Long-time behavior of exposed geomembranes used for the upstream face rehabilitation of concrete and masonry dams

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ABSTRACT: 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. 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. The prediction of the moment in which it could become necessary to replace the geomembrane assumes a very important role form a managerial point of view. In this paper, in order to verify the performance of the waterproofing system over time, several geomembrane samples have been taken from a considerable number of dams. These samples have then been subjected to physical and mechanical tests, in order to observe the evolution of the properties of the geosynthetics over the years. In a lot of cases, particularly when the results of tests on virgin samples were available, it was possible to evaluate the residual life of exposed geomembranes on the different types of dams.

Keywords: Geosynthetic, geomembrane, dam, rehabilitation, performance, durability

1 INTRODUCTION

The deterioration of concrete dams 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. In dams subject to alkali-aggregate reaction, increase in the water content aggravates the reaction. Rehabilitation generally aims to stop water infiltration and further deterioration of the structure.

Geosynthetic barriers have been used as alternative solutions to mitigate deterioration processes in existing dams, 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.

On concrete dams, the liner adopted is generally a PVC geomembrane coupled during fabrication to an anti-puncture and drainage geotextile. The liner, supplied in flexible sheets, is generally installed directly over the concrete. Sometimes an additional drainage geonet is installed behind the geocomposite to enhance drainage transmission.

On masonry faced dams, the geocomposite system must meet the demanding requirements of the exceptional roughness of the substrate and its different consistency (stone and mortar in the joints). On these dams, the system is implemented by a transition anti-puncture layer, usually a thick geotextile to achieve a smoother surface without extensive civil works.

In the 1970s, the first projects of rehabilitation of concrete dams were made on dams situated at high elevation in the Italian Alps, where traditional facings (shotcrete and concrete) were susceptible of quick ageing caused by frequent freeze-thaw cycles, low temperatures and ice action. As previous experience 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 environment.

The first entirely successful applications of concrete dam rehabilitation were made in 1976 at Lago Miller Dam, Italy, an 11 m high gravity dam constructed in 1926 at elevation 2170 m a.s.l., where a 2.0 mm thick PVC geomembrane was adopted, and in 1980 at Lago Nero Dam, Italy, a 45.5 m high gravity dam constructed in 1929 at elevation 2027 m a.s.l., where a composite geomembrane consisting of a 2.0 mm thick PVC geomembrane laminated to a 200 g/m^2 needle-punched nonwoven geotextile was adopted. The Lago Nero Dam represents the first use of this type of composite geomembrane on a dam. This type of geomembrane will then be used successfully on many dams (Cazzuffi, 1987; Cazzuffi et al., 2010).

All pioneering applications of PVC geomembranes to rehabilitate concrete dams were located in the Italian Alps, at more than 2000 m elevation. In the 1970s and 1980s, a total of eight large dams were thus rehabilitated, all in the Italian Alps.

At all of these dams, the PVC geomembrane was left exposed to the environment, which at such elevation 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.

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 assumes a very important role form a managerial 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 outflow; ii) prevent stability problems which can have as triggering factor the seepage of water through the dam.

In the last years, two different paths emerged in order to gather experimental data on the geomembranes' behaviour: (a) reproducing field conditions in laboratory or (b) taking samples from installed geomembranes in different periods of their lives; in any case geomembranes must then be put through specific laboratory tests in order to determine variations in their properties with time (Cazzuffi, 2013).

Following the second of the two above-mentioned paths, this paper analyses the behaviour of the geomembranes installed on eight Italian dams, showing the recent results of the experimental tests carried out at the Geosynthetics Laboratory of CESI S.p.A. in Milano, Italy, on samples taken directly on site.

2 REHABILITATION OF CONCRETE AND MASONRY DAMS USING EXPOSED GEOMEMBRANES

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 eight concrete or masonry dams located in the Italian Alps (Cazzuffi, 1996; Cazzuffi, 1998; Scuero and Vaschetti, 1996).

The dams considered (Figure 1) were built at the beginning of the last century and are characterised by several common features, so that it is possible to make some considerations that are acceptable for all of them (Table 1). It is important to underline that these areas are characterised by a very changeable weather, responsible of sudden change in temperature with consequent heat loads which play an important role in the durability of the dam.

The continuous exposition of the dams to atmospheric and environmental agents causes over the years a notable deterioration of the dams' upstream face and an increase of leakage with respect to the initial values was detected.

