

# Risks and alternatives to the use of PET reinforcements in lime treated backfills

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### ABSTRACT

The increasing demand to reuse excavation materials, to use soil in place or materials with high fine contents in the construction of Mechanically Stabilized Earth (MSE) structures leads to the extensive application of soil stabilization technics such as lime, cement or fly ash treatment. Soil treatment is an economical solution to exploit poor in-situ materials that cannot be implemented in their natural state. In other words, the treatment improves the physical parameters of the soils improving its workability. However, such treatments also alter the chemical parameters of soil such as alkalinity in a durable manner. The pH will remain well above 10 for an extended period even at low rates of application. For MSE structures reinforced with PET based geosynthetic uses. It is well established that PET is only suited for soil having pH ranging from 4 to 9. In highly alkaline environment, the degradation mechanism is strongly accelerated particularly when mechanical stresses are applied on the material. Therefore, the use of PET in treated backfill is a clear risk for a structure integrity. This paper will propose an extensive review treatment technics detailing the evolution of the soil alkalinity with time, then we will provide technical data showing the performances of PET reinforcement materials when exposed to alkalinity in the conditions of reinforcement applications, finally we will propose alternative solution such as the use of PVA reinforcement material and present their performances.

### 1. INTRODUCTION

Soil stabilization is a type of treatment used to improve permanent physical and chemical alteration of soils to enhance their physical properties. The impact is the permanent modification of the shear strength, reduction of the water content, improvement of the workability, control of the shrink-swell properties therefore, improving the load-bearing capacity of the soil.

Typically, soils are treated principally with mixing the soil with a binder to improve its geomechanical properties. Binders are mainly composed of lime or cement resulting in a long-term increase of the soil alkalinity. Whether it is lime or cement the main compound impacting the mechanical and physico-chemical properties is calcium hydroxide (Ca(OH)<sub>2</sub>) (IDRRIM 2015).

For MSE structures the use of soil treatment has direct consequences on the selection of reinforcement and particularly the materials used for its construction. Indeed, MSE structures are design to perform at least 75 to 120 years depending on the codes addressed, then the materials used in those structures should be properly selected.

Looking at feedback from the field, it appears that shortcuts are often taken and products such as HT-PET yarns based reinforcements are suggested to reinforce lime-treated backfills. If this option appears economically seducing, it should be remembered that it goes explicitly against codes and is highly risky for the integrity of the structure based on chemical durability of this type of products (L. Van Schoors 2013) (V. Elias 1998).

In this paper, we will focus on lime-treatment since lime is the most common binder, introducing the requirements, mechanisms and long-term properties of the treatment in MSE structures context, emphasizing on physico-chemical changes and particularly the alkalinity built up which is governing the choice of reinforcements.

Then, we will provide a condense literature review of the HT-PET yarns hydrolysis degradation focusing on the influence of alkalinity and particularly the impact of lime on the degradation mechanism and its kinetic. Providing technical evidences that HT-PET based reinforcement are not compatible with treated backfills.

Finally, we will introduce HT-PVAI yarns, presenting some durability results obtained with this product under various conditions and demonstrating why HT-PVAI based reinforcements are the best high stiffness alternative product when construction is done with treated backfill.



## 2. PRINCIPALS OF LIME-TREATMENT FOR MSE STRUCTURES

### 2.1 Soil requirements

The addition of lime to a soil induces several chemical reactions between the soil particles and the lime. Nevertheless, some geotechnical parameters shall be satisfied to ensure an optimal process:

- The presence of fine particles: Passing at 76µm > 25%.
- The Plasticity Index (PI): PI > 10.

