Performance of Geomembranes Exposed to Extreme Weather Conditions on High-Elevation Dams on the Alps

Daniele Cazzuffi[1] and Domenico Gioffrè, Ph.D.[2]

[1]CESI SpA, Milano, Italy. Email: daniele.cazzuffi@cesi.it
[2]Dept. of Civil Engineering and Architecture, Univ. of Pavia, Italy.
Email: domenico.gioffre@unipv.it

ABSTRACT

The aim of this paper is to present the performance of different types of geomembranes used for the rehabilitation of concrete and masonry dams in Europe, particularly in Italy and France. In all these applications, the geomembranes used were made by plasticized polyvinyl chloride (PVC-P) and have been left exposed on the upstream face, without external protection, to very extreme environmental factors and atmospheric agents, especially to Ultraviolet (UV) rays, at high elevations on the Alps. To verify the effective performance of the barrier system over time, several geomembrane samples—taken from a considerable number of dams—have been subjected to destructive chemical, physical, and mechanical tests. The results were interpreted with reference to the measure of some main properties, as plasticizer content, tensile characteristics, flexibility at low temperatures, volumic mass, and water vapor permeability. In particular, the plasticizer content plays a fundamental role in terms of variation of the intrinsic properties of the PVC-P geomembranes. In some cases, when the results of tests on virgin samples were available and several data points of plasticizer content versus time are available, the service life of the PVC-P geomembrane can be predicted. In fact, the prediction of the time in which it could be necessary to replace the geomembrane becomes of a crucial importance also for the owner of the dam.

INTRODUCTION

The deterioration of concrete and masonry dams at high elevations is caused by the environment (temperature changes, wetting-dehydrating and freeze-thaw cycles, impact by ice, debris, transported materials, chemical action of water) or by abnormal behaviour of the structure (expansive phenomena of concrete, problems with foundations and differential settlements). Concrete cracks and loses imperviousness, water infiltrates the dam body, and subsequent washing of fines may cause carbonation and clogging of the drains. As the drains cannot efficiently perform their function, seepage extends to the whole body of the dam and saturation of concrete occurs. Increase in pore pressure causes deviation from the initial design conditions, and stability of the structure may be at stake. Rehabilitation generally aims to stop water infiltration and further deterioration of the structure.

Geosynthetic barriers have been used as alternative solutions not only to mitigate deterioration processes in existing dams, but also to prevent the onset of seepage-induced degradation in new dams, and as the main hydraulic barrier in cases where low-hydraulic conductivity soils are not readily available (Cazzuffi et al., 2010).

In the 1970s, the first projects of rehabilitation of concrete and masonry dams were made on structures situated at high elevation in the alpine regions, where traditional facings (shotcrete and concrete) were susceptible of quick aging caused by frequent freeze-thaw cycles, low temperatures and ice action. As previous experience achieved on embankment dams was satisfactory, geomembranes technology had improved and confidence in the materials had increased, it was estimated that a robust geomembrane could sustain such an extreme environment.

In fact, the most of applications of PVC-P geomembranes to rehabilitate concrete or masonry dams were on the Alps, at elevations ranging between 1000 m a.s.l. and 2500 m a.s.l.

At all of dams considered in this study, the PVC geomembrane was left exposed to the environment, which - at such elevations - is quite demanding in terms of resistance to UV rays, to freeze-thaw cycles, to extremely low temperatures, and to high daily and seasonal temperature excursions.

The factors responsible of the geosynthetic aging can be either internal or external: in the first case, they rely on the intrinsic characteristics of the geomembrane (i.e., material composition, quality of its additives, thickness, etc.); in the second case, they depend on site-specific elements that are more difficult to manage especially in the design phase (i.e., environmental agents, biological and/or chemical factors, etc.). With regard to these factors, relevant studies (Girard et al., 2002; Rowe and Ewais, 2014) have demonstrated that the aging of the geomembrane, followed by that of the entire barrier system for fresh water application, depends mainly on four main factors: one internal (geomembrane thickness) and three external (temperature, UV radiation and exposure time). Therefore, it is possible to understand the difficulties involved in the prediction of the long-term behaviour of a geomembrane over time; given its specific characteristics, the geomembrane needs to be aged in the environment of its application, with combined cycles of temperature change, and exposure to UV light.

Temperature has a direct effect on the geomembrane's mechanical properties: in fact, high temperatures result in a reduction of the tensile modulus and in higher elongation, while low temperatures lead to the opposite effect. A greater influence on geomembrane deterioration, especially in the case of PVC-P geomembranes, is due to UV radiation. This radiation could cause the destruction of the molecular structure of the geomembrane, with a significant decrease in plasticizer content. This produces a general decrease in the geomembrane properties; for instance, it is possible to observe a decrease in the performance related to the flexibility at low temperatures, and also a lower elongation at break and a higher rigidity.

