Geogrid reinforcement in harsh environments: their role in landfill slope veneer stability design and related performance aspects under high temperatures

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ABSTRACT
Geocomposite liners of landfill barriers may experience harsh environmental conditions such as excessive loading and/or extreme high temperatures over their design life. Landfill covers and barriers are often installed on steep slopes. Smooth geomembranes have been used for decades in such structures while textured geomembranes are often chosen to allow for greater interaction between the individual geosynthetic materials and/or between the geosynthetic and the cover soil. In the first case, due to the often low available interface friction angles, very weak inter-surfaces should be considered in the veneer stability analyses. Whereas in the second case attention must be paid to the tensile load acting on the geomembrane. In fact, as some studies have demonstrated, even small strains can cause cracks in the geomembrane.

The use of appropriate geogrid reinforcement can play a decisive role to limit the tensile load in the geomembrane and to guarantee the global stability of the entire system. The serviceability of the geogrid has to be assured during the entire design life of the structure and the geogrid may also be exposed to very high temperatures.

In this paper, a comparative study of two different geocomposite liners including a smooth geomembrane and a textured geomembrane is conducted and the role of the geogrid in both systems is assessed. When assessing the performance of geosynthetic reinforcement the long term temperature regime also has to be taken into consideration. Therefore, an extensive laboratory test campaign has been performed to investigate the performance of polyester (PET) and polyvinyl alcohol (PVA) geogrids under normal temperatures and high temperatures up to 70°C. First results have shown that PVA geogrids perform significantly better under high long term temperatures compared to PET geogrids.

1. INTRODUCTION

Modern landfills are often a multi-barrier system composed of different geosynthetic/soil liners. The overall stability of a landfill may be determined by the liner system. Geosynthetics are subjected to loads and/or extreme high temperatures over their design life (Rowe, 2005; Akpinar and Benson, 2005; Koerner and Koerner, 2006).

Geomembranes (gmb) are some of the most commonly used geosynthetics in landfill liner systems. The gmb is commonly anchored at the crest level of each slope/bench hence an increased gmb tension can lead to gmb slippage/failure, anchor failure or liner system instability (Liu and Gilbert, 2003). Smooth gmb has been used for decades in such structures while textured gmb is often chosen to allow for greater interaction between the individual geosynthetic materials and/or between the geosynthetic and the cover soil. Due to the often low available interface friction angles, very weak inter-surfaces should be considered in the veneer stability analyses. Attention must also be paid to the tensile load acting on the gmb.

The use of appropriate geogrid reinforcement can play a decisive role to limit the tensile load in the geomembrane and to guarantee the global stability of the entire system. The serviceability of the geogrid has to be assured during the entire design life of the structure and the geogrid may also be exposed to very high temperatures.

One common approach to estimate geosynthetic loads on slope is to use limit equilibrium methods (e.g. Giroud and Beech 1989; Koerner and Hwu 1991). These methods are generally good in assessing the overall stability of the slope, but as they do not consider compatibility in strains between the individual soil and geosynthetic components, it is difficult to estimate how tensile stresses will develop in an individual component (Liu and Gilbert, 2005). Another possible approach is to account for strain compatibility by solving the problem numerically (e.g. Long et al. 1994; Villard et al., 1999); however, numerical approaches are generally not frequently used in practice.

In this paper, the assessment of geosynthetic tension forces is calculated applying the graphical solution proposed by Liu and Gilbert, (2005) based on a simple analytical model that maintains strain compatibility and force equilibrium (Liu and Gilbert, 2003). The study draws a comparison between two different geocomposite liners including a smooth geomembrane and a double-textured geomembrane and the role of the geogrid in both systems is investigated.

2. ROLE OF GEOSYNTHETIC REINFORCEMENT IN SMOOTH AND TEXTURED LINING SYSTEM

A comparative study of the cover lining system represented in Figure 1 was used to calculate the variation in forces on the gmb for two scenarios; a smooth gmb and a double-textured gmb.

