Performance of geomembranes seldom used in hydraulic works, installed in the experimental field of El Saltadero.

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ABSTRACT: Balsas de Tenerife (BALTEN) and Centro de Estudios y Experimentación de Obras Públicas (CEDEX) provide an experimental field into the area of the reservoir called El Saltadero, where an artificial slope with a support of porous concrete has been built in order to place a series of synthetic geomembranes. Materials placed there are novelty or come from new manufacturers in our country. The performance of their products is unknowing under our climate.

Although the performance of a great quantity of materials is being checked, this paper refers to eight of them, which are among the less used in this field of technology. The synthetic geomembranes considered are plasticized poly (vinyl chloride) with insertion of glass fiber (PVC-P), ethylene propylene diene monomer rubber with polyester veil (EPDM), medium density polyethylene (MDPE), chlorosulfonated polyethylene (CSM), ethylene-vinyl acetate copolymer (EVA/C), flexible polypropylene (fPP) and both elastomeric (POE) and thermoplastic (TPO) polyolefins.

Characteristics of polymeric geosynthetic barriers were determined prior to installation in order to check their validity and also to set the initial value to be referred to over time. Samples are taken periodically to perform tests which results make it possible to know the performance of the materials considered.

Tests carried out during fifteen years from the installation of geomembranes refer to foldability at low temperatures, Shore hardness, dynamic and static impact resistance, tensile strength, elongation at break, optical and scanning electron microscopy and, in the case of PVC-P, plasticizers loss.

Keywords: Geomembranes, durability, hydraulic works, experimental field.

1 INTRODUCTION

The Centro de Estudios y Experimentación de Obras Públicas (CEDEX) and Balsas de Tenerife (BALTÉN), provide an experimental field to research synthetic geomembranes, placed into the area of the covered reservoir “El Saltadero” (Figure 1) (Renz 2005), where a

great range of geomembranes are being tested. When they were placed there, some of them represented an innovation in this application, and others came from new manufacturers in Spain. For this reason, their performance over time was unknown. (Aguiar et al. 2008, 2012, Blanco et al. 2013a, b). This place was chosen due to its strong insolation that range between 6.5 and 8.5 on a scale of 0.5 to 14.5 (Bournay, E. & UNEP/GRID Arendal 2007).
The sampling panels where the materials are located for this research were placed on a compacted slope with a support of porous concrete, perfectly pinned and oriented south, which is the part of maximum degradation of these macromolecular products in the northern hemisphere.
The durability of a macromolecular material is commonly determined at laboratory level, through different ageing methods such as the thermal and the artificial accelerated ones. This latter method has many variations both in experimental methodology related with the situation and conditions of the samples in the chamber and the kind of radiations used. All of this makes it possible to get interesting results to compare the useful service of the different geomembranes (Koerner 1999). However, the reality is quite different because the weather and environmental conditions, as well as the solicitations to which the material is subjected, make its performance in works not to be as expected in laboratory.
The aforementioned fact has led to the industry and researching centers to make experimental fields in certain areas around the globe where the environmental conditions are usually more severe. A common case, maybe pioneer, applicable to polymeric materials, was the paints and coatings sector, with experimental fields in areas with climates as different as Florida (USA) and the Arabian Peninsula. In the case of geomembranes, some examples can be found in literature about the comparison between the durability of sheets installed in France and in the Sahara (Fayoux et al. 1993). The importance of the experimental field of El Saltadero is recognized by the International Commission on Large Dams (ICOLD), which mentioned it as an example in its last bulletin published, in its English and French versions, in Paris in 2010.

This paper refers to synthetic geomembranes of plasticized poly (vinyl chloride) with insertion of glass fiber (PVC-P), ethylene propylene diene monomer terpolymer with polyester veil (EPDM), medium density polyethylene (MDPE), chlorosulfonated polyethylene (CSM), ethylene-vinyl acetate copolymer (EVA/C), flexible polypropylene (fPP) and both elastomeric (POE) and thermoplastic (TPO) polyolefins.