As for the time of exposure, it is necessary to consider that degradation is a dynamic phenomenon and, due to the different factors on which it depends, it is not easy to model. Some attempts have been made to do this using different prediction models, for instance the Arrhenius model (Hsuan et al., 2008), but they have always been conditioned by site-specific factors, so the results are difficult to generalize, and a constant calibration of the model is required. Therefore, in order to make a precise analysis of the durability of PVC-P geomembranes, it is vital to constantly monitor their behaviour on site over time (Blanco et al., 2010; Cazzuffi et al., 2020; Scuero et al., 2017a; Scuero et al., 2017b).

One of the topics of most concern in the rehabilitation of concrete and masonry dams using exposed geomembranes is the evaluation of their residual life. The prediction of the moment in which it could become necessary to replace the geomembrane plays a very important role also from the dam's owner point of view. It is possible to identify two main purposes of the rehabilitation of dams using geomembranes: i) reduce the unavoidable deterioration of the dam upstream face that can lead to an increase of water out-flow; ii) prevent stability problems, which can have seepage of water through the dam as a triggering factor.

In the past few years, two different paths emerged in order to gather experimental data on the geomembranes' aging behaviour: (a) reproducing field conditions in laboratory or (b) taking samples from installed geomembranes in different periods of their service lives; in any case, geomembrane samples must then be put through specific laboratory tests in order to determine variations in their properties with time (Cazzuffi & Gioffré, 2020).

Following the second of the two above-mentioned paths, this paper analyzes the performance of the geomembranes installed on seven Italian and French dams, showing the overall results of a comprehensive experimental activity on samples taken directly from the sites, carried out at the Geosynthetics Laboratory of CESI S.p.A. in Italy.

DAMS ON THE ALPS

The analysis of the long-term behaviour of the geomembranes presented in this paper has been conducted by studying the performance of geomembranes taken from the upstream face of several concrete or masonry dams located in the Alps, both in Italy and in France.

The dams considered are shown in Figure 1 together with their locations on the Alps, while their main characteristics are reported in Table 1.

The dams studied were built in the first half of the last century and are characterised by several common features. They are located on the Alps between 1000 m a.s.l. and 2500 m a.s.l., where traditional facings (concrete and masonry) are susceptible to quick aging caused by frequent freeze-thaw cycles, low temperatures and ice action.

Typical Alpine climate is characterised by very cold winters and by fresh and rainy summers. Air temperature ranges between −10°C and −15°C in winter, with negative peaks of −20°C to −25°C, and between +15°C and +25°C in summer. At these elevations, solar radiation is significant, with high temperatures of rocks and structures (up to +40°C).

Over the years, the continuous exposure of the dams to both atmospheric and environmental agents cause a notable deterioration of their original upstream face and a consequent increase in leakage with respect to initial values.

Table 1. Main characteristics of dams (in alphabetical order).

Dam	Type	Height (m)	Year of construction
Camposecco	Masonry	27.00	1930
Chambon	Concrete	137.00	1929-1934
Cignana	Concrete	58.30	1928
Laghi Gemelli	Concrete	36.00	1932
Lago Nero	Concrete	45.50	1929
Piano Barbellino	Concrete	69.00	1931
Publino	Concrete	42.00	1950-1951

Between 1980 and 1997, all of the upstream faces of the studied dams were rehabilitated with the application of a geosynthetic layer in order to restore their initial watertightness : the geosynthetic used has been always a two-layers geocomposite formed by a plasticized polyvinyl chloride (PVC-P) geomembrane and a polyester (PET) needle-punched (NP) nonwoven geotextile.

The main characteristics of the geocomposite are shown in Table 2.