Between 1980 and 2000, all of the upstream faces of the eight dams here considered were rehabilitated with the application of a geosynthetic layer in order to restore their initial water tightness.

All the eight dams here presented have been rehabilitated with an exposed two-layer geocomposite, formed by: i) a polyvinyl chloride (PVC) geomembrane; ii) a polyester (PET) needle-punched nonwoven geotextile or a high-density polyethylene (HDPE) geonet (Table 2).

As for the geomembrane, its function is to assure the barrier function of the upstream face thanks to its very low coefficient of permeability.

With regard to the geotextile, this layer assumes two significant roles: i) an anti-puncturing function, through the regularisation of the surface on which the geomembrane is laid down; ii) a drainage function, as it avoids the accumulation of water between the geomembrane and the dam face; this happens as a result of the generation of a high-trasmissivity plan which allows water to flow by gravity into a special collector.

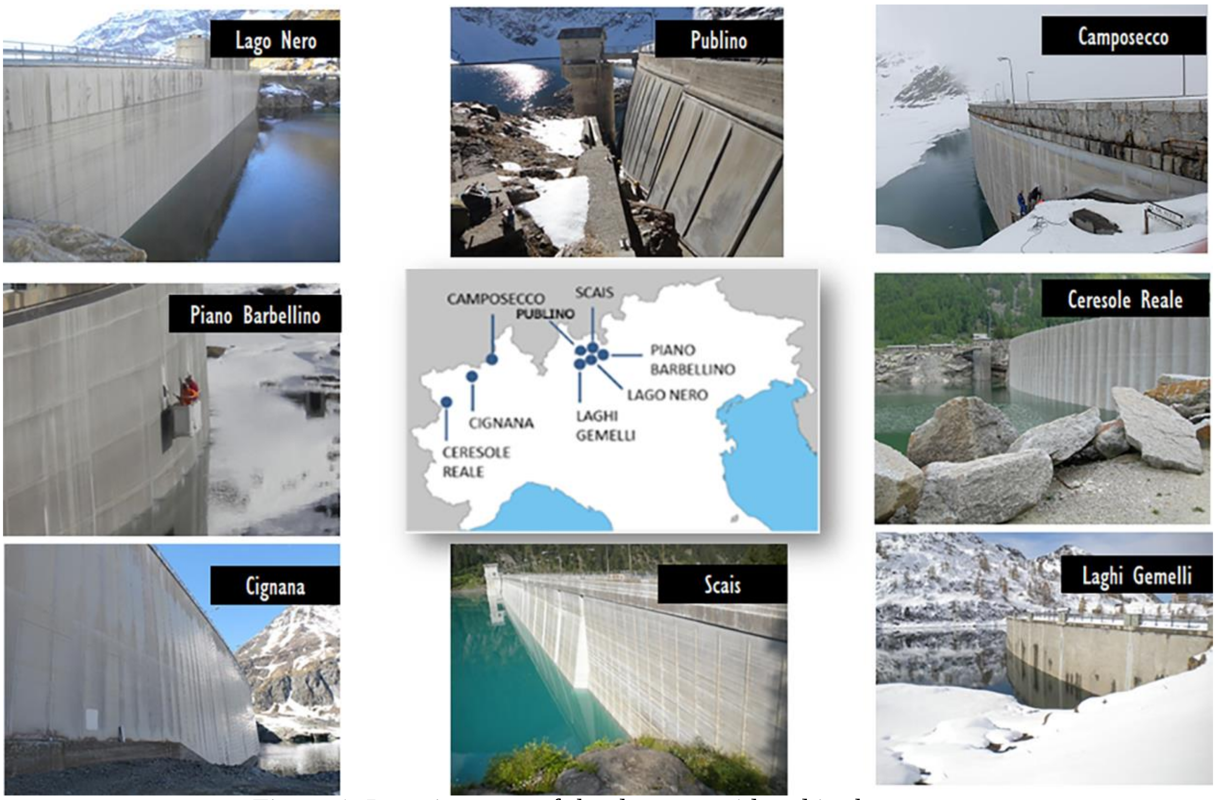

Figure 1. Location map of the dams considered in the paper.

Table 1. Main features of the dams.

