

Reinforcements made of polyvinyl alcohol yarns: Effect of wet/dry cycles and consequences on the design

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ABSTRACT:

Currently, most of geosynthetics used for soil reinforcements have application limits, sometimes because of chemically aggressive soils (lime or cement treated soils for example), sometimes due to creep elongation. In particular, it is difficult to conciliate in the same time long term mechanical performance and chemical durability in these harsh environments. Polyvinyl alcohol (PVA-L) used in high-tenacity yarns manufacturing is not degraded in any typical environment encountered in practice, from very alkaline to acidic media, and presents good creep and creep-rupture characteristics, comparable to those of high tenacity polyester (HTPET). But the chemical structure of this polymer suggests an affinity of PVA-L macromolecules with water, leading to its swelling even at ambient temperature. We have recently studied the PVA-L behavior in humid and dry conditions under constant tension to evaluate its possible use in the reinforcement of Mechanically Stabilized Earth like Reinforced Earth walls. PVA-L fibers used in geotextile manufacturing have to stand an essentially constant tension. So we performed a singular mechanical test where PVA-L yarn is subjected to a constant load until stabilization of the creep elongation, then to regular humid/dry cycles to simulate water cycle into soil. The humid/dry cycle, realized on 3 different type of PVA-L, showed a sensitivity of the yarn to water, that leads to a relative elongation of the yarn. The impact of water affinity is appreciable and we suggest a method for taking this behavior into account in the design calculation of structures in which PVA-L reinforcements are used.

1 INTRODUCTION

Poly(vinyl alcohol) (or PVA-L), used in the manufacturing of high tenacity fibers, is a polymer known for its excellent resistance in a wide variety of environments, from strongly alkaline to acidic environments. This material shows characteristics in creep-rupture quite comparable to those of high tenacity polyester fibers widely used in geosynthetic reinforcements. But the chemical structure of this material suggests an affinity of the PVA-L macromolecules with water, leading to its swelling at room temperature (L. Bourrier, 1978).

- The *molecular weight* or intrinsic viscosity, which is high concerning almost all high tenacity fibers. It does not affect the environmental sensitivity (moisture, pH, etc.) of PVA-L.
- The *hydrolysis rate* that is to say the alcohol function ratio inside the polymer. It leads to the affinity of the macromolecules with water. The polymer can absorb a relatively high quantity of water that modifies its mechanical properties. This affinity depends only on the alcohol content in the polymer.

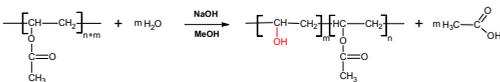


Figure 1: Polyvinyl acetate (PVA-C) hydrolysis giving polyvinyl alcohol (PVA-L) resin, with $m \gg n$ for PVA-L

This polymer is obtained by the alkaline hydrolysis of polyvinyl acetate (PVA-C, see figure 1). Its macroscopic properties depend on two chemical parameters:

Partial hydrolysis of PVA-C (~ 88% of alcohol functions) confers on the obtain PVA-L a high solubility in water. On the contrary, total hydrolysis (~ 98%) leads to the polymer insolubility in water. Water solubility decreases beyond 88% of hydrolysis because intermolecular interactions by hydrogen bonding are more important than hydroxyl function/water bond (see figure 2).

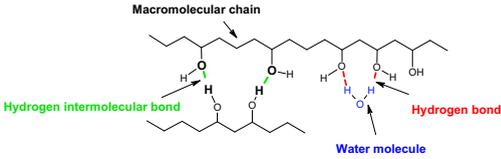


Figure 2: Scheme of water/PVA-L and intermolecular interactions by hydrogen bonding

PVA-L used in high tenacity fibers for geosynthetics manufacturing has a low affinity for water since their hydroxyl content is higher than 90%. In addition, the fiber surface is generally chemically modified by crosslinking or simple surface modification (decrease of alcohol content at its surface) during processing to limit water absorption and effect on the yarn long-term mechanical properties. So the yarn is not soluble and has a limited (but not inexistent) affinity with water.

