resistance	(kN)	>2.5	>2.8	-	-	-	-		>2.5	0.6-1.7
Foldability at low temperature	(°C)	-20	-	-20	-20		-20		-20	-20
Fire resistance	(-)	Class E		Class E or F	-		Class E		Class E	-

*__OBV:__ Österreichische Bautechnik Vereinigung (Austrian Tunnelling Association); **SIA**: Schweizerischer Ingenieur- und Architektenverein (Swiss Society of Engineers and Architects); **DB:** Deutsche Bahn AG (German Railways); **RFI:** Rete Ferroviaria Italiana (Italian Railways Infrastructures); **BBT:** Brenner Basistunnel (Brenner Base Tunnel); **MEF**: Ministere de l'Equipement Francais (French Minister of Equipment).

4 Durability of waterproofing system materials

Standard requirements for traffic tunnels are nowadays very high, requiring dry or almost dry internal surface. Lifespan of modern infrastructures is often of 100 years or more (e.g. Brenner Base Tunnel between Italy and Austria has been designed for a lifespan of 200 years). Furthermore, repair or replacement of the waterproofing system materials is very difficult when they are installed between the primary and the final linings.

Consequently, the durability of the waterproofing system materials is of overwhelming importance to avoid unforeseen costs and disruptions during the entire structure lifespan.

4.1 Geotextiles

The long-term performances of a geotextile, respectively in terms of drainage and also of filtration (when they are used as filter layer in geocomposites for drainage), are influenced by clogging. Clogging can with different mechanisms:

- Mechanical internal clogging, the accumulation of fine particles within the voids of the geotextile [19]

- Mechanical external clogging, the formation of a filter cake at the interface between geotextile and soil [20]
- Biological clogging, when fungi or algae create biofilms and slimes on the fibres (not really common in underground applications, but possible in some specific cases)
- Chemical clogging, caused by solutes precipitated on the fibres due to the reduction of the speed of the flow in the geotextile. This phenomenon can be relevant in some underground applications depending on the groundwater properties.

Groundwater rich in solutes as calcium, sodium and magnesium are more prone to cause clogging. Veylon et al. [20] report that on the side of 18 years aged geotextiles used as filters a calcite stratum has been observed, affecting the permeability. With the increase of $Ca(OH)_2$ in the water, the flow time through the geotextile increases due to the formation of a filter of precipitate on the fabric [21].

Mechanical clogging is more common in soft ground tunnels rather than in rock tunnels due to the nature of the surrounding soil.

Clogging is influenced by water solutes, by soil properties and by the properties of the geotextile. Higher porosity of the geotextile reduces the risk of clogging but at the same time reduces the permeability properties.

Nonwoven geotextiles, used in tunnel waterproofing systems, usually exhibit a lower tendency to clog because the irregular structure of the fabric creates many connected flow paths with great variation of nominal diameter and shape. Therefore, even if some particles are stopped in the geotextile, they do not completely stop the flow in that section.

Moreover, squeezing induced by ground load can reduce the permittivity of geotextiles and consequently causes the reduction of effectiveness of the drainage system. Cazzuffi et al. (2022) [22] show the design flowchart for the selection of the best geocomposite for drainage to be used in a tunnel taking into account design waterflow and the ground load acting.

Moreover, when the geotextile is part of a drainage geocomposite structure, the design of the filter must be correctly faced considering the required properties taking into account the long-term effectiveness of the system. Yoo & Kim (2016) [11] summarize the design criteria for filtration.

Polyolefins (PE, PP) geotextiles could degrade by oxidation. Even if the exact process of oxidation in solid state of polyolefins is complex and still under analysis, the principal steps of the reaction are well known [23]. This phenomenon requires energy, that is provided by temperature, high energy radiation or UV rays. Once the process is initiated it proceeds rapidly as a chain reaction if oxygen is present. Since the oxidation products act as initiators for other chains, the reaction is auto-accelerated [24]. The result of oxidation is the breakage of polymer chains and consequently the reduction of strength. In PE the oxidation can also induce cross-linking, leading to lower flexibility [25]. Of course, for tunnels and underground applications, where high temperature and UV rays are not relevant, oxidation phenomena are remarkably reduced.