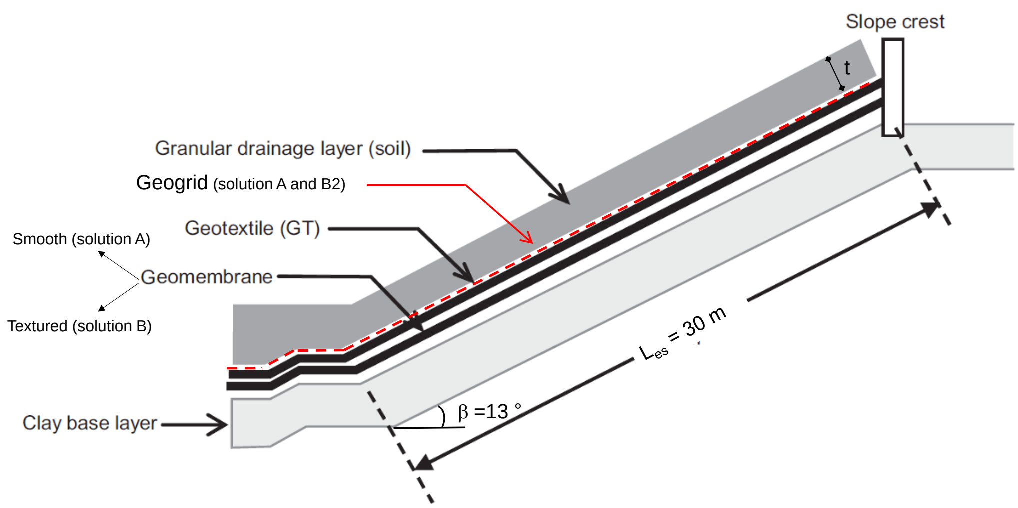

Figure 1: Scheme of the geosynthetic-soil layer system (adapted from Liu and Gilbert, 2005).

The principal characteristics of the materials considered in this study are summarized in Table 1. If the applied driving force due to the weight of the cover soil ($W \cdot \sin \beta$) exceeds the resisting force (S), a net applied shear force along the geosynthetic layer over the length of the soil (L_{es}) is induced. The net applied shear stress, ϕ_{net}, is assumed to distribute uniformly along the geosynthetic layer over the length of the cover layer. The forces acting on the top and bottom of the geosynthetic layer are assumed to be uniformly distributed along the geosynthetics over the length of the cover layer (hence, these forces can be expressed as constant shear stresses).

It could be noted from Table 1 that when a smooth geomembrane is considered, the system is not stable because the interface friction angles of the geomembrane are lower than the plane inclination angle, β (13°). The possible design solutions considered are (i) to include a reinforcement geogrid (solution A) and (ii) to use a textured gmb with higher interface friction angles (solution B1) together with a geogrid (solution B2).

Table 1 - Characteristics of the systems considered in the comparative study

Material	**Solution A - Smooth gmb lining system**		**Solution B - Textured gmb lining system**	
	Properties	Interface friction angles	Properties	Interface friction angles
Granular soil	γ_{soil}= 18 kN/m ϕ_{soil} = 32° t_{soil} = 0.5m L_{es} = 30m K_c=485kN/m	$\phi_{soil/GTX}$ = 29°	γ_{soil}= 18 kN/m ϕ_{soil} = 32° t_{soil} = 0.5m L_{es} = 30m K_c=485kN/m	$\phi_{soil/GTX}$ = 29°
Geotextile	$K_{t,GTX}$=50 kN/m	$\phi_{GTX/GMB}$ = 12°	$K_{t,GTX}$=50 kN/m	$\phi_{GTX/GMB}$ = 31°
Geomembrane	$K_{t,GMB}$=308.3 kN/m	$\phi_{GMBs/clay}$ = 11° (design value) $\phi_{GMBs/clay}$ = 9° (actual value)	$K_{t,GMB}$=308.3 kN/m	$\phi_{GMBt/clay}$ = 14° (design value) $\phi_{GMBt/clay}$ = 9° (actual value)
Required Geogrid	$K_{t,GR}$=1100 kN/m	/	$K_{t,GR}$=350 kN/m (solution B2)	/

A set of graphical solutions based on dimensionless terms proposed by Liu and Gilbert, (2005) (Figure 2) has been applied for estimating the geosynthetic tension within a geosynthetic–soil layered slope system. The graphical solutions are derived from the analytical approach presented by Liu and Gilbert (2003), in which force equilibrium and displacement compatibility between different components are satisfied.

