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# Temperature and design strength of polyester-based reinforcements in retaining wall applications

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ABSTRACT: Polyester-based geosynthetic reinforcements have been used and studied for a long time now. Their ageing behaviour according to temperature is quite well known today, as long as the temperature remains constant over time. National design standards and guidelines do not give much guidance about the design temperatures, or restrict the use of explicit reduction factors to certain levels of temperature (e.g. 20°C), without explaining how to derive actual degrees according to the place, where the temperature may effectively lower or higher.

This paper summarizes a global analysis which has been made on this matter, focusing on vertical Reinforced Earth® walls, with geosynthetic reinforcements made of high-tenacity polyester and vertical concrete facing elements.

## 1 INTRODUCTION

The current national and international design standards and design guidelines generally give the engineer a design temperature for the reinforcements inside the reinforced soil structure. It is generally a single value, identical for creep rupture and hydrolysis.

However the temperature inside reinforced soil structures vary all along the day and all along the year, and thus the rate of ageing for hydrolysis and creep rupture are changing constantly. Moreover the dependency of these two phenomena to temperature is not the same. This study presents first how the variation of temperature inside the wall was assessed according to the location and the orientation. Then it presents how the ageing factors of polyester-based synthetic reinforcements were linked to temperature and time. Results from the full model are given for a retaining wall in Lyon, France.

## 2 ASSESSMENT OF TEMPERATURE VARIATIONS INSIDE THE STRUCTURE

In this analysis we are considering the case of mechanically stabilised earth (MSE) walls with vertical concrete facing, acting as retaining wall.

The first step of the work was to assess a heat transfer model for the time-step analysis of the evolution of the temperature at any location inside such a wall, from the back of the facing or from the top surface (e.g. under pavement). The model takes into account the three different types of heat transfer: diffusion, radiation and convection. According to parameters like the location of the site on Earth, the orientation of the wall, meteorological data of temperature and periods of sunshine, the model derives the daily temperature variation inside the wall for two typical days of each month in the year: one sunny day and one cloudy day.

### 2.1 *Variations of air temperature*

The values of air temperature are taken from the meteorological databases. The daily temperature variation is represented by the following expression:

$$\theta_0 = \theta_{moy} + \Delta\theta \cdot \sin(\omega + (3.665 - 0.524 \sin \times (\omega + 0.524)))$$

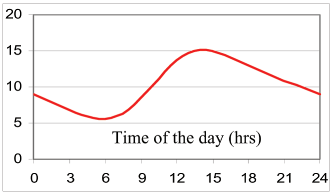

Figure 1. Daily air temperature variation. Lyon, France, month of April.

where : $\omega = \frac{2\pi h}{24}$ where $h$ the time in hours (1)

### 2.2 *Sun exposition*

The number of sunny days and cloudy days in the month is used to derive the monthly ageing factors, then added in order to assess the yearly factors.

The azimuthal orientation of the wall facing is a parameter taken into account inside the model, which includes the effect of the sun radiation during the day (Fig. 2). A complex calculation of the energy received by the wall is made, taking into account:

- The relative orientation of the facing and the Sun
- A reduction factor according to the altitude of the Sun (absorption by the atmosphere)

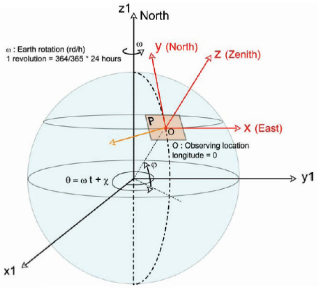

Figure 2. Assessment of the sun exposition according to location and time.

### 2.3 *Heat transfer laws*

The general heat transfer law used in the simulation is the one-dimensional expression of Fourier's equation:

$$\frac{\partial^2\theta}{\partial x^2} = \frac{1}{a} \cdot \frac{\partial\theta}{\partial t} \tag{2}$$

where $a$ is the thermal conduction capacity ($m^2/s$);

$$a = \frac{\lambda}{C\rho}$$

$\lambda$ : thermal conductivity (W/ m °C)
$C$ : specific heat (J/kg°C)
$\rho$ : density ($kg/m^3$)

The calculation is made with the help of a one-dimensional explicit finite difference approach:

$$\theta_1^{n+1} = \theta_1^n + K(\theta_0^n - 2\theta_1^n + \theta_2^n) \tag{3}$$

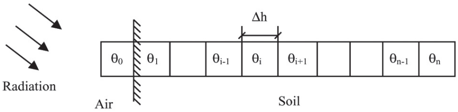

Figure 3. Sketch of the space 1d discretization.

at the time step $n$, where $\frac{a \cdot \Delta t}{\Delta h^2}$, $\Delta t$ being the time increment and $\Delta h$ the space increment.

