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Evaluation of durability of PVC-P geomembranes for tunnel waterproofing with laboratory tests

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ABSTRACT: Durability of waterproofing systems used in tunnels is of main importance because water highly influences durability, effectiveness and maintenance costs of underground structures. PVC-P geomembranes are one of the most applied technologies for tunnel waterproofing, nonetheless there is a lack of knowledge on their durability in underground applications. Even if long-term durability of PVC-P geomembranes has been analysed for outdoor applications (e.g. dams, roofs), few information are available for applications in underground conditions. In this paper the durability of two commercial PVC-P geomembranes for tunnelling applications is analysed based on the results on laboratory tests. Plasticizer absorption tests and mechanical tests are performed on the commercial geomembranes and on eight formulations of PVC-P specifically produced. The results of those tests permit to study the long-term degradation due to plasticizer loss and extrapolate the losses in time. Finally, an end-of-life time for the geomembranes has been defined merging mechanical requirements for the membrane and the long-term evolution of the degradation of the properties.

1 INTRODUCTION

Water is renown as one of the main causes of damages to underground structures and of their maintenance costs. Therefore, the use of effective and durable waterproofing systems is of overwhelming importance for tunnels. In conventional tunnelling, the waterproofing system is nowadays constituted by a geomembrane installed in between the primary and the final concrete lining (Luciani & Peila 2019).

The design life span for new tunnels is of about 100 years and, in some cases, it can rise to 150 years. This request, combined with the inner surface quality requirement of absence of leakages and moisture spots, point out the importance of durability of waterproofing system. Moreover, since waterproofing is installed behind the concrete lining of the tunnel, it is difficult or almost impossible to perform maintenance or substitute it. As a consequence, the durability requirement on waterproofing systems for tunnel applications has to be the same of the whole tunnel (i.e. 100 years). Nevertheless, there is a clear lack of knowledge on the durability of waterproofing membranes used in underground structures.

In this study the durability of plasticized PVC (PVC-P) geomembranes is analysed. PVC-P geomembranes are one of the most used material for underground applications.

Durability of PVC-P has been analysed in many applications (e.g. waterproofing of roofs, dams, channels) (Blanco *et al*. 2012; Cazzuffi 1995, 2016; Newman *et al*. 2004; Stark *et al*. 2005) but there are almost none studies on underground applications.

Moreover, there are also few reported cases in scientific literature of geomembranes naturally aged in underground applications for 30–40 years (Maehner *et al*. 2018; Usman & Galler 2014) while data for longer times do not yet exist. Therefore, the study of durability of geomembranes in these applications are still based on accelerated tests (Luciani *et al*. 2020).

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2 PVC-P DEGRADATION IN TUNNELS

PVC degradation is mainly caused by dehydrochlorination, i.e. the loss of gaseous hydrochloride from the PVC chain. The energy needed to initiate the degradation process comes from heat or ultraviolet (UV) rays. However, in underground applications, high temperatures or UV rays are absent, and so this phenomenon can be neglected.

Consequently, the main degradation phenomenon occurring to PVC-P in underground is the loss of plasticiser. Plasticizer is not chemically bonded to the polymer chain and so, during the life of the material, migrates from the geomembrane into the surface and then in the surrounding environment (Marcilla *et al.*, 2004; Storey *et al.*, 1989).

The plasticizer content is defined by the concentration expressed as percentage by weight. The loss of plasticizer is described with the plasticizer loss ratio P_L (Benneton 1994) defined as

$$P_L(t) = \frac{M_{P_0} - M_P(t)}{M_{P_0}} \tag{1}$$

with M_{P_0} the initial mass of plasticizer and $M_P(t)$ the mass of plasticizer at time t.

The study of durability of PVC-P waterproofing geomembranes consists in evaluating the evolution of this phenomenon with time and its impact on the mechanical properties of the material.

3 PLASTICIZER LOSS EVALUATION

The degradation of geomembranes is sometimes extrapolated on the long term with Arrhenius' equation. This equation permits to evaluate with accelerated tests at different temperatures a rate constant of the phenomenon. However, this simple correlation implies a constant rate of the phenomenon with time that is not realistic for the case of plasticizer loss, where the rate is dependent on the gradient of concentration between the geomembrane and the environment. Moreover, in PVC-P the rate is also influenced by the plasticizer content because as the plasticizer content reduces it becomes more difficult to the plasticizer to diffuse in the now stiffer matrix.