Some of the most important hypothesis applied in the method include (see Liu and Gilbert, 2005, for further details):

- In order to estimate the compression and tension forces, C_{soil} and T_{gs}, the soil and geosynthetic layers are treated as a composite, one-dimensional column composed of a compressive column representing the soil and a tensile column representing the geosynthetics.
- The total geosynthetic tension (T_{gs}) is calculated considering first the multiple geosynthetics layers as a single composite column in tension and then dividing the stresses between the individual layers on the basis of strain compatibility.
- The cover soil is assumed to have no tensile capacity whilst the geosynthetic layer is assumed to have no compressive capacity. The soil and geosynthetic layers are assumed to behave like elastic-plastic materials, with K_c representing the compressive stiffness of the soil and K_t representing the tensile stiffness of the geosynthetic layer. Non-linearity in these materials can be approximately accommodated by selecting secant stiffness that reflect the expected levels of deformation.
- It is assumed that no slippage occurs at the interface between the two columns (i.e. the two columns strain equally).

- For multiple components with the same axial behavior (e.g. several layers of geosynthetics in tension), the distribution of load among multiple components can be determined by assuming equal strain in all components above the plane of slippage. The equivalent stiffness for total compressive or tensile component of the column, K, is obtained by summing the individual stiffness values (Equation 1)

$$K = \sum_{i=1}^{n} K_i \qquad [1]$$

where K_i is the stiffness for the i^{th} of n components in compression or tension. For an individual component, the induced load is proportional to its stiffness relative to the total stiffness.
- The maximum possible tensile load in a geosynthetic component is its ultimate strength, T_{ult}. The tensile load is proportional to the applied shear stress, ϕ_{net}, which includes information about the slope angle, the thickness of the cover soil, and the interface shear strengths between layers in the slope. The tensile load is also proportional to the dimensionless ratio L_t/L_s. where L_t is the length of composite column in tension along slope and L_s is the total length of cover soil layer along the slope. The geosynthetic tension therefore increases with an increase in the stiffness of the geosynthetic relative to that of the soil: that is, an increase of K_t/K_c.

Additional hypothesis:

- It is assumed that the cover soil is stable and layer is placed up in a single lift along the entire slope without any buttressing. The values found correspond to the upper bound value of the tensile force acting on the layers.
- The effect of seepage is not considered.

It is worth noting that if the secant friction angles of all interfaces with geosynthetic layers within the slope are greater than the slope angle, no tension will be induced in the geosynthetic layers. However, in Solution A, a geogrid is required to stabilize the system due to the low interface shear values (gmb/clay). Solution B is stable if the design interface friction angle is considered. On the other hand, it is well known that geosynthetic interface friction angles can decrease due to several processes including such as ageing of the polymer and/or as a consequence of installation (Giroud 2012).

In this paper, the tension induced in the geomembranes (i.e., smooth and textured) is calculated by considering a decrease in the interface friction angle with respect to the designed value. Therefore, for both systems, the critical interface friction angle $\phi_{GMB/clay}$ is chosen to be equal to 9°. The calculations of the tensile loads induced in the geosynthetics in both solutions A and B by applying the Liu and Gilbert (2005) graphical method are summarized in Table 2.

