Geosynthetics: Leading the Way to a Resilient Planet – Biondi et al (eds)
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Durability of exposed PVC-P geomembranes used for rehabilitating the upstream face of dams

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ABSTRACT: This contribution presents the recent results of an ongoing research on the long-term behaviour of a PVC-P geomembranes installed on the upstream face of masonry and concrete dams. In the last 30 years, starting from sometime after the dam rehabilitation with this type of geosynthetics, the exposed PVC-P geomembrane were sampled periodically and tested in laboratory. Material properties measured at the laboratory were compared with the ones obtained from test on virgin samples, when available. The sampled geomembranes have been subjected to physical and mechanical tests and the results interpreted with reference to the variation of plasticizer, tensile characteristics, foldability at low temperatures, and specific mass. In particular, the decrease in plasticizer content resulted in a slightly increase of the geomembrane rigidity, i.e. higher modulus and tensile strength and lower strain at failure. The experimental program allowed to study the evolution of the properties of the geomembrane over the years enabling the assessment of the residual life of exposed geomembranes installed on the upstream face of dams.

1 INTRODUCTION

Geomembrane systems are one of the most sustainable rehabilitation technologies for dams. Geosynthetic barriers have been used as alternative solutions not only to mitigate the deterioration processes in existing dams, but also to prevent the onset of seepage-induced degradation in new dams, and as the main hydraulic barrier, particularly for embankment dams, in cases where low-hydraulic conductivity soils are not readily available (Cazzuffi 1987).

The use of geosynthetics as water barriers is one of the numerous uses of geosynthetics in hydraulic and geotechnical applications of geosynthetics. The use of geosynthetics in dams represents a major application of the geosynthetics since “dams have a particular status due to their impact on the environment and on safety”, as pointed out by Heibaum *et al*. (2006).

While the concept of using geomembranes in dams instead of conventional “low permeable” materials (e.g. clay, cement concrete (hereafter simply called concrete) or bituminous concrete) derived, among other considerations, from the successful use of geomembranes in canals and reservoirs, the credibility of synthetic materials in dams had been established by the good performance of embedded PVC waterstops in a very large number of concrete dams worldwide. In those dams, waterstops play an essential role in preventing water seepage through joints that are indispensable to accommodate concrete expansion and contraction. A geomembrane placed on the upstream face of a dam or inside a dam can be considered,

DOI: 10.1201/9781003386889-220

from a conceptual viewpoint, as one wide waterstop sealed at the abutments and at the bottom of a dam.

The most pioneering applications of PVC-P geomembranes, employed to rehabilitate concrete and masonry dams, were in the alpine regions in Europe, at more than 1500 m elevation. In particular, this contribution focuses on eight large concrete and masonry dams, all in the Italian Alps, that were rehabilitated with this technology in the 1980s and 1990s. In all of these dams, the PVC-P geomembrane was left exposed to the environment, which is quite demanding at such elevation in terms of resistance to UV rays, freeze-thaw cycles, extremely low temperatures, and high daily and seasonal temperature variations.

The rehabilitation of dams consisted in the application of a geocomposite on the upstream face. This geocomposite was formed by a geomembrane layer, placed externally and having a barrier function, and by a geotextile layer, placed internally with a mechanical protection and drainage function. The geocomposite usually covers the entire upstream face of the dam and the most common installation method consists of vertical strips of about 2.00 m wide, fixed to the dams by means of batten strips held by anchor bolts (Scuero & Vaschetti 1996). The geotextile component protects the geomembrane from the mechanical damage caused by irregularities in the dam upstream face; it also contributes to reduce the creeping or sagging of the geomembrane along the quasi-vertical dam face.

In this paper, PVC-P geomembranes installed on the upstream face of dams are evaluated using results of a wide experimental campaign still ongoing (Cazzuffi & Gioffrè 2018; Cazzuffi & Gioffrè 2021a). The results of the experimental tests carried out on samples retrieved directly at site integrated the data obtained in the research and contributed to monitor the variation over time of the characteristics of the PVC-P geomembranes in service; moreover, the additional tests presented here helped to confirm the methodology already employed in (Cazzuffi & Gioffrè 2021b) to predict the lifetime of the geomembrane.

2 LONG-TERM BEHAVIOUR OF GEOMEMBRANES IN DAMS

The durability of geomembranes is based on their weathering properties, and on their resistance to specific loads during service, such as extreme temperatures, frost, freeze/thaw, ice, impacts by floating debris and boats, wind and waves, fauna and flora, vandalism etc. (Hsuan *et al.* 2008).