In addition, some chemical components that may have adverse consequences on lime treatment shall be limited (IDRRIM 2015):

- The organic matter which may consume the lime. Organic content shall not exceed 1 wt%.
- The chlorides which can accelerate the lime treatment and induce swellings through the formation of chloroaluminates. Chlorides shall not exceed 2000 ppm.
- The sulphate and sulphides in soils (in the form of gypsum or pyrite) can induce the formation of ettringite causing considerable swellings. The total soluble sulphate content shall not to exceed 3000 ppm.
- The presence of phosphates and nitrates which can slow down the curing process. They shall not exceed 1200 ppm.
- 2.2 Soil-Lime reaction

Lime includes all products manufactured from the decarbonization of calcitic or dolomitic limestone:

- Quicklime is the product from the calcination of limestone (i.e. the calcium oxide or the calcium and magnesium oxide).
- Hydrated lime is obtained from the hydration of quicklime.
- Precipitated calcium carbonate.

When mixed with soil different reactions occur following a chronological order (Figure 1).



Figure 1. Chronology of lime/soil reactions

The timescale depends on several parameters such as the lime content and soil characteristics (geotechnical identification, mineralogy ...).

Independently of the type of lime used, short-term and long-term actions of lime treatment are recognized. Short-term actions consist in soil drying and soil modification improving the workability and compaction characteristics while long-term actions consist in soil stabilization and soil carbonation improving the mechanical behavior of the soil.



## Soil Drying

When the soil is mixed with lime, immediate actions induce a reduction of the water content. The lime is a dry product and its addition to soil increases the total mixture weight whereas the water weight does not change inducing a water content decrease. When using quicklime, the presence of water in soil activates the hydration of the calcium oxide, thus consuming water. The exothermic reaction induces further water consumption through evaporation (Eq.1).

 $CaO + H_2O \rightarrow Ca(OH)_2 + Heat release$  (Eq.1)

## Soil Modification

Soil modification is a step in the stabilization process or can be achieve alone using a limited amount of lime. The so-called "lime modification optimum" (LMO) can be determine using the soil-lime pH test described in ASTM D6276 (Figure 2). Generally, the LMO lies between 1 wt% to 3 wt% and draw the line between short term and long term actions of the treatment or soil modification and soil stabilization (DigueELITE 2015).



Figure 2: Example of minimum lime content or LMO following ASTM D6276.

The soil modification mechanism is based on the flocculation process. In presence of water, hydrated lime or calcium hydroxide will ionized leading to Calcium (Ca<sup>2+</sup>) ions and Hydroxyl (OH<sup>-</sup>) ions (Eq.2)

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^{-}$$
(Eq.2)

The presence of Ca<sup>2+</sup> in great quantity induces a cation exchange with the soil particles leading to the saturation of the particles surfaces with calcium. This mechanism reduces the repulsions forces between the particles and disturbs the water adsorption mechanism. Consequently, the soil particles start agglomerating in clusters, forming larger and stronger particles (Figure 3).



Figure 3. Example of lime-treatment on a clay soil (a) and a limestone soil (b) (DigueELITE 2015)



This textural modification of the soil induces an instantaneous improvement of the treated fill physical properties. The following consequences are generally observed:

- Textural change: the fill grading curve changes there are fewer fines particles.
- Plasticity: the clayey characteristic is modified modification of the Atterberg limits, decrease of the Plasticity Index.
- Swell potential: the soil is less sensitive to swelling- significant reduction in swell potential
- Shrinkage: decrease of shrinkage potential
- Compaction characteristics: Modification of the Proctor curve (flattening of the Proctor curve). The lime treatment causes a decrease of the dry density and an increase of the optimum water content.

All these short-term improvements occur in a matter of hours after treatment and facilitate backfilling conditions during construction.

The use of soil modification as a main process, solely concerns granular or intermediate backfills that are too wet or present a high plasticity index, preventing good workability and optimal compaction conditions in their natural state. The minimal lime content for soil modification results from the immediate bearing index value to be reached by the treated soil. Table 1 gives a range of values for the type of soil (SETRA 2000).

Table 1. Immediate bearing index values

| Type of soil | Immediate bearing index value after treatment |
|--------------|---|
| Granular     | 15 to 30                                      |
| Intermediate | 7 to 15                                       |

#### Soil Stabilization

In soil stabilization, the treatment influences the long-term performances of the material. The geomechanical characteristics are modified to get a sustainable strength gain and a permanent stability.

