Experimental tests for a proper evaluation of the behaviour of PVC geomembranes on dams on the Alps

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ABSTRACT
The aim of this paper is to investigate the performance of polyvinyl chloride (PVC) geomembranes used in the rehabilitation of concrete and masonry dams, particularly in Italy and in France. In all these applications, the geomembranes have been left exposed on the upstream face, without external protection, to environmental factors and atmospheric agents, especially to UV rays, even at very high elevation on the Alps.
To verify the effective performance of the barrier system over time, several geomembrane samples have been taken from a considerable number of dams, both in Italy and in France. These samples have then been subjected to destructive physical and mechanical tests, to allow the study of the evolution of the properties of the geosynthetics over the years.

1. INTRODUCTION

The deterioration of concrete and masonry dams is caused by the environment (e.g., temperature changes, wetting-dehydrating and freeze-thaw cycles, impact from ice, debris, transported materials and chemical action of water) or by abnormal behaviour of the structure itself (e.g., the expansive phenomena of concrete and/or alkali-aggregate reaction, or problems with foundations and differential settlements). As a result of cracks in the concrete and loss of imperviousness, water infiltrates the dam body, and subsequent washing of fines may cause carbonation and clogging of the drains.
The geosynthetic solution that is commonly used for the rehabilitation of concrete and masonry dams consists in the application of a geomembrane-geotextile composite on the upstream face to mitigate deterioration processes in existing dams (Cazzuffi et al., 2010, Colmanetti et al., 2010, Giroud 2016, Scuero et al. 2017b).
The use of exposed geomembranes for the rehabilitation of concrete and masonry dams was introduced in Italy in 1976, when the entire upstream face of a 11 m high Lago Miller (Brescia, Italy) masonry dam was lined with a 2 mm thick PVC (polyvinyl chloride) geomembrane as waterproofing element (Cazzuffi 1987).
In the following applications on the Alps (among which Lago Nero, Bergamo-Italy, 1980-1981; Piano Barbellino Bergamo-Italy, 1987; Cignana, Aosta-Italy, 1988-1989, Chambon, Isère-France, 1991-1996), the system progressively evolved. In fact, instead of using only one component, i.e. a PVC geomembrane, the barrier function was performed by a bi-component geocomposite, manufactured by thermal coupling of the PVC geomembrane with a PET (polyester) nonwoven needle-punched geotextile, thus obtaining also an anti-puncturing function, reducing the installation time and increasing the dimensional stability of the geomembrane itself. Moreover, the geotextile in-plane drainage capacity allowed to prevent the accumulation of water between the geomembrane and the dam itself, solving one of the major concerns for a good long-term performance of the whole system (Giroud, 2016).
From the first applications to present, this technique underwent several other changes, mainly thanks to the use of additional geosynthetics, such as geonets, as in the cases of Chambon (Isère, France) and Publino (Sondrio, Italy) dams, which allow to avoid the surface regularization before the geomembrane installation and also to increase the drainage capacity of the system during the dam service.
In all these applications, the geomembranes were left exposed on the upstream face, without external protection, to environmental factors and weather conditions, especially to UV rays, very intense also because many of these dams are at high elevation (typically greater than 1000 m and very often greater than 2000 m elevation).
It is possible to identify two main purposes of the rehabilitation of existing concrete and masonry dams using geosynthetics on the upstream face: to reduce the deterioration of the upstream face itself, which can lead to an increase of water out-flow; to prevent stability problems of the overall structure, which can be a triggering factor for the seepage of water through the dam.
However, if the effects of the physical deterioration of a dam are well-known, or at least possible to ascertain, the definition and control of the causes of such a phenomenon are more challenging, particularly if the evaluation needs to be quantitative rather than qualitative (Cazzuffi 1987, Cazzuffi, 1996, Cazzuffi, 1998, Cazzuffi 2013, Cazzuffi 2014, Rowe and Ewais, 2014, Scuero et al. 2017a).
The factors responsible of the worsening of the dam's conditions can be internal or external: in the first case they rely on the intrinsic characteristics of the geomembrane (e.g. material, quality, geometry); in the second case they depend on

site-specific elements that are more difficult to manage especially in the design phase (e.g. environmental agents, biological and/or chemical factors).
Therefore, it is possible to understand the difficulties involved in the prediction of the behaviour of a geomembrane over time; given its specific characteristics, the geomembrane needs to be tested in the environment of its application, with combined cycles of temperature change, and exposure to UV light.
Two different paths have emerged for gathering experimental data on geomembranes behaviour:

- prediction from laboratory tests - reproducing field conditions in the laboratory;
- feedback from field performance - taking samples from installed geomembranes in different periods of their lives; in all cases they must then be put through specific laboratory tests in order to determine variations in their properties over time.