Not all geomembranes have the same behavior due to their different chemistry, basic ingredients, and manufacturing process; For these reasons it is important when considering dam projects to either select an existing geomembrane or to design a new one that can best perform according to the type of environment in which it will be used, and that can provide an adequate durability for the required application.

The behavior in service of geomembranes is commonly predicted using standard accelerated ageing tests. However, these tests, although accelerated, still require too much time for providing an effective indication on the long-term behavior of geomembranes.

The most practical way to ascertain if a geomembrane will resist to the environmental loads expected in a dam project in the long term, is to retrieve samples of the same type of geomembrane already in service in a similar environment , for a period of time that should be as long as possible, ideally as long as the required service life of the geomembrane in the considered dam. Tests are then performed on these samples to determine to which extent their properties have changed during service. Testing of the physical and mechanical properties of the exhumed samples indicates if the geomembrane properties at the time of the test are within acceptable limits, and extrapolation allows the determination of the expected remaining service life. This approach has been adopted in Italy (Cazzuffi 1987; Cazzuffi & Gioffrè 2020, 2021b), using data from several concrete and masonry dams rehabilitated with exposed PVC-P composite geomembranes.

3 REHABILITATION OF CONCRETE AND MASONRY DAMS

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, installed in the ‘80s and ‘90s, and retrieved from the upstream face of eight large concrete or masonry dams in the Italian Alps (Cazzuffi 1996; Cazzuffi *et al*. 2010; Scuero & Vaschetti 2009, 2017), where most of the pioneering applications of PVC-P geomembranes to rehabilitate concrete dams were located.

The dams considered (Figure 1) were built in the ‘30s (only one in the ‘50s) and are characterized by several common features, so that it is possible to make some considerations that are acceptable for all of them. It is important to highlight that these areas are characterized by a very changeable weather, responsible for sudden changes in temperature, with consequent heat loads which play an important role in the durability of the dam and its materials.

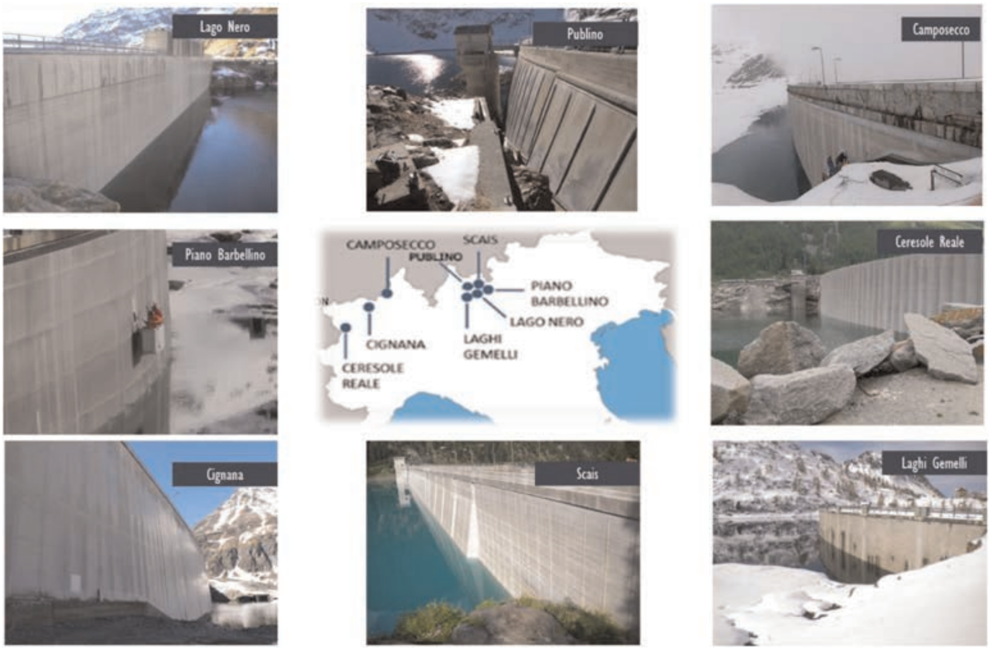

Figure 1. Location map of the dams considered in the paper.

