Durability of PVC-P geomembranes
Assessment after very long UV exposure

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ABSTRACT: Use of PVC-P geomembranes was increasing strongly in the beginning of the Eighties. This gives the opportunity to verify the global behaviour and to carry test on very old works. After reviewing the mechanism of ageing of PVC-P, these paper present old ponds were the geomembrane is exposed to UV and to different chemical solution. In particular, following works will be described:

- A manure pit pond, 18 years old, 2000 m², 6 m deep, capacity 5000 m^3, installed at the end of 1981 close to Azay le Rideau (F)
- An irrigation pond, 17 years old, 40000 m², 8 m deep. We have followed the installation of the work and some information was published in 1984 on this installation. This work is in Prefontaine in centre of France.
- A leachate pond after 10 years, 500 m², 1.8 m deep (Saint George les Baillargeaux, F)
- And an irrigation pond built in 1991 and 1992 in Canary Island, 250 000 m² and 27 m deep (Barlovento).

Supporting layer is in some cases very aggressive, inducing heavy puncturing effect. Also very often horizontal welding are on the slopes. The study of those works shows that the geomembranes used have a very good behaviour even in this case.

1 INTRODUCTION

Durability is the time during which the geomembrane remain watertight, taking in account the ageing of the material and the mechanical and physico-chemical actions on the geomembrane.

PVC-P geomembranes are very useful in hydraulic applications, due to their very good mechanical properties and their easy weldability. But their durability (and their price) depends strongly of the formula of the product. Even with accelerated ageing tests, it is necessary to wait a very long time to do a right forecast of the long-term behaviour of one formula.

Therefore, it is important to know well not only the mechanism of ageing but also the long-term behaviour of membrane and welding under permanent elongation and puncturing. Finally, it is important to compare theoretical forecast with real long-term behaviour.

Use of PVC-P geomembranes was increasing strongly in the beginning of the Eighties. This gives the opportunity to verify the global behaviour and to carry test on very old works. After reviewing the mechanism of ageing of PVC-P, these paper present old ponds were the geomembrane is exposed to UV and to different chemical solution.

2 AGEING OF PLASTICIZED PVC

This has being already developed in a lot of papers. We only recall the main points and the related aspects to be observed on site.

Plasticized PVC is a mixture of the following components: PVC resin (rigid product, chemically very resistant).

Resins are characterized by "Kwert" value. High value indicates high mechanical properties and a good creep behavior, but may become difficult to weld for to high value. With to low value, we could observe important creep of the product on long slopes.

Plasticizer (giving the flexibility to the final product). Lubricants, to avoid that the product stick to device during processing. Stabilizers, to avoid thermal decomposition of PVC during processing or welding.

UV protection: carbon black (giving dark color to the membrane) and/or titan dioxide (giving light color to the membrane and reducing the geomembrane temperature, during sun exposure).

Chalk is also added to reduce the cost of the membrane. It increases the specific mass, (without chalk, 1.24 to 1.26 g/cm^3 passing to 1.29 to 1.34 g/cm^3 and more with chalk). Chalk increases the porosity of the membrane and is sensitive to acidic products. But it improves the fire resistance, if needed.

Aging of plasticized PVC is due to 2 possible mechanism:

Loss of plasticizer

Degradation of PVC resin.

2.1 *Degradation of PVC resin*

It occurs essentially by high temperature mainly during processing (and welding, if excessive temperature is used). Degradation may produce HCl, this improving the degradation; Therefore, thermal stabilizers are added into the formula to protect the product during processing and welding. A residual stabilization is needed to protect the geomembrane during its life and sun exposure. But the consumption of stabilizer, for temperatures less than 90°C, is very slow and an efficient protection for very long time is very easy to realize (but with some additional cost, because stabilizers are expansive). The remaining thermal stabilization may be checked by test of residual thermal stability. Micro-cracks appear on the surface of geomembrane in case of insufficient thermal stability.

In the beginning, micro-cracks are only superficial and the geomembrane may still live some years after they appear. But the product is more brittle (by stress concentration) and the surface with micro-cracks become difficult to weld (the lower face is still easy to weld)

Normally, for well-formulated PVC geomembrane, such phenomena don't appear.

