EVALUATION OF THE CHEMICAL COMPATIBILITY OF GEOSYNTHETICS USED AS COMPONENTS OF A SUBAQUEOUS CAPPING SYSTEM FOR CONTAMINATED SEDIMENTS

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ABSTRACT

This paper deals with the evaluation of the chemical compatibility of two (2) geosynthetics that have been selected as part of a subaqueous capping structure for *in situ* confinement of sediments contaminated with pyrite cinders and heavy metals. The geosynthetics under study were i) a high density polyethylene (HDPE) geogrid / polyester (PET) geotextile composite and ii) a woven / nonwoven PET geotextile composite. Specimens of both geosynthetics were immersed in contaminated sediment slurries taken from the site to be capped, at temperatures of 21 and 50°C. After 1, 2, 3 and 4 months immersion, specimens were extracted and submitted to physical and mechanical tests so as to monitor the evolution of their residual properties. Analyses of the chemical compatibility test results have demonstrated that the HDPE geogrid / PET geotextile composite does not present any apparent chemical incompatibility with the pyrite cinders. The same conclusion applies to the PET geotextile composite, even if it underwent noticeable strength reduction immediately after being immersed in the contaminated sediment slurry. This could be explained by the physical interaction between the sediment particles and the PET fibres.

RÉSUMÉ

Le présent article porte sur l'évaluation de la compatibilité chimique de deux (2) géosynthétiques qui ont été présélectionnés comme élément de renforcement au sein d'une structure de recouvrement immergée destinée au confinement de sédiments contaminés par des cendres de pyrite et des métaux lourds. Les géosynthétiques à l'étude sont : i) un composite formé d'une géogrille en polyéthylène haute densité (PEHD) et d'un géotextile en polyester (PET) et ii) d'un composite formé d'un géotextile tissé et d'un non tissé, tous deux en PET. Des éprouvettes des deux (2) géosynthétiques ont été enfouis dans des sédiments contaminés prélevés sur le site à réhabiliter, à des températures de 21 et 50°C. Après 1, 2, 3 et 4 mois d'immersion, les éprouvettes ont été soumises à des essais de caractérisation physiques et mécaniques dans le but d'évaluer l'évolution de leurs propriétés résiduelles. L'analyse des résultats des essais chimiques montre que le composite formé de la géogrille de PEHD ne présente aucun signe d'incompatibilité chimique avec les sédiments contaminés. Cette même conclusion s'applique au composite fait des géotextile tissé et non-tissé, même si ce dernier a subi une baisse significative de sa résistance immédiatement après immersion. Celle-ci serait la conséquence d'une interaction entre les particules de sédiments et les fibres des géotextiles.

1. INTRODUCTION

Subaqueous capping is an economically advantageous and technically feasible alternative for *in situ* remediation of contaminated sediments. This concept involves the placement of a structure made of clean isolating material such as granular material, rockfill and/or geosynthetic products on top of the contaminated sediments in order to protect the aquatic environment to their direct exposure (Palermo, Clausner, Rollings *et al.*, 1998).

Contaminated sediments are often deposited in a very soft state. The construction of a capping structure over these sediments could lead to bearing capacity, settlement and stability problems, especially when the installation takes place on an inclined river bed. This situation could be overcome by the installation of a reinforced geosynthetic fabric (see Figure 1).

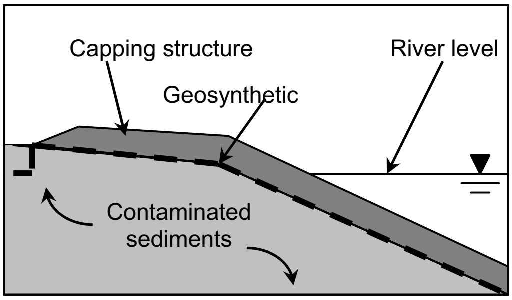

Figure 1. Subaqueous capping structure for contaminated sediments remediation

Chemical degradation of the geosynthetic fabric by the contaminated sediments is one of the many mechanisms that could affect the geosynthetic's behaviour over its design life and is certainly one of the most difficult to predict. Since contaminated sediments' composition is often site specific, laboratory evaluation of the chemical compatibility between these sediments and the selected geosynthetic is certainly the best way for verifying if considerable degradation of the geosynthetic is to be expected over time and to confirm if the proposed geosynthetic fabric is suitable in such environment.