Following the second of these paths, in this paper we analyse the behaviour of PVC-P geomembranes used in the rehabilitation of concrete and masonry dams. Their ages range from 21 to 38 years, and they were all installed on dams located on the Alps, both in Italy and in France. The survey conducted on several dams and the sampled geomembranes were subjected to physical and mechanical tests (Cazzuffi and Gioffrè 2017, Cazzuffi and Gioffrè 2018). The results were interpreted with reference to the plasticisers content, tensile characteristics, foldability at low temperatures, volumic mass and water vapour permeability.

2. DAMS AND GEOMEMBRANES PROPERTIES

The analysis of the long-term behaviour of the geomembranes presented in this paper has been conducted studying the performance of several samples 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.

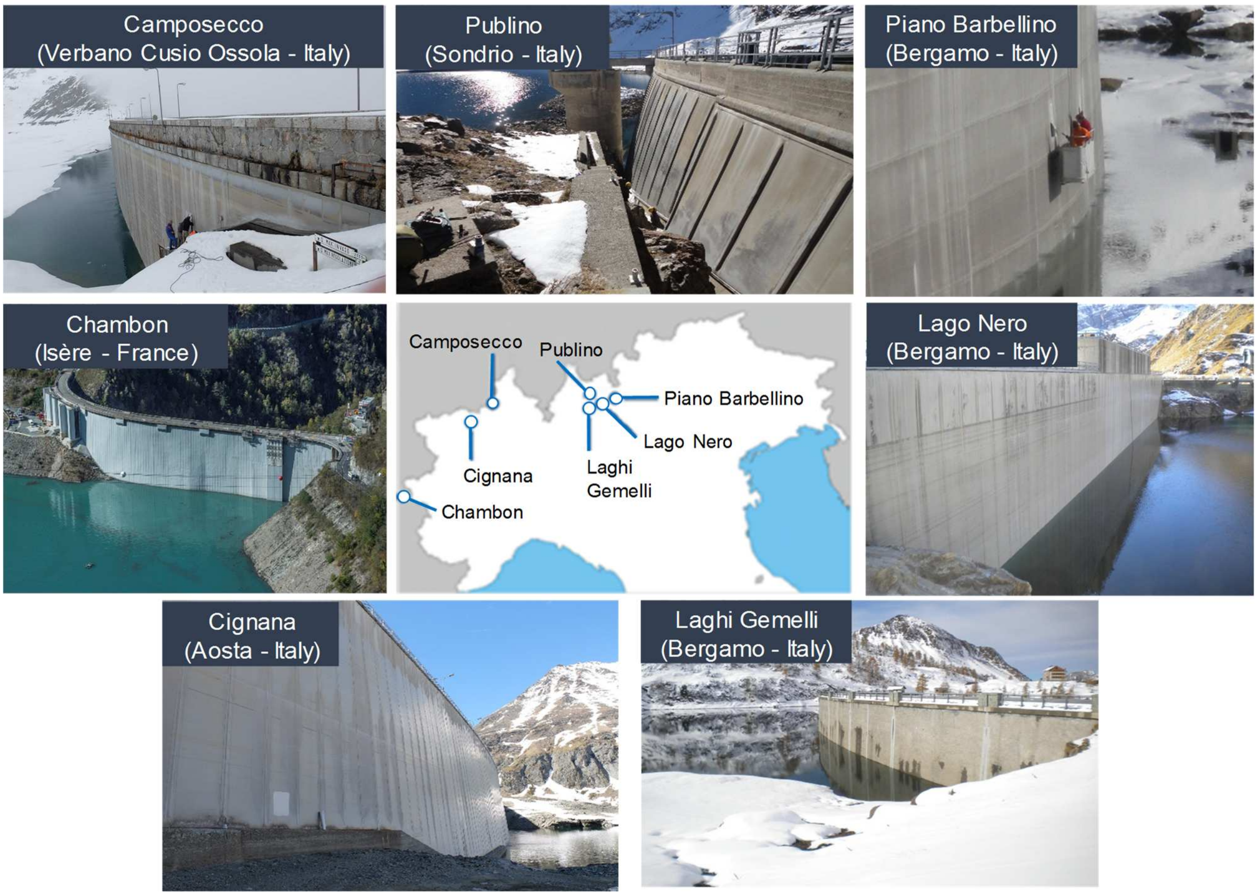


Figure 1. Dams considered in the paper and their location on the Alps. All photos are taken from various CESI technical reports except for Chambon dam provided by courtesy of CarpiTech.