2.2 *Loss of plasticizer.*

This is the most common way of aging for plasticized PVC. The initial plasticizer content is about 33 % in weight of the geomembrane (for well-plasticized formulas). The loss of plasticizer induces an increase of rigidity, easily detected by increase of modulus in tensile test. In the same test, we observe also a decreasing of the strain at the failure and increasing of the stress at the failure; but it is less sensitive than the modulus.

During the same time, low temperature brittleness increase, from about – 35°C to 0°C or more. In case of shock, "star" failures are visible on the geomembrane, at each important impact.

Simultaneously, an isotropic shrinkage, due to the loss of volume, is observed.

The loss of plasticizer is according to Fick law: if you change the thickness of a geomembrane with given formula, the time to obtain the same loss of plasticizer varies like the square of the thickness. (In our company, we are often using a linear model, to extrapolate result of test for warranty purpose. This is pessimistic, but give a supplementary security, to take in account unexpected chemical contact, lack of maintenance, etc).

From one formula to another, durability may change considerably, from 1 or 2 years for wrong and cheap formulas, to more than 20 years. This may be explained by:

- Maladjusted plasticizer.

- Poor stabilization.
- Poor UV protection.
- Excess of chalk.
- Poor quality of raw materials. Use of recycled and regenerated products: in this case, the formula may be not constant, and even unknown, and includes resins already degraded.

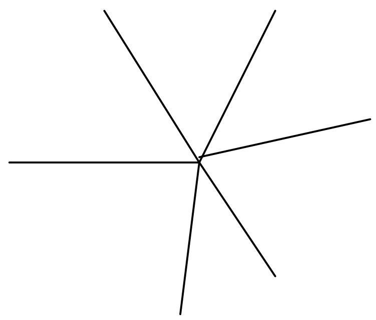

Figure 1: Star failure of PVC geomembrane, indicating brittle behavior.

Very often, the published papers are concerning pathology, because pathologies the base of new improvements, either in technique or in quality system. But this may give, at the end, a wrong image of the reality. We often heard that "PVC doesn't resist to UV. The following case histories demonstrate that correctly formulated PVC geomembranes have long time life for UV exposure.

3 MANURE PIG POND OF MARCAY (FRANCE) 1981/1982

This pond is situated in Vienne department, 100 km to the south of Loire River, to store the manure of a pigsty. A first pond was built in December 1981 and January 1982.
- Area of geomembrane: 2000 m²
- Depth of the pond: 6 meters
- Slopes: 1.5 (horizontal) / 1 (vertical)
- Geomembrane: PVC ALKORPLAN® 1 mm thick, light grey color.

The installation is done in a cheap way, generally used in this time for such works. Earthworks were without particular care and the surface of the supporting layer was not compacted. Geomembrane is laid directly on the soil, without geotextile. The prefabricated panels are rectangular, with all welding parallel. Prefabrication welding is done with hot wedge device. The 2 or 3 panels used for the pond are assembled on site parallel and welded with hot air manual device. Geomembrane in excess in corners is simply folded. Due to this method, weldings are horizontal on 2 slopes. For PVC geomembrane this is without consequence, if welding is correctly done. This material is relaxing partially its stress, but keep a residual resistance, and we never observe an opening of welding, if initial value of peeling was acceptable.

Examination of the pond in 1999 and 2000 shows that behavior of geomembrane is still excellent:
- No micro-cracks visible on the surface of the membrane.
- No perforation nor brittle failure (no star failure).
- Good behavior of horizontal weldings on the slopes.
- Good behavior of the geomembrane under permanent elongation, on irregular area of the support.

No important shrinkage, even during the visit in January 1999, where the temperature was about 0°C (see pictures below)

Figure 2: Marcay manure pig pond; view after 18 years

Figure 3: Marcay Pond (1981/1982); irregularities of supporting layer

The figure 2 shows a general view of the site, horizontal welding on slopes (we see the welding on the top of slope) and the fold in the corner. The figure 3 shows the pond in the opposite direction and irregularities of supporting layer, without damage for the geomembrane

4 PREFONTAINE POND (FRANCE) 1982

This pond was initially built for a sugar factory in Corbeilles en Gâtinais, in July and August 1982. To far from the factory, he is used now for irrigation. Its characteristics are:

- Area of geomembrane: about 40 000 m²
- Depth of the pond: 6.5 meters
- Slopes: 2.2 (horizontal) / 1 (vertical)
- Geomembrane: PVC 1 mm thick, black.