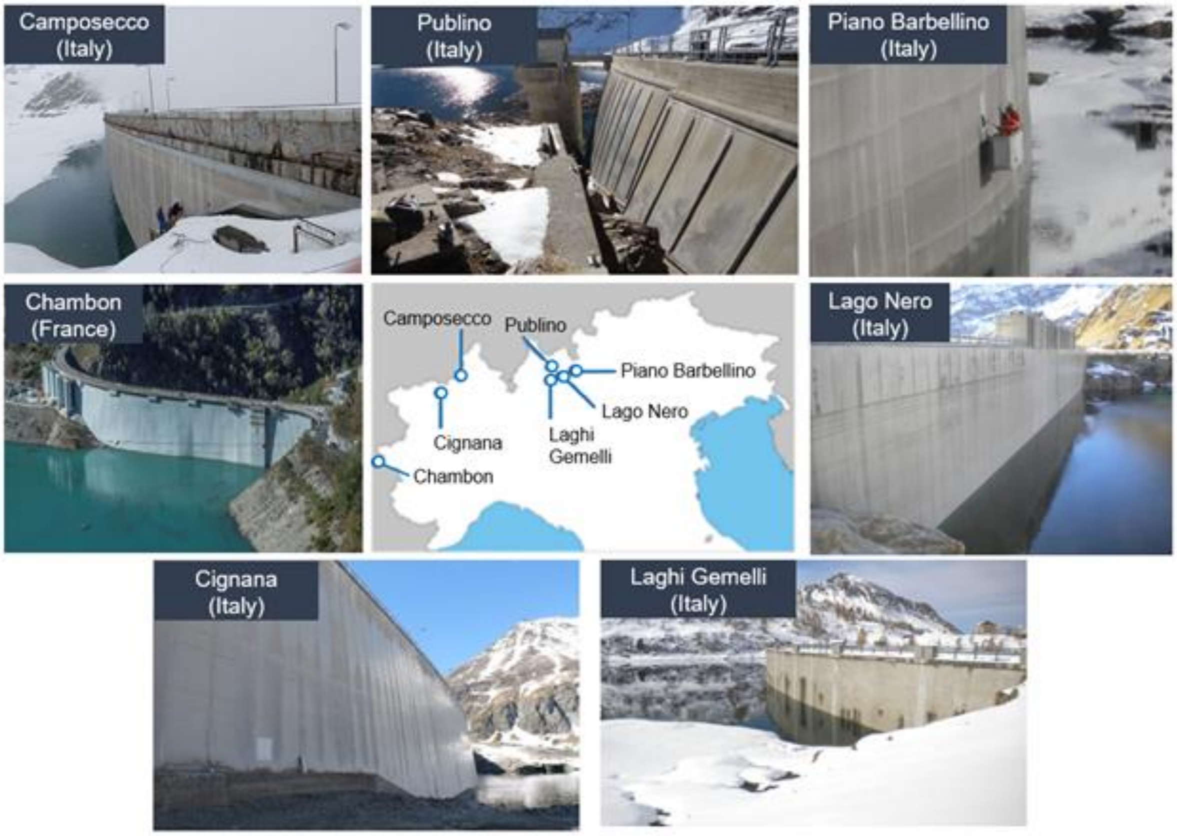


Figure 1. Dams considered in the paper and their locations on the Alps.

Figure 2. Chambon Dam: Alpine climate in summer and in winter seasons.

Table 2. Properties of the two-layers geocomposite used for the upstream face rehabilitation of masonry and concrete dams.

	Thickness (mm)	Layer	Type	Polymer	Function
Exposed two-layers thermobonded geocomposite	2.0 – 2.5	External	Geomembrane	PVC-P	Barrier
	3.0 – 3.5	Internal	NP nonwoven geotextile	PET	Protection and drainage

Since in all cases here presented the geomembrane is coupled with a geotextile, we will refer hereafter to the entire waterproofing system only as geomembrane, as this is the layer that provides the barrier function we want to analyze in this paper.

EXPERIMENTAL EVALUATION OF THE PERFORMANCE OF PVC-P GEOMEMBRANES

In order to evaluate the variation of the characteristics versus time of the PVC-P geomembranes installed on the seven dams, a good number of geomembrane samples have been taken at different time periods since application and evaluated vs. time using the same types of tests (Table 3).

Samples have been taken at locations above and under the water level and in different parts of the upstream face, with the aim of studying the different behaviour of the same type of geomembrane in different conditions of exposure.

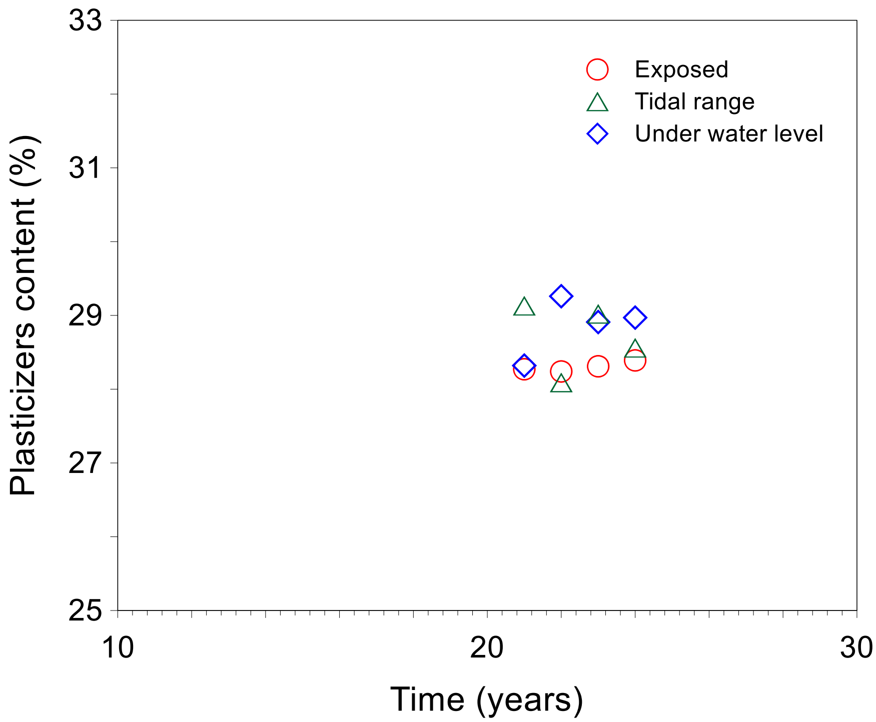


Figure 3. Plasticizers content evolution over time in different zone of the Chambon dam.

Table 3. Upstream face rehabilitation and sampling on the different dams.