For all these 8 dams, the PVC-P geomembrane was left exposed to the environment, which at such elevation is quite demanding in terms of resistance to UV rays, freeze-thaw cycles, extremely low temperatures, and high–daily and seasonal–temperature excursions.

Between 1980 and 2000, all of the upstream faces of the 8 dams here considered were rehabilitated with the application of a geosynthetic layer in order to restore their initial watertightness.

The rehabilitation was performed by installing an exposed two-layers composite geomembrane, formed by: i) a plasticized polyvinyl chloride (PVC-P) geomembrane; ii) a polyester (PET) or polypropylene (PP) needle-punched nonwoven geotextile. In just one case an extra layer of high-density polyethylene (HDPE) geonet was added. Given its very low coefficient of permeability, the geomembrane was installed to ensure the barrier function of the upstream face.

The geotextile layer was installed to fulfill two main functions:: i) anti-puncturing function, through the regularization of the surface on which the geomembrane is laid down; ii) 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-transmissivity plane which allows water to flow by gravity into a special collector.

In all of the cases presented here, the geomembrane is always coupled with another geosynthetic; therefore in the following we will refer to the entire waterproofing system as composite geomembrane, as this is the layer providing the barrier function we want to analyze in this paper.

4 EVALUATION OF THE RESIDUAL LIFE OF EXPOSED GEOMEMBRANES

In order to evaluate the variation over time of the characteristics of the PVC-P geomembranes installed on the eight dams here considered, a good number of samples have been taken after the geomembrane application and all of them have been subjected to the same type of tests.

Samples were retrieved both above and below the water table level and in different parts of the upstream face, with the aim of studying the different behaviour of the same geomembrane under different conditions of exposure.

When determining 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 present the results of the tests made on samples taken above the water level, as this is the area which suffers most from the direct exposure to atmospheric agents. The results obtained are thus referred to as the worst case scenarios for each geomembrane and this helped us to conduct a precautionary analysis of the geomembrane durability.

All the samples taken from the dams upstream faces have been tested at the Geosynthetics Laboratory of CESI S.p.A. in Milano, Italy. These tests allowed the comparison among different samples during the degradation process of the geomembranes. The cases of Camposecco and Ceresole Reale are particularly significant, as for these dams the test results on virgin samples are available. The analyses conducted for these cases are, therefore, more valuable as the knowledge of the materials initial condition allows the reconstruction of the entire life behaviour of the geomembrane.

Before the tests, samples were prepared by separating the geotextile layer from the geomembrane. Only the tests made on the geomembrane layer (Table 1) will be discussed in the following.

Table 1. Laboratory tests and reference standards.

Test	Reference standard
Plasticizer extraction	EN ISO 6427
Nominal thickness	EN 1849-2
Volumic mass	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

The results obtained show a constant small decrease of the plasticizers' content (Figure 2a), while temperature of cold flexibility rises with time; moreover, dimensional stability grows longitudinally and declines transversally in the years.

Mechanical parameters show that the geomembrane get stiffer over time (Figure 2b), with a growth of tensile strength and a reduction of the correspondent strain, both in the longitudinal and in the transversal direction.

Long-term performance of PVC-P geomembranes depends on several aspects referred to exposure environment and polymer and additive formulations. The service life of PVC-P geomembranes can be predicted based on experimental results. Through a careful monitoring of the variation over time of the characteristics of the PVC-P geomembranes in service, it was possible to define a methodology of lifetime prediction for the geomembrane installed in dams when the results on virgin samples are available. In particular, the plasticizer content plays a fundamental role in terms of variation in physical properties of the PVC-P geomembranes (Giroud 1995; Giroud & Tisinger 1993).

In order to evaluate the most critical service life of the PVC-P geomembrane, two approaches can be used: (1) the curve of plasticizer content versus time is extrapolated until the end-of-service-life plasticizer content is reached; or (2) 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 end-of-service-life criterion expressed in terms of plasticizer loss ratio.

Giroud (2021) proposes, for the end-of-service-life criterion, a plasticizer content value of 17.5% for PVC-P composite geomembranes bonded to a nonwoven needle-punched geotextile (which are the most frequently used in the considered dams). This value was based on laboratory tests (Luciani *et al*. 2019, 2020) and on data collected from monitored structures,

According to approach (1), which used the curve of plasticizer content versus time, Figure 3a and Figure 3b show the lifetime assessment of exposed PVC-P geomembranes for Ceresole Reale and Camposesso dams, respectively.Vertical lines in Figure 3a and 3b show that the lifetime assessment of the exposed geomembranes for Ceresole Reale dam and Camposecco dam, assuming a linear decrease of plasticizer loss ratio over time, are approximately 42 years and 48.5 years in terms of plasticizer content criterion, respectively.

