Evolution over time of PVC-P geomembrane used at Barlovento Reservoir

M. Blanco & A. M. Noval
Laboratorio Central de Estructuras y Materiales (CEDEX), Madrid, Spain.

M. A. Crespo
Renolit Ibérica, S. A. Sant Celoni, Barcelona, Spain.

D. Cazzuffi
Cesi SpA, Milano, *Italy.*

J. P. Giroud
J. P. Giroud Inc. Ocean Ridge,USA.

E. Aguiar & T. Vara
Balsas de Tenerife (BALTEN), Santa Cruz de Tenerife, *Spain.*

ABSTRACT: The 'Laguna de Barlovento' reservoir was, at the time of its construction, one of the most important European hydraulic projects because of its high capacity and challenging location. The engineers decided to waterproof it with a plasticized polyvinyl chloride (PVC-P) geomembrane. PVC-P geomembrane is exposed to atmospheric agents without any external protection.
This paper documents the initial characteristics of the geomembrane and its performance since its installation in 1991 until 2014. The results presented here, include quantification of geomembrane thickness, content and nature of plasticizers, tensile properties, foldability at low temperatures, dynamic impact resistance, puncture resistance, welding strength and welding peeling resistance, as well as the use of optical and scanning electron microscopy.
To identify the plasticizers nature, had been used analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Gas Chromatography (GC) and Mass Spectrometry (MS).

Keywords: Max. Reservoir, geomembrane, PVC-P, evolution, characteristics.

1 INTRODUCTION

Plasticized polyvinyl chloride (PVC-P) began being used in Spain in Mediterranean area in 1984 in particular, in the city of Ibi (Alicante) replacing to Butyl Rubber (IIR) which was the geomembrane used in the seventies. Afterwards, its use was extended to the Canary Islands and, later, to all the Spanish country.
It is mainly used reinforced with polyester fabric and, in some cases, homogeneous like in La Florida reservoir, or with glass fibber in it like in Valle Molina reservoir (Blanco 2012, Crespo 2011, Aguiar & Blanco 1995, Blanco et al. 1995, Blanco & Leiro 2012).
The use of this type of geomembrane is very common since the first work dated by ICOLD (1991, 2010). That was Dosbina Dam (Slovakia), waterproofed in the year 1960 until nowadays (Cazzuffi et al. 2010, Cazzuffi 2013, 2014).
Water Council of La Palma, island placed in the Canary Archipielago, carried our an extensive plan involving the construction of reservoirs, many of them waterproofed with PVC-P: San Mauro, Montaña del Arco, Adeyahamen, Bediesta, Las Lomadas, Manuel Remón and La Laguna de Barlovento. At this moment is being constructed El Vicario reservoir, with a big capacity and waterproofed with a 1.5 mm PVC-P geomembrane fleecebacked with a Polypropylene geotextile.
This paper shows the evolution over time of the polymeric synthetic geomembrane (GBR-P) of plasticized polyvinyl chloride (PVC-P) installed in one of the reservoirs cited before, La Laguna de Barlovento reservoir.
This paper documents the initial characteristics of the geomembrane, as well as its performance since its installation until the year 2014. It presents the results of content and nature of plasticizers, tensile properties (tensile strength and elongation at maximum load), foldability under low temperatures,

dynamic impact resistance (mechanical resistance to percussion), puncture resistance (static impact resistance), welding resistance, as well as the application of techniques of reflection optical and scanning electron microscopy.
To identify the plasticizers nature, had been used analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR), Gas Chromatography (GC) and Mass Spectrometry (MS).

2 THE RESERVOIR

The reservoir was built between 1971 and 1975 and its waterproofing was exclusively a layer of compacted clay. In spite of the previous analysis made in laboratory related to the clays, leaks were detected soon because the cited clays were from volcanic nature with basaltic interlayers. All this led to a solution that passed through the waterproofing with a geosynthetic barrier (Fayoux 2004, Fayoux et al. 1993).
The reservoir of 'La Laguna de Barlovento' is located in the northeast of La Palma Island, in the area known with the name of 'Las Cabezadas', in the municipality of Barlovento (Fig.1). Its characteristics are presented in Table 1, where are included capacity, inclination of the side slopes, crest level and perimeter, as well as its location, nature and thickness of the geomembrane, quantity of used material and year of installation. The bottom of the reservoir was waterproofed with a PVC-P geomembrane too, but homogeneous in this case, that is, without reinforcement, used for doing it 80.000 m^2 of this sheet.
In the context of this paper, there was not reference to this geomembrane, because there are less data values due to be installed in the bottom of the reservoir, all time covered by water; there are only the initial characteristics and some data when it was emptied to perform a reparation.