The dams studied were built in the first half of the last century and are characterised by several common features, meaning it is possible to make some considerations that are acceptable for all of them. 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 ageing 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℃ and −15℃ in winter, with negative peaks of −20℃ to −25℃, and between +15℃ and +25℃ in summer. At these elevations, solar radiation is significant, with high temperatures of rocks and structures (up to +40℃).
Over the years, the continuous exposure of the dams to atmospheric and environmental agents causes a notable deterioration of their upstream face and an 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 water tightness, comprising an exposed two-layer geocomposite formed by: a plasticised polyvinyl chloride (PVC-P) geomembrane and a polyester (PET) needle-punched nonwoven geotextile. The main characteristics of the geocomposite are shown in Table 2.

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

	Thickness (mm)	Layer	Type	Polymer	Function
Exposed two layer thermobonded geocomposite	2.0 – 2-5	External	Geomembrane	PVC-P	Barrier
	3.0 – 3.5	Internal	Needle-punched nonwoven geotextile	PET	Protection and drainage

Since in all the 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 which provides the barrier function we want to analyse in this paper.
Moreover, being the rehabilitation of existing dams the main issue here discussed, we will consider the only possible system of installation on such structures, which is the so-called upstream installation, because the alternative method, internal installation, is possible only in the construction of new dams , as clearly illustrated in the recent ICOLD bulletin on the matter (ICOLD, 2010).
The PVC-P geomembrane component 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 variations.
Although the original composition of the geomembranes is unknown, a typical composition is 50–70% PVC resin, 25–35% plasticisers and 2–5% other additives, which include UV light absorbents such as carbon black, pigments such as titanium dioxide, stabilisers such as calcium stearate, and fillers such as calcium carbonate (Hsuan et al. 2008).
Among the above-mentioned constituents, plasticisers play a fundamental role in terms of variation of the physical properties of the virgin material. In fact they have the major responsibility in obtaining the desired qualities that make it suitable for the different application purposes.
Plasticisers improve PVC physical properties by transforming it from stiff and brittle to flexible, thus facilitating the installation process and increasing ductility and dilatability (Blanco et al., 2008;, Blanco et al. 2010; Blanco et al., 2012a and 2012b, Blanco et al., 2018). As a matter of fact, the addition of plasticisers to the PVC resin results in the reduction of the polymer glass transition temperature, which is the temperature at which the material changes from a hard and relatively brittle state into a molten or rubber-like state.
At the same time, however, the content in plasticisers is one of the characteristics which are more affected by the variations due to the exposition of the material to the aggression of atmospheric agents. This is why the variation of the content in plasticisers, in particular its decrease, represents a very effective index of the material degradation, as it reveals the loss of all those properties that were obtained only thanks to their presence in the PVC mixture.

The degradation of PVC geomembranes over time depends on several causes, some of whom are determined by the intrinsic properties of the geomembrane, while some others are governed by the environmental conditions in which the geomembrane is posed.
For the PVC-P geomembranes tested in this research, based on the various tests performed and observations in the field (Carreira and Tanghe, 2008), a loss of plasticiser less than 30% of the initial value (virgin sample) allows the geomembrane to fulfil their working requirements in the dams. The limit may vary according to the external environment, type of application and design of the barrier system.
Therefore, plasticiser loss is the critical variable for lifetime prediction and when the results of tests on virgin samples are available, it will be possible to evaluate the lifetime of the exposed geomembranes studied in this research.
In order to make a precise analysis of the durability of PVC geomembranes, it is absolutely necessary to monitor constantly their behaviour over time. In fact, a good monitoring programme allows following the predictable worsening of some properties of the geomembrane, but also discovering other factors of degradation that could not be foreseen in the design phase.
Moreover, it is easy to understand how two identical geomembranes will have different conditions depending on the place where they have been installed.
Therefore, considering that the geomembranes are left exposed without any kind of protection, site inspections and regular controls are necessary in order to evaluate the geomembrane deterioration over time and the opportunity of adopting corrective measures to slow this process down.