Since plasticizer loss can be analysed as a mono-dimensional diffusion problem, in order to have a better evaluation of the physical phenomenon, the evaluation of plasticizer loss can be performed using Fick's law of diffusion

$$\frac{\partial c(x,t)}{\partial t} = D\frac{\partial^2 c(x,t)}{\partial x^2} \tag{2}$$

with $c(x,t)$ the value of plasticizer concentration at time t and in the coordinate x inside the thickness of the membrane and D is the diffusion coefficient.

In tunnel applications, one side of the membrane is constantly cleaned by the flow of the water drained from the rock mass, and therefore it is possible to consider the plasticizer concentration on the external surface always equal to zero. On the other side of the geomembrane, in contact with concrete, diffusion is considered negligible. As an initial condition the concentration in all the points of the geomembrane is set constant as the initial value.

Solving Equation (2) in the given boundary and initial condition it is possible to obtain the concentration at any time inside the membrane as

$$c(x,t) = -\sum_{n=1}^{\infty} C_0 \frac{4}{(2n-1)\pi} e^{-D\left(\frac{2n-1}{2L}\pi\right)^2 t} \sin\left(\frac{2n-1}{2L}\pi x\right) \tag{3}$$

One of the factors governing the computation is the diffusion coefficient D, that must be dependent on the concentration and temperature in order to account for PVC-P behaviour.

To evaluate the dependence of D on these parameters, plasticizer absorption tests have been performed.

4 PLASTICIZER ABSORPTION TESTS

4.1 *Test procedure and materials*

Plasticizer absorption tests permit to evaluate diffusion coefficient of plasticizer in a geomembrane. Small specimens of geomembrane of regular and known surface are cut with a metallic hollow cutter, cleaned on the surface, dried in a desiccator and weighted. Specimens are then immersed in plasticizer at a specific temperature and the change of weight is measured overtime. The diffusion coefficient is obtained by fitting the data of weight-time curve with the diffusion law (Griffiths *et al.* 1984; Storey *et al.* 1989).

Tests have been performed at 4 different temperatures: 20°C, 45°C, 60°C and 75°C.

Since the study aims to evaluate the durability of waterproofing geomembranes used in underground applications, two commercial geomembranes have been considered: geomembrane A, that is a 2 mm PVC-P coloured geomembrane with filler, and geomembrane B, a 2 mm PVC-P translucent geomembrane without filler.

In addition to these commercial materials, 8 specifically produced geomembranes have been testes. These geomembranes have been formulated with different plasticizer contents, with and without filler. The production of both geomembranes with and without filler aims to evaluate the parameters for both commercial geomembranes. Table 1 summarises the composition of the 10 tested materials. For materials A and B, Table 1 reports the sum of the content of PVC and stabilizer because separated values are not available.

The plasticizer used for the tests is the same used to produce the geomembranes.

Table 1. Tested materials composition.

Material	PVC (%)	Stabilizers (%)	Plasticizer (%)	Filler (%)
A	56.0		24.0	20.0
B	73.3		26.7	0.0
1	67.4	2.6	30.0	0.0
2	72.4	2.6	25.0	0.0
3	77.4	2.6	20.0	0.0
4	82.4	2.6	15.0	0.0
5	47.4	2.6	30.0	20.0
6	52.4	2.6	25.0	20.0
7	57.4	2.6	20.0	20.0
8	62.4	2.6	15.0	20.0

4.2 *Results*

From the analysis of the results on the same material at different temperature, an exponential relation between diffusion coefficient D and temperature T has been observed, analogous to Arrhenius' equation. The correlation can be expressed as

$$D(T) = D_0 \cdot e^{-\frac{E_A}{R \cdot T}} \tag{4}$$

where D_0 is a constant, E_A is the activation energy, R the gas constant and T is the temperature.

Similarly, from the results of absorption tests performed at the same temperature on geomembranes with different initial plasticizer content, the dependence of diffusion coefficient on plasticizer content has been evaluated. In this case a potential law has been obtained:

$$D(c) = D_1 \cdot c^b \tag{5}$$

where D_1 and b are constants, and c is the content of plasticizer.

The values of diffusion coefficient obtained for material A is in good agreement with the ones of the geomembranes with filler, and the one of material B with the ones of geomembranes without filler, thus confirming that the results of the tests can be applied to the two commercial geomembranes.

Diffusion coefficient for materials with filler are higher than the ones of materials without filler, confirming that the degradation of geomembranes without any filler is slower. Figure 1 and Figure 2 show examples of the results obtained in terms of temperature and concentration correlation. Figure 2 also compares the results for the two commercial geomembranes (A and B) and the 8 specifically produced geomembranes: Material A fits very well with the results of geomembrane with filler, while material B has a slightly worse fit.