PET geotextiles could be affected by hydrolysis. In presence of water and with acid or neutral pH, water is absorbed and hydrolysis takes place throughout the cross-section of the fibre causing the progressive reduction of strength. Whereas, in alkaline environments the aggressive ions cannot penetrate the fibres and the hydrolysis takes place on the surface. The consequent strength reduction is due to the fibres cross section reduction [24]. Therefore, the application of PET geotextiles in direct contact with fresh concrete, such as in tunnel waterproofing, should be avoided, due to the presence of water and of pH>9 in the concrete, which are the typical environment parameters inducing hydrolysis.

4.2 PVC-P geomembranes

Degradation of PVC is mainly due to dehydrochlorination. Dehydrochlorination is the loss from PVC of gaseous HCl and the formation of a double bond between the carbon atoms. Once the reaction is initiated in a monomer it propagates in the adjacent one with a chain reaction. The starting energy for the first reaction can derive from a thermal source or from UV. The result of thermal and UV degradation is a more brittle material and crack formation [26]. In plasticized PVC (PVC-P) microbial attack can affect durability because fungi degrade the plasticizer [27]. Sabev et al. [28] analysed different PVC-P samples buried in ground and identified 42 fungal species while bacteria attacks are not relevant. The consequence of this biological degradation is a stiffer material with higher tensile strength. In PVC-P, thermal degradation of plasticizer can occur, but it is strictly depending on the plasticizer molecule. Plasticizers decompose in a range of temperature around 180–300 °C, that is the same range of PVC dehydrochlorination. However, in underground applications UV rays or high temperatures are not present and therefore both dehydrochlorination and plasticizer decomposition are not really common.

Therefore, the most relevant degradation phenomenon of PVC-P geomembranes in underground applications is plasticizer loss. Since plasticizer is not chemically bonded to the PVC chain, it can migrate with time outside the geomembrane. As plasticizer is lost, the material becomes stiffer, with higher surface hardness and tensile strength, but with a more brittle behaviour. Moreover, plasticizer loss may cause the shrinkage of the geomembrane. Giroud & Tisinger [29] suggest a theoretical equation to compute the shrinkage of a geomembrane.

In any case, very few examples are reported in the scientific literature on PVC-P geomembranes monitoring for studying the eventual effects of degradation in tunnelling. Usman and Galler [30] report the analyses on ten samples from five different tunnels in Austria after about 30 years of operation. The PVC-P is in some cases stiffer than modern geomembranes and has a lower plasticizer content. However, the lack of information on the original properties of the material does not permit establishing a correct correlation. The authors conclude that the degradation level does not compromise the serviceability of the geomembrane itself. Maehner et al. [31] take samples of PVC-P geomembrane from a 43 years old railway tunnel structure in Germany. The PVC-P geomembrane has a thickness of 1.5 mm and is protected by a 1.0 mm thick rigid geomembrane and by a nonwoven geotextile. The original material has not been found and therefore no comparison has been possible with the original properties. Nevertheless, the mechanical properties of the aged geomembrane and also of the geomembrane weldings fulfils the actual requirements and no damage has been found. In fact the tensile strength of the aged material is >12 N/mm^2 and the elongation at failure >150%. The clear lack of reported case histories and the shortage of information on the original properties and on the ageing environment for the reported ones do not permit a deeper analysis of data coming from underground naturally aged PVC-P geomembranes. Therefore, at the present state of the knowledge, accelerated ageing tests seem the best available tools for a long-term evaluation of durability of waterproofing systems.

To achieve this goal, several ageing tests have been developed to investigate long-term durability of PVC-P geomembranes. These tests differ for the environment and for the conditions of ageing, considering different degradation phenomena (e.g. loss of plasticizer, chemical effect of the environment, UV rays, biological degradation). The control requirements are usually tensile properties variation and weight change. These are not directly representative of chemical or compositional variations in the material and in many applications are not sufficient as parameters for a complete evaluation of the performance at the long term.