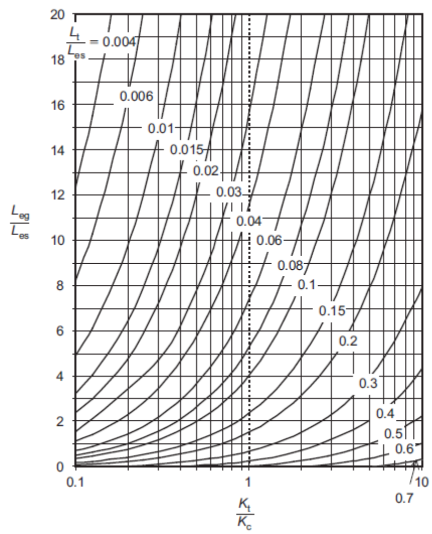

Figure 2 - Dimensionless length in tension, L_t/L_{es} against stiffness in ratio K_t/K_c and ratio of exposed length of geosynthetic layer to exposed length of placed cover soil layer, L_{eg}/L_{es} (Liu and Gilbert, 2005).

Table 2: Estimation of tension in geosynthetics induced by placement of the cover soil, applying method of Liu and Gilbert (2005)

	Solution B1 - Textured gmb system	**Solution B2 - Textured gmb system + geogrid**
1.	β = 13° γ_{soil}= 18 kN/m ϕ_{soil} = 32° t_{soil} = 0.5m	β = 13° γ_{soil}= 18 kN/m ϕ_{soil} = 32° t_{soil} = 0.5m
2.	L_{es} = 30m; L_{eg} = 0m (one single lift)	L_{es} = 30m; L_{eg} = 0m (one single lift)
3.	K_t= 358.3 kN/m K_t/K_c=0.74 ; L_t/L_{es} =0.47	K_t= 708.3 kN/m K_t/K_c=1.46 ; L_t/L_{es} =0.52
4.	ϕ_{net}=0.313 $\Delta\tau_{gs}$=0.147 ΔT_{gs}=8.93 kN/m	ϕ_{net}=0.313 $\Delta\tau_{gs}$=0.163 ΔT_{gs}=9.9 kN/m
5.	Tensile load carried by every single layer: GTX: 14% GMB: 86%	Tensile load carried by every single layer: GTX: 7% GMB: 43.5% GR: 49.5%

The results show that:

In Solution A the use of the geogrid not only stabilizes the system but also reduces the tensile load carried by the gmb. The use of a textured gmb permits higher slope inclinations (Solution B) but, if the actual critical interface friction angle is lower than the design value (for example due to installation damage), the gmb will be subjected to tensile load and will carry the majority (86%) of the tension load, ΔT_{gs} (Solution B1). If a reinforcement geogrid is placed in this system (Solution B2), the resulting tensile load carried by the textured gmb is reduced by half (from 86% to 43.5%).

3 EFFECT OF ELEVATED TEMPERATURE ON GEOSYNTHETIC REINFORCEMENT

Consideration is given to equation 2 (which is used to calculate the design strength of the geosynthetic reinforcement) to see where the influence of temperature is most critical to the overall design strength of the reinforcement. Depending upon the Country where the design is being undertaken, equation 2 may vary slightly. Each of the reduction factors reduce the ultimate tensile strength of the geosynthetic reinforcement down to the project design/allowable strength.

$$\mathrm{R}_{\mathrm{B,k}} = \frac{\mathrm{R}_{\mathrm{B,k_0}}}{\mathrm{A}_1 * \mathrm{A}_2 * \mathrm{A}_3 * \mathrm{A}_4 * \mathrm{A}_5} [\mathrm{kN/m}] \quad \text{and} \quad \mathrm{R}_{\mathrm{B,d}} = \frac{R_{B,k}}{\gamma_M} [\mathrm{kN/m}] \qquad [2]$$