This paper deals with the laboratory evaluation of the chemical compatibility of two (2) reinforced geosynthetics that have been pre-selected for the construction of a cap structure over sediments contaminated with pyrite cinders. A short description of the project's background is presented in paragraph 2. The methodology applied during laboratory testing is described in paragraph 3. In paragraph 4, the experimental results are presented and commented. Finally paragraph 5 discusses about the minimum reduction factor against chemical degradation that should be considered in the determination of the geosynthetics long term allowable tensile strength.

2. BACKGROUND

The site under study involves a former industrial plant located on the shore of the Saint-Lawrence River. The 40 years plant's operation, combined with various untreated industrial effluents, lead to the contamination of the river sediments situated in the vicinity of the plant. Various contaminants have been found in the sediments, mainly pyrite cinders which are associated with various heavy metals such as Iron (Fe), Selenium (Se), Zinc (Zn), Lead (Pb), Copper (Cu), Arsenic (As), Chromium (Cr) and Mercury (Hg). Organics were not found in significant concentration in the sediments. Table 1 provides the typical concentrations of the contaminants found in the sediments.

Table 1. Average heavy metals concentration found in pyrite cinders

Parameter	Concentration (in mg/kg)
Arsenic	86
Cadmium	11,7
Copper	1 050
Iron	378 571
Mercury	2,2
Lead	84,4
Selenium	50,5
Zinc	3 671

The site is located near a small residential community, which takes its water from the St. Lawrence River. In this region, the river is also used for recreational purposes. A human health risk assessment study reveals that the levels of risk associated with the presence of the contaminated sediments are below levels considered acceptable by regulatory agencies (dermal contact, incidental ingestion, drinking water and fish consumption). However, it has been shown that the contaminated sediments pose significant risk to the benthic organisms. Based on this, an integrated rehabilitation of the industrial land under study should also involve the remediation of the contaminated sediments.

2.1 Geotechnical properties of the contaminated sediments

Two (2) major geotechnical investigations have been carried out in order to characterize the contaminated sediments. Table 2 provides their main geotechnical properties. The sediments could be described as very soft, silt-sized, heterogeneous material with no appreciable strength, that have been deposited in very gentle slopes. Given the consolidation characteristics of the sediments, it is expected that much of the consolidation settlements caused by the construction of the capping structure would be completed within 1 to 2 years.

Table 2. Sediments main geotechnical properties

Properties	Value*
Classification (USCS)	ML
Thickness (m)	1 to 1.5 m (0-4)
Slope (^{o})	3 (0-11)
Specific gravity, G_s	4,5 (3.5-4.8)
Natural water content, w_N (%)	95 (32-261) **
Liquid limit, w_L (%)	29 (26-33)
Plastic limit, w_P (%)	Not measurable
Saturated unit weight, γ_{SAT} (kN/m^3)	16,3
Void ratio, e	4,3
Standard penetration test, N (# blow/ ft)	0-1
Undrained shear strength (vane) (kPa)	0-50
Consolidation coefficient, c_V (m²/year)	4 **
Modified compression index, $C_{c\varepsilon}$	0,19**

* Numbers shown in parentheses are minimum and maximum values respectively. ** Tests performed on specimens that have been stirred and later allowed to settle down.

2.2 Cap system

For this particular project, various remediation alternatives have been studied. These could be classified as removable, such as sediments dredging, dry excavation of sediments, and non-removable alternatives, such as no action, *in situ* capping, or *in situ* treatment.

From the economical, environmental, ecological and social point of views, the *in situ* capping was found to be the best alternative since:

- It generates little environmental impacts during construction (compared to dredging operations);

- It is an appropriate alternative to enhance the creation of new aquatic habitats;
- Provides an attractive area for human aquatic activities;
- It is economical compared to the other alternatives.

The very soft nature of the sediments leads to anticipate the possibility of stability problems such as bearing capacity and slippage failures. Installation of a reinforced geosynthetic is an interesting way to obviate this situation (see Figure 1). In this context, the geosynthetic has to fulfill two (2) main functions:

- Reinforcement, i.e. retaining the cap structure from slipping during the anticipated design life;
- Filtration, i.e. retaining sediment particles while allowing the water to flow during the consolidation of the sediments under the cap structure weight and/or by wave action.

2.3 Selected geosynthetics

A selection program has to been undertaken in order to find the best suited geosynthetics for this particular application. Two (2) geosynthetics have been retained, namely:

- A geogrid / geotextile composite;
- A woven / non-woven geotextile composite.

Both geosynthetics are customized products that have been specifically developed for this project. Table 3 and table 4 present the main properties of the geogrid and geotextile composites respectively.