Figure 1. Partial view of the experimental field of synthetic geomembranes in the reservoir of El Saltadero

2 GEOMEMBRANES

The nature of the synthetic geomembranes placed in the experimental field, in order to check their durability, covers a wide range of materials. Thus, some homogeneous sheets of flexible poly (vinyl chloride) with external plasticization, with insertion of glass fiber, and reinforced with synthetic fabrics, were installed; even a geomembrane of this material with internal plasticization was applied. Polyethylene in different varieties is the material with more samples exposed in the experimental field. Also terpolymer rubbers of ethylene propylene diene monomer have been studied. In this paper, geomembranes less used than the aforementioned and so more unknown, have been selected to study their performance.
Plasticized poly (vinyl chloride) with insertion of glass fiber (PVC-P) was studied. This material was not applied in hydraulic works until a few years ago, although it was used in building. Results obtained in this experimental field allowed its installation in a reservoir of large capacity as is Valle Molina. Another innovative geomembrane presented is EPDM with an insertion of polyester veil.
Also, the performance of geomembranes of EVA/C, CSM and fPP, with a very little use in Spain, was checked. It has been reported that EVA/C has been installed in some reservoir in the area of the Pyrenees and the CSM in reservoirs with floating cover as Aguadulce (Roquetas de Mar-Almería). The fPP was used in reservoirs as La Contraviesa (Torvizcón-Granada) and Los Cardones (Alajeró-Island of La Gomera).
Finally, the performance of both elastomeric (Aguiar et al. 2010) and thermoplastic polyolefins is presented. The thermoplastic ones have been used in the waterproofing of the reservoir of Los Partidos in Tenerife and the dam of Puente Porto in Zamora (Alonso et al. 2010a, b, Blanco et al. 2010a)
The performance over time of these materials has been studied through a periodic control, for which technicians of BALTEN carry out inspection visits to the experimental field and take samples that later are sent to Madrid to be analyzed in the Central Laboratory of Structures and Materials of the CEDEX.

3 EXPERIMENTAL

Characteristics of the polymer geosynthetic barriers considered were determined before their installation in order to check their validity and also to get initial values to use as the basis for comparison while monitoring them over time. The tests carried out periodically are extensively described in the literature (Blanco et al. 2012, Cea de & Blanco 2005) and the most important ones are presented in the paragraphs of this section.
The experimental methodology was carried out according to the standard UNE-EN 13 361. Puncture resistance tests were made according to the method developed by this research team, which nowadays, belongs to the standards of the Spanish organization of standardization and certification AENOR (Blanco et al. 1996, UNE 104 317).
Although tensile strength and elongation at break tests were conducted in both longitudinal and transverse directions, the results presented in this paper are referred to the longitudinal direction. Furthermore, dynamic impact tests were made on both faces of the specimen, although the results presented in this paper are referred to the external face, that is to say, the visible face of the hydraulic work.
All tests carried out initially have exceeded the minimum requirements demanded for this kind of geomembrane according to the Reservoirs Handbook (2010) written by the CEDEX following a re-quest of the Spanish Ministerio de Medio Ambiente y Medio Rural y Marino.

3.1 *Foldability at low temperatures*

Samples of geomembranes of the materials considered were subjected to the foldability test at low temperatures, for which they were folded on themselves at an angle of 180º after remaining 5 hours in a cold store at a given temperature. After this, it was observed if there were signs of deterioration in the samples, as cracks, breaks or other surface imperfections.
Folding temperature depends on the nature of the macromolecule that compounds the polymeric geosynthetic barrier and this is a test to check the suitability of the material. Temperatures used for the foldability test of the different materials are presented in Table 1. The test has been passed by all geomembranes installed during this time period.

Table 1. Folding temperature (ªC) according to the nature of the synthetic geomembrane

CSM	-40
EPDM	-55
PEMD, fPP, TPO, POE	-75
PVC-P, EVA/C	-20

3.2 *Shore hardness*

Shore-A hardness has been determined in all the thermostable materials tested, while Shore-D hardness has been determined in thermoplastic products. Results are presented in Table 2. It should be noted from the results the increase experimented by the EPDM rubber and the small variation of the rest of the materials studied.
The test has not been carried out in reinforced geomembranes: fPP, CSM and PVC-P with insertion of glass fiber, due to the interference of the reinforcement.

Table 2. Evolution of Shore hardness over time

Years from its installation	Material				
	MDPE*	EVA/C	EPDM	POE	TPO
0	47	32	64	93	31
1	48	35	69	93	31
3	48	35	75	95	31
5	47	37	72	95	35
7	48	34	69	84	32
9	47	39	73	85	35
11	50	35	74	83	32
13	48	35	78	87	--
15	47	36	81	86	--

* Shore-D for thermoplastics and Shore-A for thermostable materials

3.3 *Tensile characteristics*

Tensile strength and elongation at break values are presented in Tables 3 and 4 respectively. Tensile strength values of PVC-P experiment an increase over time mainly because of the loss of plasticizers.
The same trend is observed in EPDM, but in this case the increase is due to the vulcanization that is happening in the rubber, that implies an increase of the hardness of the geomembrane. In geomembranes of MDPE, EVA/C and POE the tensile strength decreases.
Elongation at break decreases in all the homogeneous sheets, mainly in the case of rubber. In reinforced geomembranes fPP and CSM, there is not a notable variation of both tensile

strength and elongation, because of these characteristics are linked to the textile reinforcement which experiments very few changes while it is covered by the resin.