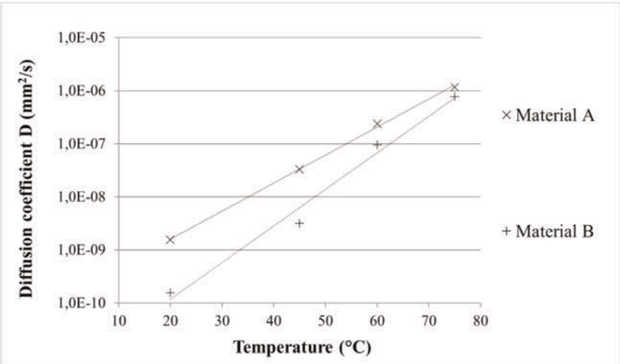

Figure 1. Results of plasticizer absorption tests of the two commercial geomembranes (y axis in log scale).

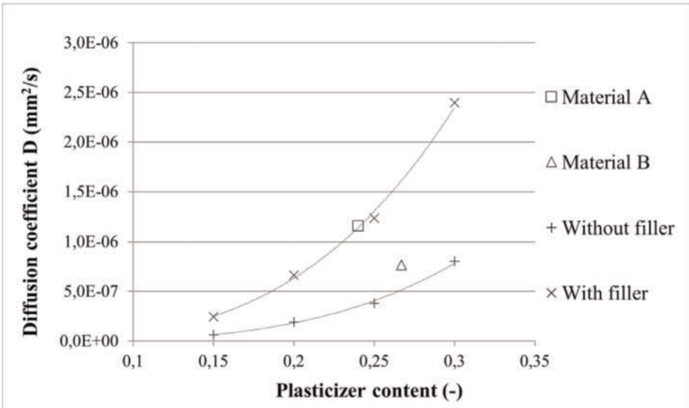

Figure 2. Results of plasticizer absorption tests at 75°C.

4.3 *Long-term extrapolation of plasticizer loss*

Using Equations (3), (4) and (5), it is possible to evaluate the variation of concentration with time at different temperatures and the plasticizer loss ratio.

Table 2 reports the diffusion coefficients used in the extrapolation, as derived from the plasticizer absorption tests results.

Table 2. Diffusion coefficients for 15°C extrapolation.

Material	D_1 (mm²/s)	b (–)
A	$7.47\ 10^{-7}$	4.94
B	$2.44\ 10^{-8}$	4.94

Figure 3 reports the results of the extrapolation in terms of plasticizer loss ratio for the two commercial geomembranes at 15°C. This temperature has been chosen as representative of the site temperature for shallow and urban tunnels in ordinary conditions.

The rate of degradation is relatively high in the first years and reduces with time.

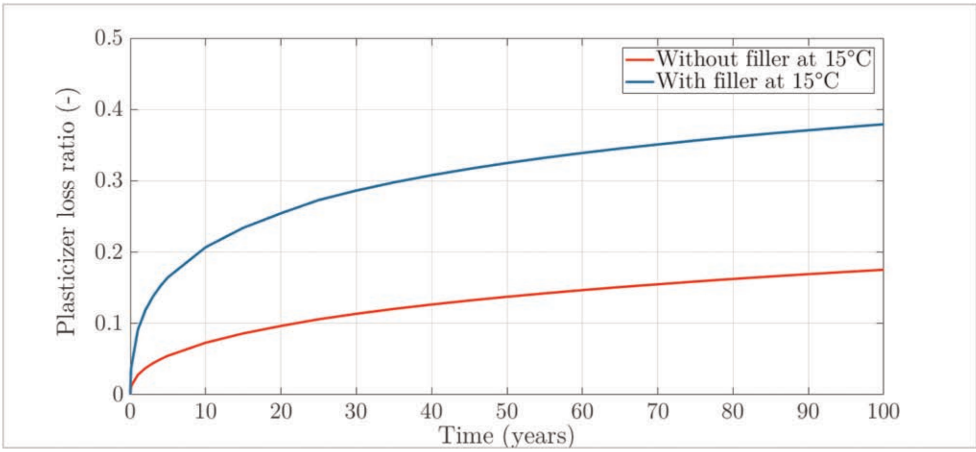

Figure 3. Long-term extrapolation of plasticizer loss of the two commercial geomembranes at 15°C.

5 PLASTICIZER LOSS EFFECT ON GEOMEMBRANES

As plasticizer content changes within the geomembrane its mechanical properties change. The mechanical properties of the 10 materials used in the absorption tests have been tested.

With the reduction of plasticizer content, Shore A hardness, tensile strength and elastic modulus of the geomembrane increases. On the contrary, elongation at break reduces.