Dams	Type	Height [m]	Year of construction	Location	Environment	Solar radiation
Camposecco	Masonry	27.00	1930	located in the Italian Alps, between 1500 m a.s.l. and 2500 m a.s.l.	Very cold winters and fresh and rainy summers. Air temperature ranges between −10°C and −15°C in winter, with negative peaks of −20°C ÷ −25°C, and between +15°C and +25°C in summer	At these elevations, the solar radiation is very significant, with high temperatures of rocks and structures (even +40°C).
Ceresole Reale	Concrete	52.00	1931			
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			
Scais	Concrete	64.70	1939			

Table 2. Upstream face rehabilitation of dams: properties of the geocomposite usually adopted

	Thickness (mm)	Layer	Type	Polymer	Function
Exposed two-layers thermobonded geocomposite	2.0÷2.5	1	geomembrane	PVC	barrier
	3.0÷3.5	2	needle-punched nonwoven geotextile	PET	protection and drainage

3 DURABILITY OF EXPOSED PVC GEOMEMBRANES

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 analyze in this paper.

Durability is defined as being the period of time during which a geomembrane remains watertight, taking into account the aging of the material and the effects of mechanical and physical action. Due to their excellent mechanical resistance and easy weldability, PVC geomembranes present many advantages when applied to hydraulic structures.

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 (Table 3)

Among all these factors, previous studies (namely Girard et al., 2002 and Bartolomeo, 2003) demonstrated that the deterioration of the geomembrane, and then of the entire waterproofing system, depends mainly on these four factors: temperature, UV radiation, geomembrane thickness and exposure time.

Table 3. Factors affecting durability of exposed PVC geomembranes.

Internal factors	composition of PVC	
	quality of its additives	
	reciprocal percentage of additives	
	thichness of the geomembranes	
External factors	Loads	gravity, puncture, waves or ice formation in the reservoir and other similar actions that change the state of stress of the geomembrane
	Environmental	temperature, UV radiation, dry-wet cycles, chemical or biological attack by substances or micro-organisms contained in water

The properties of PVC, and then of the geomembrane, derive from the reciprocal percentage of resin and other components (Blanco et al, 2010). PVC is a plastic material that proved to be characterised by high performances in terms of durability, versatility and cost (Krauskopf, 1993).

PVC derives from the polymerisation of the monomer vinyl chloride and the material used for the manufacture of PVC geomembranes is constituted by a mixture of the following components (Hsuan et al., 2008):

- PVC Resin – Represents approximately 60% of total weight (rigid product, very chemically resistant). Resin is characterized by the "K value" (molecular weight and viscosity). A high value corresponds to high mechanical characteristics and good flexibility at low temperatures, but its welding may become more difficult. It can be observe that very low values are accompanied by important creep of the product on long slopes;
- Plasticizers – Confer flexibility to the final product and represent approximately 35% of total weight:
- Lubricants – Help to improve the process;
- Pigments – Confer a certain colouring and may also, depending on the pigment, assist in UV and heat stabilization. Good examples of pigments that assist in geomembrane stabilization are carbon black (confers a black colouring to the geomembrane) and/or titan dioxide (confers a light colouring and reduces the temperature of the geomembrane, during exposure);
- Heat stabilizers – Avoid thermal decomposition during the process or welding;
- UV stabilizers – Guarantee or improve the protection of the PVC-P geomembrane relative to UV action;
- Chalk – Are added to reduce the cost of the geomembranes. They increase the mass, the porosity of the geomembrane and the sensitivity to acid products. On the other hand they can slightly increase fire resistance;
- Recycled – PVC-P geomembranes can use recycled PVC. This recycled material has the advantage of reducing the cost of the product without detracting from its final quality, including its mechanical characteristics. To ensure this, the recycled material should be chosen with great care, there should be good control at the factory and there should also be a good system for its incorporation in the manufacturing process;
- Other additives – Fungicides, fire resistant additives, amongst others, can also be used.

In particular, plasticizers play a fundamental role in terms of variation of the physical properties of the virgin material.

Plasticizer loss is the most common form of aging of the PVC geomembranes. Plasticizer loss induces an increase in rigidity, easily detectable through the increase of the modulus in the tensile test. In the same test, a reduction of the strain at failure and an increase of the stress at failure can be observed. During the same period, low temperature brittleness increases, from approximately -30º to 0ºC or more.

Plasticizer loss first occurs in the interior of the geomembrane to the surface by diffusion, and then from the surface to the external environment by evaporation. The phenomenon of plasticizer diffusion through the geomembrane is very frequently associated with Fick's law. However, Fick's law is no longer valid when we study the long term behaviour of a geomembrane. The phenomenon of plasticizer loss is never linear. The combination of a variety of actions during the life of the geomembrane may increase or reduce plasticizer loss.