Dam	Type	Year of upstream face rehabilitation	Year of sampling
Camposecco	Masonry	1994	1994[1], 1996, 1999, 2016
Chambon	Concrete	1991-1996	2017
Cignana	Concrete	1988-1989	1996, 1999, 2013, 2016
Laghi Gemelli	Concrete	1997	1997[1], 2000, 2010
Lago Nero	Concrete	1980-1981	1995, 1997, 2010
Piano Barbellino	Concrete	1987	1995, 1997, 2010
Publino	Concrete	1989	2011, 2015

[1]available test results on virgin samples before application

According to a consolidated experience, the analysis of the long-term behaviour of the geomembranes presented in this paper has been conducted reporting the results of several samples of geomembranes taken from the exposed face of the dams only above the water level, which is the section of the geomembrane subjected to more relevant exposure to atmospheric agents.

This choice is validated also in the case of Chambon dam, for which the results in terms of plasticizers content are illustrated in Figure 3.

In fact, from test results shown in Figure 3, it is clear that the plasticizers contents referred to the exposed samples (i.e. above the water level) are slightly lower when compared to the ones from under water level or from tidal range (in which water protects from UV rays).

Therefore, the results hereafter presented refer to the worst conditions for each geomembrane, i.e. to the exposed samples (taken above the water level).

All of the samples from the dams' upstream faces were tested at the Geosynthetics Laboratory of CESI S.p.A., Italy. The experimental results, obtained by means of different tests on samples of PVC-P geomembranes taken in different periods since application, allowed reconstruction of the entire life of the geomembrane, in particular when the results on virgin samples are available, such as the cases of Camposecco and Laghi Gemelli dams.

Before testing, the specimens were prepared in laboratory by separating the geotextile layer from the geomembrane layer. For the purposes of this study, discussion is only presented on the test made on the geomembrane layer, i.e the layer directly exposed to the extreme conditions.

The laboratory tests and the reference standards are shown in Table 4.

Table 4. Laboratory tests and reference standards.

Test	Reference standard
Plasticizer extraction	EN ISO 6427
Nominal thickness	EN 1849-2
Volumic mass (density)	EN ISO 1183-1
Hardness (Shore A)	EN ISO 868
Cold flexibility	EN 495-5
Dimensional stability	EN 1107-2
Tensile properties	EN ISO 527-3
Water vapour transmission	EN 1931

Based on the test results, the following main considerations can be drawn:

- The plasticizer content values in the samples are shown in Figure 4, in which the dashed lines represent the linear regressions of the data for each dam. A constant decrease in plasticizers content over time can be observed for all samples.
- The variations in nominal thickness and volumic mass versus time are shown in Figures 5a and 5b, respectively. With regards to nominal thickness, the results obtained show an average small decrease. On the other hand, almost constant values of volumic mass were obtained.
- The experimental results indicate that the temperature of cold flexibility increase with time while dimensional stability grows longitudinally and decreases transversally over the years, as it depends on the boundary conditions of the geomembrane, as determined by the specific vertical application system.
- The mechanical parameters show that the geomembrane became stiffer over time, with a growth of tensile strength and a reduction of the corresponding strain, both in the longitudinal and transversal direction (Figure 6).
- The experimental results of the vapour transmission test demonstrate a decrease in permeability coefficient, thus an improvement in barrier behaviour of the geomembranes (Figures 7a and 7b).