Table 3. Properties of the geogrid / geotextile composite

Properties	Standard	Value
	Reinforcement	
Material	--	Uniaxial GG
Polymer		HDPE
Tensile strength	ASTM D6637-A	54 kN/m (M)^{L}
Elongation at break	ASTM D6637-A	13 % (M)^{L}
Melt Index	ASTM D1238	11.3 g/10 min (21.6 kg)^{L}
OIT	ASTM D3895	55 min^{L}
	Filtration	
Material	--	NW GTX
Polymer	--	PET
Filtration Opening Size	CAN/CGSB-148.1-10	< 60 µm^{S}
	Composite	
Bonding process	--	Lamination
Interface friction angle	ASTM D5321	31° (peak) 30° (residual)

Notes: GG=geogrid; GTX=geotextile; M=machine direction; XM=cross-machine direction; NW=non-woven; W=woven; HDP =high density polyethylene; PET=polyester; L=property measured in laboratory; S=as specified by the manufacturer.

Table 4. Properties of woven / non woven geotextile composite

Properties	Standard	Value
	Reinforcement	
Material	--	W-GTX
Polymer	--	PET
	Filtration	
Material	--	NW GTX
Polymer	--	PET
	Composite	
Bonding process	--	Needle-punching
Mass / unit area	ASTM D5261	1085 g/m^{2} ^{S}
Tensile strength	ASTM D4595	105 kN/m (M)^{S} 20 kN/m (XM)^{S}
Elongation at break	ASTM D4595	10 % (M)^{S}
Tensile strength	ASTM D5035	88 kN/m (M)^{L} 71 kN/m (XM)^{L}
Elongation at break	ASTM D5035	32 % (M)^{L} 33 % (XM)^{L}
Tear resistance	CAN/CGSB 4.2-12.2	2300 N (M)^{L} 2000 N (XM)^{L}
Filtration opening size	CAN/CGSB-148.1-10	< 50 µm^{S}
Interface friction angle	ASTM D5321	32° (peak) 29° (residual)

Notes: GTX=geotextile; M=machine direction; XM=cross-machine direction; NW=non-woven; W=woven; PET= polyester; L=property measured in laboratory; S=as specified by the manufacturer

Shear tests have been performed to evaluate the friction angle at the geosynthetics / sediments interface. The tests involved three (3) distinct vertical stresses (0.5, 1 and 2 times the capping structure weight). Once the sediments were consolidated, shear stress was initiated at the interface and residual friction angles of 29 to 30° were measured for the two (2) geosynthetics. Given that the sediments slope is less than 11°, it could be anticipated that the shear resistance between the consolidated sediments and the geosynthetics would be enough to sustain the capping load shortly after its construction (see section 2.1).

2.4 Need for chemical compatibility testing

Geosynthetics used in permanent reinforcement application could be subjected to various degradation mechanisms which should be addressed during their selection. Koerner (1994) identifies eight (8) degradation mechanisms, including chemical degradation.

Elias (2000) states that the use of HDPE geosynthetic in conjunction with transitional metals, such as those found in the sediments to be capped, could be questionable from the chemical compatibility point of view and that immersion tests should be conducted. PET would apparently not be affected by transitional metals. However, it is recognized that certain PET yarns used underwater are vulnerable to hydrolysis, especially in very acidic or alkaline solutions.

Even if the tensile strength of the reinforced geosynthetic is expected to be mobilized on a relatively short period of time (typically 1 to 2 years), it has been judged relevant to proceed with the chemical compatibility evaluation of the selected geosynthetics with the contaminated sediments, so as to make sure that the geosynthetics' properties will not change significantly during this period.

3. METHODOLOGY

Chemical compatibility testing was performed based on an adaptation of ASTM D6389 and ASTM D6213 standards for the geotextile and the geogrid composites respectively. The geosynthetic samples were immersed in a slurry made of contaminated sediments taken from the site. For the geogrid / geotextile composite, only the geogrid has been immersed in sediment slurry. The geosynthetic samples were divided into two (2) groups, in which the slurry temperature was kept at 21 or 50 °C respectively.

Geosynthetic specimens were extracted after 1, 2, 3 and 4 months immersion and tested according to the experimental program defined in table 5. Comparison of the residual properties of the immersed samples to those of the original products allows to determine if chemical compatibility problems could be expected. At least three (3) specimens were tested for the determination of each monitored property.

