Long term behavior and life expectancy of EPDM geomembranes installed in water reservoirs

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ABSTRACT

This paper presents the long term behavior of EPDM geomembranes installed in 5 water reservoirs as well as in one experimental field in Spain.

The initial properties of the EPDM geomembranes and their evolution over time have been measured regularly. This periodic testing was done on following properties: foldability at low temperature, hardness Shore-A, tensile properties, dynamic impact, puncture resistance. Samples were also evaluated using optical reflection microscopy and scanning electron microscopy.

Additional tests were carried out to check the influence of orientation, thickness and exposure to UV.

This document ends by giving some comments on the acceptable change of critical performance properties for an approximation of service life of EPDM geomembranes.

1. INTRODUCTION

In the first half of the 20th century, polymeric membranes began to be used, in isolated cases, both in building and in civil engineering projects. In 1959, a plasticized PVC (polyvinyl chloride) geomembrane was installed to waterproof the dam of Contrada-Sabetta in Italy (ICOLD 1991, Cazzuffi. et al. 2013). In 1968, the dam Odiel Perejil in Spain was waterproofed with a chlorinated polyethylene geomembrane which remains in very good conditions to date (Blanco & Zaragoza 2003, ICOLD 2010). The international commission on large dams (ICOLD) states that the first use of a geomembrane in a water reservoir was in 1969 in the Hawaiian islands, more precisely in the Kualapuu reservoir in Molokai (Blanco et al 2012a). The used geomembrane was made of butyl rubber. Butyl rubber is also the first type of geomembrane used in Spain to waterproof hydraulic structures (Blanco et al. 2010a, de Cea 2002, 2003).

The butyl rubber polymer is obtained from combined diene monomers to become macromolecules with unsaturated double bonds in the main carbon chain. Therefore, this macromolecule contains a big quantity of double bonds with their corresponding "σ" and "π" bonds. Those double bonds make the butyl vulnerable to electrophilic reagents, such as ozone, which in small proportions and under stress is able to break the "π" bonds and therefore to damage the butyl geomembrane (Navarro et al. 1989).

In order to increase the oxidation resistance and the durability of elastomers, later research created another type of elastomer, a terpolymer made of three monomers: ethylene, propylene and diene (EPDM). EPDM main carbon chain is fully saturated and is therefore less sensitive to ozone oxidation. Even though several dienic monomers have been used, the most used at present are one lineal, 1-4-hexadien and 3 cyclics: 5-ethyliden-2-norborneno, 5-vynil-2-norborneno y diciclopentadien (Davis et al. 1998).

In previous papers, EPDM geomembranes' behavior has been compared with other polymeric geomembranes (PVC-P, HDPE) (Blanco et al. 2005, 2012b); their durability in a water pond has been evaluated (Blanco et al. 2012c, 2013, Noval et al. 2015) and a comparative study of several elastomeric geomembranes placed in different ponds was presented (Blanco et al. 2009a). This document is in line with this last paper and presents the performance of different EPDM rubber geomembranes installed in 5 water reservoirs (El Boqueron, Los Dos Pinos, La Casa de las Chumberas, El Golfo and Torrealta-1) and 1 experimental field 'El Saltadero' (Blanco et al. 2009b).

Picture1. 'El Golfo' water reservoir.

2. WATER RESERVOIRS

This work is the result of the collaboration between the center for Public works Studies and Experimentation (CEDEX), the Taibilla canals community, the Tenerife water reservoirs (BALTEN) and the La Palma island council (Blanco 2009, Leiro et al. 2002, Blanco et al. 2010b).

In Spain, there are 200 hydraulic structures whose geomembranes are submitted to a periodic inspection with sample collection and testing in order to evaluate their evolution over time. Some of those structures are waterproofed with EPDM geomembranes. The 6 oldest structures have been considered for the purpose of this study. The general characteristics of the EPDM samples coming from the 5 water reservoirs and the one experimental field are presented in Table 1.

The EPDM geomembranes come from two different manufacturers. 'El Boquerón', 'Los Dos Pinos', 'La Casa de las Chumberas', 'El Golfo' and 'Torrealta-1' come from the same manufacturer, while the one in the experimental field "El Saltadero" comes from a different producer.