Plasticizers 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). 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 minimum quantity of plasticizer admissible to ensure durability depends on the actions on the geomembrane as well as the type of plasticizer used. In the case of our geomembranes, based on the various tests carried out and observations in the field, a residual value of plasticizer of approximately 30% on average (this value may vary according to the external environment, type of application and design of the waterproofing system) allows the geomembrane to remain watertight (Carreira and Tanghe, 2008).

4 EVALUATION OF THE RESIDUAL LIFE OF EXPOSED GEOMEMBRANES

4.1 *Geomembrane sampling*

In order to evaluate the variation over time of the characteristics of the PVC geomembranes installed on the eight 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 (Table 4).

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 (Figure 2).

In the determination of the life expectancy of a geomembrane, it is important to identify the more critical portion of the upstream face, as the first failure will affect negatively the whole waterproofing system. Therefore, here we will present the results of the tests made on samples taken above the water level, as this is the area which suffers more the exposure to atmospheric agents. The results obtained are thus referred to the worse conditions for each geomembrane and this helped us to conduct a precautionary analysis of the geomembrane durability (Cazzuffi and Gioffrè, 2017).

Table 4. Geomembrane sampling.

Dams	Type	Years after application
Camposecco	Masonry	Virgin sample (1994), 2 years (1996), 5 years (1999), 22 years (2016)
Ceresole Reale	Concrete	Virgin sample (1992), 5 years (1997), 11 years (2003), 15 years (2007), 19 years (2011)
Cignana	Concrete	7 years (1996), 10 years (1999), 24 years (2013), 27 years (2016)
Laghi Gemelli	Concrete	Virgin sample (1997), 3 years (2000), 13 years (2010)
Lago Nero	Concrete	14 years (1995), 16 years (1997), 29 years (2010)
Piano Barbellino	Concrete	8 years (1995), 10 years (1997), 23 years (2010)
Publino	Concrete	22 years (2011), 26 years (2015)
Scais	Concrete	18 years (2011), 20 years (2013)

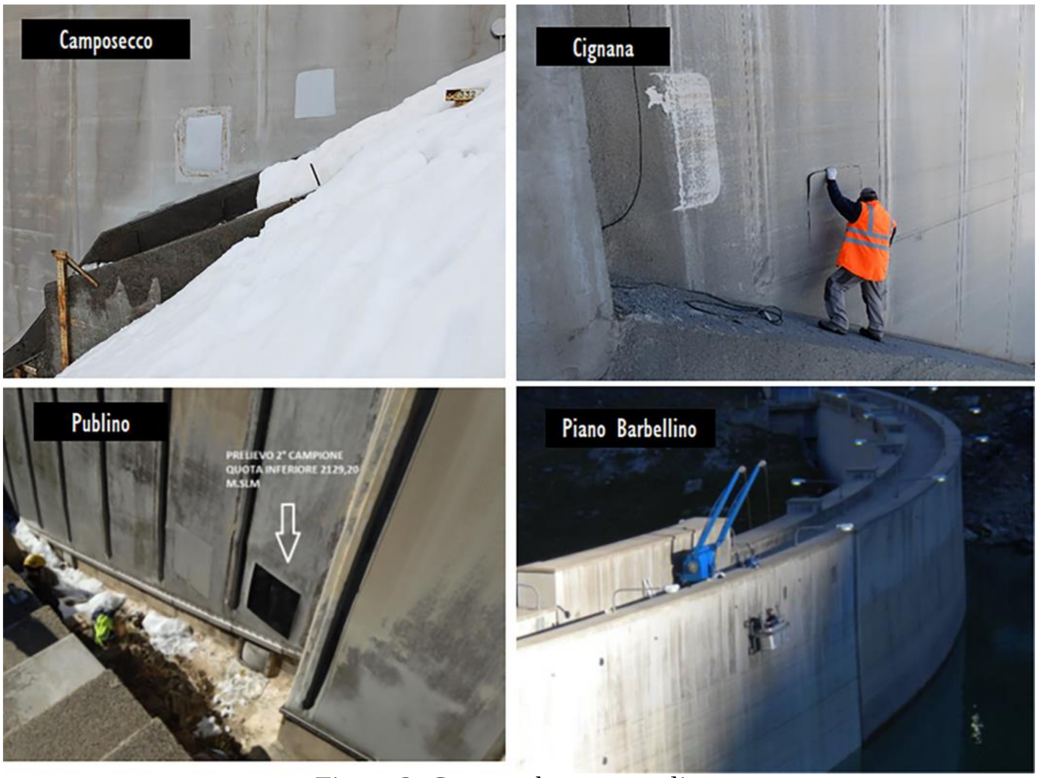

Figure 2. Geomembrane sampling.

