TECHNICAL SESSIONS

HDPE geomembrane's behaviour after 20 years in sevice at Areias de Vilar Water Reservoir

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ABSTRACT: A high-density polyethylene geomembrane installed 20 years ago at Areias de Vilar Water Reservoir has experienced degradation and damages, such as tears, punctures and stress cracking. In order to study its behaviour, samples were taken from the west cell, from the four slopes, in two locations (above and below the water level). Tensile tests, static puncture tests and standard (Std) oxidative induction time tests (OIT) were carried out. The results show that the tensile strength at yield, the strain at break and the puncture resistance of the geomembrane remain close to the its initial values, while the tensile strength at break and the strain at yield showed a decrease. Also Std-OITs measured were low and approaching a residual value.

Keywords: water reservoir, HDPE geomembrane, UV exposition, laboratory tests

1 INTRODUCTION

The Water Treatment Plant of Areias de Vilar (WTP) includes a Raw Water Reservoir (RWR) consisting of two cells. Cells' lining system include a high density polyethylene (HDPE) geomembrane.

The geomembrane, installed at the reservoir in the late 1990s, shows degradation and various damages, such as creases, tears, punctures and stress cracking. The existing damage is mainly located on the east cell, resulting in the necessary replace the geomembrane in the short term.

In order to study the degradation in the properties of the geomembrane installed on the west cell and schedule its replacement, in 2019, seven samples were taken from this cell for laboratory tests.

Some of the main properties of the geomembrane were evaluated, namely tensile properties (strength at yield, strength at break, strain at yield and strain at break), static punching resistance and standard (Std) oxidative induction time (OIT).

This work aims to investigate the degradation that occurred in the main properties of the HDPE geomembrane after 20 years in service at Areias de Vilar Water Reservoir. Results obtained are compared to the geomembrane's initial properties, or, when that is not possible, with the minimum values presently recommended by Geosynthetic Research Institute (GRI)-GM13 (2019), for the Std-OIT.

2 THE AREIAS DE VILAR WATER RESERVOIR

The Water Reservoir is located in the north of Portugal, at the municipality of Barcelos, close to the Cávado River. It includes two cells, with a global capacity of 175 000 m^3 (Figure 1). This volume of water corresponds to a water reserve of more or less 24 hours. The cells are limited by embankment dikes, 6.5 m high, with slopes of 2.25H:1V (where H is horizontal and V is vertical). The reservoir lining system comprises a HDPE geomembrane, 1.5 mm thick, at the slopes, and, a bituminous concrete mat, at the base. The lined area is, approximately, 20 000 m^2. The geomembrane rests on a needled punched non-woven geotextile, made of polypropylene.

Figure 1. View of the Areias de Vilar Water Reservoir

Table 1 summarizes the main characteristics of the reservoir.

Table 1. Main characteristics of the Areias de Vilar Water Reservoir

Location	Areias de Vilar, Barcelos, Portugal
Capacity	175 000 m^3
Area	3.6 ha
Lined area	20 000 m^2
Hydraulic head over the lining system	6.5 m
Excavation volume inside the reservoir	93 640 m^3
Embankment volume	91 540 m^3
Embankment dikes maximum height	6.5 m
Embankment dikes slopes	2.25H:1V (where H is horizontal and V is vertical)
Top embankment width	5.0 – 6.0 m
Construction year	1997-1999
Geomembrane (slopes)	HDPE, 1.5 mm

3 EXPERMENTAL WORK

3.1 *Geomembrane initial properties*

Table 2 shows the values required on specification for the HDPE geomembrane, 1.5 mm thick, installed at Areias de Vilar Water Reservoir. It was not possible to obtain the correspondent Technical Data Sheet, nor laboratory test results for the geomembrane. However, at the time of the reservoir's construction, it was current practice to specify the values provided by the manufacturers in the Technical Data Sheet. Therefore, it is here assumed that the required properties of the geomembrane correspond to its initial properties.

Table 2. Inferred initial properties of the geomembrane (based on specification for the HDPE geomembrane)

Proprieties	Test method	Initial properties
Density	ASTM D792 or DIN 53479	> 0,94 g/cm^3
Tensile strength at break	ASTM D638 or DIN 53455	> 30 N/mm^2
Tensile strength at yield		≥ 15 N/mm^2
Strain at break		> 550 %
Strain at yield		≥ 15 %
Melt Flow Index	ASTM D238 or DIN 53735	< 1,0 g/10 min
Resistance to tear	ASTM D1034 or DIN 53515	> 125 N/mm
Resistance to static puncture	DIN 54307	> 3 kN
Dimensional stability	ASTM D1234 or DIN 53377	± 2%

3.2 *Sampling and sample locations*

Seven geomembrane samples were exhumed from the four slopes of the west cell. This cell presents less damage compared to the east cell, which will be replaced soon. Six samples were taken from the north, east and south facing slopes, in two locations (Figure 2): above the water level (emerged) and below the water level (submerged). The remaining sample was taken from the west-facing slope above the water level, on an area where the geomembrane had a pronounced crease (Figure 3).

