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Long-term performance of the HDPE geomembrane at the "San Isidro" reservoir

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ABSTRACT: The long-term performance of the high density polyethylene geomembrane used as waterproofing system of the "San Isidro" reservoir (Canary Islands, Spain) is described in this paper. The geomembrane characteristics and its behaviour with time are evaluated. This includes interpretation of tests to quantify the geomembrane thicknesses, tensile properties, tear resistance, dynamic and static puncture, foldability at low temperature, and seam strength. In addition, microscopy techniques, X-rays microanalysis, carbon black, crystallinity, density and oxidation induction time tests were carried out. Overall, the long-term test results indicate a very good performance of the HDPE geomembrane installed at a subtropical climate location.

Keywords: geomembrane, high density polyethylene, reservoir, durability

1 INTRODUCTION

Polyethylene is probably the first polyolefin used in hydraulic projects in Spain. Specifically, a low density polyethylene (LDPE) geomembrane was the first synthetic barrier installed in Spain three decades ago. At the time, the geomembrane was not exposed (i.e. it was buried), although its thickness was particularly small (approximately 0.3 mm). The use of LDPE benefited both small farms, which needed water management for irrigation, as well as large corporations, which used the geomembrane as part of greenhouse infrastructure.

Polyethylene geomembranes were subsequently used in projects where they remained exposed throughout their design life. In this case, the selected geomembranes were thicker than those used previously and incorporated additives in their formulation in order to better resist exposure to ultraviolet radiation. At this point, polyethylene materials with different densities were manufactured, including the very low density polyethylene (VLDPE) that, because of its high static puncture resistance, has been used in reservoirs built on soft foundation soils and where there is a comparatively higher risk of penetration of inorganic materials into the geomembrane (Blanco et al., 2010a). Among the various types of geomembranes being currently manufactured, high density polyethylene (HDPE) geomembranes are nowadays the most commonly used in Spain (Blanco et al., 2010b).

The use of HDPE probably emerged in the region of Castilla y León, where numerous reservoirs were waterproofed using this thermoplastic material. Subsequently, the use of HDPE geomembranes extended across the country, both mainland and also in the Canary Islands (Blanco et al., 2008). The Hydrologic Plan of Canary Islands was developed in the 1980's and aimed at cost-effectively managing the water resources in the islands, including the constructions of geomembrane-lined water reservoirs. Initial characterization and post-construction monitoring programs were established to assess their performance and to investigate the appropriate use of different types of geomembranes (Amigó and Aguiar, 1994).

There are two main reasons for good acceptance of HDPE in multiple applications. First, the comparatively larger market and competition among manufacturers has resulted in HDPE prices that are often more competitive than those of other types of geomembrane. Second, HDPE is a very stable polyolefin, with a comparatively high long-term durability (Koerner, 2005), which has made it the material of choice for lining of landfills. Accordingly, much of the research on HDPE geomembranes stems from their use in landfill applications (Sangam, 2001, Pons, 2012, Rowe et al., 2003, Islam, 2009, Rowe and Islam, 2009).

Because the properties of geomembranes may degrade over time, a key assessment of these materials involves the study the different degradation mechanisms (Kay et al., 2004, Koerner et al., 2007) as well as the quantification of durability using realistic parameters (Peggs et al., 2002).

The "Centro de Estudios y Experimentación de Obras Públicas" (CEDEX) has monitored the behaviour of different geomembranes over time in several reservoirs across Spain in order to assess their durability since installation (Blanco et al., 2008, Blanco et al., 2010b). In particular, the assessment of the performance of the San Isidro reservoir presented in this paper is a collaborative effort involving the Spanish agencies CEDEX and "Balsas de Tenerife" (BALTEN).