4.2 *Laboratory tests*

All the samples taken from the dams' upstream faces have been tested at the Geosynthetics Laboratory of CESI S.p.A. in Milano, Italy (Cazzuffi, 2014). The tests allowed the comparison among different samples during the degradation process of the geomembranes. The cases of Camposecco, Ceresole Reale and Laghi Gemelli are particularly significant, as for these dams the test results on virgin samples are available; knowing the initial conditions, the analysis is more precious as it allows to reconstruct the entire life of the geomembrane.

Before the tests, samples were prepared by the separation of the geotextile layer from the geomembrane. Here we will discuss only the test made on this second layer, according to the standards reported in Table 5.

Table 5. Laboratory tests and reference standards.

Test	Reference standard
Plasticizers extraction	ISO 6427
Nominal thickness	UNI 8202/6
Volumic mass (density)	UNI 7092
Hardness (shore A)	UNI 4916
Cold flexibility	UNI 8202/15
Dimensional stability	UNI 8202/17
Tensile properties	UNI 8202/8
Water vapour transmission	UNI 8202/23

The results obtained show a constant small decrease of the plasticisers content (Figure 3a) and temperature of cold flexibility rises with time, while dimensional stability grows longitudinally and declines transversally in the years.

Mechanical parameters show that the geomembrane get stiffer over time, with a growth of tensile strength and a reduction of the correspondent strain. Figure 3b shows tensile strength and strain versus time in the longitudinal direction.

With regard to the waterproofing properties, the results of the vapour transmission test demonstrate in general the decrease of the permeability coefficient (Figure 3c), thus an improvement of the water-tightness of the geomembranes.

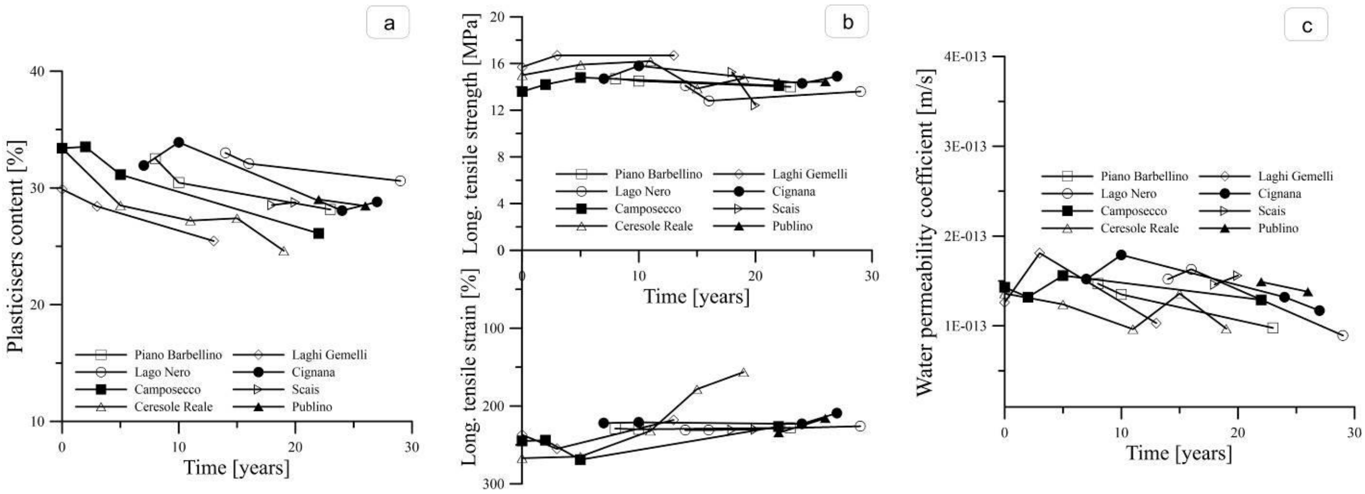

Figure 3. a) Variation of plasticizers content vs time; b) Variation of longitudinal strength and strain vs time; c) Variation of water permeability coeffcient vs time

In order to evaluate the residual life of exposed geomembranes (especially in that dams in which virgin samples are available), the plasticisers content versus time has been analysed in detail (Figure 4).
In the case of the considered geomembranes, it was concluded that a residual value of plasticizer of 70% on average of the sample virgin value (this value may vary according to the external environment, type of application and design of the waterproofing system) allows the geomembrane to guarantee a good performance on site.