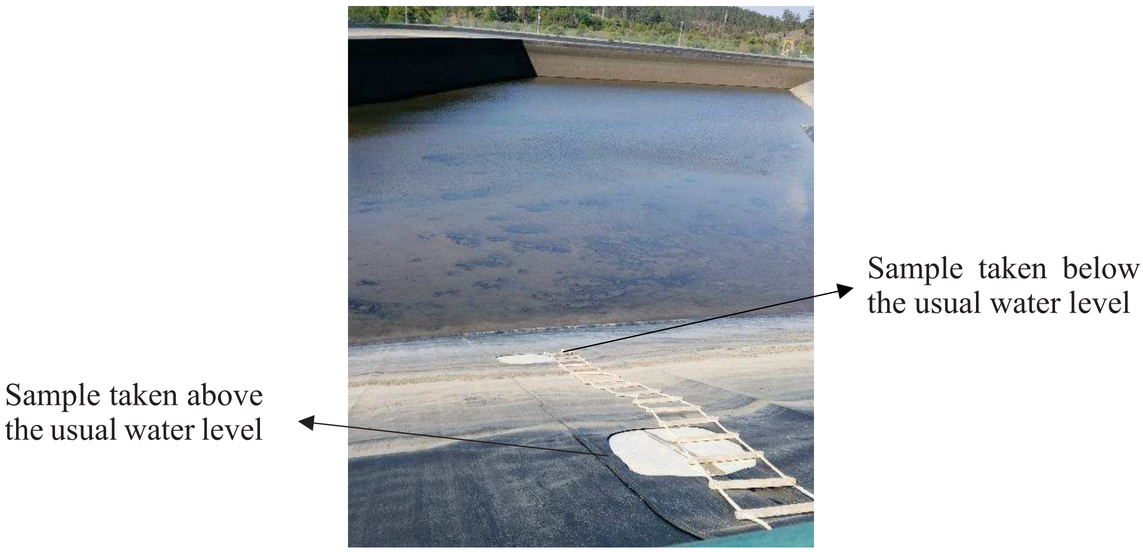

Figure 2. Sampling at south-facing slope

Figure 3. Sampling at west-facing slope

3.3 *Test methods*

3.3.1 *Tensile test*

Tensile tests were carried out in accordance with ASTM D6693 standard, using dumbbell-shaped specimens (type IV) taken in the machine direction (MD), at an elongation rate of 50 mm/min, and temperature of 23 ± 2ºC, instead of the 21 ± 2ºC recommended by the standard procedure. The strengths and strains at yield and at break were evaluated.

Tests were performed at 23 ± 2ºC in order to compare with the initial tensile properties of the geomembrane, since these properties were evaluated based on the ASTM D638 standard, according to which the tests must be carried out at that temperature. The ASTM D6693 standard is currently recommended by the ASTM D35 - Geosynthetics Committee. It should be noted that the test procedures are similar in both standards, with the exception of temperature.

According to Rowe *et al.* (2009), the mechanical properties are useful to evaluate the degradation of geomembranes as a result of oxidation (thermo-oxidations and photo-oxidatationtem). It seems that oxidation increases crystallinity, which makes the geomembrane more fragile. Initially, oxidation can lead to an increase in tensile strength at yield and a decrease at strain in yield. However, as oxidation proceeds, degradation increases and the geomembrane becomes extremely fragile. As a result, the tensile strength decreases.

3.3.2 *Static puncture test*

Static puncture test tests were carried out in accordance with NP EN ISO 12236 standard, which is similar to the standard DIN 54307, used to evaluate the initial properties of the geomembrane, so the results are comparable.

Besides the puncture resistance, the distance travelled by the plunger before perforation (displacement at break) was also measured. As mentioned by Blanco et al. (2015), this displacement allows the evaluation of the resistance to puncture in actual conditions, as it gives an idea of the adaptability of the geomembrane to the soil conditions.

3.3.3 *Standard oxidative induction time test*

Standard oxidative induction time tests (Std-OIT) were carried out in accordance with ASTM D3895 standard, to infer the relative concentration of antioxidants in the geomembrane. Tests were conducted at 200 °C and 35 kPa oxygen pressure.