2 THE RESERVOIR

The "San Isidro" reservoir was constructed in 1991 as part of a water management program of the Canary Islands. Construction of the reservoir involved over 8,000 m^2 of a 1.5 mm-thick HDPE geomembrane. Additional characteristics of the San Isidro reservoir are listed in Table 1. Figure 1 shows an aerial view the reservoir, which has a capacity of almost 50,000 m^3. The reservoir is located in the Tenerife Island of the Canary Islands archipelago. The Canary Islands are a Spanish autonomous community located off the northwest coast of mainland Africa. The average temperature in the Tenerife Island is 21.3ºC, with only minor fluctuations between the winter and summer average temperatures (18.9 ºC and 23.5 ºC, respectively). The islands have a subtropical climate, with long warm summers and moderately warm winters. They are under the influence of the trade winds, which are comparatively cool and wet, arriving to the islands from the northeast.

Figure 1. Reservoir of "San Isidro" waterproofed with HDPE.

Table 1. Characteristics of "San Isidro" reservoir.

Location	Granadilla de Abona
Capacity, m^3	49,799
Height, m	11.0
Perimeter, m	328.19
Crest perimeter, m	212.7
Type of geomembrane	HDPE
Geomembrane thickness, mm	1.50
Quantity of geomembrane, m^2	8,310

3 SCOPE OF THE EXPERIMENTAL TESTING PROGRAM

The initial characteristics of the HDPE geomembrane were determined in order to assess their conformance with product specifications and to define initial property values to use as a basis for comparison of the subsequent long-term test results. For this purpose, samples were collected periodically in different zones of the reservoir and tests were repeated regularly to check the evolution of the various geomembrane properties.

The experimental methodology used in this research project was developed by the European standard EN 13361 (2005). Puncture resistance tests conducted in this study were originally developed by the CEDEX research team and now constitutes the nomr UNE 104 317 (2011). This standard was also adopted by the Spanish Organization of Normalization and Certification AENOR (Blanco et al., 1996).

Tests carried out at the beginning, had passed the minimum requirements established for these types of geomembranes according to the Reservoirs Handbook (Ministerio de Medio Ambiente, y Medio Rural y Marino, 2010) written by CEDEX following a request of "Ministry of the Environment and Rural and Marine Affairs", a ministerial department of the Spanish Government (Table 2).

4 RESULTS AND DISCUSSION

4.1 *Thickness*

Thicknesses of the specimens of both north and south samples of the HDPE geomembrane have been measured with a micrometer and the average of ten measures is presented in Figure 2. While the measurements show some scatter, specimens collected in the north slopes are observed to consistently have lower thickness values than those collected in the south slopes. It should be noted, however, that HDPE geomembranes not always show a uniform thickness.

Table 2. Minimum requirements for HDPE geomembranes

Characteristics	HDPE
Folding at low temperature:	
Temperature at which cracks are quantified, ºC	-75
Dynamic puncture resistance:	
Height of the plunger, mm, min.	500
Static puncture resistance:	
Displacement of the plunger, mm, min.	8
Strength at break, MPa, min.	25
Strength at yield point	17
Elongation at break, %, min.	700
Elongation at yield point, %, max.	17
Tear resistance, N/mm	140
Carbon black content, %	2-3

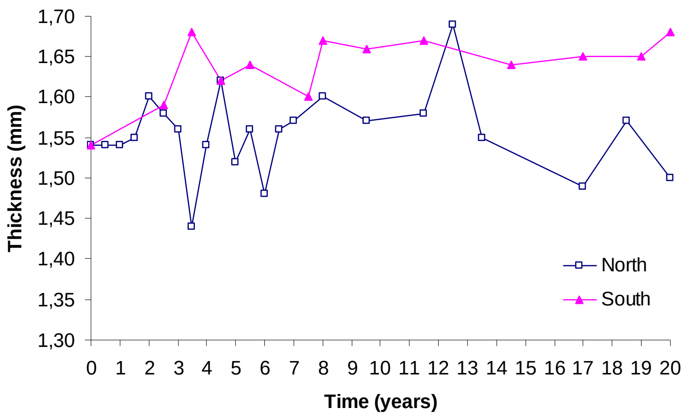

Figure 2. Evolution of the thickness in north and south samples extracted in the crest area.

4.2 *Folding at low temperature.*

Geomembrane specimens of the “San Isidro” reservoir were subjected to folding at low temperature test. This test involves keeping the geomembrane specimens during 5 hours at a temperature of -75 ºC. The specimens were then folded at an angle of 180º during 3 seconds. The specimens were subsequently inspected to identify any evidences of cracks, fissures or any other sign of surface imperfections.