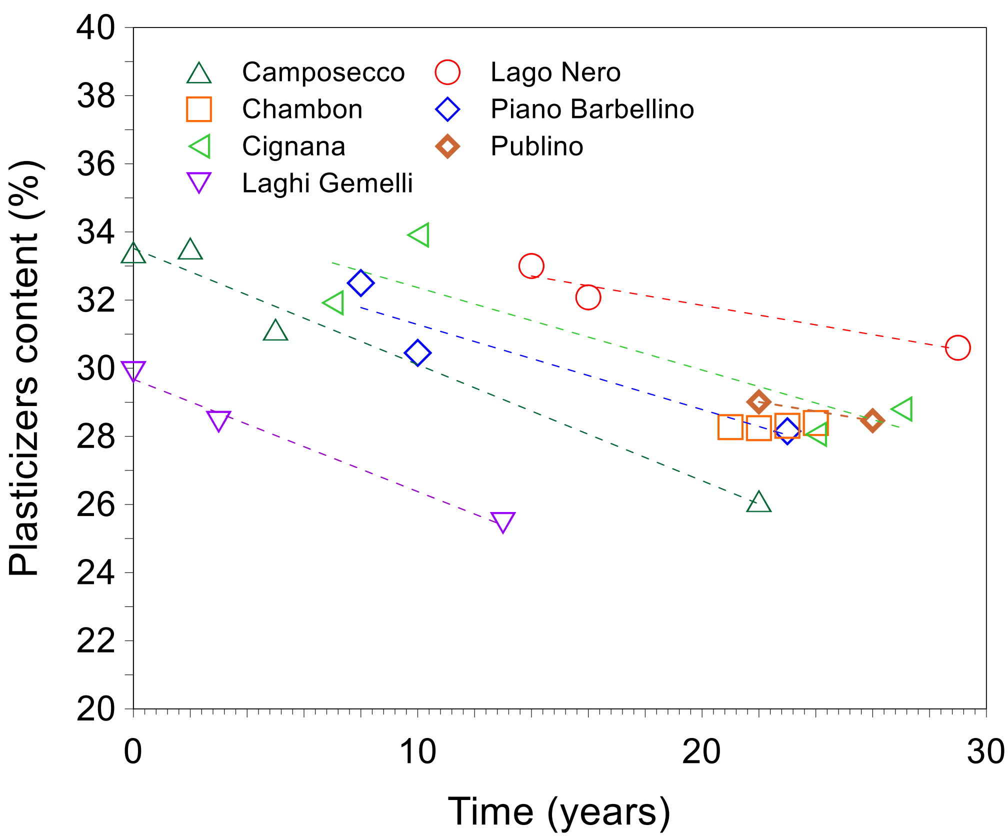
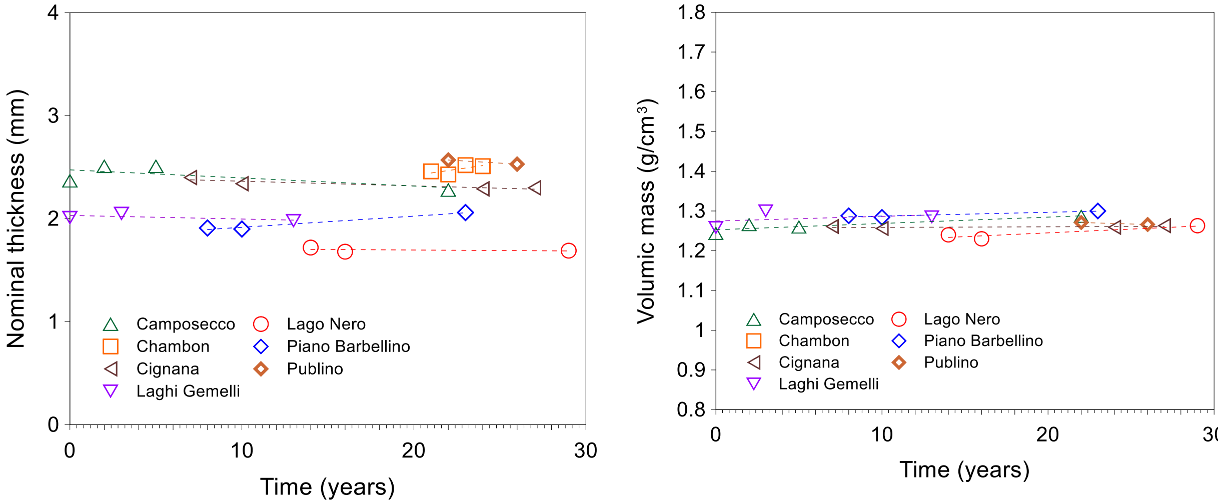


Figure 4. Plasticizers content evolution over time in the different dams.



a) Nominal thickness b) Volumic mass

Figure 5. Nominal thickness and Volumic mass evolution over time.