A minimum value for Std-OIT was not defined in the specification, however, at the time of geomembrane installation, Technical Data Sheets did not always include this property. According to GRI-GM13 (2019), currently, the minimum value required for this property is 100 minutes.

The Std-OIT indicates the amount of antioxidant that remains in the geomembrane. This information is extremely useful, since the antioxidants protect the geomembrane from degradation. Usually, the durability of HDPE geomembranes decreases with oxidation.

It is generally accepted that the chemical degradation model for an HDPE geomembrane involves three distinct stages (Hsuan and Koerner, 1998):

(I) antioxidant depletion;
(II) induction to the onset of the polymer chemical degradation;
(III) significant chemical degradation that takes place from the end of Stage II to geomembrane failure.

According to Rowe and Ewais (2015), the geomembranes' service life is considered to be the sum of the three stages and can be as brief as one year to more than a century depending on the initial geomembrane characteristics and exposure conditions.

4 TEST RESULTS AND DISCUSSION

Table 3 shows the results of the tests performed, as well as the inferred initial properties of the geomembrane. Mechanical test results include, in brackets, standard deviations obtained, in order to illustrate their dispersion. For Std-OIT, instead of the average, test results depict the values obtained in the two specimens tested per sample.

Table 3. Measured properties and initial properties of the geomembrane

Proprieties	Inferred initial values	Sample	Slopes facing			
			North	South	East	West
Strength at break (N/mm^2)	> 30	emerged	23,1 (4,4)	20,1 (7,8)	25,3 (2,8)	20,0 (7,1)
		subemerged	19,0 (6,9)	23,2 (7,2)	21,6 (8,7)	-
Strain at break (%)	> 550	emerged	526 (95)	371 (225)	543 (69)	425 (110)
		subemerged	411 (205)	502 (152)	424 (206)	-
Strength at yield (N/mm^2)	≥ 15	emerged	17,4 (0,7)	16,8 (0,5)	16,5 (1,1)	15,8 (1,2)
		subemerged	16,9 (0,3)	15,6 (0,9)	15,9 (1,0)	-
Strain at yield (%)	≥ 15	emerged	8 (0,3)	9 (0,2)	9 (0,3)	9 (0,2)
		subemerged	8 (0,3)	9 (0,9)	9 (0,4)	-
Puncture resistance (kN)	> 3	emerged	3,8 (0,5)	4,1 (0,3)	4,4 (-)	4,6 (0,2)
		subemerged	4,1 (0,6)	4,1 (0,5)	4,5 (0,2)	-
Displacement at break (mm)	-	emerged	50 (23,5)	79 (15,8)	96 (-)	98 (7,8)
		subemerged	70 (28)	82 (22,1)	100 (6)	-
Std-OIT (minutes)	> 100 *	emerged	3,6 – 4,4	1,7 – 5,9	3,7 – 4,1	0,9 – 2,0
		subemerged	6,6 – 7,0	11,1 – 12,2	3,9 – 4,5	-

* specified by GRI – GM 13 (2019)

4.1 *Tensile properties*

Results obtained for tensile strength at break, as well as for strain at break and at yield were lower than the initial values. In contrast, the strength at yield was higher than the initial value, for all samples. Apparently, the results suggest that these properties were affected by the aging of the geomembrane. However, the great scatter obtained for the tensile strengths at break and for the corresponding strains, expressed by the high standard deviations, and the fact that the initial values were not obtained from laboratory tests, makes this appreciation to be viewed with some caution.

Results also showed that the exposure conditions (above *versus* below the water level) do not seem to affect the tensile strength and strains at break and at yield. Likewise, it is observed that the orientation of the slopes also does not seem to have an influence on the results of the tensile strength and corresponding strains at rupture and at yield. By taking into account the standard deviations, results obtained can be considered similar for the emerged and submerged samples and in the different slopes, contrary to what would be expected. Indeed, it could be anticipated that these properties would present lower values for exposed samples, namely, in the samples taken above the water level, and taken from south-facing slope. As pointed out by Koerner et al. (2017), among the several factors that contribute to the degradation of HDPE geomembranes, UV radiation is the most severe one.

The results obtained in the present study are consistent with those reported by Tarnowski and Baldauf (2006), Baldauf *et al.* (2012) and Reis et al. (2017). The former carried out tensile tests on four HDPE geomembranes exposed for approximately 30 years, reporting that the mechanical properties of three geomembranes did not present significant changes.