The strong point of PVA-L is its excellent resistance to acidic and alkaline media. The polymer has no brittle bond and the effect of high and low pH is extremely limited. It can be compared to the chemical resistance of polyethylene. In addition, high tenacity fibers have a high orientation (in the direction of drawing processing) and a high crystallinity, which decreases the water diffusion into the material.

In this study, we have considered the affinity of PVA-L with water – even limited by chemical modification and drawing – and the consequences on its mechanical behavior in soil reinforcement.

2 MATERIALS AND PROCESS

2.1 Materials

We have tested in this study 3 different sources of PVA-L fibers and one PET for the purpose of comparison. Their properties are detailed in table 1.

Table 1: Properties of studied fibers

Polymer	Density (dTex)	Max. Strength (N)	Elongation at break (%)
PET	1440	108	13.4
PVA_1	1330	90	6.5
PVA_2	2000	123	6.6
PVA_3	1800	130	6.5

For all PVA-L fibers included in our tests, the degree of hydrolysis as defined above is about 98%. It is important to note that PET has a very low affinity with water, so the diffusion of water molecules into the fiber is extremely low and limited.

2.2 Wet/dry cycles

Fibers used in the manufacturing of geotextiles have to support a relatively constant tension in Mechanically Stabilized Earth applications. So, in this test, we have studied the behavior of PVA-L fibers in simulated constant tension and alternated humid/dry conditions.

The mechanical test has been performed in two steps:

- First, the sample is submitted to creep under a constant load (30% of the short time strength obtained by tensile tests) during four days, until the relative stabilization of the measured elongation
- Then, the constant load is maintained and the sample is exposed to regular humid/dry cycles as it can be anticipated for soil reinforcements.

The duration of humid and dry environment have been predetermined by sorption/desorption tests. Each sample has been exposed to water for 24 hours and then to dry conditions for 15 hours.

The test was performed on a tensile test machine, in such a way that the tension applied could never be lower than the desired level (the yarn is further elongated any time the tension tends to reduce). But shrinkage is not permitted and in this case the tension can increase. We consider that this behavior is the one which corresponds to the behavior of a fiber in an MSE structure: the reinforcement will elongate to keep the required tension, but will not shorten – its tension will increase if necessary.

Thus, this testing procedure can be characterized by two simultaneous solicitations, one mechanical and the other environmental.

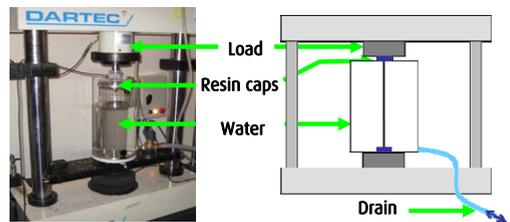


Figure 3: Measurement process used in humid/dry cycles tests

The tests have been performed in a tempered room to create a constant dry environment. The relative humidity is 50% ($\pm 5\%$) and the temperature 21°C, maintained during the 20 days of the test.

During the test, the sample is maintained by its ends with epoxy resin caps clipped in the jaws. This is to prevent it from slipping during the mechanical solicitation. The stiffness of the resin has been chosen

in order to avoid physical interference during the mechanical test.

The mechanical testing machine is instrumented by a 50daN ± 0.01 daN charge sensor. The control in displacement is insured by a LVDT captor of ± 50 mm maximum displacement. A testing program has been established under TEMATEST environment to reproduce the specificities of the test described above.

The water movements linked to the water drain off have been measured and have no influence on the measurements.

3 RESULTS & DISCUSSION

3.1 Water affinity

PVA-L yarns show a water affinity than can lead to a slight increase of their elongation under constant loading.

It modifies the balance of tension between different yarns locally submitted to the same elongation in the structure. This leads to redistribution of the tensions between wet and dry yarns, as it is not possible to ensure that all yarns will be simultaneously wet. Dry yarns will be submitted to a higher tension than wet yarns, all being locally submitted to the same elongation.

It is possible to take this into account in the justification of the structure long term stability by introducing a new reduction factor called RF_{wa} .

To determine the impact of additional elongation in presence of water, a campaign of creep tests under cyclic humid and dry conditions has been carried out.