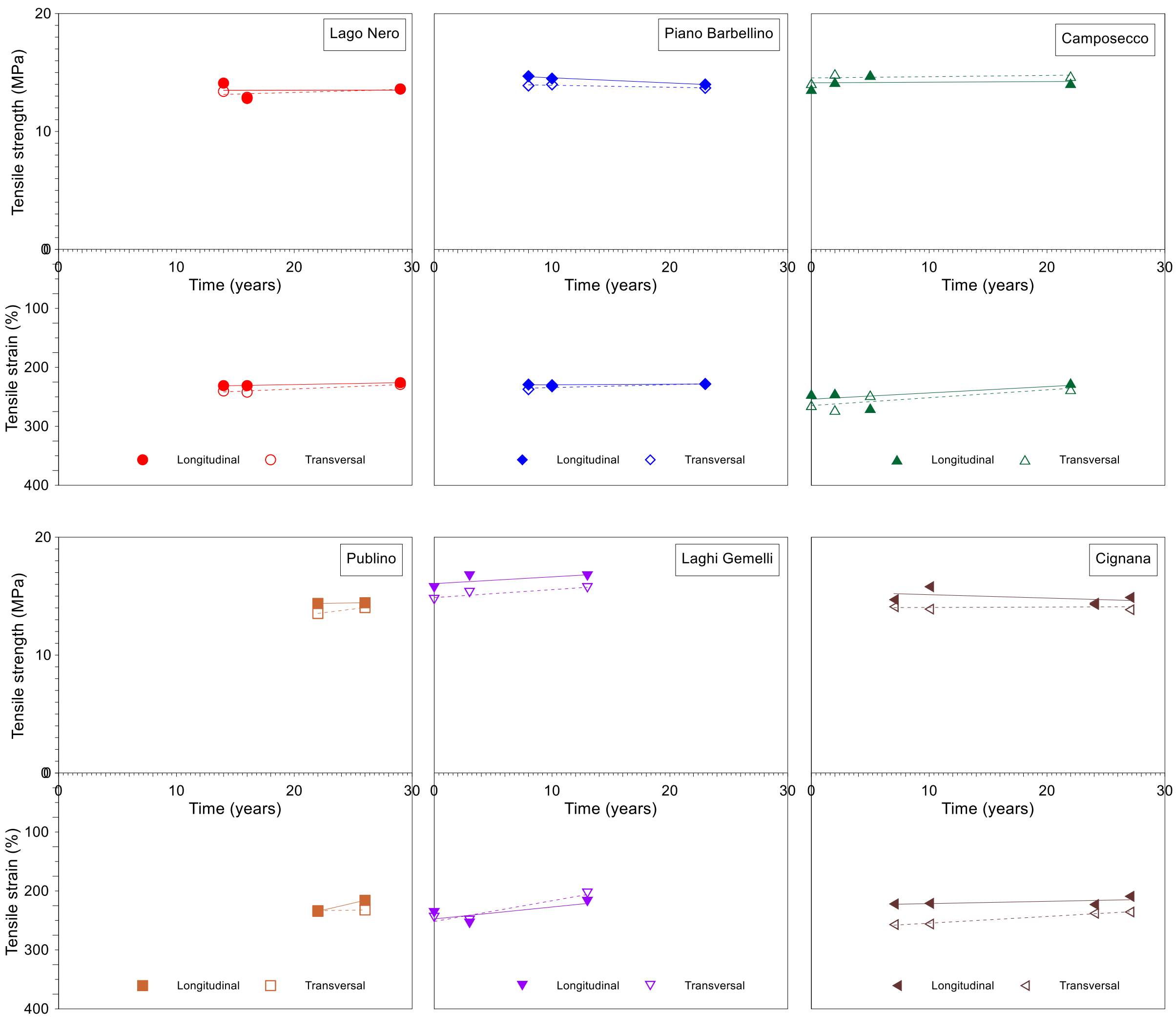
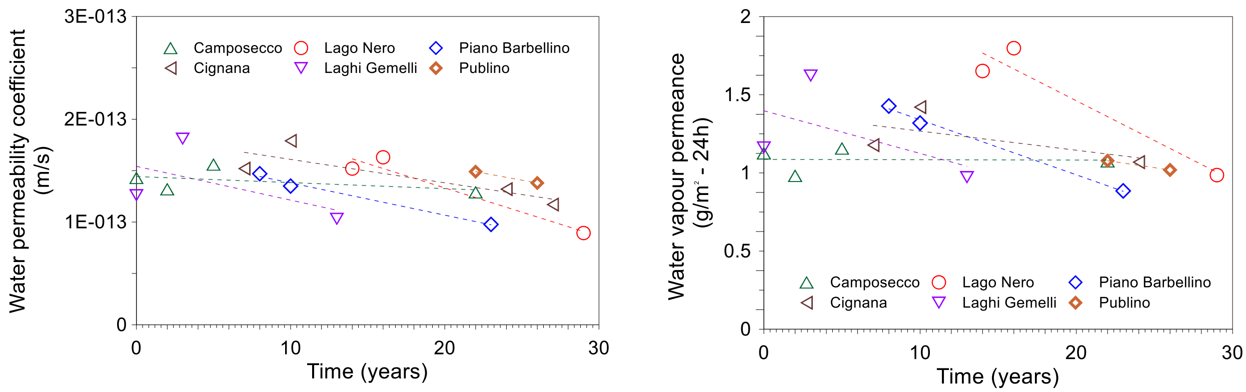


Figure 6. Tensile strength and tensile strain evolution over time.



a) Water permeability coefficient b) Water vapour permeance

Figure 7. Water permeability and water vapour permeance evolution over time.

CRITERION AND PREDICTION OF THE END OF SERVICE LIFE FOR PVC-P GEOMEMBRANES

According Giroud & Tisinger (1993), if several data points of plasticizer content versus time are available, the service life of the PVC-P geomembrane can be predicted by the following method: the plasticizer content data points are converted into plasticizer loss ratio data points and the curve of plasticizer loss ratio versus time is extrapolated until the extrapolated plasticizer loss ratio is equal to the end-of-service-life criterion expressed in terms of plasticizer loss ratio using Eq. (1) as follows:

$$p_{L\,eosl} = \frac{C_{Po} - C_{P\,eosl}}{C_{Po}\left(1 - C_{P\,eosl}\right)} \tag{1}$$

where p_{Leosl} is the end-of-service-life criterion expressed in terms of plasticizer loss ratio, C_{Po} is the initial plasticizer content and C_{Peosl} is the end-of-service-life criterion expressed in terms of plasticizer content.

Based on laboratory tests (Luciani et al., 2020) and on data from monitored structures, a plasticizer content value of 17.5% for PVC-P geomembranes bonded to a nonwoven needle-punched geotextile (which are frequently used in dams) can be used as end-of-service-life criterion expressed in terms of plasticizer content (Giroud, 2021; Cazzuffi & Gioffré, 2021).