3. SAMPLING ON DAMS AND LABORATORY TESTS ON PVC-P GEOMEMBRANES

In order to evaluate the variation over time of the characteristics of the PVC-P geomembranes installed on the seven dams here considered, a good number of samples have been taken some periods after application and all of them have been put through the same tests.
Samples have been taken both 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 geomembrane in different conditions of exposure.
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 above the water level which is subject to more exposure to atmospheric agents.
This choice is validated also in the case of Chambon dam, for which the results in terms of plasticisers content are illustrated in Figure 2.
From test results shown in Figure 2, it is very clear that the plasticisers content referred to exposed samples are lower if compared to the ones from under water level or from tidal range.
Therefore, the most of results here presented refer to the worse conditions for each geomembrane (Cazzuffi and Gioffrè, 2017).
Samples were taken in different periods after application (Table 3)

Table 3. Upstream face rehabilitation and sampling on the different dams (in alphabetical order).

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

All the samples taken from the dams' upstream faces were tested at the Geosynthetics Laboratory of CESI S.p.A., Italy. The tests allowed comparison among the different samples during the service of the geomembranes in the different dams. The cases of Camposecco and Laghi Gemelli are particularly significant, as for these dams the test results on virgin samples are available.
Before running the tests, the specimens were prepared in laboratory by the separation of 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.
The laboratory tests and the reference standards are shown in Table 4.

Table 4. Laboratory tests and reference standards.

Test	Reference standard
Plasticiser 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

On the basis of test results, the following main considerations can be drawn:

- The plasticiser content values in the samples are shown in Figure 3, in which the dashed lines represent the linear regressions of the data for each dam. A small constant decrease in plasticisers content over time can be observed for all samples.
- The variations in nominal thickness and volumic mass versus time are shown in Figures 4a and 4b respectively. With regard 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 rises with time while dimensional stability grows longitudinally and declines 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 correspondending strain, both in the longitudinal and transversal direction (Figure 5).

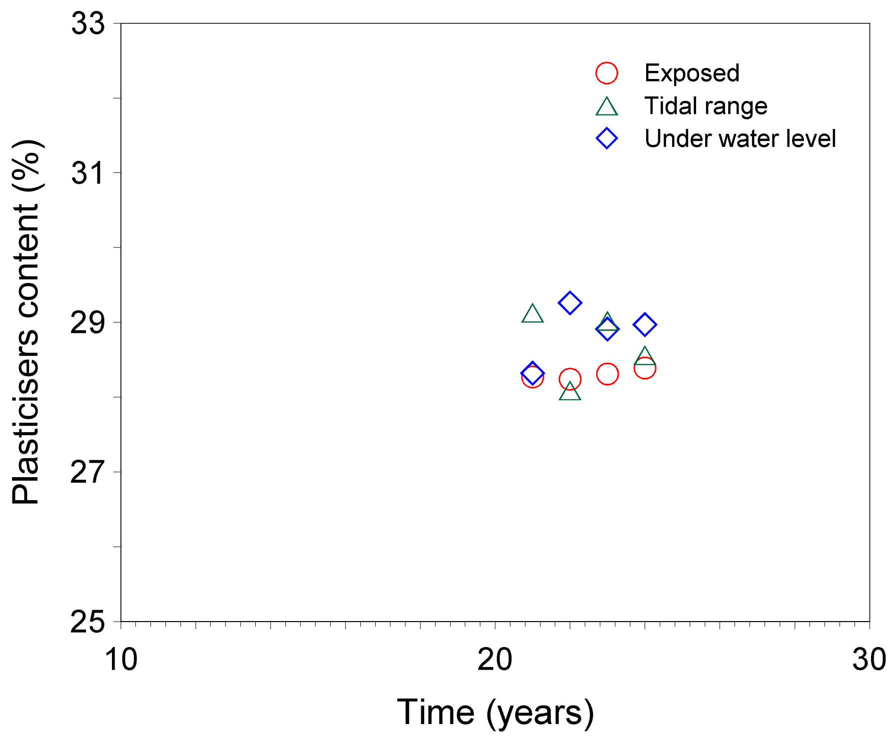


Figure 2. Plasticisers content evolution over time in different zone of the Chambon dam.