Here, the quantity of lime added is sufficiently high (superior to the LMO) to generate long-term pozzolanic reactions between the calcium of the lime and the silica and alumina from the soil particles (Eq. 3 and 4).

$$Ca(OH)_{2} + SiO_{2} + H_{2}O \xrightarrow{pH > 12.4} Calcium Silicate Hydrate (CSH) (Eq. 3)$$

$$Ca(OH)_{2} + Al_{2}O_{3} + H_{2}O \xrightarrow{pH > 12.4} Calcium Aluminate Hydrate (CAH) (Eq. 4)$$

The pozzolanic reactions form cementitious products enhancing the shear strength and the stiffness of materials. The lime treatment progressively increases the soil cohesion but has little impact on the friction angle (G. Herrier 2013).

This stabilization process is made possible when the silica and the alumina become soluble. The solubilization only happens at elevated pH (pH > 12.4). As the lime is a strong alkaline product, the treatment increases the pH of the soil. However, to achieve a pH of 12.4 a sufficient amount lime, superior to the LMO, shall be added. Indeed, if the pozzolanic reactions do not happen (i.e. pH<12.4) the treatment will be limited to soil modification.

In order to cover the lack of homogeneity due to the mixing process, lime is always added in excess as compare to the LMO value determined to insure the durability of the treatment.

#### Carbonation reaction

Finally, carbonation reaction occurs along the life of the treated structure. Whether it was aimed for modification or stabilization, the remaining calcium hydroxide can react with the carbon dioxide present in the soil and form cementitious products. The carbonation process will further improve the cohesion strengthening the fill. Additionally, it may decrease the fill permeability by disturbing the porosity network depending on the compaction characteristics (Le Runigo 2008).



## Treatments durability

Treatment durability is particularly important when soil stabilization is expected. Indeed, stabilization significantly changes the geotechnical characteristics of the treated backfill to achieve long-term permanent strength and stability.

External factors can alter the design performance along the service life. Therefore, the durability of soil stabilization shall be considered at the formulation stage to preserve the long-term performances of the treatment. This often results in adding an excess of lime to cover the uncertainties.

Indeed, the long-term strength gain can be considered durable only when the chemical stabilization mechanism describe above remains active. This means keeping the pozzolanic reactions alive. As long as there is enough calcium hydroxide in the soil, the pH will remain sufficiently high to ensure the solubility of silica and alumina and thus the pozzolanic reaction will keep ongoing.

One of the principal impacting environmental factor is hydraulic solicitations. These can be found in hydraulic structures (dams, shore protections, river banks...) or in any structure as a result of continuous rainfalls.

The presence of water and its circulation inside a stabilized backfill can alter the long-term performances by leaching out the calcium hydroxide which ultimately will reduce the pH and alter the cementitious compounds formed. With a low pH, pozzolanic reactions are inhibited and the shear properties will start decreasing. The stabilization is no longer durable and a decrease of the backfill mechanical performance is expected.

This reduction of performance will depend on several factors:

- The lime content and its impact on the treated soil permeability. A higher lime dosage generally induces a lower soil permeability, given that the compaction requirements are respected (Le Runigo 2008), preventing the water circulation inside the treated soil.
- The mineralogy of the soil: the degree of mechanical alteration of the cementitious compounds during leaching depends on the soil microstructure. A silty soil, with rounded elements, provides protection against the cementitious phases alteration. On the opposite in a clayey soil, with micas, the cementitious phases are more impacted by the water flow. The loss of performance will be more important.

Consequently, to obtain a durable treatment in MSE structures a proper drainage management is highly recommended as it will prevent water circulation inside treated backfill (drainage, membrane at the top of the structure...). It should be noted that the drainage management is also important to avoid contaminations of adjacent areas. Indeed, soil treatment techniques use chemical additives, which can have a deleterious impact on the surrounding vegetation growth.

## Long-term properties: pH evolution

Treatment long-term properties have been the subject of numerous study. It was shown that whether the treatment is done for modification/workability or stabilization, long-term changes are observed on the soil mechanical and physico-chemical properties.