Table 1. Characteristics of La Laguna de Barlovento reservoir.

Location	Las Cabezadas (Barlovento)
Capacity, hm^3	3.1
Height, m	22
Crest level, m	739
Crest perimeter, m	1593
Slopes	2.75:1
Type of geomembrane	PVC-P
Thickness, mm	1.50
Quantity, m^2	170,000
Year of installation	1991

3 EXPERIMENTAL ACTIVITIES

Initially, were determined the characteristics of the polymeric geosynthetic barrier before its installation with the objective of confirm its validity and, moreover, to have the original values for realize its periodical monitoring. For this reason, samples had been extracted in different zones of the reservoir and the tests had been repeated to check the evolution of these characteristics over time.
The experimental methodology used in this research followed that developed by the European Standard EN 13361. Puncture resistance test were performed following the technology developed by this research team and that is now included in the Spanish Standards of AENOR (Blanco et al. 1996, UNE 104 317).

Figure 1. View of the PVC-P geomembrane of the La Laguna de Barlovento reservoir.

The table 2 include some of the characteristics originally determined. All the initially performed tests assess the conformance with the minimum requirements of the standards specifications for this type of geomembrane at that time. Those specification complied with the current Reservoir Manual (2010) written by the CEDEX for the Ministry of Environment and Rural and Marine Affairs.

Table 2. Characteristics of La Laguna de Barlovento reservoir.

Characteristics	Value
Thickness, mm	1.50
Content of plasticizers, %	35.1
Tensile strength, N/50 mm	
Longitudinal	1328
Transverse	1258
Elongation at point of maximum load, %	
Longitudinal	
Transverse	23
	25
Displacement of plunger before perforation, mm	
External face	16
Internal face	16
Seam resistance, N/50 mm	
Shear	1323
Peel	583

3.1 *Foldability at low temperature*

Specimens of the material from the reservoir were subjected to the foldability test at low temperature. They were folded at an angle of 180º during 3 seconds after to spend 5 hours into a cold chamber at -20ºC. After the test, specimens were inspected to identify any evidence of cracks, fissures or other sings of surface imperfections.
Specimens collected from the crest area of the southern slope did not present any deterioration after 23 years. Meanwhile, specimens collected from the northern, eastern and western areas did not pass the test. Specifically, half of the specimens showed cracks during the tests conducted 17 years after

the installation. This behaviour highlights the importance of quantifying the effect of UV radiation in this type of thermoplastic material (Aguiar et al. 2002, 2003, Blanco et al. 2003, 2012). Specimens collected from intermediate and submerged areas passed the test.

3.2 *Mechanical resistance to percussion (dynamic impact resistance)*

From the point of view of the dynamic impact resistance all the specimens collected in this study passed the test. This includes both initial samples as well as those collected throughout the 23 years following installation, regardless of the place in the reservoir where the samples were collected from. The mechanical resistance to percussion tests involves dropping a 0.5 Kg plunger ending in a semi-spherical shape and a diameter of 12.7 mm from a height of 500 mm. The geomembrane did not show holes in the impact zone.

3.3 *Tensile characteristics*

Tensile strength and elongation at maximum load values of the specimens collected in the north of the crest area are showed in Figures 2 and 3 respectively. Neither the elongation at break nor the tensile strength results did present significant changes over the 23 years of service. The good mechanical performance is due to the protection given by the PVC-P resin to the polyester scrim that is the responsible of the mechanical response in this reinforced geomembrane.

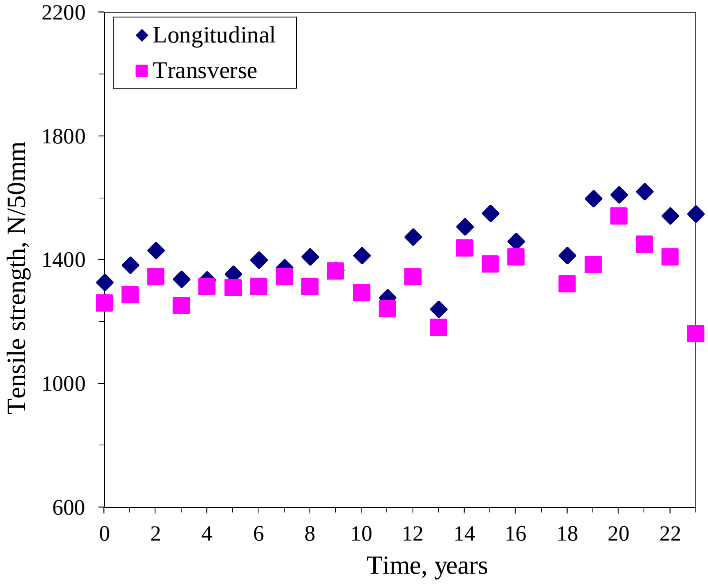

Figure 2. Tensile strength evolution over time.