Table 3. Evolution of the tensile strength over time

Years from its installation	Tensile strength, MPa							
	PVC-P	MDPE	EVA/C	fPP*	CSM*	EPDM	POE	TPO
0	14.1	24.6	22.5	1810	1500	8.3	19.5	9.4
1	14.1	22.8	22.3	1540	1653	8.3	17.6	9.9
3	14.7	23.1	22.0	1545	1530	7.3	18.5	9.1
5	14.6	20.7	18.7	1570	1495	8.2	16.5	9.3
7	15.0	21.9	19.2	1410	1537	8.1	18.8	9.0
9	17.1	21.0	19.7	1420	1510	7.8	19.2	9.1
11	15.4	21.0	18.4	1425	1583	8.1	19.2	10.3
13	16.2	21.2	19.9	1387	1530	8.6	20.6	--
15	18.5	21.1	18.2	1430	1483	9.3	15.0	--

* Being a reinforced sheet, the tensile strength is expressed in N/50 mm

Table 4. Evolution of elongation at break over time

Years from its installation	Elongation, %							
	PVC-P	MDPE	EVA/C	fPP*	CSM*	EPDM	POE	TPO
0	248	747	888	28	29	428	814	517
1	212	688	768	31	26	425	716	545
3	209	738	774	31	27	400	788	497
5	208	708	722	29	34	379	764	480
7	207	718	737	32	30	343	762	462
9	198	667	785	32	30	276	717	477
11	180	625	745	35	31	201	713	423
13	173	558	760	28	28	133	710	--
15	158	548	763	25	28	127	607	--

* Being a reinforced sheet, elongation is at the point of maximum load

3.4 *Impact resistance*

From the point of view of dynamic impact, all the samples of thermoplastic geomembranes passed the test over time, since none of them suffered perforation in the impact zone after throwing a 0.5 kg plunger drop ended in a hemispherical ball of a 12.7 mm diameter, from a height of 500 mm.

Table 5. Evolution of the static puncture resistance over time

Years from its installation	Static puncture resistance, N/mm							
	PVC-P	MDPE	EVA/C	fPP	CSM	EPDM	POE	TPO
0	522	498	476	442	647	248	230	166
1	516	490	397	233	579	225	220	179
3	557	480	387	398	470	214	270	145
5	563	545	414	305	524	207	287	192
7	586	595	385	237	511	223	269	208
9	603	589	390	482	476	252	305	212
11	634	548	388	539	481	262	304	202
13	639	555	358	551	485	324	310	--
15	655	574	405	552	471	255	325	--

In the case of thermostable geomembranes, the height of the plunger was 350 mm, but a significant event took place, since after several years from installation of the material, the plunger drop height was more than 500 mm, which is the value required for thermoplastic materials. This fact is due to processes which involve a greater crosslinking of the rubber.
Tables 5 and 6 present the variation of the puncture resistance and the displacement of the plunger before perforation, respectively. In general, the puncture resistance increases over time and, at the same time, the displacement of the plunger before perforation decreases. The performance regarding the static puncture is considerably better in EPDM, EVA/C, polypropylene and polyolefins.

Table 6. Displacement of the plunger before puncture over time

Years from its installation	Displacement of the plunger before puncture, mm							
	PVC-P	MDPE	EVA/C	fPP	CSM	EPDM	POE	TPO
0	25	18	*	33	12	42	33	35
1	24	15	*	34	12	44	34	34
3	23	13	*	34	11	37	42	30
5	23	20	*	30	11	35	38	28
7	23	20	*	36	11	30	40	29
9	23	21	50	36	11	30	41	27
11	23	22	47	44	11	26	43	17
13	22	21	44	45	11	25	42	--
15	20	20	42	47	11	16	40	--

* The displacement was more than 54 mm, maximum permitted by the test equipment

3.5 *Microscopic analysis*

The microscopic evolution of the geomembranes has been carried out according to the experimental conditions of the literature (Soriano et al. 2006, 2010). Microphotographs were taking by reflected optical microscopy (ROM) at (x 40) and (x 60) magnifications in order to study their texture and morphology.