The water reservoirs 'Torrealta-1' and 'La Casa de las Chumberas' are located in the south east of Spain and store water for potable water production. The other ponds are located in the Canary Islands archipel and the water is used for agricultural consumption.

On May 11, 2011, an earthquake devastated the city of Lorca, causing important damages to buildings and loss of human life. The earthquake epicenter was practically in the slope of the water reservoir 'La Casa de las Chumberas'. The EPDM geomembrane supported perfectly the earthquake impacts, while nearby buildings were almost destroyed. The pond was at full capacity at the time of the earthquake.

Table 1.Characteristics of the water reservoirs

Type	Water reservoir					
	El Boquerón (EB)	Los Dos Pinos (DP)	La Casa de las Chumberas (CA)	El Saltadero (ES)*	El Golfo (EG)	Torrealta-1 (TA)
Location	La Laguna	Los Llanos de Aridane	Lorca	Granadilla de Abona	Frontera	Orihuela
Capacity (m^3)	51,747	400,000	225,000	458,000	145,000	250,000
Height (m)	11.00	15.00	13.14	21.00	13.00	8.50
Top termination level (m)	376.7	385.0	355.7	112.0	-	172.5
Termination perimeter (m)	340.7	764.0	594.5	699.0	-	780
Slope	2.25:1	2.0:1	2.5:1	1.75:1	2.0:1	2.5:1
Geomembrane thickness (mm)	1.50	1.52	1.20	1.16	1.52	1.14
Installed material (m^2)	8,991	44,116	44,781	*	20,000	40,000
Year of installation	1992	1999	1999	1998	1995	2003

* Geomembrane installed in the experimental field.

3. EXPERIMENTAL

At first, the initial characteristics of the geomembranes were checked in order to have reference values for assessing the evolution over time of EPDM geomembranes. After the installation, periodic controls were made, taking samples in different parts of the water reservoirs. Most of the conducted tests follow the testing protocols described in European standard EN 13361. The puncture resistance tests were carried out according to the standard UNE 104 317 developed by the CEDEX and the BALTEN which currently belongs to AENOR (Blanco et al. 1996).

Even though tensile strength and elongation at break have been determined in longitudinal and transversal direction, the results in this work will only refer to longitudinal direction. Dynamic impact tests were carried out on both sides of the samples, but in this document, the data only refers to the external side, the side not being in contact with the substrate and exposed to weathering.

All tests conducted on the new material have exceeded the minimum requirements for EPDM geomembranes according to the Manual of Water reservoirs (MARMA 2010) written by the CEDEX for the Spanish Environment Ministry.

3.1 *Foldability at low temperature (EN 495-5)*

This test has been successfully passed by all tested samples, new and the ones tested after weather exposure up to 22 years. After being stored for 5 hours in a refrigerator at -55ºC samples were folded 180º around a mandrel during 3 seconds. No cracks or fissures were observed in the fold area, whatever the folding direction.

3.2 *Hardness shore-A (ISO 7619)*

Below Table 2 shows the hardness of the EPDM geomembranes tested in their initial state and 11 years after installation. Over time, we can observe a significant increase of hardness due to the continuation of the vulcanization process that decreases the molecular mobility (Kumar et al., 2004) and makes the geomembrane more rigid.

Table 2. Hardness Shore-A after 11 years of exposition

Water reservoir	Time of exposition	
	0 years	11 years
El Boquerón	69	75
Los Dos Pinos	66	74
La Casa de las Chumberas	65	80
El Saltadero	58	79
El Golfo	64	76
Torrealta-1	61	80

3.3 *Dynamic (EN 12691) and static puncture resistance (UNE 104 317)*

After eleven years of exposure, the dynamic puncture test has been successfully passed by all the tested samples. The puncturing tool is a 0.5 kg mass that ends in a semi-spherical shape with a 12.7 mm diameter. Thrown from 350 mm high the geomembrane samples didn't suffer any perforation in the impact area. Watertightness was checked after the test.

Over time, dynamic puncture resistance of exposed geomembranes increases. After only a few years of installation, the puncturing tool can be thrown from a height of 500 mm (required limit for thermoplastic materials) without damaging the samples, no cracks are observed in the impact area. This fact can be related to the increase over time of the reticulation of the macromolecules that is typical for this elastomeric material.