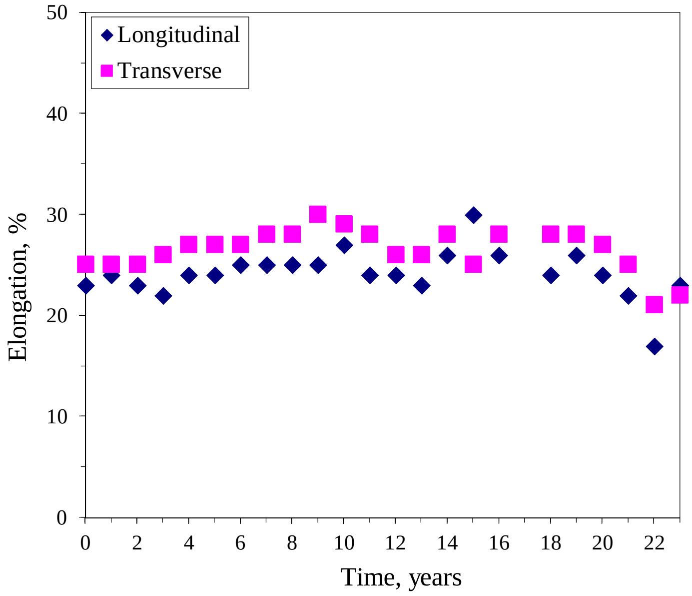

Figure 3.Elongation at maximum load evolution over time.

3.4 *Puncture resistance (static impact resistance)*

The performance in the static impact test is presented in Figures 4 and 5 where are showed the variation of the puncture resistance and the displacement of the plunger before perforation, respectively. Samples were collected in the norther slope of the crest area. Puncture resistance values are observed to increase over time, while displacement of the plunger before perforation decrease. These displacement values are comparatively small because of the polyester reinforcement. Nevertheless, in the last sampling, at 23 years, both characteristics decrease their values.

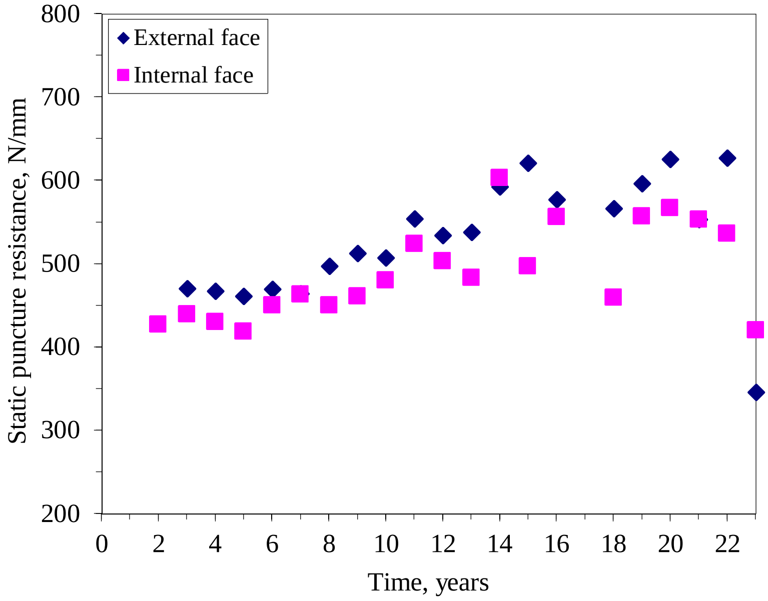

Figure 4. Puncture resistance evolution over time.

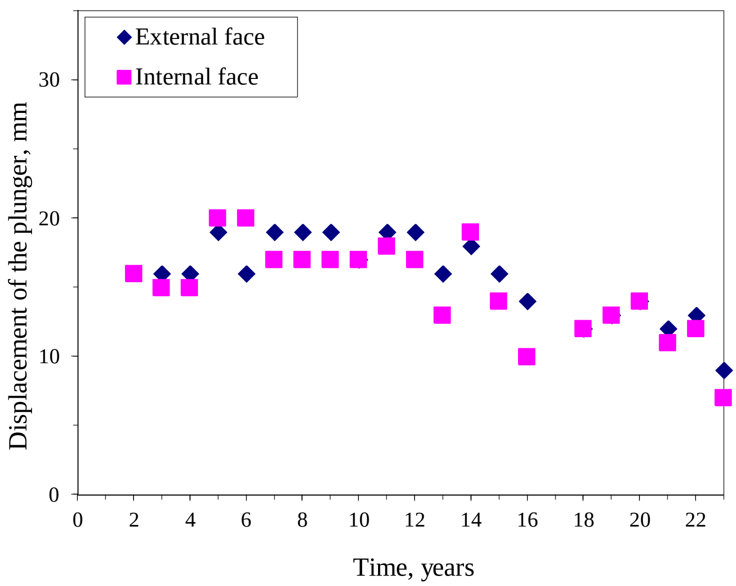

Figure 5. Displacement of the plunger before perforation evolution over time.