In the scope of MSE structures and the choice of reinforcement we will focus on one particular physico-chemical properties which is the evolution of the pH of the soil. Indeed, a durable pH in the soil will lead to different reinforcement choices dues to materials compatibility.

In their work, Deneele et al. (2016) have presented an accelerated leaching study aimed to compare lime-treated silty soil with 1wt% and 3wt%. They showed that the pH of these soils after a percolation protocol equivalent to about 11.5 years of heavy water circulation present durable values of 9 and 12 respectively. The non-treated soil sample keeping a constant pH value of 8.

This result confirms what has been shown in field analysis by several authors such as DeBel and al. (2013) who followed the pH evolution of a silty soil over about two years and showed that a stable pH value between 11.5 and 12 was obtained after only 112 days. We can also cite the work of C. Jung and al. (2008) who studied six structures aged of 5 to 11 years old, measuring pH values at different depth. An average pH value around 10.5 was obtain for all structures with none of the structure showing a pH lower than 9 at any depth.

All those studies demonstrate that lime-treatment impact the long-term physico-chemical characteristic of the soil and particularly its alkalinity which can be expected to present a pH>9 whether the treatment is done for modification (short-term) or stabilization (long-term). This is particularly true for MSE structure when the drainage recommendations are followed as they limit considerably the water circulation in the backfill.



#### 3. HT-PET REINFORCEMENT DURABILITY: ALKALINE ENVIRONMENT CONSIDERATIONS

It is well established that HT-PET principal degradation mechanism is hydrolysis. Polyester hydrolysis occurs following two different mechanisms depending on the exposition environment (Van Schoors 2007).

Two different environmental conditions are generally considered in MSE structures applications:

- Acid or neutral environment 1≤pH≤9.
- Alkaline environment pH>9.

In acidic or neutral environments, hydrolysis occurs under a mechanism called internal hydrolysis well described in the literature. The water molecules diffuse into the polymer matrix leading to a homogeneous degradation of the polyester chains through a random chain scission process. This mechanism induces a diminution of the mechanical performances of HT-PET yarns at a moderate rate after a considerable induction period.

In alkaline environment, the hydrolysis mechanism is radically different. The reaction is catalyzed by hydroxyl anions (OH<sup>-</sup>) which transforms the esters functions into alcohol and carboxylate ions. Carboxylate ions can then recombine with cations (such as Na<sup>+</sup>, Ca<sup>2+</sup>, ...) to form carboxylate salts.



Figure 4. PET alkaline hydrolysis

This degradation mechanism has been theorized by Elias and al. (1998) who stated that the molecular split described Figure 4 modifies the dielectric properties of the polyester surface creating a barrier which hydroxyl ions cannot penetrate. As a result, the hydrolysis intensity at the fiber surface is increased, creating shorter polymer chains which can later be dissolved in the solution, ultimately leading to a drop of the fibers diameters. This phenomenon can be assimilated to a surface erosion of the polyester fibers occurring at a very fast rate. The rate of alkaline hydrolysis is also highly depended on the type of alkaline environment as well as the type of cations present in the environment.

Figure 5 shows the results of hydrolysis exposure test carried out at 23°C and 50°C over 15 years in various solutions (K.L. Nait Ali 2009). Two alkaline compounds were used in this study sodium hydroxide and calcium hydroxide (or lime). Despite the difference of one point in pH value, it is easily noticeable that the ageing in calcium hydroxide is much faster than in sodium hydroxide. The results show that at 23°C HT-PET yarns loose about 40% of strength when exposed to saturated lime solution in only 2 years.

The fast degradation rate observed in lime is not only the result of calcium hydroxide being a very strong di-base (carrying two hydroxyl) but also to the presence of Ca<sup>2+</sup> cations which have been shown to accelerate the surface hydrolysis rate (H.F Schroeder 2000).



Figure 5. Hydrolytic degradation of PET yarns in various media (1<pH<13) at (a) 23°C and (b) 50°C over 15 years.

The results presented here, clearly show that lime or calcium hydroxide is extremely damaging for HT-PET yarns even at low temperature. Indeed, at 23°C after two years the yarn lost almost 40% its original strength.