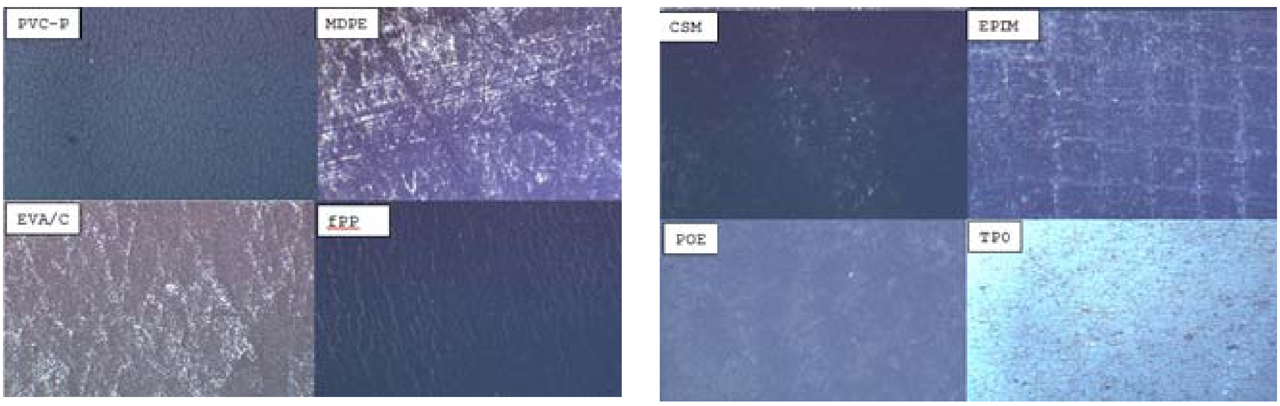

Figure 2. Microphotographs (x 60) of the external side of the geomembranes after thirteen years of their installation by reflected optical microscopy.

Figure 2 presents the external side at (x40) magnifications of the different geomembranes after thirteen years of installation. In addition, the condition of the aforementioned geomembranes after thirteen years of installation has been tested by scanning electron microscopy (SEM) at (x90) and (x900) magnifications. Figure 3 presents the appearance of the external side of the materials at (x90) magnifications.

Reflected optical microscopy shows a very important ageing in PVC-P and fPP geomembranes. Scanning electron microscopy detects a significant cracking in the sheets of PVC-P, MDPE, EVA/C, fPP and POE.
Microphotographs of EPDM geomembrane, obtained by both kinds of microscopy, present grooves of the fabric used in the vulcanization of the rubber.

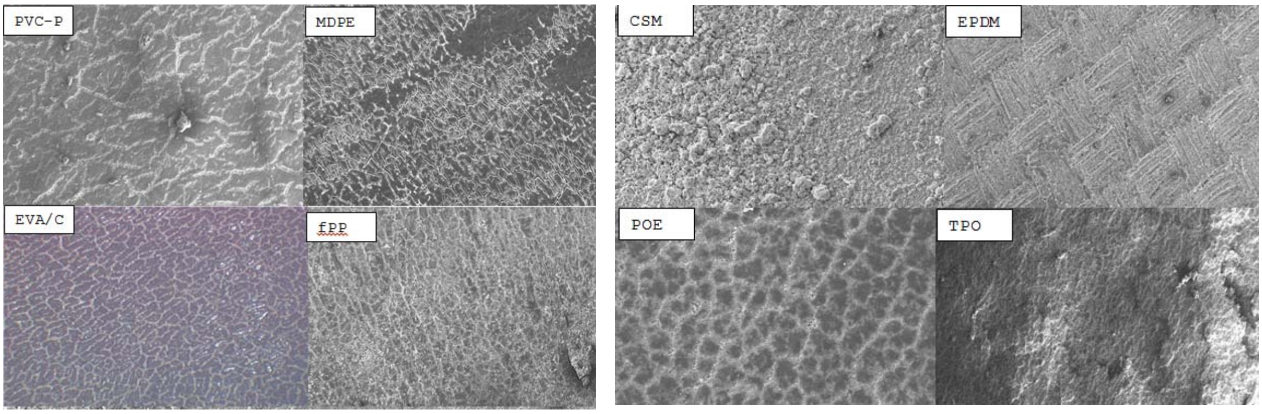

Figure 3. Microphotographs (x 90) of the external side of the geomembranes after thirteen years of their installation by scanning electron microscopy.