For this same reason, the static puncture resistance of the EPDM geomembrane samples tends to increase over time while the distance made by the plunger before break tends to decrease. The Figure 2 presents the evolution of the puncture resistance and the distance travelled by the plunger during the 19 and 20 years of the El Golfo and El Boqueron water reservoirs.

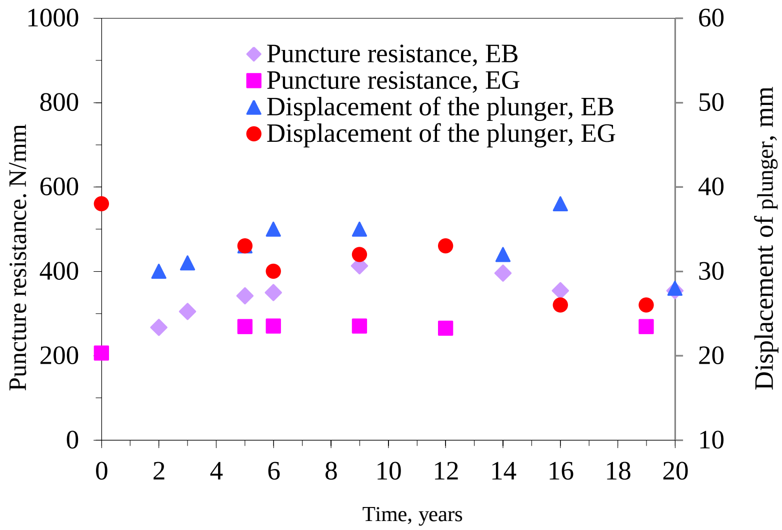

Figure 2. Evolution over time of the puncture resistance and displacement of the plunger before perforation of the El Boquerón and El Golfo water reservoirs

3.4 *Tensile properties (ISO 527)*

Figure 3 shows the evolution in tensile strength and elongation at break over the 19 and 20 years of the EPDM geomembranes installed in the El Golfo and El Boqueron water reservoirs.

It can be seen that in both reservoirs that the elongation at break decreases significantly over time. The decrease in elongation can be explained by the fact that, in the case of EPDM, during the oxidation phenomenon (induced by the temperature and UV exposure), the combination reactions of the carbon chains (cross-linking) prevails upon the cleavage reaction of the principal carbon chain (Kumar et al., 2004). Consequently, a decrease in molecular mobility and an increase in molecular mass can be seen (Kumar et al., 2004). These reactions are similar to the process of curing used during EPDM geomembrane production.

The values of the tensile strength at break undergo a slight increase over time due to the continuation of the vulcanization process after the geomembrane production. Nevertheless, after some years, we can observe a decrease of those values. While this decrease is pretty low after 20 years in the El Boqueron water reservoir, it is more important in the El Golfo water reservoir. This decrease of tensile strength could be related to the degradation of the polymer that induces its fragmentation.

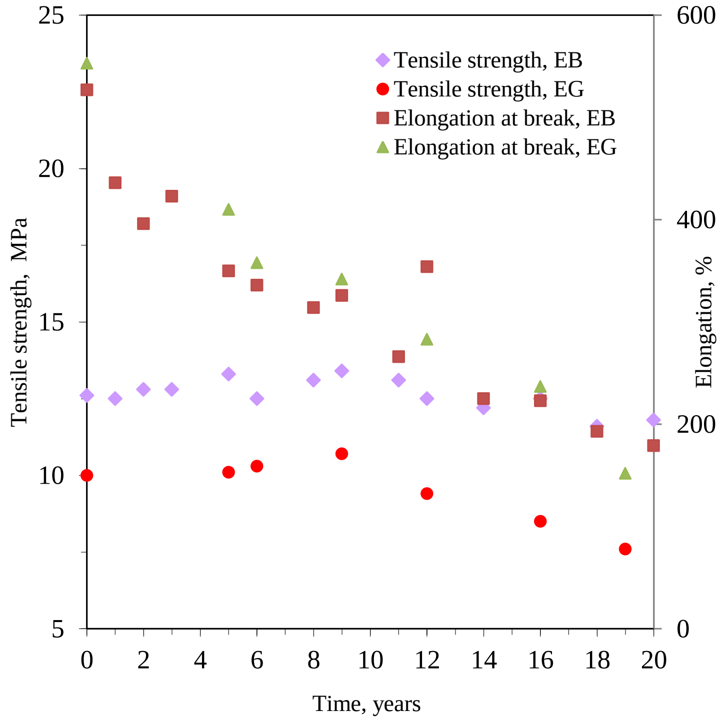

Figure 3. Evolution of tensile strength and elongation at break over time of EPDM geomembranes coming from El Boquerón and El Golfo water reservoirs.