The pond is partially excavated in limestone. Perimetral embankment is done with the excavated limestone. Supporting layer is:

- on the bottom: compacted limestone and thin sand layer (average thickness 4 cm), without geotextile;
- on the slopes: sand layer 10 to 20 cm thick and a non woven polyester needle punched geotextile 300 g/m²

Figure 4 Préfontaine PVC 1mm thick 40000 m² 1982; view after 18 years

One of the authors was in this time working in CEMAGREF and in charge of the control of the intallation of this membrane. Some information about this work and this control was published (Fayoux, 1983). The main problem during the construction was a poor quality of welding of prefabricated panels, done by hot wedge device. Due to the necessity to finish the pond before 12 September, beginning of the sugar production, it was not possible to return the panels to prefabrication site. We were obliged to control each welding and to reinforce the weakest. Unfortunately we didn't had any tensile machine to assess the peeling resistance. But some of them were very easily peeled with hand and surely the peel resistance was in some part, less than 2 N/mm. Normally, such poor area were reinforced, but it was difficult to see all weak area and impossible to make a new time the totality of welding.

Examination of the pond in September 1999 shows the good behavior of the geomembrane:


Figure 5: Préfontaine 1982 general view; note the irregular support


Figure 6: Préfontaines, detail of access ramp; note horizontal welding (right)

– No micro-cracks visible on the surface of the membrane.
– No perforation nor brittle failure (no star failure).
– Good behavior of horizontal weldings on the slopes.
– Good behavior of the geomembrane under permanent elongation, on irregular area of the support.
– No important shrinkage.

We note on the figure 5 some irregularities of the supporting layer, due to stones through the sand layer. Horizontal welding is visible on figure 6. And figure 7 shows heavy puncturing due to stones below the geomembrane and the very good resistance of the PVC geomembrane for this kind of stress.

In spite of the poor initial quality of welding, we only find 2 openings of welding, one 5 cm length, the second two meters length. This must be repair in the same time we will take a sample

Figure 7: Préfontaine: note heavy puncturing due to stones below the geomembrane, without failure after 18 years.

5 LEACHATE POND, SAINT GEORGES LES BAILLARGEAUX, FRANCE

This pond was dedicated to collect leachate of municipal solid waste. Built in 1982, he was remove in 1992, to extend the waste disposal. We profit of this opportunity to take samples and to assess the behavior of the geomembrane in contact with leachate or exposed to UV. Results were published in Sardinia (Fayoux and Al. 1993). Its characteristics are:

- Area of geomembrane: 500 m²
- Depth of the pond: 1.8 meters
- Slopes: 1.5 (horizontal) / 1 (vertical)
- Geomembrane: PVC 1 mm thick, light grey color.

Geomembrane was directly laid on a compacted clay layer, 1 meter thick, without geotextile.

Tests were carried out on samples removed in 1992, and also on an A4 format sample kept away from light by the manufacturer since 1982. These tests have also been compared with initial characteristics determined in 1982 by the manufacturer during production. Unfortunately, these initial tests were performed according to a different procedure (DIN test) than the test used in 1992 (NFP 84501. This gives a higher dispersion on failure characteristics, but modulus at 5 % is quite the same).

Analyses demonstrate clearly that the area most affected by UV is on the top of the slopes, particularly horizontal area and the waves zone were the geomembrane receive simultaneously leachate contact and UV exposure.

After ten years, and for the most UV exposed area, the plasticizer content pass from 33.6 % (percentage of the total weight of the geomembrane) to 24 % (the initial percentage includes about 1 % of more volatile products used for the processing, like lubricants. Consequently, the kinetic must be determined with an initial value of 32.6 %)

Even with this level of plasticizer content, the stress and elongation at failure show little change and no correlation with the initial modulus and therefore no correlation with the location in the pond. But the modulus at 5 % of elongation is very sensitive to the modification of plasticizer content. It vary from about 20 MPa form the initial value, to 53 to 121 MPa after exposure to UV, depending on the position on the slope (70 MPa on the top, 53 MPa at 40 cm above the bottom with UV exposure about 6 to 9 months a year).