In the case of the Camposecco Dam, where the initial plasticizer content is 33.41%, the end-of-service-life criterion expressed in terms of plasticizer loss ratio is determined using Eq. (1) as follows if an end-of-service-life criterion characterized by a plasticizer content of 17.5% is considered:

$$p_{Leosl} = \frac{0.3341 - 0.175}{0.3341\left(1 - 0.175\right)} = 0.577 = 57.7\% \tag{2}$$

Similarly, the calculated end-of-service-life criterion expressed in terms of plasticizer loss ratio is 50.2% for Laghi Gemelli Dam, where the initial plasticizer content is 29.88%.

The lifetime assessment of the exposed geomembrane for Camposecco and Laghi Gemelli dams was made based on the variation of plasticizer and assuming a linear decrease in the content of plasticizer over time.

Figure 8 shows the assessment of lifetime of exposed geomembranes for the two dams of Camposecco and Laghi Gemelli, for which the results on virgin sample are also available.

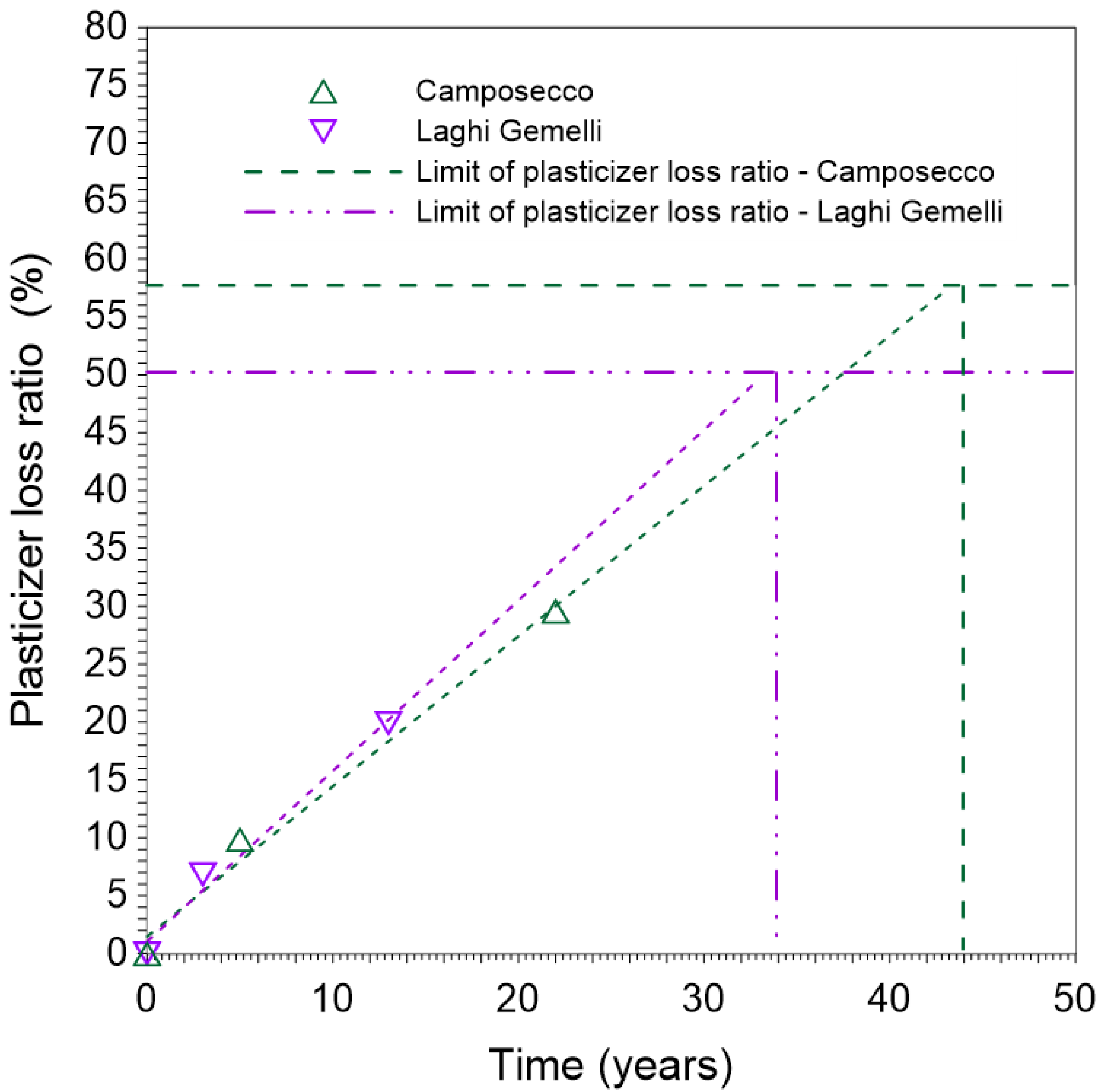


Figure 8. Evolution of loss of plasticizer vs. time and evaluation of geomembrane lifetime.