The temperature used to conduct the folding tests depends on the geomembrane material and its macromolecule characteristics. Accordingly, the objective of this test is to assess the suitability of the material, not to reproduce the temperature conditions at which the geomembrane will be subjected to in service. All HDPE geomembrane specimens of this project tested during the initial 20 years in service did not show signs of cracking after folding at low temperature.

4.3 *Dynamic and static puncture resistance*

The dynamic puncture resistance test involves dropping a 0.5 kg plunger from a height of 500 mm. The plunger end has a semi-spherical shape with a diameter of 12.7 mm.

This test was passed by all the specimens of this study, both the original ones and the samples which were taken after 20 years of installation, independently of the location inside the reservoir. None of them suffered perforation in the impact area; as verified with a watertight test. In thermoplastic materials, as this HDPE geomembrane, the height from which the plunger fell without causing any damage on the impact area decreases as the resin aged.

The static puncture resistance test was conducted using a dynamometer INSTRON (mod. 1195) according to the standard UNE-EN ISO 12236 and UNE 104317. The variation of resistance to static puncture and the displacement of the plunger before perforation are shown in Figure 3. In general, both resistance to static puncture and the displacement of the plunger before perforation values increased over time. This increase could be due to loss of strength with time. The behaviour at static impact is considerably better in elastomeric materials than in thermoplastic materials such as HDPE, while in dynamic impact the reverse is true (Blanco, 2012).

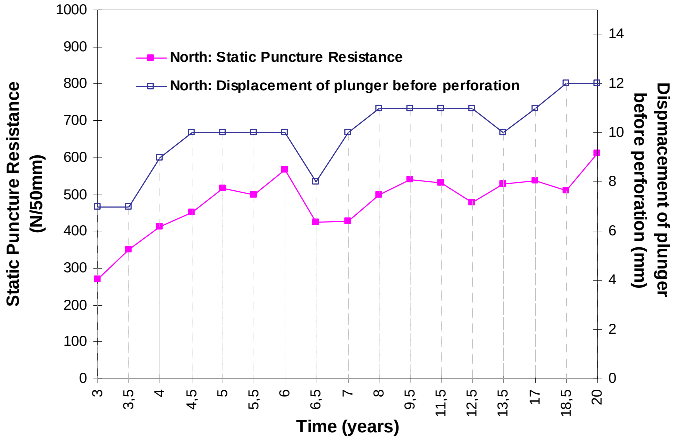

Figure 3. Variation of resistance to static puncture and the displacement of the plunger before perforation in north specimens.

4.4 *Tensile characteristics*

The tensile properties of HDPE geomembrane specimens were measured over 20 years of exposure using a dynamometer INSTRON (mod. 1195) according to the standard UNE-EN ISO 527-3. The variation in tensile properties over 20 years is shown in Figure 4. The tensile strength at yield did not suffer much with time. At the beginning of the service life had decreased by 12% but after seventeen years of service the percentage of property retained was 107%. However at this stage, elongation at yield point had reduced by 20% of the initial value. This can be attributed to the increase in crystallinity. These trends could indicate an increase embrittlement of the geomembrane.

The general trend of the tensile strength at break and elongation at break was similar, with some anomalous values from the eight to the twelve year of service life but with a trend to decrease over time. Two of these values had reduced by up 50% of the original value ("half life"). These anomalous values could be due to the surface damage; thus, scratches on the surface made during installation, service life or sample removal could have a large effect on tensile properties.