Nevertheless, these parameters, easy to be measured, give a qualitative assessment of the ageing and also tunnel designers are more familiar with these mechanical characteristics rather than with chemical observations. The existing accelerated ageing tests can be subdivided considering the ageing environment and degradation mechanisms simulated:

- Oxidation test, in an air environment accelerated by heat
- Immersed test, in water environment accelerated by heat and/or by emphasizing peculiar the chemical conditions (e.g. solutions of calcium hydroxide and sulphur composites to simulate aggressive groundwater)
- Micro-organism test
- UV weathering test

The data obtained from accelerated ageing tests have to be extrapolated to the long term. This is often done with the Arrhenius' equation. However, this equation cannot correctly simulate the plasticizer loss phenomenon. Luciani et al. [32] suggest the use of Fick's diffusion law, taking into account also the dependency of the degradation on the plasticizer concentration. With this equation Luciani et al. [32] have evaluated a life span of about 150 years for two commercial PVC-P geomembranes at 15°C based on laboratory accelerated ageing tests, thus confirming the suitability of this type of polymer to maintain the required properties during the entire lifetime of the infrastructure.

Durability of PVC-P geomembranes depends on several aspects:

- the composition of the material (additives, filler, type of plasticizer).
- application environment: the chemical nature of surrounding soil and groundwater can reduce the durability of the geomembrane in case of particularly aggressive water
- application temperature: the temperature in underground structures is less dependent on the seasonal variation and in shallow tunnels in temperate climate the temperature can be quite constant, around 15°C. Higher temperatures, up to 40°C, that accelerate degradation phenomena, exists only in very deep tunnels (e.g. Brenner Base tunnel, Lyon-Turin base tunnel [33]) and in this case the waterproofing system and materials must be carefully selected
- thickness of the geomembrane: the thickness of the geomembrane has an influence both on its capability of face puncture loads without damages and also on its durability. Since the degradation in mainly due to plasticizer loss, a thinner geomembrane results in a lower migration path and thus in a lower durability. Geomembranes with thickness lower than 2 mm are usually not used; nowadays, in important tunnelling applications, higher thickness should be recommended.

5 Conclusions

An important tool for the selection of an adequate list of properties for geosynthetics in tunnelling constructions are the existing harmonised European Standards EN, currently in a process to be updated. These harmonised standards on geosynthetics have ben developed in the frame of the CEN TC 189 (Geosynthetics) activities.

In particular, the standard EN 13256 [34] specifies the relevant characteristics of geotextiles and geotextile-related products and the appropriate test methods to determine these characteristics, in particular to allow these materials to perform the function of mechanical protection of geosynthetic barriers used in tunnels and underground structures.

Moreover, the standard EN 13252 [35] specifies the relevant characteristics of geotextiles and geotextile-related products used in drainage systems and the appropriate test methods to determine these characteristics and to allow these permeable materials to perform the crucial function of drainage in waterproofing systems of tunnels and underground structures.

Finally, the standard EN 13491 [36] specifies the main characteristics of geosynthetic barriers, including polymeric geosynthetic barriers as PVC-P, clay geosynthetic barriers and bituminous geosynthetic barriers, when used as fluid barriers and separation layers in the construction of tunnels and associated underground structures, and the appropriate test methods to determine these characteristics. The intended use of these products is in fact to adequately control the eventual leakage of fluids through the entire life of these constructions.

These European Harmonised Standards EN may be used to derive design values by taking into account factors within the context of the definitions given in EN 1997 1 [37]. The design life of the specific product should be in fact determined, since its function may be temporary, as a construction expediency, or permanent, for the lifetime of the structure itself.

In any case, the construction ecosystem is of strategic importance also to the European Union, as it delivers the buildings and infrastructure needed by the rest of the economy and society while being a key element for the implementation of important EU strategies and initiatives, including the European Green Deal and the EU Climate Adaptation Strategy.

Within the construction ecosystem, road and railway tunnels take an important share of the European infrastructure market, playing a central role in securing business continuity and supporting fast connections, including for emergency services.

Despite tunnels and other underground structures being unique structures, there are no European design standards or harmonised guidelines, and their structural design is based primarily on national standards, knowledge and experience. Thus, there is need for developing common European design standards for tunnels and other underground structures within the established framework of the Eurocodes (EN 1990 – EN 1999), already covering many other types of structures.