$R_{B,d}$ Design value of the tensile strength of geosynthetic reinforcement
$R_{B,k}$ Characteristic value of the long-term tensile strength
$R_{B,k0}$ Characteristic value of the short-term tensile strength
A_1 Reduction factor for creep strain and creep rupture behaviour (depending on the load duration)
A_2 Reduction factor for damage caused during installation, transportation and compaction
A_3 Reduction factor for processing (seams, connections, joints) if applicable
A_4 Reduction factor for environmental impacts (resistance to weathering, chemicals, microorganisms, animals)
A_5 Reduction factor for the impact of dynamic action
γ_M Partial safety factor for the structural resistance of flexible reinforcement elements

3.1 Effect of elevated temperature on A_4 (environmental reduction factor)

It is very important to recognize that when elevated temperatures are mentioned, the environmental scenario must also be considered. The current research format of testing (PET) geosynthetic reinforcement at elevated temperatures assumes a fully saturated environment with the main process of hydrolysis taking place. If there is no water present in the system then elevated temperatures will not lead to the breakdown of reinforcement by hydrolysis. The presence of water molecules in the form of vapour will negatively impact the strength of the reinforcement in relation to hydrolysis, although it is currently very difficult to establish definitive reduction values for this scenario (we can say that it will not be as significant as the fully saturated environment but worse than the dry environment, but we consider that the chemical reaction will be much slower than the fully saturated condition).

Extensive research and testing (Retzlaff) on polyester (PET) reinforcement has been undertaken to determine the reduction factor A_4 for the chemical resistance of PET multifilament yarns used in the manufacture of geosynthetics for soil reinforcement in relation to hydrolysis. Table 3 summarises the effect of elevated temperatures on the retained strength of the reinforcement for the same design life (100 years). For a constant temperature of 50°C in a fully submerged state, the reinforcement yarns fully lose their strength and it can also be seen that even as temperatures rise above 10°C, there is a negative influence on the % of retained strength.

Table 3. Effect of temperature on retained strength/reduction factor assuming same design life (100 years) for PET reinforcement

Design Life (years)	Design temperature (°C)	Retained strength (%)	A_4/RF_{CH}
100	10	99.5	1.01
100	20	97.3	1.03
100	35	75.5	1.32
100	50	0	failure

A_4/RF_{CH} Reduction factor for chemical and environmental effects

Further extrapolation of the research data indicates (Table 4) that if the A4 reduction factor is kept constant (1.03) that at 50°C the reinforcement has a design life of only 1.5 years compared to a design life of 100 years for a constant temperature of 20°C.

Table 4. Effect of temperature on design life assuming same retained strength for PET reinforcement

Design Life (years)	Design temperature (°C)	Retained strength (%)	A_{4}/RF_{CH}
490	10	97.3	1.03
100	20	97.3	1.03
11	35	97.3	1.03
1.5	50	97.3	1.03

A_{4}/RF_{CH} Reduction factor for chemical and environmental effects

3.1.1. Role of PolyVinylAlcohol (PVA) geosynthetic reinforcement

An intensive testing program to enable the evaluation of the performance of geogrid reinforcement manufactured from PVA raw materials exposed to elevated temperatures was commissioned approximately one year ago. The authors had hoped that the final test results would be available for inclusion into this technical paper. Unfortunately this has not been the case, however the reason behind this is positive regarding the performance of the PVA reinforcement under elevated temperatures.

In terms of the regulatory body requirements for which the test regime was originally commissioned, testing can only be terminated once the material shows at least a 50% reduction in mechanical properties. The material samples removed on 20 July 2015, which were subsequently evaluated after circa. one year of testing, has not yet shown the required 50% reduction. Testing condition intensity have consequently been increased, the next planned extraction of samples is unfortunately after the conference date. Information obtained to date however shows significantly better performance by PVA raw materials when compared to other raw materials under equivalently extreme conditions.

3.2 Effect of elevated temperature on A_1 (creep reduction factor)

Elevated temperatures are also shown to have a significant effect on the reduction factor for creep (Figure 3) with the % value of retained strength reducing at a constant rate (dependent of temperature).