3.5 *Welding resistance*

The results of the welding strength resistance test are correct, as all the specimens broke in the edge or close to the seam, but never through the seam itself. Test values of samples collected in the north of the crest area, are presented in Figure 6. In Figure 7 are presented the results of the peeling test of same samples. The high values obtained in this test, as a quantitative test, indicate the good execution of the seams.

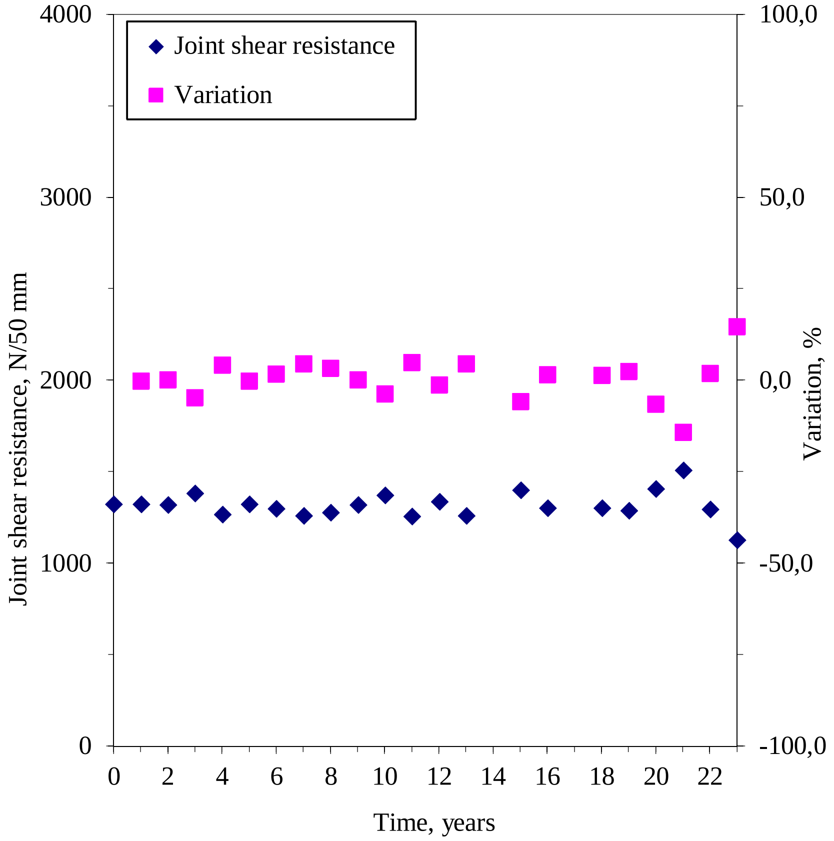

Figure 6. Welding strength resistance evolution over time.

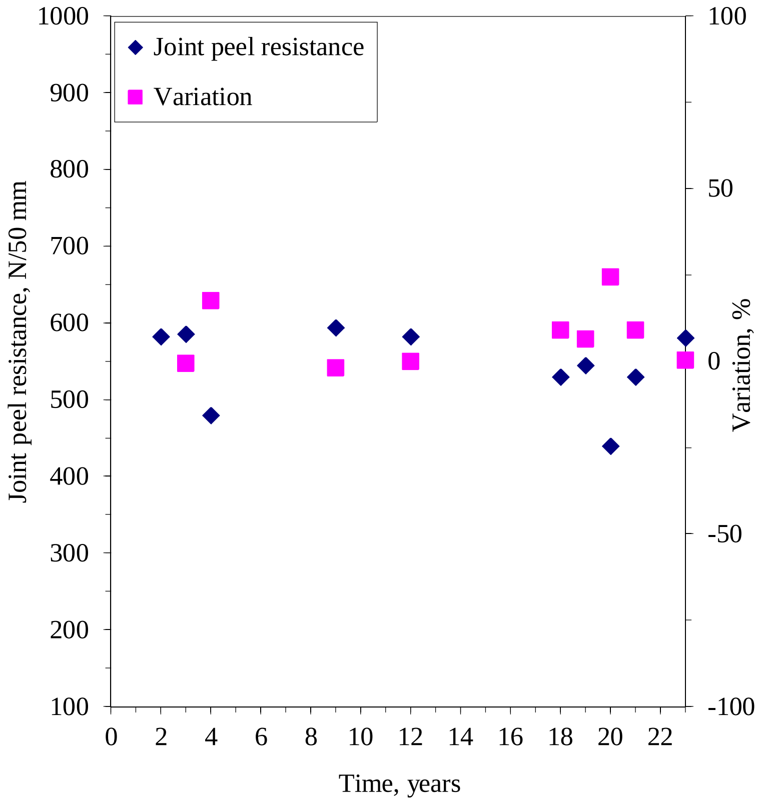

Figure 7. Welding peeling resistance evolution over time.