The standardisation works can build upon the initial technical assessment of the Eurocodes applicability for the design of underground structures as performed by the JRC Expert Network on the standardisation needs for underground structures in the period 2020-2022. An Ad-Hoc Group on Tunnelling and Underground Structures under CEN TC 250 (Structural Eurocodes) is recommended to be established and prepare a Project Plan with the items to be treated in the various CEN TC 250 Sub Committees [38].

For sure, the preparation of an Ad-Hoc Eurocode on Tunnelling and Underground Structures will have a quite important impact on the overall international scientific community, both in Europe and also in the rest of the world.

References

1. ITA WG 6, *Study of methods for repair of tunnel linings*. International Tunnelling Association (2001)
2. CETU, *Guide de l'inspection du génie civile des tunnels routiers – Livre 1: du désordre á l'analyse, de l'analyse á la cotation*. (2015).
3. F. Sandrone, V. Labiouse, *Identification and analysis of Swiss National Road tunnels pathologies*. Tunnelling and underground space technology, 26 (2), 374–390 (2011).
4. A. Luciani, D. Peila, *Tunnel waterproofing: available technologies and evaluation through risk analysis*, International Journal of Civil Engineering, 17 (1), pp. 45-59, (2019).
5. Ø. Dammyr, B. Nilsen, K. Thuro, J. Grøndal, *Possible concepts for waterproofing of norwegian TBM railway tunnels*. Rock Mechanics and Rock Engineering, 47(3), pp. 985–1002 (2014).

6. D. Cazzuffi, A. Scuero, G. Vaschetti, *Hydraulic and transport tunnels, and shafts*, Chapter 18, ICE Handbook of Geosynthetic Engineering: Geosynthetics and their applications (2022).
7. J. L. Mahuet, *Recomandations sur l'étanchéité et le drainage des ouvrages souterrains*. Tunnels et ouvrages souterrain, 159, 41–59 (2005).
8. J.L. Mahuet, *Racommandations relatives à l'utilisation et la mise en oeuvre d'un compartimentage associé à un dispositif d'étanchéité par géomembrane synthétique.* Tunnels et ouvrages souterrain, 2, 11–17 (2005).
9. Ministère de l'Equipement. *Fascicule 67 - III du Cachier des Clauses Techniques Générales (CCTG) - Etanchéité des ouvrages souterrains.* Ministère de l'Equipement, des Transports at du Logement - Secrétariat d'Etat au Logement - Secrétariat d'Etat aux Transports, (2014).
10. E. Dal Negro, M. Leotta, E. Pavese, *Advanced waterproofing at Farringdon Station*. Tunnelling Journal, 30–35 (2016).
11. C. Yoo, B. Kim, *Geosynthetics in Underground Construction*, in: Proceedings of EuroGeo 6, 25-28 September (2016).
12. R. M. Koerner, *Design with geosynthetics*. Xlibris Corporation (2012).
13. Y.-S. Jang, B. Kim, J.-W. Lee, *Evaluation of discharge capacity of geosynthetic drains for potential use in tunnels*, Geotextiles and Geomembranes, 43(3), 228-239 (2015).
14. ÖBV, *Guideline: Tunnel waterproofing*. Österreichische Bautechnik Vereinigung (2015).
15. J. L. Mahuet, *Prolongement de la ligne B de part-dieu à jean macé du metro de Lyon*. Tunnels et ouvrages souterrains, (62), 59–69 (1984).
16. J. L. Mahuet, *Bilan et évolution de la mise en oeuvre des GSB dans les ouvrages souterrains,* in Proceedings of 8 Rencontres Géosynthétiques (2011).
17. SIA 272, *Abdicthungen und Entwässerungen von Bauten unter Terrain und im Untertagbau*. Schweizerischer Ingenieur- und Architektenverein (2009).
18. DB, *Richtlinie 853.4101 – Eisenbahntunnel planen, bauen und instand halten*. Deutsche Bahn Netz AG (2011).
19. N.-E. Sabiri, A. Caylet, A. Montillet, L., Le Coq, Y. Durkheim, *Performance of nonwoven geotextiles on soil drainage and filtration*. European Journal of Environmental and Civil Engineering, 1–19 (2017).
20. G. Veylon, G. Stoltz, P. Mériaux, Y.-H. Faure, N. Touze-Foltz, *Performance of geotextile filters after 18 years' service in drainage trenches*. Geotextiles and Geomembranes, 44 (4), 515–533 (2016).
21. Y. Halse, R. Koerner, A. E. Lord, *Effect of high levels of alkalinity on geotextiles. Part 1: Ca(OH)2 solutions*. Geotextiles and Geomembranes, 5 (4), 261–282 (1987).
22. D. Cazzuffi, M. Cunegatti, P. Recalcati, *Drainage geocomposites and PVC geomembranes for the lining of a highway tunnel in Greece*, Geosynthetics magazine (2022).
23. Y. Hsuan, H. Schroeder, K. Rowe, W. Müller, J. Greenwood, D. Cazzuffi, R. Koerner, *Long-term performance and lifetime prediction of geosynthetics*, in Proceedings of the 4th European Conference on Geosynthetics, Edinburgh, September. Keynote paper (2008).
24. S. Allen, *Geotextile durability*, in Geotextiles, 177–215 (2016).