All along the tests, a minimum tension of 33% of their maximal short-time strength (determined beforehand) is applied on the yarns. The first part of the test is similar to a creep test, in dry conditions. The following figure 4 presents the results obtained.

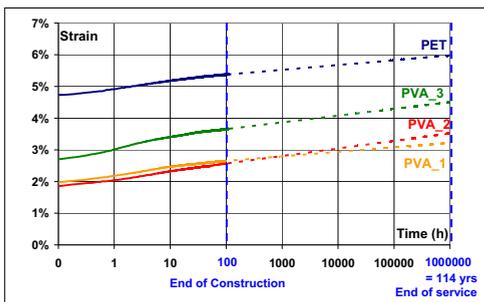


Figure 4: Creep curves of PET and PVA-L fibers, under 30% of their short-term strength (logarithmic curves)

We observe a difference in the initial strain between PVA and PET. The elongation of PET under mechanical solicitation is more important because the intermolecular cohesion is weaker in the case of PET. So the sliding of its molecular chains under mechanical solicitation is easier. But globally, the behavior of all fibers under creep test is very similar.

The second part of the study is the modification of the fiber environment by the application of humid/dry cycles as explained above. The following figures 5 to 8 present the results obtained (blue dotted lines correspond to ϵ_0 the initial strain after creep tests presented in figure 4). Zones colored in blue correspond to humid conditions, where the fiber is totally immersed into water.

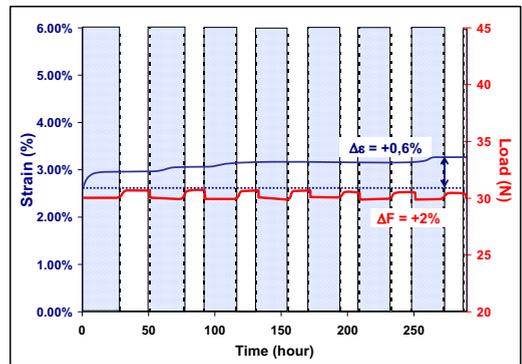


Figure 5: Evolution of strain (blue curve) and load (red curve) for PVA_1 after several humid/dry cycles

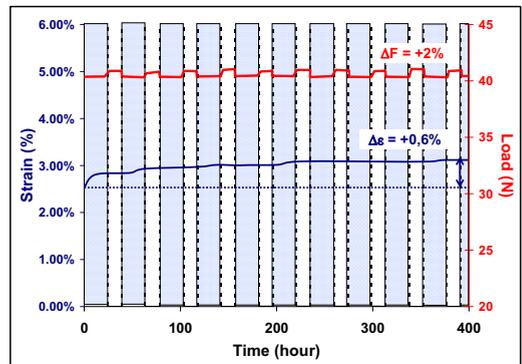


Figure 6: Evolution of strain (blue curve) and load (red curve) for PVA_2 after several humid/dry cycles

The polymers are sensitive to the presence of water. The 3 PVA-L fibers (figures 5 to 7) show an increase of their elongation under humid conditions more important than PET fiber (figure 8).

In addition, PVA-L exhibits a lower elongation under dry conditions compared to PET, so the relative elongation of PVA-L is more significant.

The relative strain measured during wet/dry cycles (figure 5 to 8) corresponds to additional elongation in comparison with the initial elongation of the fiber after creep test.

- PET: $\Delta\varepsilon/\varepsilon_0 = 3.7\%$
- PVA_1: $\Delta\varepsilon/\varepsilon_0 = 22.6\%$
- PVA_2: $\Delta\varepsilon/\varepsilon_0 = 23.4\%$
- PVA_3: $\Delta\varepsilon/\varepsilon_0 = 13.7\%$

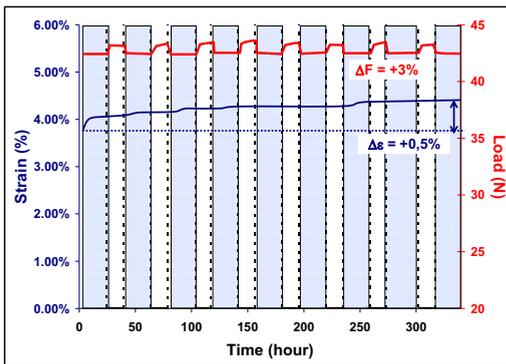


Figure 7: Evolution of strain (blue curve) and load (red curve) for PVA_3 after several humid/dry cycles