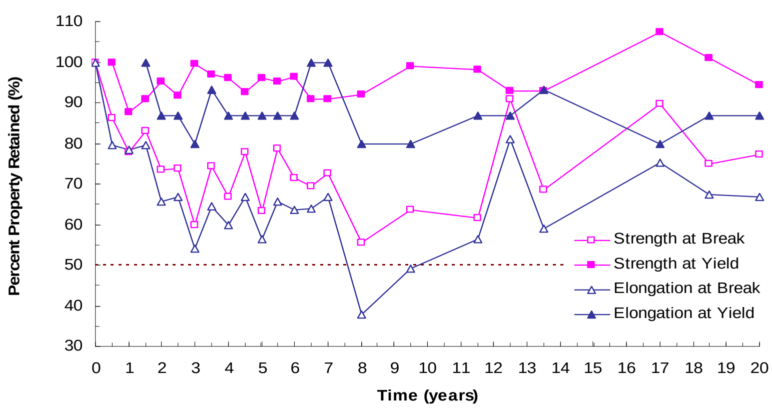

Figure 4. Changes with time in tensile properties of the HDPE geomembrane in samples collected from the north slope.

4.5 *Seams resistance*

Seams resistance determined by shear resistance test was made using a dynamometer INSTRON (mod. 1195). This test presented acceptable values as samples broke in the edge or close to the seam, but always outside of it. When the purpose is to have quantitative values and the specimens had the enough dimension, peel tests were carried out and good values were obtained.

4.6 *Tear resistance*

Tear resistance tests were conducted according to the standard UNE-ISO 34-1 in the specimens of the HDPE geomembrane. This test was carried out in HDPE for periodic controls because some isolated cases of tearing occurred close to the seams due to the weakening of seam process in other HDPE geomembranes. No appreciable variation is observed during twenty years of service life of the geomembrane in the reservoir. In general issues, the values in transverse direction were lower than in the longitudinal direction and the specimens of the south slope had higher values than the specimens of the north slope.

4.7 *Reflection Optical Microscopy and Scanning Electron Microscopy*

Microscopy evaluation of HDPE geomembrane of "San Isidro" reservoir was conducted following procedures described by Blanco et al. (2002) and Soriano et al. (2006). Microphotographs were taken by Scanning Electron Microscopy (SEM) at x90 and x900 magnifications using a ZEISS microscope (mod. EVO 50). Figure 5 shows the exposed surface at x900 magnifications of both, north and south slope specimens at different ageing times (138, 162 and 174 months).
The SEM image (Figure 5a) shows that after 138 months the surface of the north slope specimen had some signs of deterioration while the south slope specimen (Figure 5b) presented grooves of manipulation as well as a uniform and homogeneous surface. The superficial cracking is clearly observable in Figure 5c at 162 months of service life in the north slope; however, only one crack appeared in the south specimen (Figure 5d) one year after (174 months of service life).

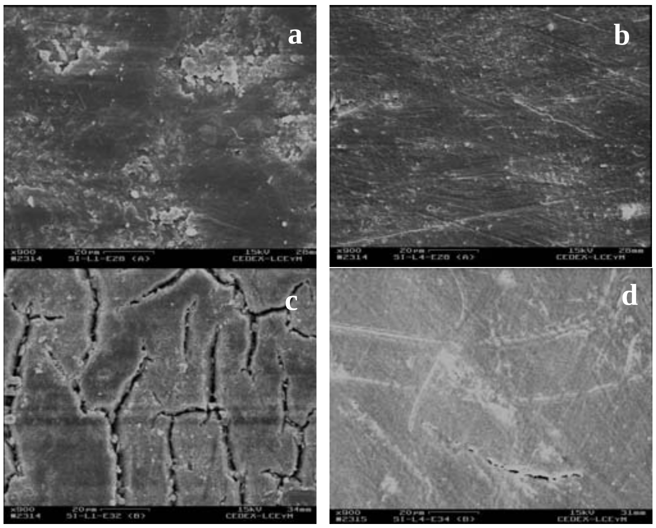

Figure 5. Microphotographs SEM (x 900) of the external face in north slope (left images) and south slope (right images) at 138, 162 and 174 months of service life.

4.8 *X-Ray microanalysis*

X-Ray microanalysis was conducted to corroborate the existence of a biofilm over the geomembrane, as other authors had observed in geomembranes of different nature (Pons, 2012). Table 3 shows the elements presented in both north and south specimens in the samples which were in contact sometimes with the water of the reservoir. The elements detected were practically the same but the different proportions are due to the fact that this test is made in a specific point of the geomembrane.