3.6 *Reflection optical microscopy and scanning electron microscopy*

Microscopic evaluation of the geomembrane had been performed in the experimental conditions indicated in the bibliography (Soriano et al. 2006, 2010). The microphotographs were taken by reflection optical microscopy (MOR) with 40x and 60x magnifications in order to visualize the geomembrane texture and morphology. The Figure 8 shows the external and internal face (exposed and non-exposed sides respectively) of the geomembrane samples collected in the norther slope of the crest area, using 40x magnification after 23 years of installation. Also the geomembrane was evaluated using scanning electron microscopy (SEM) with 90x and 900x magnifications. The figure 9 also shows the two sides of the geomembrane after 23 years using 90x magnification.
Reflection optical microscopy showed an external face with a high superficial cracking while the internal was in good state of preservation. The results obtained using scanning electron microscopy confirmed these observations.

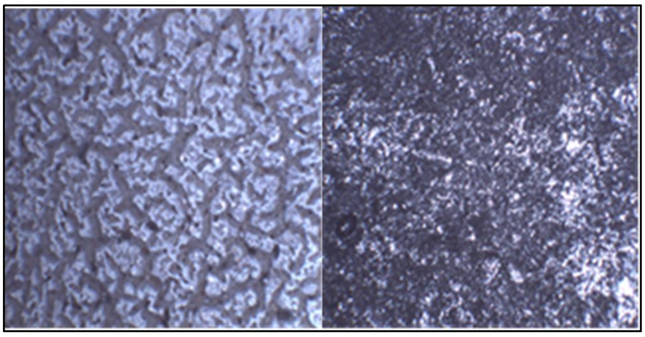

Figure 8. Microphotographs obtained using MOR (x 40) of PVC-P geomembrane after 23 years of installation. External and internal face.

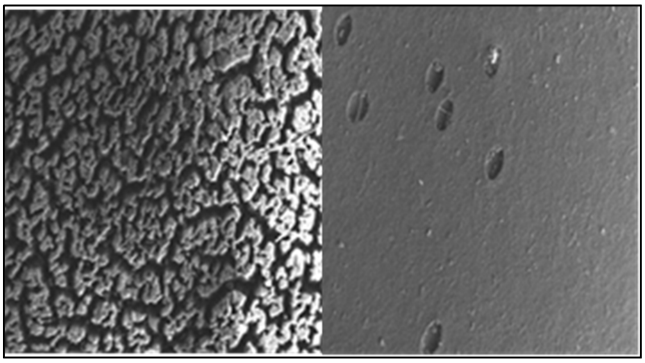

Figure 9. Microphotographs obtained using SEM (x 90) of PVC-P geomembrane after 23 years of installation. External and internal face.

3.7 *Plasticizers*

Plasticizers content determination of the initial geomembrane lead to a value of 35.1%. In Figure 10 can be observed the decrease of this value and the plasticizer loss in relation with the original value over the 23 years after its installation in samples collected in the north of the crest area. During the plasticizer extraction test, ethyl ether extract all the organic products with low molecular weight, so, not only plasticizers are extracted, but also other organic additives like UV absorbers, antioxidants and stabilizers among others. This fact has been taken into account in plasticizers content and plasticizers loss calculations (Giroud 1995, Giroud & Tisinger 1993).