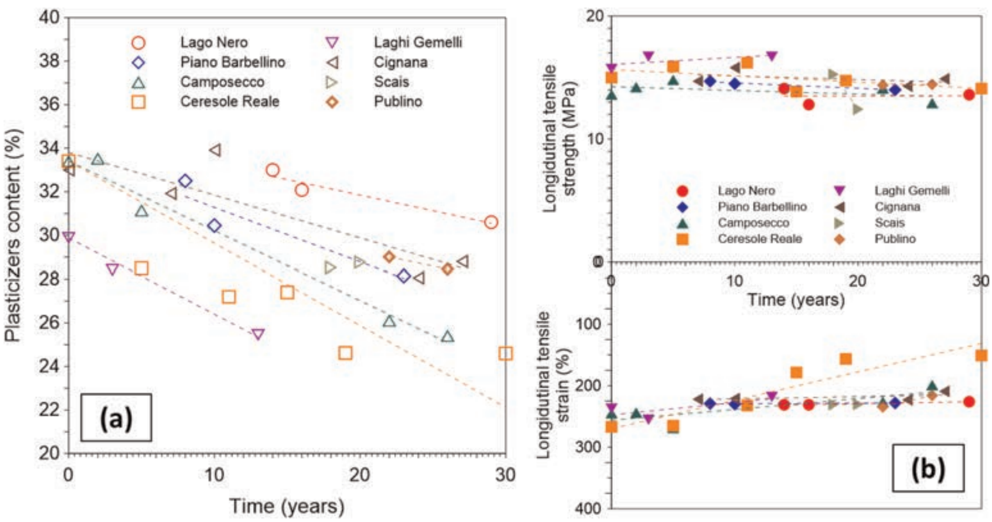

Figure 2. Test results: (a) Plasticizers content vs time; (b) Longitudinal tensile strength and strain vs time.

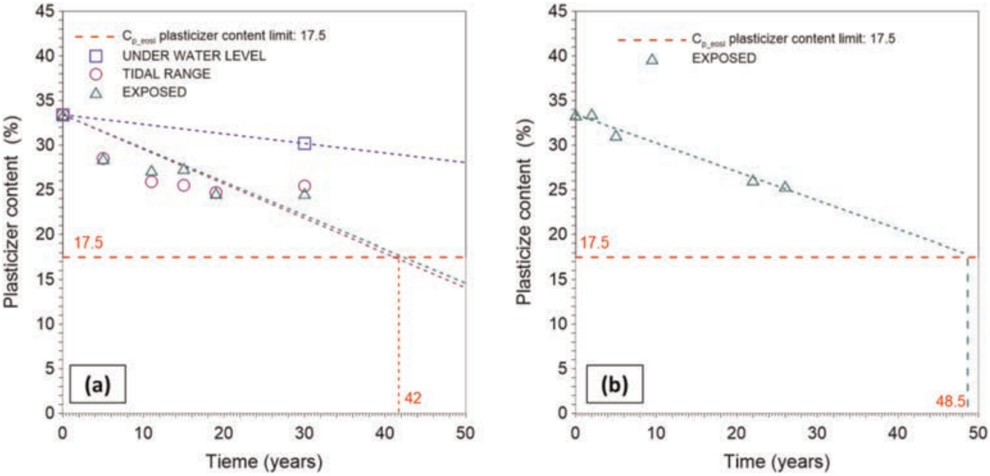

Figure 3. Lifetime assessment of exposed PVC-P geomembranes: (a) Ceresole Reale dam; (b) Camposecco dam.

5 CONCLUSIONS

The range of possible applications of geomembranes as water barriers in dams is quite wide. In fact, geomembranes can be applied to all types of dams, either in new construction or for in rehabilitation, both in dry conditions or underwater.

Long-term behaviour of a PVC-P geomembranes installed on the upstream face of masonry and concrete dams have been discussed in this paper, particularly in dams where test results on virgin samples are available.

Data on the performance of dams rehabilitated using geomembranes have been provided. These data show a remarkable performance of composite geomembranes in dams, even when the geomembrane component is exposed to atmospheric agents.

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