25. J. H. Greenwood, H. F. Schroeder, W. Voskamp, *Durability of geosynthetics*. CRC Press, Taylor & Francis Group (2015).
26. ISO/TS 13434, *Geosynthetics – Guidelines for the assessment of durability*. International Organization for Standardization (2008).
27. G. Booth, A. Cooper, J. Robb, *Bacterial degradation of plasticized PVC*. Journal of Applied Bacteriology, 31 (3), 305–310 (1968).
28. H. Sabev, P. Handley, G. Robson, *Fungal colonization of soil-buried plasticized polyvinyl chloride (pPVC) and the impact of incorporated biocides*. Microbiology, 152 (6), 1731–1739 (2006).
29. J. P. Giroud, L. Tisinger, *Relationship between PVC geomembrane density and plasticizer content*. Geosynthetics International 2 (3), 567–586 (1995).
30. M. Usman, R. Galler, *Ageing and Degradation of PVC Geomembrane Liners in Tunnels*, in Proceedings of the International conference on Chemical, Civil and Environmental Engineering, Singapore, November (2014).
31. D. Maehner, C. Peter, B. Sauerlaender, *Langzeitverhalten von Kunststoffdichtungsbahnen*. Tunnel, 37 (1) (2018).
32. A. Luciani, C. Todaro, D. Martinelli, D. Peila, *Long-term durability assessment of PVC-P waterproofing geomembranes through laboratory tests*. Tunnelling and Underground Space Technology, 103 (2020).
33. P. H. Flüeler, M. Farshad, C. Löwe, H. Kramer, H. Böhni, *New Evaluation Procedure of the Waterproofing Systems for the Swiss Alpine Base Tunnels*, in: (Re) Claiming the Underground Space. Routledge, p. 441-447 (2003).
34. EN 13256, *Geotextiles and geotextile-related products. Characteristics required for use in the construction of tunnels and underground structures*, (2016).
35. EN 13252, *Geotextiles and geotextile-related products. Characteristics required for use in drainage systems*, (2016).
36. EN 13491, *Geosynthetic barriers. Characteristics required for use as a fluid barrier in the construction of tunnels and associated underground structures*, (2018).
37. EN 1997-1, Eurocode 7: *Geotechnical design - Part 1: General rules*, (2004).
38. A. Athanasopoulou, W. Bogusz, D. Boldini, M. Brandtner, R. Brierley, S. Dimova, G. Franzen, H. Ganz, U. Grunicke, N. Malakatas, A. Pecker, K. Roessler, A. Sciotti, A. van Seters, M.L. Sousa, *Prospects for designing tunnels and other underground structures in the context of the Eurocodes,* A. Athanasopoulou, S. Dimova, G. Franzen, A. van Seters (Editors), Publications Office of the European Union, Luxembourg, doi:10.2760/307164, JRC130784 (2022).