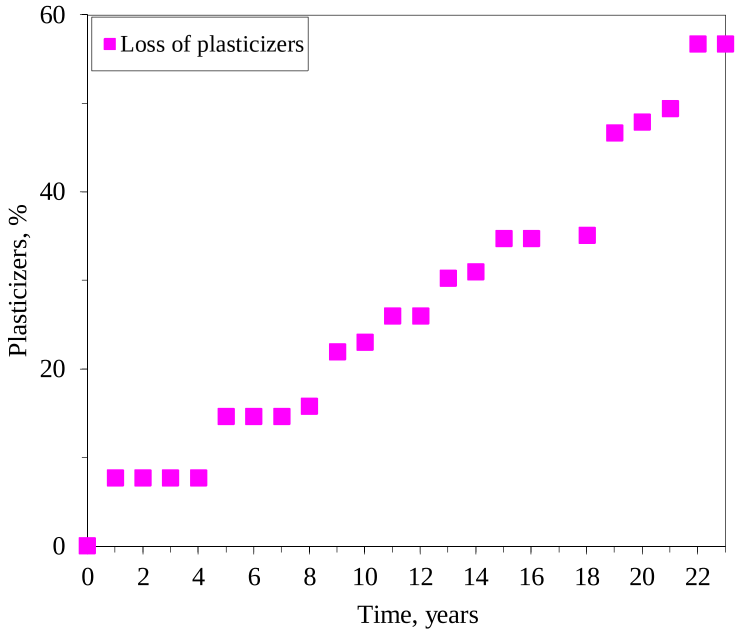

Figure 10. Plasticizers loss evolution over time.

3.7.1 *Influence of sampling location*

Table 3 presents the results obtained after 20 years of the geomembrane installation. They show the influence, in the plasticizers loss, of slopes orientation and the location inside the reservoir where samples were collected (Blanco et al. 2012). The southern slope is the least affected by solar radiation that is less intense due to its orientation to the north. The greatest plasticizers loss was measured in the crest area of the reservoir, then in the intermediate and, finally, in the sub-merged area: these results were in line with the results obtained in similar situations on Italian dams (Cazzuffi, 2014).
Table 3 shows also the tensile characteristics, elongation at maximum load and the displacement of the plunger before perforation in puncture resistance test.

3.7.2 *Plasticizer identification*

The plasticizer used in the geomembrane formulation was determined by extraction with ethyl ether, following the procedure described in scientific bibliography (UNE 104 306).
Once the plasticizer was isolated, it was analysed by Fourier Transform Infrared Spectroscopy (FTIR) using a Nicolet 310 FTIR, where the characteristics bands of alkyl phthalates can be clearly observed (Blanco et al. 2008, 2009, 2010, 2013).
Identification of the additive was carried out with Gas Chromatography combined with Mass Spectrometry (CG-MS).
A gas chromatograph GC Agilent 6890N was used along with a capillary column of phenyl methyl polysiloxane DB%-MS (30 m x 0.25 mm x 0.25 µm). The process was coupled to a quadrupole mass detection system Agilent 5793 MSD in electron impact mode. The first technique allows determination and separation of a number of products that constitute the plasticizer. The second technique allows identification of the actual products.
The gas chromatography technique generated a chromatograph with a single peak. This product was analysed by Mass Spectrometry whose spectrum presented the following data: MS, m/e (relative intensity): 446(M+), 307(C18O4H27+,25), 167(C8H7O4+,19), 149(C8H5O3+,100), 85(C6H13+,25), 57(C4H9+,29). These fragmentations indicate that the plasticizer is a diisodecyl phthalate.
The diisodecyl phthalate has a molecular weight of 446, which is well above the molecular weight of 400 that is the recommended minimum value, as reported by the American PVC Geomembrane Institute (2004), to get a geomembrane with a long-term durability. Also the protons of phthalic acid are replaced by ramified alkyl radicals, leading to a plasticizer migration that is greater into air than

into water. Nonetheless, the radical includes ten Carbon atoms, a comparatively high length that hinders this process. These characteristics of the plasticizer used at the site are consistent with the observed good performance of the geomembrane over time.

Table 3. Characteristics of the geomembrane after 20 years of installation in function of the sampling area.

Sampling area	Characteristics						
	Plasticizers loss, %	Tensile strength, N/50mm		Elongation at point of maximum load, %		Displacement of plunger before perforation, mm	
Slope		Longitudinal	Transverse	Longitudinal	Transverse	External face	Internal face
Crest							
North	47.8	1610	1540	24	27	14	14
South	40.6	1463	1387	24	27	17	15
East	55.5	1663	1540	19	27	12	12
West	53.2	1587	1240	23	24	12	12
Intermediate							
North	40.3	1317	1310	22	26	14	14
South	39.3	1503	1487	24	27	19	15
East	43.5	1480	1463	22	28	18	16
West	44.5	1453	1280	22	25	13	13
Submerged							
North	35.0	1387	1257	21	26	17	16
South	36.7	1433	1347	25	28	16	12
East	39.0	1527	1450	21	28	14	18
West	40.3	1357	1253	24	29	15	18

4 CONCLUSIONS

After 23 years of the geomembrane installation, in the foldability at low temperatures test, the analysed specimens did not show cracks in the flexion zone, except the ones collected from the northern, eastern and western areas of the reservoir crest that started to show cracks after 17 years of installation.