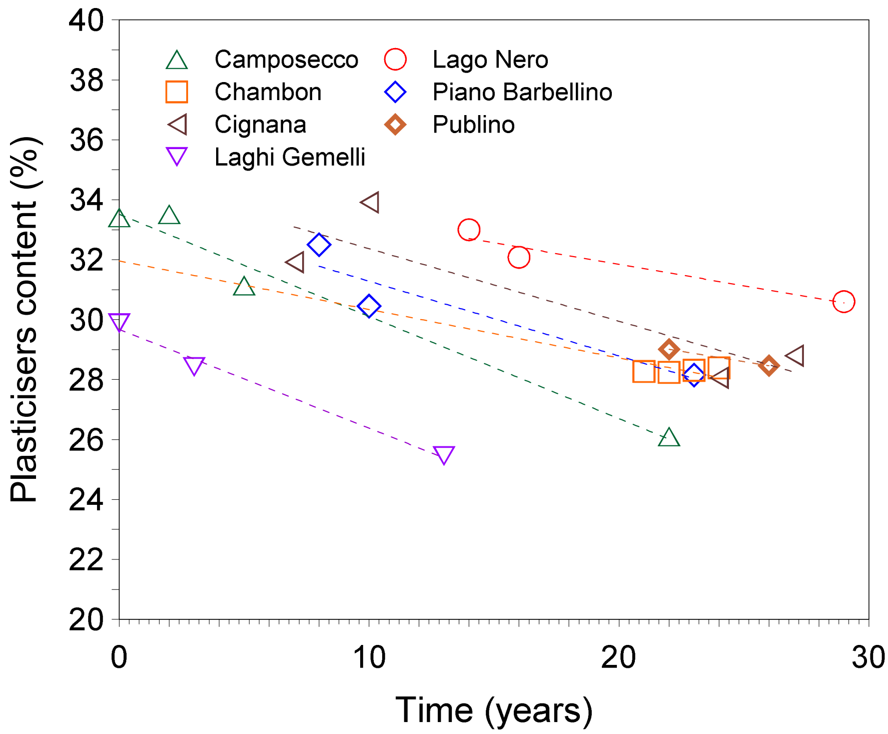
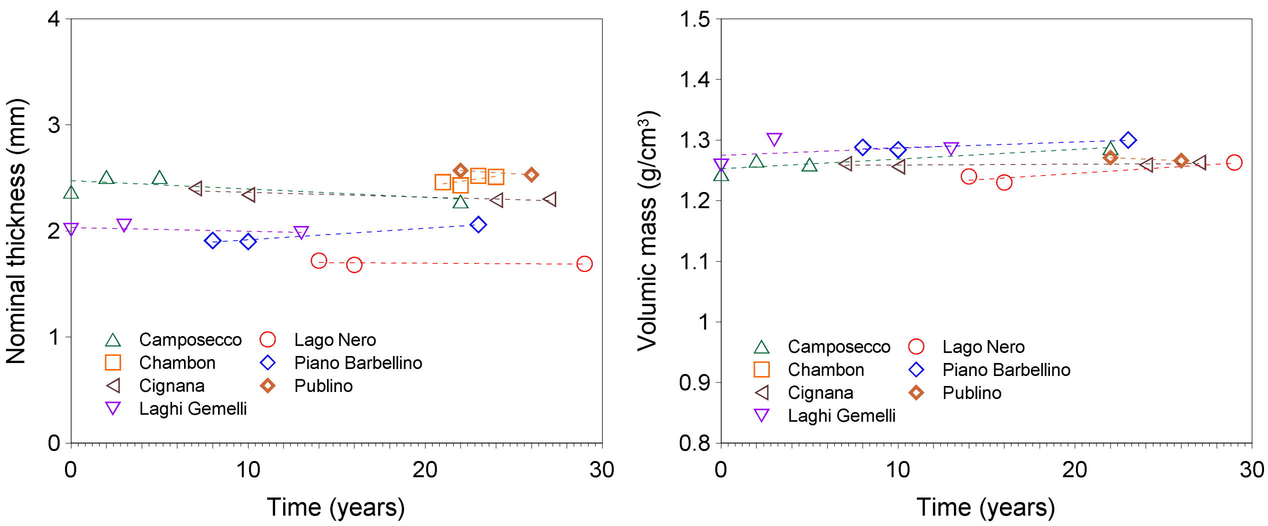


Figure 3. Plasticisers content evolution over time in the different dams.



a) Nominal thickness

b) Volumic mass

Figure 4. Nominal thickness and Volumic mass evolution over time.