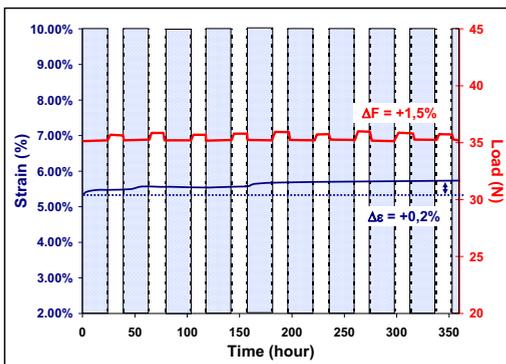


Figure 8: Evolution of strain (blue curve) and load (red curve) for PET after several humid/dry cycles

The additional elongation measured for PET corresponds to the effect of plasticizing generated by limited water diffusion into the material. In the case of PVA-L, the observed fact is that plasticizing is much more important as the mobility of water molecules in the fiber is easier because of their affinity with the polymer.

Concerning the evolution of the applied load, we observe that during the fiber drying an extra tension of

about 2% (compared to the initial applied load) is measured for PVA_1 and PVA_2 fibers. In the case of PVA_3, the extra tension is about 3%, that is to say a more important effect of drying on this material compared to the others. That can be due to a slight difference in the surface treatment of these fibers or to their process of production. The extra tension is slightly lower for PET fiber, about 1.5%. It means that during drying the loss of humidity induces shrinkage, a volume variation inside the fiber. According to the previous observations, and thanks to the information that we have concerning the chemical and crystalline structure of the studied fibers, we propose the following interpretation:

- In contact with water, the fiber swells due to the diffusion of water. The PVA-L macromolecules are more movable since the distance between them increases due to the presence of water molecules and/or clusters. The material elongates under the effect of load until a threshold strain. This limit of elongation is reached after several humid/dry cycles, at ambient temperature. This phenomenon is known and its mechanism identified in the case of hydrophilic materials, which is the case of the studied PVA-L.

- When the material dries, the free volume existing between molecules is reduced; the chains get closer since water molecules have diffused out of the fiber. The tension under load increases. Then, the material relaxes (the chains slide slowly to decrease the pressure between wet and dry zones) and the applied load on the fiber decreases very slowly. This phenomenon is similar to shrinkage; it is obviously reversible (J. Verdu *et al.*, 1984)

The mechanisms of water retaken and drying detailed previously do not change with temperature. Indeed, if the material stays at its vitreous state (temperature inferior to glass transition temperature which is about 90°C for high tenacity PVA-L), then the molecules have a constant and limited mobility, whatever the considered temperature under this limit. The diffusion of water molecules is governed here by the mobility of polymeric chains and not by the diffusion of water molecules (considering the crystalline structure of high tenacity fibers).

3.2 Consequences for our application

In most of common applications, we can admit without difficulty that soil reinforcement elongate of additional 0.6% when it is wet for the first time, if this is compatible with the associated technology (facing elements in particular). This humidification would take place rather early in the life of the structure, most probably during the construction stage when the reinforcements are placed in the fill and

their sheathing, if any, might be damaged during compaction, in contact with a soil which water content must be compatible with the objective of densification under the effect of compaction.

However, this homogeneous humidification of all fibers of a same product in the same zone is not probable (same horizontal level, parallel and relatively close fibers so subjected to the same elongation). Thus, we have to consider that a number of PVA-L fibers are subjected to humidification inside the structure while others are still dry, because they are protected by a coating for example or by their particular position in the embankment. In this case, under constant load, a part of the wet fibers will relax while dry fibers will be subjected to an additional tension.

We propose here a simple method to determine the effect of PVA-L water affinity on several fibers packed together as it is the case in soil reinforcement.