### 2.4 *Specific case of the facing*

The solar radiation and the heat convection are additionally applied between the air temperature ($\theta_0$) and the facing temperature ($\theta_1$):

$$\theta_1^{n+1} = \theta_1^n + K(\theta_0^n - 2\theta_1^n + \theta_2^n) + \frac{\Delta t}{C\rho\Delta h}(In - Is) \tag{4}$$

where:
$In$ : power released by the solar radiation
$Is$ : convection + radiation of the facing = $Ic + Ir$

Convection : $Ic = 1.9(\theta_1 - \theta_0)^5/_4$

Radiation : $Ir = \varepsilon \cdot C \cdot (\theta_1^4 - \theta_0^4)$

### 2.5 *Boundary conditions*

A simplified "yearly" simulation is made with the assumption that the temperature at a distance of 16 m is constant, equal to the yearly average temperature. With a time step of 12 hrs, and no consideration of daily temperature variations and sun radiation, this allows to derive the variation of temperature at a distance of 3 m along the year.

The "daily" model is finer as it represents the first 3 meters from the facing. The daily model consists of 50 segments, each of them 6 cm long. The time step is set to 10 min, i.e. 240 time steps to cover a full day. Sunny days are simulated taking into account the sun radiation, whereas this factor is excluded for cloudy days.

## 3 HYDROLYSIS

### 3.1 *Hydrolysis according to temperature*

The study of the effect of temperature on the hydrolysis rate has been studied for a long time. The following expression is considered to be well representing the results of these studies for high tenacity polyester yarns used in geosynthetic products:

$$\eta = \frac{\Delta R}{R_0} = 2.8E^{-4} \cdot e^{-12500\left(\frac{1}{273+T} - \frac{1}{293}\right)} \tag{5}$$

rate of hydrolysis per year at a constant temperature $T$ in °C.

### 3.2 *Hydrolysis rate according to temperature*

The daily relative loss of strength due to hydrolysis is:

$$\eta(\text{day}) = \sum_{\text{day}} \eta(t_i) \tag{11}$$

The yearly loss of strength after the incubation time is defined as:

$$\eta(\text{year}) = \sum_{\text{month}=1}^{12} \left(n_s \cdot \eta(\text{day}_s) + n_c \cdot \eta(\text{day}_c)\right) \quad (12)$$

### 3.3 *Design temperature for hydrolysis*

After integrating the loss of strength dye to hydrolysis over one typical year, it is possible to back-calculate an equivalent constant temperature for hydrolysis. This temperature $T_{\text{hydrolysis}}$ is derived from the following expression:

$$\eta = (\text{year}) = 2.8E^{-4} \cdot e^{-12500\left(\frac{1}{273+T_{\text{hydrolysis}}} - \frac{1}{293}\right)}$$

## 4 CREEP RUPTURE

There is no such a clear relationship between temperature and creep rupture ratio as for hydrolysis. This essentially lies in the fact that creep rupture is not measured as a constant degradation of the material, but a physical limit related to the concept of time-to-rupture.

Under a constant loading ratio $R/R_0$, $R_0$ being the short term tensile strength of the reinforcement, we get from the yarn manufacturers curves giving the time $T_R$ for which rupture is expected.

For high-tenacity polyester, the relationship between $R/R_0$ and $T_R$ is generally presented in the following way:

$$\frac{R}{R_0} = \alpha - \beta \log_{10} T_R \text{ with } T_R \text{ expressed in hrs.} \quad (13)$$

In this study: $\alpha = 0.818$ and $\beta = 3.1 \cdot 10^{-2}$.

This relationship corresponds to a constant temperature, generally 23°C.

### 4.1 *Relationship to temperature*

Creep and creep rupture of polyester are a well-known phenomena. Especially the development of the Stepped Isothermal Method (SIM) for the prediction of creep rupture has led to strong results for high-tenacity polyester.

Thornton et al, 1998, and Greenwood et al, 2000, have described the method and given the correspondence between a step in temperature and the modification in time-to-rupture. The variation in temperature is linked to the time-to-rupture through a shift on the $\log_{10} Tr$ axis of the creep rupture curve.