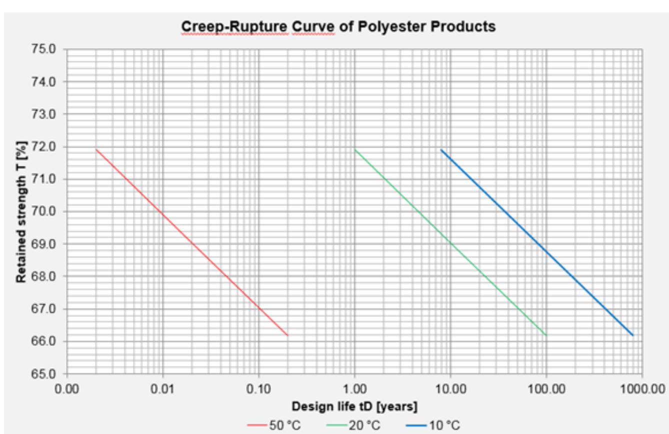

Figure 3 – Effect of temperature on retained reinforcement creep strength for PET reinforcement

Recent research (Kasozi et al) on the effects of elevated temperature on reinforcement strength and strain (using HDPE polymer) using simple test apparatus of short term tensile strength testing in a sealed heated unit showed a reduction in the strength and an increase in the strain values as the temperature rose (Figure 4). An interesting point is that the research primarily considered the temperatures externally and internally within a reinforced soil structure and discovered that the increase in temperature between the in-soil temperature and the outside temperature was ~50%.

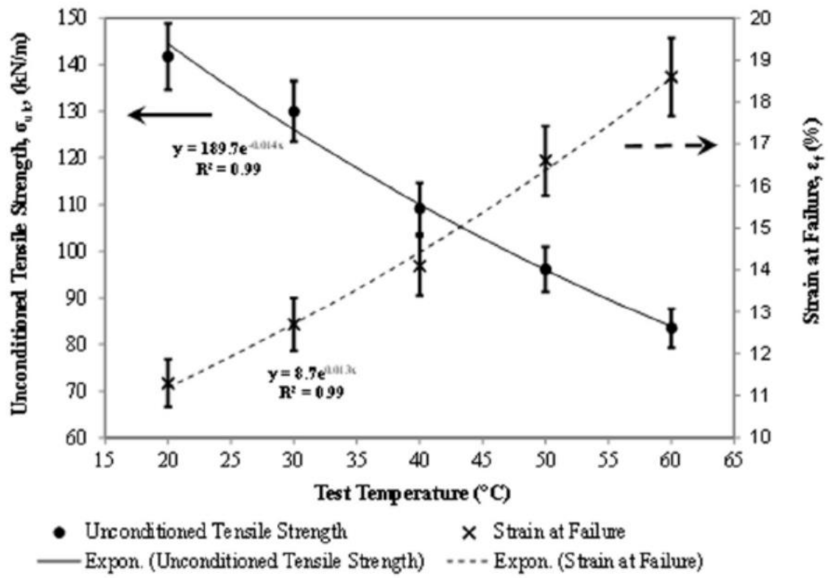

Figure 4 – Relationship between strength and strain for increasing temperatures (Kasozi et al)

The effect of temperature increase on the creep factor results in an increase in the reduction factor which in turn results in a reduction in the retained strength of the reinforcement (Table 5)

Table 5. Effect of temperature on reduction factor for given design life of PET reinforcement (100 years)

Design Life (years)	Design temperature (°C)	Retained strength (%)	$A_{1.}/RF_{CR}$
100	10	68.8	1.45
100	20	66.2	1.51
100	35	62.3	1.61
100	50	58.5	1.71

$A_{1.}/RF_{CR}$ Reduction factor for creep

Further research into the effect of extreme temperatures on the retained strength of the PET reinforcement show that as temperature increases the percentage of retained strength quickly reduces, for example, it only takes ~30 days for the reinforcement to lose 15% of its short term tensile strength under a constant temperature of 90°C and the results appear to suggest that the reinforcement is losing 5% of its strength every 10 days.