To simplify the analysis, we suppose that geosynthetic reinforcements based on HTPVA-L fibers, have the following characteristics:

- Parallel fibers, oriented in the direction of the axial load
- Identical fibers (same chemical structure and surface modification), with a perfect match in their load/elongation curve in the solicitation zone
- Isotension of the fibers during manufacturing.

Considering the results obtained in the tests, we can characterize the behavior of the product by 2 stiffnesses:

- a stiffness in “dry” condition, before humidification J_d
- a stiffness in “wet” condition” J_w

It is important to distinguish those 2 states because wet fibers have different mechanical behavior compared to dry fiber (maximal strength of wet fiber is 10% less important than dry fiber). Elongation is the same for both dry and wet yarns.

Then, the relationship load/elongation of the product is linked to these 2 stiffnesses and to the proportion ρ_d of dry fibers ($0 \leq \rho_d \leq 100\%$):

$$T = [\rho_d J_d + (1 - \rho_d) J_w] \varepsilon$$

With ε = elongation (%) and T = load (N)
 Dry fibers are clearly more tensioned than wet fibers. So there are 2 limits that can be considered in the analysis of the strength of the product:

- a) dry fibers shall not go beyond their maximal strength R_d
- b) dry fibers are neglected and wet fibers shall not go beyond their maximal strength R_w

Condition a) brings to the following equations

$$\varepsilon_{\max;a} = \frac{R_d}{J_d} \quad \text{Hence} \quad R_a = \left[\left(1 - \frac{J_w}{J_d} \right) \rho_d + \frac{J_w}{J_d} \right] R_d$$

Condition b) brings to the following equation

$$\varepsilon_{\max;b} = \frac{R_w}{J_w} \quad \text{and} \quad T = (1 - \rho_d) J_w \varepsilon$$

hence $R_b = (1 - \rho_d) R_w$

It is enough that condition a) or b) be verified:

$$T \leq R_d \cdot \max \left(\left(1 - \frac{J_w}{J_d} \right) \rho_d + \frac{J_w}{J_d}; (1 - \rho_d) \alpha \right)$$

where α is the ratio between dry fibers strength and wet fibers strength, that is to say 0.9, whatever the proportion ρ_s of dry fibers (which have never been wet) since the latter is not known by advance and will necessarily fluctuate by decreasing with time. The graph 10 below presents the obtained results.

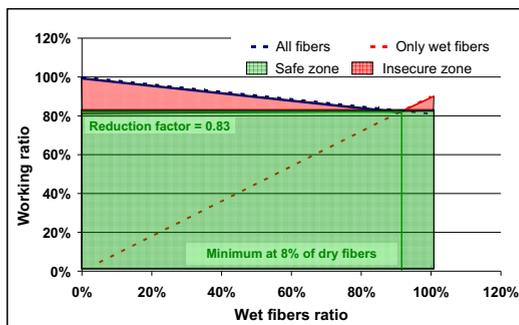


Figure 9: Stability zone – working ratio vs wet fibers ratio

In the previous case, PVA_1 and PVA_2, we have at 30% of their short-time strength, which is a typical working load ratio :

$$\frac{J_w}{J_d} = 0,81$$

The critical proportion of dry fibers is 8% and the reduction factor which should be applied to the resistance is **0.83** (multiplying factor as in the logic of reduction factors introduced in ISO TR 20432). This reduction factor is not dependent on temperature until the polymer glass temperature (~80°C). It has to be considered in addition to installation damage effects and creep-rupture. On the other hand, no reduction factor for chemical degradation needs to be considered in the justification on MSE structures reinforced with PVA-L fibers.

4 CONCLUSION

The tests developed for this specific material were used to answer a question that seemed to be ignored so far, which is the affinity of this polymer with water. The tests and their interpretation made it possible to quantify the effect that this phenomenon has on the behavior of geosynthetic reinforcement. Finally we can now propose an adaptation of the methods for the calculation of PVA-L long-term resistance. The most important is that we are now confident in the quality of the fiber of PVA-L, able to design long-term reinforcements based on PVA-L fibers and ready to implement when the project requirements dictate.

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