3.6 *Plasticizers*

In the case of the PVC-P geomembrane, plasticizers were extracted with ethyl ether (UNE 104 306) and to determine their content, a correction according to the scientific literature (Giroud & Tisinger 1993, Giroud 1995) was made, because together with the plasticizers, other organic additives are dragged. Plasticizers lose has been tested over time and the evolution is presented in Figure 4. Their identification has been carried out by Fourier transform infrared spectroscopy, which spectrums show typical bands of alkyl phtalates (Crespo 2011, Blanco et al. 2010b).

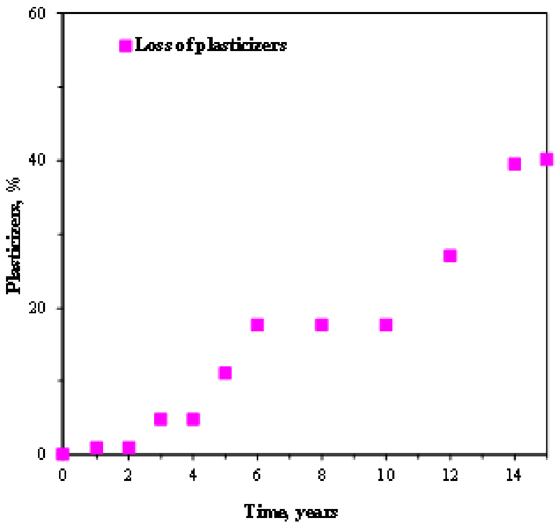

Figure 4: Loss of plasticizers over time.

Gas chromatography mass spectrometry (GC-MS) made it possible to stablish the number and type of plasticizers that became part of the composition of the geomembrane. Chromatography led to a chromatogram with two products. Then, mass spectrometry gave rise to the following results:

- First peak: MS, m/z (relative intensity): 446(M+), 307($C_{18}O_4H_{27}$+,86), 167($C_8H_7O_4$+,16), 149 ($C_8H_5O_3$+,100). Fragmentations indicate that it is di-n-decyl phthalate.
- Second peak: MS, m/e (relative intensity): 446(M^+), 307($C_{18}O_4H_{27}^+$,25), 167($C_8H_7O_4^+$,19), 149($C_8H_5O_3^+$,100), 85($C_6H_{13}^+$,25), 57($C_4H_9^+$,29). Fragmentations indicate that it is diisodecyl phthalate.

The molecular weight is 446, so the geomembrane is predicted to have a great durability.

4 CONCLUSIONS

The performance of eight polymeric synthetic geomembranes seldom used, has been monitored over 15 years, in order to check their suitability to be used in hydraulic works.
For this purpose, they were placed in an experimental field, with a strong insolation, in the south of the island of Tenerife.
Initially all the geomembranes have exceeded the minimum requirements established for this kind of materials, however, it has to be taken into account that all the macromolecular materials, due to their organic nature, suffer an ageing process over time that will be greater or smaller, depending on the adverse conditions of the place where they are installed, especially the effect of solar radiation.
This study about the performance of the geomembranes coming from the experimental field of El Saltadero, the following points can be highlighted:

1.- Tests have been passed by all the geomembranes installed over this period of time.

2.- Results obtained in the determination of Shore hardness show an important increase in the case of EPDM rubber and a small variation in the rest of the materials considered.

3.- In the materials reinforced with synthetic fiber fabrics, fPP and CSM, tensile strength and elongation depend on the textile of the reinforcement, so their variations over time are small due to the fibers are protected by the resin which avoid the exposure to solar radiation. In all homogeneous sheets, elongation decrease over time, mainly in the case of elastomers.

4.- Resistance to dynamic impact test has been passed by all the samples over time. In general, puncture resistance increases over time and, at the same time, the displacement of the plunger before perforation decrease. The performance regarding the static puncture is considerably better in EPDM, EVA/C, polypropyilene and polyolefins.

5.- Reflected optical microscopy shows in PVC-P and fPP geomembranes an important ageing. Scanning electron microscopy detects a significant cracking in the sheets of PVC-P, MDPE, EVA/C, fPP and POE.

Microphotographs of EPDM geomembrane, obtained by both kinds of microscopy, present grooves of the fabric used in the vulcanization of the rubber.

6.- The PVC-P geomembrane with insertion of glass fiber presents a good durability because of its high average molecular weight, 446, and with a loss of plasticizers in the order of 40% after 15 years from installation.

7.- All the geomembranes considered have fulfilled their function during these years, including the new implantation ones, as PVC-P with insertion of glass fiber, EPDM with polyester veil and POE. Therefore, they can be considered suitable to be used in the waterproofing of hydraulic works.

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