Figure 4 shows the results of tensile tests. It is evident that as the plasticizer content reaches values of about 15–20% the behaviour of the geomembrane passes from a soft-rubber like to a hardening elasto-plastic one with an evident yielding point. This means that for certain values of elongation of the geomembranes a plastic irreversible deformation occurs, causing the reduction of the section. For both geomembranes with and without filler, this occurs for a plasticizer content of about 15% and the yielding point is reached for a deformation of about 6%.

Moreover, plasticizer loss causes the shrinkage of the geomembrane that creates tensile stresses in the geomembrane with time. Shrinkage progress with plasticizer loss can be evaluated with the correlation proposed by Giroud (1995).

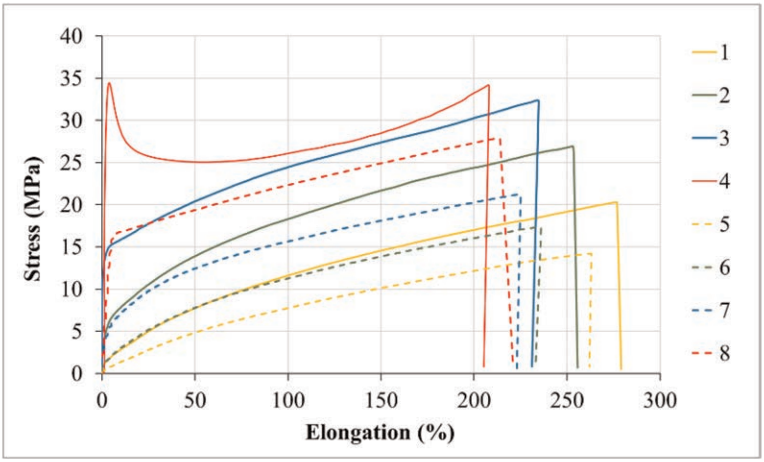

Figure 4. Tensile tests results on the 8 produced geomembranes.

6 DURABILITY ASSESSMENT

Benneton (1994) suggested that the end of effectiveness of a waterproofing PVC-P geomembrane can be defined at the moment when the plasticizer loss ratio is equal to 0.5. However, the author does not give any explication about the origin of this assumption.

In order to define a performance-based end-of-life threshold, it is needed to establish a correlation between the action on the geomembrane and the mechanical properties during the life of the structure.

Once the tunnel is built, the waterproofing geomembrane is in perfect contact with the two concrete lining (with protection layers installed to avoid that some unevenness of the concrete can damage the geomembrane). On the long term, the geomembrane only transmits the geological load to the final concrete lining. This load is constant and uniform on the surface of the geomembrane, therefore there is not a specific request for mechanical properties. In case of any unpredicted unevenness (e.g. voids in the lining, protruding elements), the deformation of the geomembrane would be very small and compatible with the elastic behaviour of the geomembrane. Furthermore, as shown, with degradation tensile strength and surface hardness increase reducing the risk of penetration of external grains.

The only consequence of plasticizer loss that seems to affect the effectiveness of the waterproofing geomembrane is shrinkage, that, in association with the more rigid behaviour of the material with lower plasticizer content, can induce plastic deformations. Plasticization is not necessarily a limit condition for the effectiveness of the geomembrane but represents a change of behaviour and causes the reduction of thickness and possible opening of small holes.

Therefore, in order to be on the safe side, the end-of-life value for the geomembrane is defined as the limit value of plasticizer loss ratio resulting in a plastic deformation of the geomembrane. For the tested materials this means or the 15% of plasticizer content, or an elongation due to shrinkage higher than 6%. For both commercial geomembranes tested the lower of these two values correspond to a plasticizer loss ratio of about 0.45, slightly lower than Benneton's limit.

From Figure 3, it is possible to state that both the commercial geomembranes tested are still within the defined end-of-life limit of plasticizer loss ratio after 100 years in an urban tunnel at 15°C.

7 CONCLUSIONS

The need of having effective underground structures calls for the request of durability of 100 years of the PVC-P geomembranes used for waterproofing.

Plasticizer loss from the geomembrane, that is the main degradation phenomenon in tunnel application, can be described has a diffusion problem. Through plasticizer absorption tests on 10 materials, the dependence of diffusion coefficient on temperature and concentration has been defined and an equation predicting the phenomenon has been proposed.

On the base of conservative evaluation on the possible consequences of shrinkage of the geomembrane, a threshold value of 0.45 has been defined for the plasticizer loss ratio as end-of-life value of the two commercial geomembranes analysed.

Both the commercial geomembranes tested fulfil this requirement for an application of 100 years in a shallow tunnel, thus confirming the capacity of the used materials to achieve the required goal during the life of the structure.

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