3.5 *Influence of the exposition*

In a previous paper related to the El Boqueron reservoir (Blanco et al. 2012d), the performances of samples extracted at the bottom (geomembrane protected by water) and on the embankments (exposed geomembrane) were compared after 5 and 16 years after installation. It was observed that the differences in properties between the different expositions were minimal.

In order to check the influence of the orientation on the evolution of the material, a phenomenon that affects the thermoplastic materials and specifically the PVC-P geomembranes (Aguiar et al. 2003, Blanco et al. 2003), samples have been taken from the north, south, east and west embankments after 11 years in the different water reservoirs. In Table 3 are listed the initial values and values after 11 years related to tensile strength, elongation at break, and distance made by the plunger before break. It can be seen, that the orientation in this case is not a decisive factor in the performance of this thermoset material.

Table 3. Influence of the orientation in the performance of the EPDM geomembranes coming from the different water reservoirs after 11 years of installation.

Slope	Water Reservoir	Characteristic		
		Tensile strength (MPa)	Elongation at break (%)	Depth of the plunger before perforation (mm)
Original	EB	12.6	527	40
	DP	9.6	489	38
	CA	9.8	465	39
	EG	10.0	553	38
	TA	8.9	434	35
	ES	11.0	492	41
North	EB	13.4	326	35
	DP	10.1	288	31
	CA	9.9	283	30
	EG	9.4	283	33
	TA	9.6	180	23
	ES*	11.1	189	29
South	EB	12.3	288	31
	DP	9.9	326	32
	CA	10.6	256	30
	EG	10.3	337	30
	TA	10.6	232	28
East	EB	--	--	--
	DP	10.1	273	25
	CA	10.7	188	25
	EG	10.4	325	32
	TA	10.4	221	22
West	EB	--	--	--
	DP	--	--	--
	CA	10.2	228	26
	EG	10.4	325	30
	TA	10.1	268	27

3.6 *Optical microscopy and scanning electron microscopy*

The microscopy evaluation of the EPDM geomembranes has been carried out following the experimental protocol indicated in the bibliography (Soriano et al. 2006, 2012). The observations by optical reflection microscopy were done using 40x and 60x magnification in order to see the texture and morphology of the samples. Figure 4 presents the exposed side of the different geomembranes at 40x magnification, 11 years after installation. The aspect of the different geomembrane samples was also checked 11 years after the installation through scanning electron microscopy at 90x and 900x magnification. Figure 5 shows the aspect of the exposed face of the geomembrane samples at 90x magnification.

The optical reflection microscopy shows that the surface of the geomembranes is homogeneous and uniform. The samples extracted in the experimental field 'El Saltadero' show a grid path on the surface related to the separation fabric used in the vulcanization process during the production. The geomembrane itself is homogeneous.

Scanning electron microscopy shows superficial aging of geomembranes being more pronounced in the samples coming from 'El Boqueron' and 'El Golfo' where micro cracks are detected.

Microalgae identified as diatoms were observed by scanning electron microscopy. After the disappearance of the microalgae, its cellular walls are settled on the geomembrane, especially on its micro cracks. After an X-ray microanalysis it was confirmed that they consist of 100% silica (Point 1 of figure 6).