Table 3. X – Ray microanalysis results from both north and south samples.

Element	North Weight (%)	South Weight (%)
Na	6.61	2.03
Mg	0.96	8.54
Al	10.14	4.34
Si	31.49	28.73
Cl	0.00	2.41
K	0.77	1.44
Ca	1.45	2.93
Ti	0.00	1.59
Fe	0.00	1.99
O	48.58	46.00
Total	100	100

The presence of diatoms, a type of microalgae, was demonstrated by the high proportion of Silica (Si), one of the constituents of the diatoms which are enclosed within a frustule made of silica.

It should be taken into account the presence of Titanium in the X-Ray microanalysis; this could be due to the additive TiO_2 which is specially used in the geomembranes to protect to the UV radiation but for the HDPE, in very little proportions comparing with the geomembranes of PVC-P.

4.9 *Carbon black*

The carbon black content was 2.5% in the HDPE specimens, which is a correct value. Indeed, values ranging from 2 to 3% are recommended. The dispersion observed in the microphotographs was good, without accumulation points of this additive. It could be observed that the dispersion of carbon black had a value of 2 on a 1-7 scale, the lower the value, the better the dispersion.

4.10 *Crystallinity and density*

The degree of HDPE crystallinity of semicrystalline materials correlate to its density . The crystallinity was evaluated using a differential scanning calorimeter (DSC). The samples were located in both the north and south crest area, so it is probably that photo-oxidation mechanisms were taking place. This oxidation increases the crystallinity and the most common processes are the chemicrystallization and the annealing (Pons, 2012). It might be supposed a chemicrystallization process due to the fact that melting temperature did not shift significantly over time and remained relatively constant at about 127ºC for all test. Besides, the thermogram shapes were similar which implied similar melting behaviour of the crystallites (Sangam, 2001).

Specimens collected from the north slopes showed higher crystallinity values than specimens collected in the south slopes (56.52% vs 52.69% at 20 years of service life), as well as density values. An increase in the geomembrane crystallinity could be due to the HDPE oxidation that produces chain scission and smaller chains, which can crystallise more easily. These increases are consistent with results from tensile tests, which suggest that the geomembrane is becoming more brittle. The higher crystallinity of geomembrane located in the north slope indicates that they have higher stiffness with lower strain due to the reduced amorphous zone in the formulation, to which the geomembrane ductile response can be attributed.

4.11 *Oxidative Induction time*

The Oxidative Induction Time (OIT) is an accelerated ageing test that provides an index useful in comparing the relative resistance to oxidation of a variety of hydrocarbon materials (Blaine et al., 1997). It should be noted that the consumption of antioxidants is the first step in the degradation of HDPE geomembranes and this amount is calculated using the standard S-OIT test (200º C, 35kPa) or the high pressure (HP) OIT test (150º C, 3500kPa) (Hsuan and Koerner, 1998).

The lifetime of antioxidant is determined based on the depletion rate of the OIT values. The initial OIT of the original material in “San Isidro” reservoir at the time of installation was not available, so it was rather difficult to deduce the exact rate of the depletion of antioxidants. It is considered that the modern geomembranes are typically in the range of 100 or more minutes (Rowe et al., 2003) and in this research work an S-OIT value of 100 minutes has been used. The test was conducted according to the UNE-EN 728 standard. Only seven samples were available to determine the OIT test, four of the north slope and three of the south slope.

Figure 6 reproduces the OIT data by plotting the natural log of OIT against time where two linear response curves result. The slope of the lines represents the OIT rate in this temperature. The line of North Slope specimens shows a rate of depletion of antioxidant of 0.0094 months^{-1} while south slope specimens have a value of 0.0076 months^{-1}. Therefore, the geomembrane in the north slope will have depleted the antioxidant in 47 years of service life and the geomembrane in south slope in 58 years. This finding is consistent with the results obtained by other researchers for HDPE geomembranes (Sangam and Rowe, 2002, Rowe et al., 2009; Rowe et al., 2010); three geomembranes were studied at service temperature of 20 ºC (similar temperature that the average temperature of the Canary Islands) and the antioxidants were depleted after approximately 60, 80 and 100 years (Peggs, 2003). The reason is that the samples exposed to the greater amounts of sunlight, the highest temperatures and the most abundant amounts of oxygen, might be expected to have experienced the greatest photo-oxidation (UV) and thermo-oxidation (temperature) (Rowe et al., 2003). In this particular case, the north slope samples are orientated towards the equator and they receive more ultraviolet radiation from the sun and therefore, they are more degraded than the south slope samples.