Baldauf *et al*. (2012) studied the durability of a HDPE geomembrane in service in a water reservoir in Spain, for 17 years. The tested samples were taken in two locations, one above the water level and another in an intermittent area (below/above the water level). For both samples, the tensile strength and corresponding strains values were similar to the initial values, indicating that the exposure conditions of the geomembrane (emerged versus partially submerged) had no influence on its mechanical properties.

Minor variations in tensile strength at yield were also obtained by Reis et al. (2017), in a study carried out with HDPE geomembranes exposed in different locations in Portugal, for about 12 years.

Different results were obtained by Rowe and Ewais (2015). These authors report a decrease in tensile strength and in strain at break of a HDPE geomembrane exposed for 16 years, mainly in specimens tested in the machine direction. According to the authors, the decrease in mechanical properties may be related to several factors, including changes in structure, oxidation and damage caused during construction and/or operation.

4.2 *Puncture resistance*

In overall terms, puncture resistances obtained in this study were higher than the initial values, regardless of the exposure conditions of the slope orientation. However, as previously mentioned, the initial value of this property has not been determined in the laboratory (see section 3.1). Therefore, it is possible that the initial value was higher than the one inferred. Thus, it is assumed that the puncture resistance of the HDPE geomembrane has not changed significantly over time.

The initial displacement at break (distance travelled by the plunger before perforation in the puncture test) is unknown. However, results obtained in the current study suggest that the exposure conditions of the geomembrane (above and below the water level) and the orientation of the slopes have no significant impact on the values of this property, if one takes into account the scatter of the results.

4.3 *Standard oxidative induction time*

Std-OIT obtained from the different slopes were similar to each other and all very low (0.9 to 12.2 minutes) compared to the minimum recommended by the Geosynthetic Research Institute (GRI)-GM13 (2019), which is presently 100 minutes.

It was found that the submerged samples presented higher Std-OIT than the emerged samples, varying between 3.9 and 12.2 minutes, for the former, and between 0.9 and 5.9 minutes, for the latter. Nevertheless, considering the scatter in results per sample, these are minor differences.

The slope orientation appears to have low impact on Std-OIT results. It is not clear why the samples with high exposition to UV radiation (south-facing slope and samples taken above the water level), for which higher antioxidant consumption would be expected, do not show lower Std-OIT than the samples taken from the north-facing slope, or samples taken below water level.

The Std-OIT obtained for all samples indicates that the amount of antioxidants present in the geomembrane is approaching a residual value, which means that little to no available antioxidants remain in the geomembrane installed at Areias de Vilar Water Reservoir. These results are consistent with those reported by Rowe and Ewais (2015), by Tarnowski and Baldauf (2006) and by Baldauf et al. (2012), in the previously mentioned studies. According to Rowe and Ewais (2015), geomembranes with residual or near-residual OIT may be in either Stages II or III, as defined in section 3.3.3. These geomembranes are at risk of stress cracking as some antioxidants, while still present, are not sufficiently mobile or effective to protect them gfrom degradation, particularly near the surface exposed to UV radiation.

It is important to note that the Std-OIT measurements carried out in this study were performed on the upper surface of the geomembrane (exposed surface). Tarnowski and Baldauf (2006) found that the values of this property depend on the location of the specimens in the sample, obtaining higher values for specimens taken from the middle layer of the geomembrane. They concluded that the thickness has a major influence on antioxidant depletion and, therefore, on durability of the geomembranes.

5 CONCLUSIONS

This study investigated the degradation that occurred in the main properties of the HDPE geomembrane, 1.5 mm thick, after 20 years in service at Areias de Vilar Water Reservoir.

Laboratory tests were carried out in seven samples taken from the west cell, on different slopes, above and below the water level. The properties evaluated were tensile properties (strength at yield, strength at break, strain at yield and strain at break), static punching resistance and standard oxidative induction time (Std OIT).

Results obtained were compared with the initial properties of the geomembrane, inferred from the geomembrane specification, or, when that was not possible, with the minimum values currently recommended by Geosynthetic Research Institute (GRI)-GM13 (2019), for the Std-OIT.

It was found that the tensile strength at yield, the strain at break and the puncture resistance of the geomembrane remains close to the initial values, while the tensile strength at break and the strain at yield showed a decrease. Also Std-OITs measured were lower than the minimum required according to GRI-GM13 (2019) and approaching a residual value.

The results obtained suggest that the amount of antioxidants in the geomembrane is approaching to a residual value, which may not be enough to ensure protection against short-term degradation, especially on the upper surface, higher exposed to UV radiation.

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