Table 1: St Georges. Properties of PVC geomembrane

	Plasticizer content	Stress at failure (MPa)		Elongation at failure (%)		Modulus at 5 % elongation	
		L	T	L	T	L	T
Initial test (DIN)		21.3	20.4	319	328	20.0	18.6
Test on check sample A4 (NFP)	33.6	15.5	15.4	252	277	20.8	18.5
Bottom	22.9	17.9	16.8	252	243	32	
Slope		16 to 19.9		125 (1 value) to 256			
Top	24.2					70	
Waves zone	24.0					121	
Middle (40 cm above bottom)	27.3					53	

Another test was used by the central research laboratory of Solvay, using the energy absorbed by the geomembrane during passage of a falling mass through the geomembrane. Characteristics of the mass are:

- Weight: 2.1 kg
- Impact extremity: hemisphere, diameter 12,5 mm
- Height of fall: 1 meter
- Sample is fixed on a circle diameter 25 mm
- Failure energy is determined in J/mm of thickness of geomembrane, using accelerometer in the falling mass.

Test was carried out for a temperature of 0°C without significant change in the properties (values are between 6.3 and 5.4 for plasticizer content between 29.9 and 24). But if the membrane become brittle or present micro-cracks, failure energy decrease strongly. This was not the case here. All failures were ductile, meaning that geomembrane is not becoming brittle.

6 BARLOVENTO RESERVOIR (CANARIES ISLANDS, SPAIN)

6.1 *Location, history and characteristics*

This reservoir is located on La Palma Island (Canaries Islands), close to the sea and at an altitude of 700 m. It is used for irrigation. This work was built between October 1971 and October 1975 and waterproofed with compacted clay, with following characteristics.

- Stored volume: 5,500,000 m^3
- Maximal depth: 37 m (30 m for the slopes and 7 m more, in the bottom, due to the slope of the bottom of about 5%).

The reservoir was initially waterproofed with compacted clay, without success. In spite of very good laboratory tests results concerning the watertightness of the clay, the leakage was too high for the use of the work. It is to note that such problems are very often mentioned in the bibliography; but here, due to the properties of the volcanic clay, inducing very deep cracks, the problem was particularly important. After a lot of test and trials, either in laboratory or on site, the Administration decided on a rehabilitation of the work with a geomembrane. For economical considerations, an unprotected membrane was chosen.

The foundation of the bottom is composed of volcanic clay, presenting a high compressibility, with random insertions of basalt and, sometimes, collapsing soils. The expected settlements are about 1 m (total and/or differential settlement). PVC geomembrane was chosen, due to its high capacity of elongation.

To limit the settlements to this value and to avoid the risk of collapse of sensitive soils, the Administration decided to limit the maximal depth of water to 27 m. Taking in account that the lower point of the bottom is 7 m below the toe of the slopes, the geomembrane covered only the lower 2/3 of the slopes (20 m, measured vertically). Moreover, the water level will be increased slowly, and following the results of the monitoring. This consists of:

- Settlement gauges
- Piezometers (cells)
- Control of the flow rate of the drains
- The general characteristics of the flexible lining system are:
- Surface: 250,000 m^2 (bottom: 80,000 m^2; slopes: 170,000 m^2).
- Maximal depth: 27 m (slopes are not totally covered)
- Geomembrane: PVC 1.5 mm thick, not reinforced on the bottom and reinforced on the slopes.
- The Servicio Hydraulico de las Canarias supervise the project.

6.2 *General design*

6.2.1 *Bottom of the reservoir*

- compacted clay
- spunbonded geotextile of PP, 500 g/m^2, coated with bitumen emulsion, to respect the filters conditions related to the material of the supporting layer.
- draining layer, 0.40 m thick. Theoretical granulometry: 8/40 mm. But practically, it was not possible to find enough of such material on the island and most of the draining layer is constituted with material 8/100, sometimes more. Thus, the surface of this layer is improved with material 8/20, applied manually. A network of drainpipes completes the draining layer.
- spunbonded geotextile of PP, 500 g/m^2. (thicker than initially determined, taking into account the change of the granulometry).

- layer of compactable sand 0/6 mm, 0.1 m thick.
- spunbonded geotextile of PP, 280 g/m²
- PVC not reinforced geomembrane, 1.5 mm thick.

6.2.2 *Slopes*

- slope: 2.75/1
- vertical high covered with geomembrane: 20 m
- length of the slopes: 60 m
- draining layer of porous concrete, installed on an adjusted and compacted slope
- spunbonded geotextile of PP, 500 g/m²
- reinforced geomembrane, 1.5 mm thick.