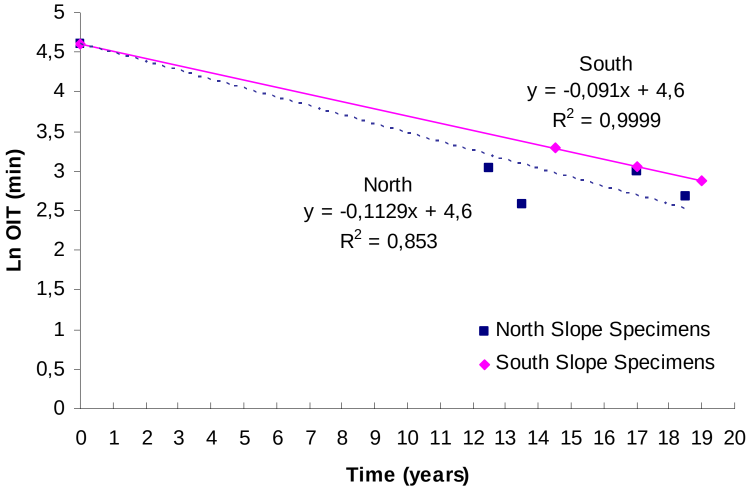

Figure 6. Ln(OIT) versus ageing time for Std-OIT Test.

5 CONCLUSIONS

The San Isidro reservoir was lined in 1991 using an HDPE geomembrane, which was subsequently monitored for 20 years to assess degradation mechanisms. This involved periodically collecting and testing a significant number of geomembrane samples, which resulted in a significant database of long-term performance data for the exposed HDPE geomembrane.

The geomembrane samples collected from the north slope are orientated towards the equator and, consequently, receive more ultraviolet radiation from the sun than samples collected from the south slope. Accordingly, some of the test results showed differences between samples collected from the north and south slopes. This included:

- Results from thickness tests, which showed comparatively lower thickness values in samples collected from the north slopes
- Tensile strength at yield did not change significantly with time. However, elongation at yield point had decreased by 20% after seventeen years of installation in samples collected from the north slope. These trends could be attributed to the increase in crystallinity and could indicate an increase embrittlement of the geomembrane.
- The HDPE tear resistance evolution did not present an appreciable variation over time. The values in transverse direction were lower than in the longitudinal direction and the specimens of the south slope had higher values than the specimens of the north slopes.
- Scanning Electron Microscopy provided images that identified a deterioration of the geomembrane over time, and the differences in ageing between north and south specimens were found to be significant.
- Geomembrane specimens collected from the north slopes resulted in higher crystallinity (and density) than specimens collected from the south specimens. This increase could be due to HDPE oxidation that produces chain scission and smaller chains, which ones can crystallise easily.
- The OIT tests indicate in the north slope specimens the antioxidants will be depleted in 47 years of service life while in south slope specimens it will be in 58 years.

On the other hand, other test results showed no significant differences between samples collected from the north and south slopes. This included:

- Results from the low temperature folding test, as no specimens showed cracks, fissures or any other sign of deterioration.
- Results from the dynamic puncture test, in which all specimens passed the test but the drop height tended to decrease over time, as expected for thermoplastic materials.
- The photographs obtained in order to determinate the carbon black dispersion indicated that all the cases obtained correct values. X-Ray microanalysis corroborated the existence of a biofilm over the geomembrane.

Overall, the long-term test results indicate a very good performance of the HDPE geomembrane installed at the San Isidro reservoir, both at the north and south slope locations. This is particularly relevant considering the subtropical climate and year-long sun exposure at the Canary Islands.

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