4. CONCLUSIONS

The paper has discussed the behaviour of PVC-P geomembranes installed without any external protection on the upstream face of dams located on the Alps, both in Italy and in France. An experimental programme was conducted in order to study the life expectancy of exposed geomembranes and tests were conducted on samples taken directly from sites over the last 25 years. The results obtained show a small constant decrease in plasticisers content and an average 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, for the time being, the parameter that shows steadier, and therefore clearer, behaviour is the plasticisers content. Therefore, in perspective this parameter could be a good indicator for the evaluation of the life expectancy of geomembranes.

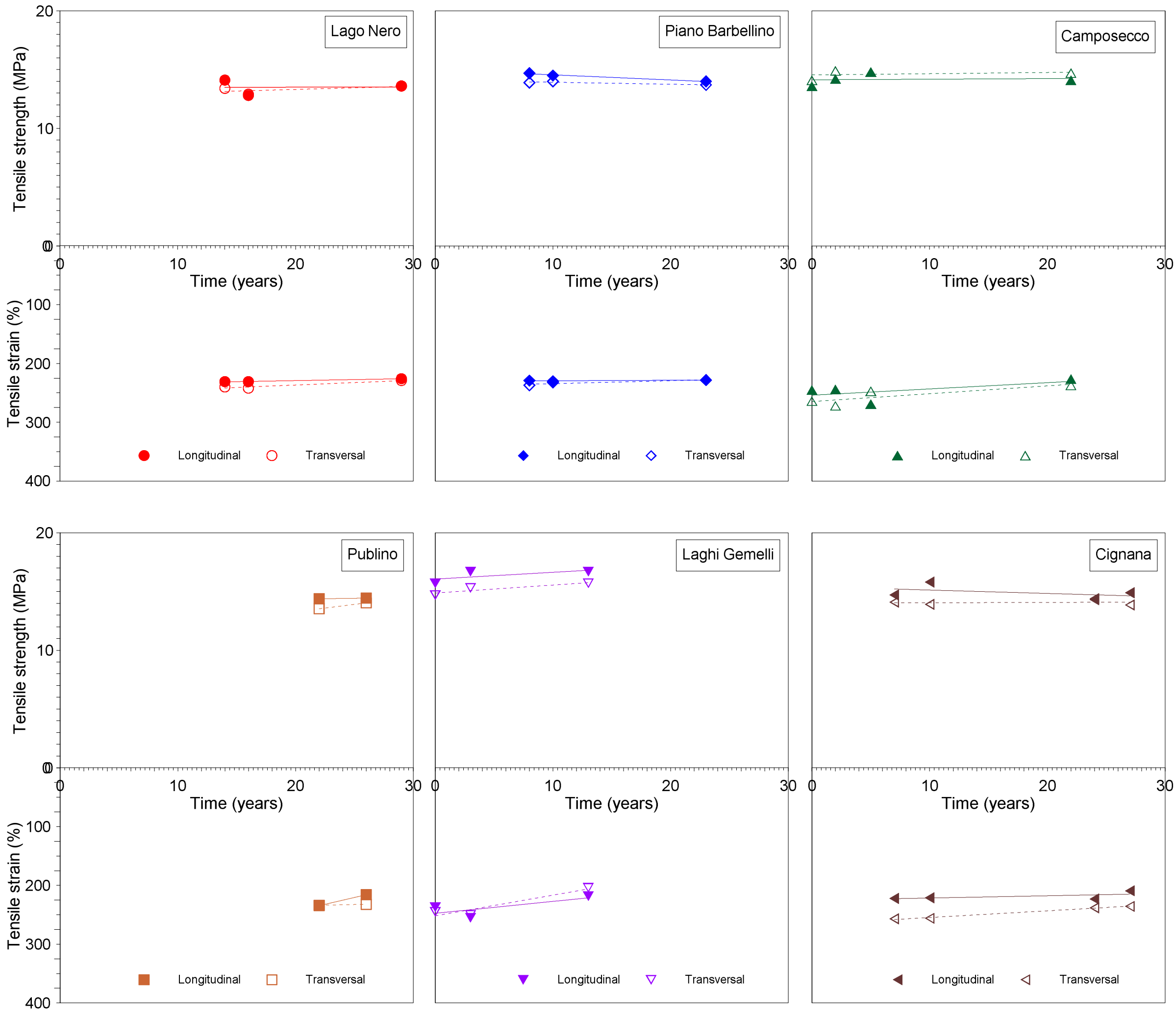


Figure 5. Tensile strength and tensile strain evolution over time.

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