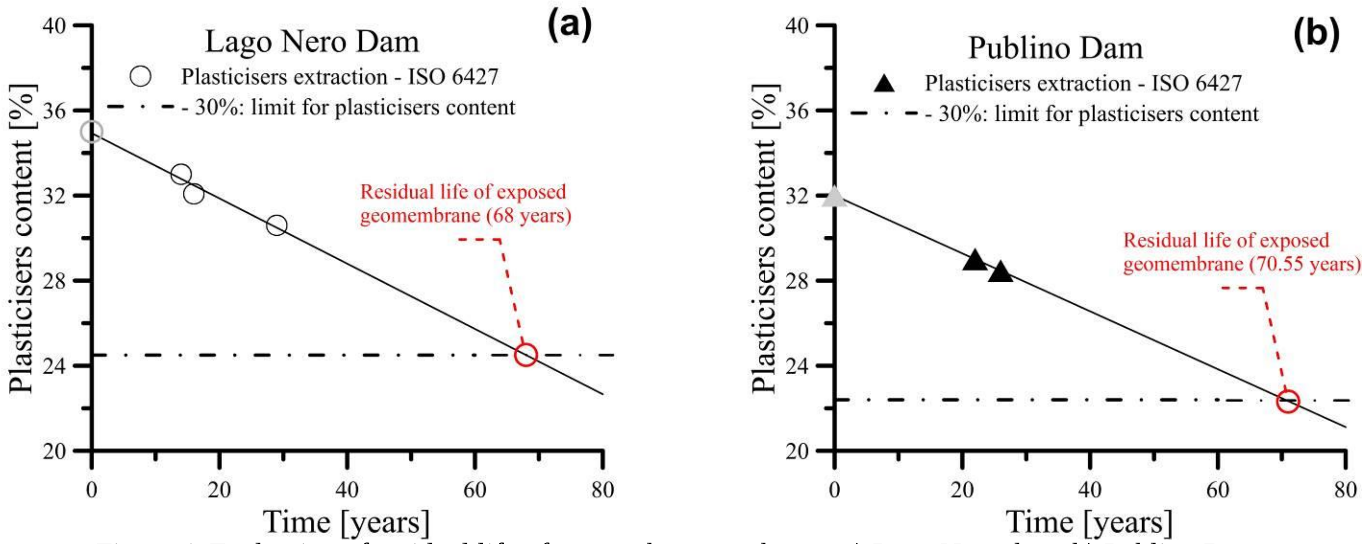

Figure 4. Evaluation of residual life of exposed geomembrane: a) Lago Nero dam; b) Publino Dam.

5 CONCLUSIONS

In order to be able to precisely define the durability of a PVC geomembrane it is indispensable to have an understanding of its real behaviour in the long term. It is important that the study of real long term understanding is as wide ranging as possible, permitting the coverage of the greatest number of hypotheses according to climatic and other variations which may occur.

The paper discusses the behaviour of PVC geomembranes installed on the upstream face of eight Italian dams without any external protection. An experimental programme was launched in order to study the life expectancy of exposed PVC geomembranes and several tests were conducted on samples taken directly on site in the last twenty years. The results obtained show a constant small decrease of the plasticisers content. Mechanical parameters show that the geomembrane get stiffer over time, with a growth of tensile strength and a reduction of the correspondent strain. With regard to the waterproofing properties, the results of the water vapour transmission test demonstrate in general the decrease of the water permeability coefficient, thus an improvement of the water-tightness of the geomembranes.

The parameter that shows a steadier, and therefore clearer, behaviour is the plasticisers content. Thanks to its stability, it reveals to be a good indicator for the evaluation of the life expectancy of geomembranes.

On the basis of test results, an evaluation of residual life of exposed geomembrane was carried out for the dams in which virgin samples was available.

Moreover, test results show that geomembranes need a constant monitoring and frequent site survey. In effect, it is important to identify the signs of deterioration and evaluate if they belong to the normal trend of the geomembrane life or if a sudden worsening of the waterproofing system conditions has happened due to other unexpected reason.

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