The full relationship between load ratio, time to rupture and temperature ($\theta$ in °C, constant) is written as flows:

$$\frac{R}{R_0} = \alpha - \beta[\log(T_R) + \lambda(\theta - 23°\text{C})] \quad (14)$$

The shifting factor $\lambda$ is generally comprised between 0.10 and 0.11 for polyester, the value used in this study is 0.105.

### 4.2 *Creep rupture «ageing»*

It is necessary to define an "ageing" increment for creep rupture at each time step.

Let us consider that the load ratio is fixed, and that at the time $t_i$ the temperature is $\theta_i$. The equation (14) gives us the corresponding time-to-rupture. The ageing increment is defined as the following ratio:

$$\delta_{CR}(t_i) = \frac{\delta t}{T_R\left(\frac{R}{R_0}; \theta_i\right)}$$ which is the ratio of the time step over the time-to-rupture. (15)

The daily ageing is then computed by adding the ageing increments:

$$\delta_{CR}(\text{day}) = \sum_{\text{day}} \delta_{CR}(t_i) \quad (16)$$

The yearly creep rupture ageing is then calculated in the same way as for hydrolysis:

$$\delta_{CR}(1yr) = \sum_{\text{month}=1}^{12} \left(n_s \cdot \delta_{CR}(\text{day}_s) + n_c \cdot \delta_{CR}(\text{day}_c)\right) \quad (17)$$

The time-to-rupture taking into account the temperature variations then corresponds to:

$$T_{\text{Rupt}}\left(\frac{r}{R_0}\right) = \frac{1}{\delta_{CR}(1yr)} \text{ expressed in years.} \quad (18)$$

### 4.3 *Design temperature for creep rupture*

Converting $T_{\text{Rupt}}$ in hours and using the equation (14), we can now back-calculate the equivalent constant temperature. It is worth noting that this temperature does not depend on the load ratio chosen for the analysis. So this is the value that should be used for the design.

## 5 RESULTS

Here are the results for a virtual retaining wall with concrete facing and polyester-based reinforcing geostraps, situated in Lyon and oriented towards the West. The West orientation is for the latitude of Lyon the worst case. Table 1 gives the results obtained at the back of the 14 cm thick concrete facing. The maximum temperature reached during the year at this location is 25.9°C and the average yearly temperature is 11.5°C. Figure 5 shows the envelope of temperature in the first 1.5 m from the facing for the month of July.

## 6 CONCLUSIONS

This paper intends to propose a global study of the temperature effect on the ageing of the reinforcements

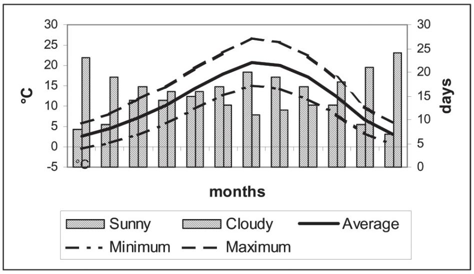

Figure 4. Typical daily temperatures according to the month and number of sunny and cloudy days.

Table 1. Equivalent constant temperature and reduction factors for hydrolysis and creep rupture 2 cm at the back of the facing elements (14 cm thick concrete panels).

| Equivalent temperature | Service life (yrs) | | | |
|---|---|---|---|---|
| | 3 | 50 | 70 | 100 |
| Hydrolysis 14.9°C | 100% | 100% | 100% | 99.7% |
| Creep rupture 15.9°C | 70.3% | 66.6% | 66.2% | 65.7% |

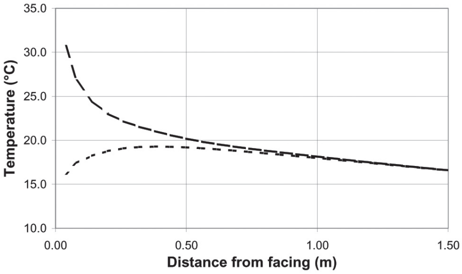

Figure 5. Minimum and maximum temperature for the month of July, in function of the distance from the facing.

in the MSE structures. The design temperature is of great influence on the reduction factors used in the design. A better assessment of the actual reduction factors will allow us to have a deeper knowledge of the actual safety level in the structures.

Of course this studywill be extended to:

- other areas,
- types of material different from PET,
- other applications, especially slopes, road sub-bases.

Sub-tropical areas are of high interest as they show elevated temperatures, as well as heavy sun exposition and strong temperature variations. The aim of a full study would be to assess design temperatures for hydrolysis and for creep rupture, using this method.

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