6.2.3 *Anchorings*

The geomembrane is anchored on the top, the toe, and in 3 or 4 anchoring trenches on the slopes. A drainage system is put upstream of those anchoring trenches, to evacuate water due to condensation or leakage. Thus, the anchoring trenches have a longitudinal slope of 1% to force the water to an exit point. The distances between anchoring trenches increase from the top to the toe and are respectively: 14.10 m, 15.20 m, and 18.80 m.

6.3 *Installation of the geomembrane*

The geotextiles, in all the work, are systematically joined by sewing.

The geomembrane is prefabricated in rolls of 6 x 70 m. Welding is usually done by automatic hot wedge devices, and, for details, hot air manual devices.

Geomembrane is cut at each intermediate anchoring and horizontally welded on a reinforced membrane buried in the anchoring trench. The upper membrane is welded on the lower at the same level. In case of wind, welding is working in tensile and peeling mode.

The installation of the geomembrane was done between July 1991 and November 1991, and between August 1992 and November 1992. The timing was not determined by the installation of the geomembrane, but imposed by the rate of production of the material for the supporting layer. In November 1991, the geomembrane was installed on 90% of the slopes and half of the bottom.

The reservoir was filed very slowly, due to the distribution of the rainfall and slopes stay along time exposed to UV.

6.4 *Long term behavior of the geomembrane*

A storm with wind speed of about 160 km/h, had no effect on horizontal welding of anchoring.
Like other irrigation ponds in Canaries islands, this reservoir is under a permanent control of the local administration (BALTEN). This Administration is picking regularly samples to assess the evolution of mechanical properties and plasticizer content.

Some results were recently published (Blanco and Aguiar, 2000). Conclusions are that "the geomembrane of Barlovento Reservoir, even taking in account the relatively recent installation (9 years), presents characteristics qualified as excellent."

Unfortunately, it was no numeric value published in this paper and we are expecting to get those numeric values and authorization to publish them or make the oral presentation during the Conference.

7 WELDING ON OLD PVC GEOMEMBRANE (BELGIUM)

Even after several years of exposure a PVC-P geomembrane is still easy to weld.

We had the opportunity to evaluate the weldability because plans where made for the extension of an existing reservoir. The reservoir was located in the middle part of Belgium. The design of the

Figure 8: Barlovento Reservoir; Canaries Island PVC geomembrane 1.5 mm, 1991

reservoir was classic, compacted sand with drainage tubes and a PVC geomembrane 1 mm thick. The angle of the slopes was 2.5/1 and the membrane was secured against wind uplift trough an anchoring trench 40x40 cm, in this part a PES geotextile of 300 g/m² was put underneath the geomembrane. The reservoir was made in 1988 and the first study to enlarge the reservoir was carried out in 1995.

After cleaning of the geomembrane with water and soap we removed the last traces of dirt with a cleaner based on trichloroethylene. The tests where carry out with a hand welding machine type Leister Triac. We choose this method because hand welding is more difficult to perform and on site there are always places that can only be waterproofed with hand welding.

In 1995 the owner decided that the enlargement would not satisfy his further needs and he decided to construct a new reservoir. However in 1999 he came back with the demand for enlargement and this time it was also realized. We obtain following results in peeling tests, according DIN 16726 5.7:

- Reference: average peeling value: 7.4 N/mm
- Sample 1995: average peeling value: 6.4 N/mm
- Sample 1999: average peeling value: 5.6 N/mm

In the recent technical guide for reservoirs in France we find a specification of 3.5 N/mm. Results of welding test on a PVC geomembrane 11 year old prove that even with manual welding, we obtain high and secure value for the bonding.

8 CONCLUSIONS

Those case histories demonstrate clearly that correctly formulated PVC geomembranes are able to resist a very long time to direct UV exposure. This is not a surprise; Cazzuffi as published often on PVC geomembranes used to waterproof dams, and still performing after more than 20 years.

We observe also other interesting properties in the long-term behavior of PVC geomembranes:

- Horizontal welding on slopes resists without problems, even in case of storm.
- The geomembrane resist to high elongation and heavy puncturing, even associated to UV and stay waterproof under this kind of action even after 18 years.

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