Tensile strength characteristics did not change significantly during the service life of the geomembrane. This is because the scrim used as reinforcement is the responsible of the tensile characteristics as much tensile strength resistance as elongation at maximum load. In this geomembane the scrim is still protected by the PVC resin that is in a good condition, so it is not affected by the UV radiations.

Mechanical percussion resistance along the years is correct due to the scrim reinforcement. Puncture resistance, in general, increase with time and the displacement of the plunger before perforation decrease as consequence of the hardening of the geomembrane because of the plasticizers loss.

Welding strength resistance results were adequate because breaks in all specimens happened near the seam but always outside of the seam itself. This shear test is considered qualitative, while peeling test is considered quantitative. In this case, peeling test results led high values for a PVC geomembrane.

Reflection optical microscopy same as scanning electron microscopy showed, after 23 years of service life, an external face with a noticeable cracking while the internal face showed a surface in good conditions with only some small craters.

Plasticizer was identify as Diisodecyl phthalate, which molecular weight is 446, that is, significantly higher than the required value of 400, to give the qualifying of long-term durability to a geomembrane. However, being an ester with ramified alkyl radicals this plasticizer tends to migrate into air. Nevertheless, this process was minimized by the comparatively long hydrocarbon chains.

5 REFERENCES

Aguiar, E. & Blanco, M. 1995. Experience in Connection with the Performance of Plasticized poly(vinyl chloride) Sheeting in Tenerife Basin Sealing. *Proc. Symposium on Research and Development in the Field of Dams:* 361-375. Crans-Montana (Suiza), septiembre.

Aguiar, E., Blanco, M., Romero, A., Sacristán, A., Soriano, J. & Vara, T. 2002. Efectos de la orientación en la degradación del poli(cloruro de vinilo) plastificado utilizado como geomembrana sintética en la impermeabilización del embalse de la Cruz Santa. *Aislamiento e impermeabilización:* **24**, 14-21.

Aguiar, E., Blanco, M., Soriano, J. & Vara, T. 2003. Influencia de la orientación en la degradación del poli(cloruro de vinilo) plastificado utilizado como geomembrana sintética en la impermeabilización del embalse de La Tabona. *Ing. Civil*: **130**, 95-103.

Blanco, M. 2012. Spanish experience in the use of synthetic geomembranes for hydraulic works. *Keynote Lecture, in Blanco et al. (Eds.) Eurogeo5, Ed. R. B. Servicios Editoriales, S. L.*: 7-23 (electronic proceedings) Vol. 1: XXI-XXXIX (printed volumes). Valencia, septiembre.

Blanco, M., Crespo, M. A., Noval, A. M., Leiro, A., Mateo, B., Aguiar, E., Vara, T. & Giroud, J.P. 2013. La durabilidad de geomembranas de PVC-P en función del aditivo utilizado como plastificante. Proc. Congreso Geosintec Iberia 1, 138-146. Sevilla, noviembre.

Blanco, M., Cuevas, A., Castillo, F. & Aguiar, E. 1995. Evolución de geomembranas de poli(cloruro de vinilo) plastificado utilizadas en la impermeabilización de embalses en la isla de Tenerife. P*roc. III Congreso Iberoamericano de Patología de la Construcción. V de Control de calidad.* La Habana (Cuba).

Blanco, M., Cuevas, A., Castillo, F. & Aguiar, E. 1996. Puesta a punto de una nueva metodología experimental para la determinación de la resistencia a la perforación de geomembranas sintéticas. *Ing. Civil*: **103**, 65-69.

Blanco, M. & Leiro, A. 2012. Evolución de la geomembrana de PVC-P instalada en la impermeabilización del embalse de La Florida. Geoaméricas 2.012, Lima (Perú), mayo.

Blanco, M., Leiro, A., Soriano, J., Aguiar, E., Armendáriz, V. & Vara, T. 2003. Influencia de la orientación en el deterioro de la geomembrana sintética utilizada como pantalla de impermeabilización en el embalse de la Cruz Santa. *Proc. VII Congreso de Patología de la Construcción.* Mérida (México), septiembre

Blanco, M., Leiro, A., Soriano, J., Crespo, M. A., Zornberg, J. G., Aguiar, E., Rico, G. & Pargada, L. 2012. Long-term performance of the “Laguna de Barlovento” reservoir waterproofing using a PVC-P geomembrane, in Blanco et al. (Eds.) Eurogeo5, Ed. R. B. Servicios Editoriales, S. L.: Vol. 2: 55-63 (electronic proceedings) Vol. 1: 265-273 (printed volumes). Valencia, septiembre, 2.012.