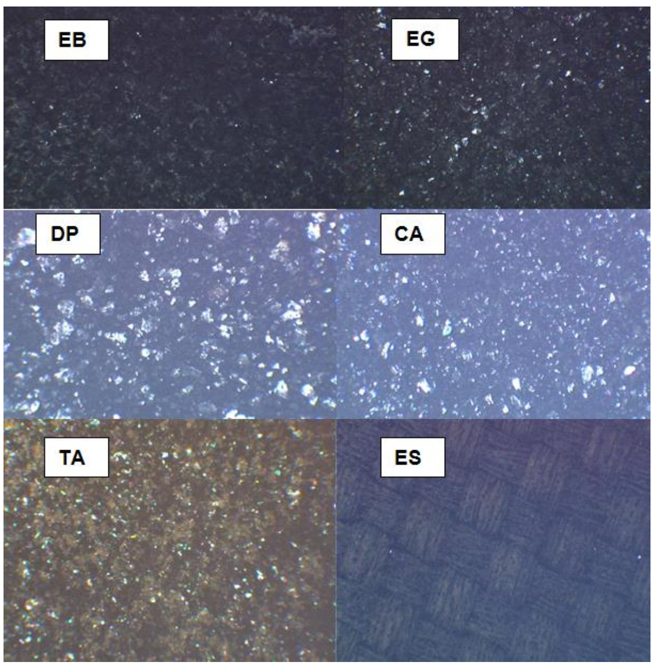

Figure 4. Microphotography (40x) of the exposed face of the EPDM geomembranes after 11years of installation by optical reflection microscopy.

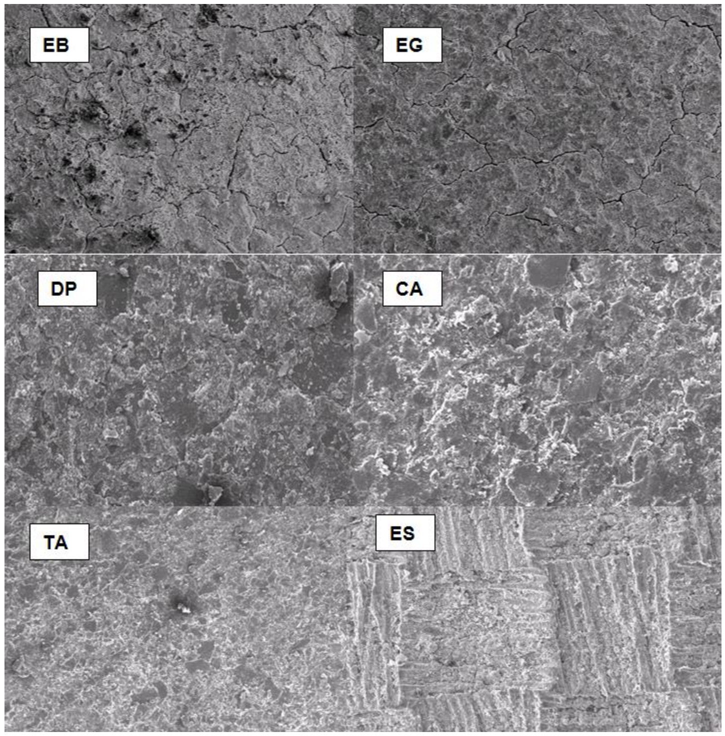

Figure 5. Microphotography (90x) of exposed side of EPDM geomembranes after 11 years of installation by scanning electron microscope

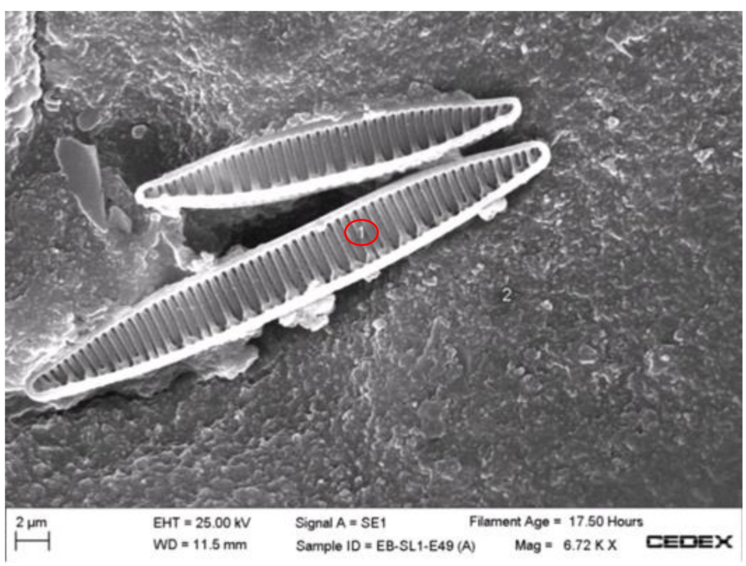

Figure 6. Silica walls of diatoms in the 'El Boquerón' water reservoir after 21 years of installation.