Vertical lines in Fig. 8 show that the lifetime assessment of the exposed geomembranes for Laghi Gemelli and Camposecco dams, assuming a linear decrease of plasticizer loss ratio over time, is approximately 34 years and 44 years since application, respectively.

For sure, in the future, this assessment has to be validated considering additional sampling in the coming years and, possibly, a larger number of dams for which the value of the plasticizer content on virgin samples is also available.

CONCLUSION

The paper discussed the behaviour of PVC-P geomembranes installed without any external protection on the upstream face of dams located at high elevations on the Alps, both in Italy and in France, and subjected to extreme climate conditions. An experimental program was conducted in order to study the life expectancy of exposed geomembranes, and tests were conducted on samples taken directly from the dam sites over the last 25 years. The results obtained show a constant decrease in plasticizers content and a diminution of the nominal thickness. The temperature of cold flexibility rises with time, while dimensional stability grows longitudinally and declines transversally over time; these results obviously depends on the boundary conditions of the geomembrane determined by the specific vertical application system.

The mechanical parameters show that the geomembrane tends to become stiffer over time, with an increase in tensile strength and with a reduction in the correspondent strain, both in the longitudinal and transversal direction.

In conclusion, the parameter that shows steadier, and therefore clearer, behaviour is the plasticizers content and could represent a good indicator for the evaluation of the life expectancy of geomembranes when results on virgin samples are available. With an appropriate knowledge of the initial parameters, in fact the evaluation of the geomembrane service life is more valuable, as it allows reconstruction of the entire life of the geomembrane itself, even in such extreme conditions of high elevations and low temperatures.

REFERENCES

Blanco, M., Rico, G., Pargada, L., Castillo, F., and Crespo, M. A. (2010). “Influence of plasticizer type in PVC-P geomembranes durability”. *III National Waterproofing Congress: Building and Public Works and Reservoirs*, Barcelona, 347-357.

Carreira, T., and Tanghe, H. (2008). “Durability of PVC-P geomembranes in hydraulic structures”. *Proceedings of the 4th European Geosynthetics Conference EuroGeo 4*, Edinburgh, p. 9.

Cazzuffi, D., and Gioffrè, D. (2020). “Lifetime assessment of exposed PVC-P geomembranes installed on Italian dams”. *Geotextiles and Geomembranes*, 2020, 48(2), pp. 130-136.

Cazzuffi, D., and Gioffrè, D. (2021). “Reply to the discussion by Giroud on Lifetime assessment of exposed PVC-P geomembranes installed on Italian dams”. *Geotextiles and Geomembranes*, 2021, (in press).

Cazzuffi, D., Giroud, J. P., Scuero, A., and Vaschetti, G. (2010). “Geosynthetic barriers systems for dams”. Keynote Lecture, *Proceedings of the 9th International Conference on Geosynthetics, 9 ICG 2010*, Guaruja, Vol. 1, 115-163.

Girard, H., Poulain, D., Benetton, J.-P., and Fayoux, D. (2002). “Durability of PVC-P geomembranes used in hydraulic structures: feedback on experience”. *Proceedings of the 7th International Conference on Geosynthetics, 7 ICG 2002*, Nice, 709-712.

Giroud, J. P. (2021). “Discussion on “Lifetime assessment of exposed PVC-P geomembranes installed on Italian dams” by D. Cazzuffi and D. Gioffrè”. *Geotextiles and Geomembranes*, 2021, (in press).

Giroud, J. P., and Tisinger, L. G. (1993). "The Influence of Plasticizers on the Performance of PVC Geomembranes". *Proceedings of the 7th Symposium of the Geosynthetic Research Institute*, Koerner, R. M. and Wilson-Fahmy, R. F., Eds., Philadelphia, PA, USA, pp. 169-196.
Hsuan, Y. G., Schroeder, H. F., Rowe, R. K., Müller, W., Greenwood, J., Cazzuffi, D., and Koerner, R. M. (2008). "Long-term performance and lifetime prediction of geosynthetics". Keynote lecture, *Proceedings of the 4th European Geosynthetics Conference EuroGeo 4*, Edinburgh.
Luciani, A., Todaro, C., Martinelli, D., and Peila, D. (2020). "Long-term Durability Assessment of PVC-P Waterproofing Geomembranes through Laboratory Tests". *Tunneling and Underground Space Technology*, Volume 103.
Rowe, R. W., and Ewais, A. M. R. (2014). "Ageing of exposed geomembranes at locations with different climatological conditions". *Canadian Geotechnical Journal*, 52, 326–343.
Scuero, A., Vaschetti, G., and Subramanian, V. (2017a). "Geomembranes for long-term rehabilitation of dams". *Proceedings of Workshop on Latest Repair & Rehabilitation Technologies for Dams*, Colombo.
Scuero, A, Vaschetti, G. and Bacchelli, M. (2017b). "The Use of Geomembranes in Dams". *Long-Term Behaviour and Environmentally Friendly Rehabilitation Technologies of Dams (LTBD 2017)*, 506-514.