Table 6. Effect of extreme temperature on strength reduction for PET reinforcement

Temperature (°C)	Time required to reach % residual strength (days)		
	95% strength	90% strength	85% strength
60	273.1	546.2	819.3
70	99	198	296.9
80	33.8	67.5	101.3
90	10	20.1	30.1

4. SUMMARY

When a (HDPE) gmb is under tensile stress and/or shear stresses at the same time as oxidation the dynamics of degradation change and as indicated by Peggs and Rowe, geomembrane elements in a barrier system which is under constant load (tension) will deteriorate at an accelerated pace particularly when exposed to elevated temperatures. It can therefore be safely assumed that decoupling the barrier system from imposed loads and decreasing tension in the geomembrane will increase the expected service life.

There are concerns (Peggs) about double textured gmbs on side slopes where there is a higher shear resistance on the upper surface than on the bottom surface, which results in the liner becoming a load bearing member of the lining and/or cover system due to an induced shear stress. This relationship is an oxymoron because the liner is designed to be without stress but at the same time the texturing is provided to hold neighboring surfaces/soil layers. When slides do occur on slopes and gmbs rupture/tear it is often assumed that the reason is the movement of the soil. It is also possible that the gmb may experience stress cracking due to the induced shear stresses which in turn initiates soil movement. It is the opinion of Peggs that the use of smooth gmbs on the slopes will have a positive impact on the service life of the gmb and cover soils would be better served with a form of veneer stability.

A comparative study between a smooth and textured gmb lining system on a slope has considered the benefit of geosynthetic reinforcement and shown that for the smooth gmb the use of the geogrid reinforcement not only stabilizes the system but also reduces the tensile load carried by the gmb. The use of a textured gmb permits higher slope inclinations but, if the actual critical interface friction angle is lower than the design value (for example due to installation damage or smoothing of asperities), the textured gmb will be subjected to additional tensile load and will carry the majority of the tension load. If a reinforcement geogrid is placed in this system the resulting tensile load carried by the textured gmb is reduced by half.

For the inclusion of geosynthetic reinforcement in elevated temperatures, it is the reduction factors A_1 (creep reduction factor) and A_4 (environmental reduction factor) which are most affected by temperature. The most influential factor is A_4 (environmental effects) rather than A_1 (creep), nevertheless, the creep factor remains influenced by change in temperature. As a designer of veneer reinforcement cover systems it is important to consider the effects of potential elevated temperatures on the long term behavior of the reinforcement. It is equally important that the correct environmental situation is modelled, because the majority of the research on elevated temperatures assumes a fully saturated environment (i.e. a worst case scenario). Presently, it is difficult to accurately model the influence of temperature on hydrolysis for 'semi-saturated' environments. This is especially relevant and dependent upon the choice of polymer used in the reinforcement. If consistently elevated temperatures are likely to be present in the cover system then it may be prudent to adopt a more resilient polymer (e.g. PVA). The remaining option is to significantly increase the relevant reduction factors for creep (A_1) and (if a fully saturated environment) environmental effects (A_4), which could lead to an unduly expensive reinforcement because of the requirement for a very high short term tensile strength (i.e. because this strength will be factored down/reduced significantly due to the high reduction factors for A_1 and A_4).

The results of ongoing testing of PVA are showing positive results relating to the resistance under high temperatures. The final results and interpretation will be available before the end of 2015.

The recent research by Kasozi et al provides an interesting summary of the relationship between atmospheric temperature and soil temperature, and it is considered beneficial to obtain more accurate readings of the project in-situ soil temperature and moisture content regime to accurately predict the project conditions, which in turn will lead to projects that are designed more accurately and better value engineered. Long life battery powered monitoring units are now available which can monitor temperature and moisture parameters for several years and such monitoring is recommended for veneer reinforcement projects to build up a database of actual conditions in relation to temperature and moisture which in turn will help to develop more accurate assessments of the reduction factors of geosynthetic reinforcement in relation to elevated temperatures.

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