3.7 *Others factors influencing the durability of the geomembrane and service life*

When the El Boqueron water reservoir was built, an extra piece of EPDM membrane of 1.0 mm thick had been installed at the top perimeter to protect the EPDM geomembrane underneath. 22 years after installation, samples were taken from the protective liner and from the protected zone (covered part) as well as from exposed zones on north and south embankments.

Table 4 presents the measured values of tensile strength, elongation at break and hardness-A 22 years after installation. It is noted that the variation of elongation at break and hardness-A is significantly lower in the covered geomembranes than in the exposed ones. This fact could be explained by the fact that the exposed geomembranes are more exposed to oxidation, UV and high temperature, inducing a higher crosslinking rate of the exposed geomembrane. The protected geomembrane presents a lower vulcanization rate and less oxidation of the EPDM polymer and the paraffin oils that are part of its composition (Noval 2015). The most deteriorated membrane is the protective liner at the top termination because it was more exposed to weathering and perhaps because it has a smaller thickness.

Table 4. Characteristics of the EPDM geomembrane coming from the water reservoir 'El Boquerón' 22 years after installation.

Samples	Characteristics		
	Tensile Strength MPa	Elongation at break, %	Hardness Shore-A
Initial	12.6	527	69
Exposed			
North	11.7	167	77
South	11.8	201	78
Protected			
North	13.4	362	66
South	10.2	272	64
Protective liner			
North	9.4	129	82
South	11.3	203	78

Currently there are few published studies that show the service life of EPDM geomembranes and even fewer in hydraulic structures. PVC-P geomembranes base the evaluation of their durability mainly on the content of plasticizers and HDPE geomembranes on the values of stress cracking, the oxidation induction time (OIT), and the carbonyl index (Noval 2015, Noval et al 2014). EPDM geomembranes have no predictive method to determine their durability in a clear way. Following the literature, the end of service life of a geomembrane should be when one of the essential properties of the liner reaches 50% of its initial value (Hsuan & Koerner, 1998).

In the present study, elongation at break has been considered as the main characteristic to evaluate the EPDM geomembrane durability or service life given the fact that it is the factor that changes the most over time.

Following the previously mentioned criteria of 50%, a graphic has been done (Figure 7) for the water reservoir 'El Boqueron'. The figure shows the values of elongation at break of the geomembranes at north and south embankments, 21 years after installation and the values corresponding to 100% and 50% of the initial elongation (527% and 263.5%) and the values corresponding to 100% and 50% of the minimum recommended elongation for new EPDM geomembranes described in the Manual of Water reservoirs (MARMA 2010), respectively 400% and 200%.

In this specific case, we can see that after 21 years of exposition, the elongation at break of all embankments is below the criteria of 50% of the initial elongation value.

If we consider the value of 50% of the minimum recommended elongation for a new EPDM geomembrane, the North embankment doesn't accomplish this criterion after 21 years of exposition and the South embankment is very close to this value of 200%.