Blanco, M., Rico, G., Pargada, L., Aguiar, E. & Castillo, F. 2009. Determinación de los ftalatos utilizados como aditivos en la geomembrana de la balsa de La Florida mediante cromatografía de gases-espectrometría de masas. *Ing. Civil:* 154, 87-95.

Blanco, M., Rico, G., Pargada, L., Aguiar, E., Castillo, F. & Crespo, M. A. 2010. Influencia del tipo de plastificante en la durabilidad de las geomembranas de PVC-P. *Proc. 3er Congreso Nacional de Impermeabilización: Edificación, Obra Civil y Balsas y 3er Simposio Nacional sobre proyecto, construcción e impermeabilización de balsas*: 347-357. Barcelona, octubre.

Blanco, M., Rico, G., Pargada, L., Castillo, F. & Aguiar, E. 2008. Estudio de plastificantes utilizados en geomembranas de PVC-P empleadas en impermeabilización de obras hidráulicas. *Rev. Plast. Modernos:* 96 (629), 386-391.

Cazzuffi, D. 2013. Long term behaviour of exposed geomembranes used for the upstream face rehabilitation of concrete and masonry dams. *Proc. Congreso Geosintec Iberia 1, 26-36. Sevilla, noviembre.*

Cazzuffi, D. 2014. Long term performance of exposed geomembranes used for the upstream face rehabilitation of dams in Northern Italy. *10t International Conference on Geosynthetics.* .Berlín, septiembre

Cazzuffi, D., Giroud, J.P., Scuero, A. & Vaschetti, G. 2010. Geomembranes in dams:wordwilde applications and long-term behaviour. *Keynote lectura Proc.of the 9th International Conference on Geosynthetics. Vol I, 115-163, Guarujá (Brasil).*

Crespo, M. A. 2011. Comportamiento de barreras geosintéticas poliméricas (GBR-P) a base de poli(cloruro de vinilo) plastificado de distinta formulación, instaladas en embalses. *Tesis Doctoral.* Universidad Complutense de Madrid.

Fayoux, D. 2004. La impermeabilización del embalse de la Laguna de Barlovento. *Proc. Jornadas sobre impermeabilización con materiales sintéticos*. La Palma (España), abril.

Fayoux, D., Gousse, F. & Rummens, F.1993. Assessment on a PVC geomembrane in a landfill after ten years. *Proc. of the 4th International Landfill Symposium*: Vol. 1, 369-378 Cerdeña (Italia).

Giroud, J. P. 2005. Evaluation of OVC geomembrane shrinkage due to plasticizer lost. *Geosynthetics International*, **2** (6), 1099-1113.

Giroud, J. P. & Tisinger, L. G. 1993. The influence of plasticizers on the performance of PVC geomembranes. *Proc. of Geosynthetic Liner Systems: Innovation, Concerns and Design, IFAI*, Roseville, Minn, 169-196.

International Commission on Large Dams. 1991. Watertigth Geomembranes for Dams. State of the Art *Bulletin ICOLD* Nº 78, Paris

International Commission on Large Dams, 2010 Geomembrane sealing systems for dams, Bulletin ICOLD n° 135, Paris

Ministerio de Medio Ambiente, y Medio Rural y Marino 2010. Manual de diseño, construcción, explotación y mantenimiento de balsas. Madrid.

PVC Geomembrane Institute (PGI). 2004. PVC Geomembrane Material Specification 1104. University of Illinois, Urbana, IL.

Soriano J., Blanco, M., Aguiar, E. & Cea, J. C. de 2006. Las técnicas de microscopía óptica de reflexión y electrónica de barrido en el conocimiento del estado de las geomembranas sintéticas. *Ing. Civil:* 143. 17-22.

Soriano, J., Blanco, M., Aguiar, E. & Burgos, J. 2010. La microscopia como método de análisis en el estudio de geomembranas sintéticas de PVC-P. *Proc. 3er Congreso Nacional de Impermeabilización: Edificación, Obra Civil y Balsas y 3er Simposio Nacional sobre proyecto, construcción e impermeabilización de balsas:* 411-422. Barcelona.

Stark, T. D., Choi, H. & Diebel, P. W. 2005. Influence of plasticizer molecular weight on plasticizer retention in PVC geomembranes. *Geosynthetics International*: nº 2.

UNE-EN 13 361 Barreras geosintéticas. Características para su utilización en la construcción de embalses y presas.

UNE 104 306. 2000. Materiales sintéticos. Determinación del contenido en plastificantes en láminas de poli(cloruro de vinilo) plastificado, PVC-P, utilizadas en impermeabilización.

UNE 104 317. Materiales sintéticos. Determinación del recorrido del punzón antes de la perforación en geomembranas sintéticas impermeabilizantes instaladas en balsas.