Additionally, some authors have reported that tensile loading of HT-PET yarns further accelerates the hydrolysis rate particularly when subjected to alkaline hydrolysis due to the erosion mechanism.

Finally, given the recommended level of compaction in MSE structures HT-PET based reinforcement products, even if protected with a coating (polyethylene, PVC...), will lead to certain amount of yarns being exposed to the surrounding environment and thus to strong alkalinity. This is reminded in many standards but often undermined at the design level.

The combination of all these concluding remarks clearly highlight the fact that HT-PET reinforcement products are not adapted to lime-treated backfill and the risk involve in doing so are extremely high for the integrity of the reinforcement and ultimately for the structure.

## 4. HT-PVAL: A HIGH STIFFNESS ALTERNATIVE

#### 4.1 Durability mechanism

HT-PVAI yarns are known to degrade following an oxidation mechanism (Sakurada 1985). If the oxidation mechanism can be accelerated in acidic environments, the exposition of HT-PVAI fibers to alkaline environment has never shown considerable impact on the mechanical strength even after long time exposure at elevated temperatures (L.K. Nait Ali 2014) (Y. Bian 2018) (M. Nishiyama 2006).

Its chemical behavior associated to its high stiffness (twice as compare to HT-PET yarns) combined to a reasonable cost makes HT-PVAI reinforcement products the best alternative material for MSE structures build using treated backfills.

To fully understand the degradation mechanism of HT-PVAI yarns a durability study exposing yarns to three different solutions ( $H_2SO_4$  pH=2.4, distilled water pH=7 and sodium hydroxide pH=12) has been launched. Ageing conditions were conformed to EN 14030. In this study the tensile properties were followed as a function ageing time and the results are presented Figure 6.



Figure 6. Evolution of the retained strength at break of HT-PVAI aged yarns as a function of exposure time in  $H_2SO_4$ ,  $H_2O$  and NaOH solution.



Part of these data were presented in a previous paper (Y. Bian 2018) and here we are providing the complete results. The results clearly show that alkaline environment has no impact on the tensile properties of HT-PVAI yarns even after extended exposition period (more than 500 days) at elevated temperature. As expected, it shows that PVAI oxidation will only be accelerated when expose to strong acidic medium.

As matter of comparison we have exposed HT-PVAI yarn and HT-PET yarn to a solution of saturated lime at a temperature of 80°C for about 10 days (Figure 7). The picture clearly shows the difference in behavior between HT-PVAI and HT-PET yarn. While the HT-PET yarn is completely degraded and cannot be handle anymore, the HT-PVAI yarn shows only a little color change due to heat exposure (Y. Bian 2018), but no loss in strength as 100% of its initial strength was recovered after the exposure.

These results clearly show that HT-PVAI yarns are well suited to provide long-term performances when exposed to strong alkaline and thus compatible to be used with lime-treated backfill. Indeed, if other materials such as polyolefin based reinforcements provide a good chemical compatibility, their long-term creep performances are disadvantageous. Also, it is possible to consider aramid based reinforcement but their cost effectiveness would limit their utilization.



Figure 7. Comparison between HT-PVAI and HT-PET yarn exposed to a saturated lime solution at 80°C.

## 5. CONCLUSIONS

Often when high and long-term stiffness is required HT-PET yarns based geotextile reinforcements are preferred to other materials in MSE structure design. HT-PET yarns benefit from excellent mechanical properties, good chemical resistance (as long as pH<9) at a particularly attractive cost. Indeed, they are probably one of the most cost effective reinforcement fiber on the market.

This paper provide evidence to establish that HT-PET based reinforcement is not acceptable when designing a MSE structure with treated backfill. The literature review as well as technical data demonstrate that there is an extremely high risk of compromising the structures integrity when using this HT-PET based reinforcement, even if the products are coated for installation damage protection.

Alternatively, HT-PVAI yarns based reinforcement is suggested as the best candidate for MSE structure as it combines chemical compatibility, high stiffness and long-term mechanical performances.



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