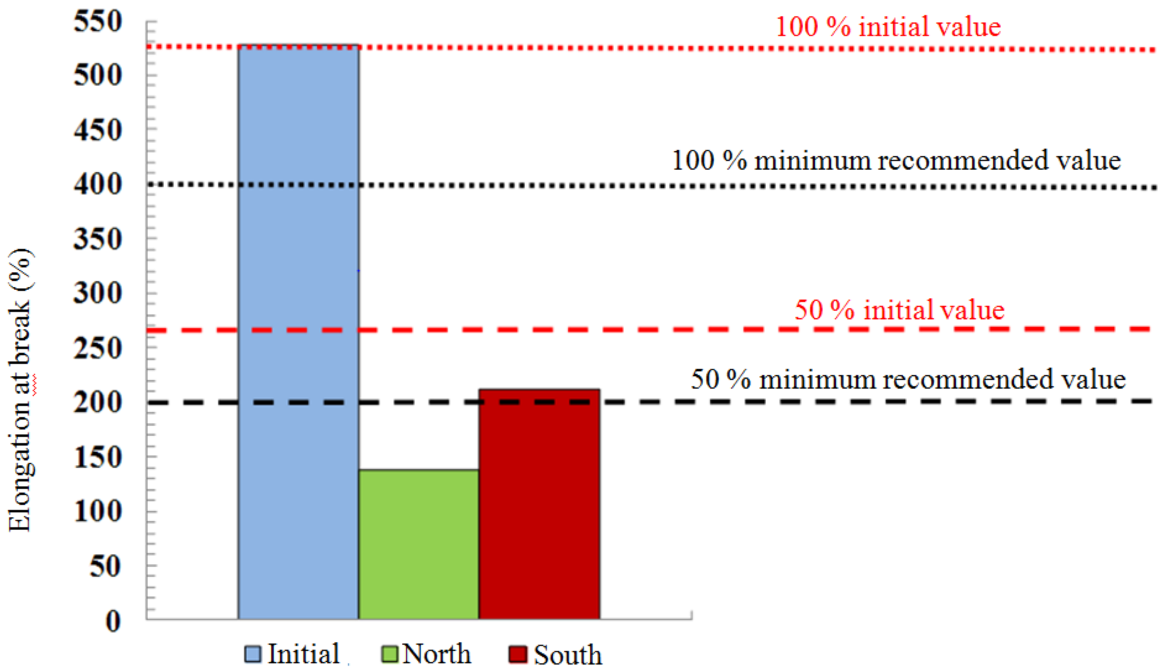

Figure 7.Initial elongation at break and after 21 years of installation of the geomembrane at 'El Boqueron'

If we consider the testing results of the different water reservoirs after 11 years of installation, all taken samples at the South embankment are over the criteria of 50% of the initial elongation. Geomembranes at North embankment from 'Torrealta' and 'El Saltadero' didn't reach that value. The samples taken from the East and West embankment of 'La casa de las Chumberas' didn't reach this criterion either. Nevertheless, it is important to mention that all investigated EPDM geomembranes in the different water reservoirs are still accomplishing their function of waterproofing.

The elongation at break seems to be a good criterion to define the service life of EPDM geomembranes but it can be said that the criterion of 50% of the initial elongation or of the minimum recommended elongation for EPDM geomembranes is too strict. There is a need to define new acceptable criterions like a reduction of the elongation at break higher than 60%. For this reason, a periodic follow-up of different EPDM geomembranes should be made in order to define a specific acceptable criterion that is representative of the real end of service life of EPDM geomembranes, especially for those used in water reservoirs.

4. CONCLUSIONS

1. Foldability at low temperature (-55ºC) showed no cracks, breaks or any other indication of degradation after conducting the tests on all tested samples, even after 22 years of exposition to weathering.
2. Hardness Shore-A increases over time as a consequence of a higher crosslinking of the macromolecules.
3. Dynamic puncture resistance improves over time. The height of fall of the puncturing tool that initially is 350 mm, after some years the height exceeds 500 mm. This performance is due to the higher vulcanization of the material.
4. Static puncture resistance increases over time as a consequence of its higher rigidity and, therefore the distance made by the plunger before perforation decreases; however its value after 11 years of installation can triplicate the initial value of some thermoplastics.
5. The values of tensile strength increase over time as a consequence of vulcanization processes after production; nevertheless, at a certain time those values start to decrease probably due to the oxidation of the resin that leads to its fragmentation. The elongation at break decreases over time due to the continuation of the vulcanization of the material and eventually because of the oxidation of paraffinic oils.
6. Microscopic techniques present geomembranes with symptoms of deterioration. In addition, scanning electron microscopy detects isolated microcracks.
7. The evolution in time of the properties do not change significantly with the orientation of the samples, however it is suspected that a higher thickness could improve the performances of the geomembrane in time.
8. Even if EPDM geomembranes have a higher UV resistance than some thermoplastic geomembranes, they are affected by UV as non exposed samples are in a better condition after 22 years of exposition. The high UV resistance of EPDM geomembranes could be related to the high content of carbon black in its composition that absorbs UV radiations.
9. The best property to evaluate the service life of EPDM geomembranes seems to be the elongation at break as it is the property that changes most over time. The criterion of 50% loss of elongation at break seems very restrictive, therefore the criterion should be higher than 60% as all inspected geomembranes still perform their waterproofing job even 22 years after installation and loosing up to 68% of its initial elongation at break.

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