Table 5. Monitored geosynthetic properties

Properties	Geogrid composite	Geotextile composite
Physical Properties	Weight variation	Dimensional stability (ASTM D6389)
Mechanical Properties	Tensile strength (ASTM D6637-A)	Tensile strength (ASTM D5035) Tear strength (CAN 4.2-12.2)
Polymer Properties	OIT (ASTM D3895) Melt Index (ASTM D1238)	Microscopic observation

4. TEST RESULTS

4.1 Geogrid Composite

Figures 2 and 3 present the evolution of the geogrid properties with immersion time at temperatures of 21 and 50°C respectively.

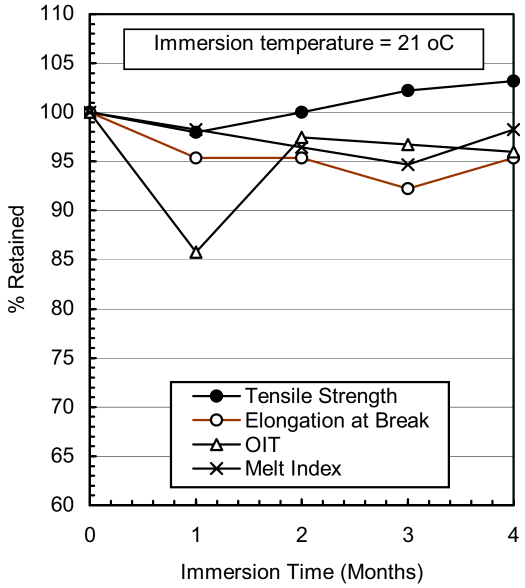

Figure 2. Evolution of the HDPE geogrid properties with immersion time at 21°C

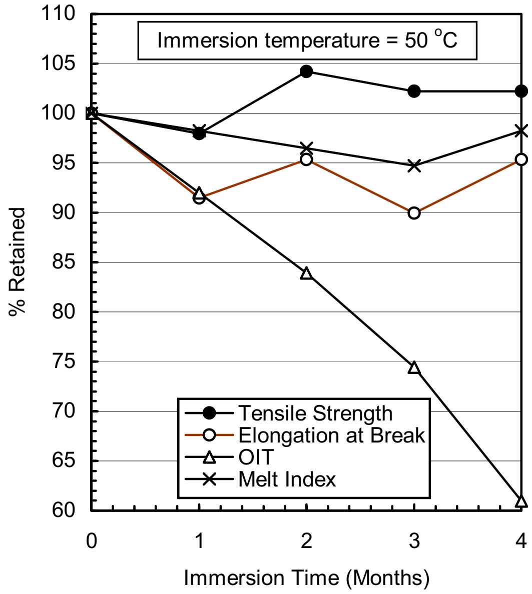

Figure 3. Evolution of the HDPE geogrid properties with immersion time at 50°C

From these figures, it could be seen that the geogrid's tensile strength, elongation at break and melt index remain relatively stable over time, with values ranging between 90 and 105 % of those measured on the original material.

While the OIT values at 21°C decrease slightly with immersion time, the OIT values at 50°C drops significantly. After four (4) months immersion, it decreases by 40 % of its initial value (see Fig. 2). A similar behaviour has been observed on HDPE geomembranes and could be explained by the fact that the antioxydant depletion rate, and consequently the OIT, is highly influenced by temperature (Hsuan & Koerner, 1998). Hence, the observed OIT reduction is an intrinsic behaviour of a stabilized polyethylene resin with antioxydants. Since temperatures as high as 50°C are not expected to be met during the design life of the capping structure (the geosynthetic will be mainly submerged in water), such behaviour does not appear to be critical.

In summary, there is no evidence of chemical incompatibility between the HDPE geogrid and the contaminated sediments.

Hsuan & Koerner (1998) noted that there is strong evidence that HDPE geomembranes physical and mechanical properties would be preserved as long as they contain antioxydants. Even if HDPE geogrids and geomembranes may contain different antioxydant packages, it appears that this conclusion is also applicable to HDPE geogrids.

4.2 Geotextile Composite

Figures 4 to 7 present the evolution of the geotextile composite's monitoring properties in machine and cross-machine directions, at 21 and 50°C. In addition to the tests performed on specimens immersed for 1, 2, 3 and 4 months, tensile tests were performed on samples immersed for only 1 hour.

From these figures, one could notice that the geotextile composite underwent significant resistance reduction immediately after its immersion in the sediments slurry (after 1 hour). It appears that these reductions are independent of the product direction (machine and cross-machine directions), immersion time or immersion temperature. Figures 4 to 7 show that the composite tensile strength retained between 70 and 80% of its initial value while the elongation at break retained between 40 and 60 % of its initial value. After immersion, the composite tear resistance is ranging between 40 and 50 % of the one measured on the original product.

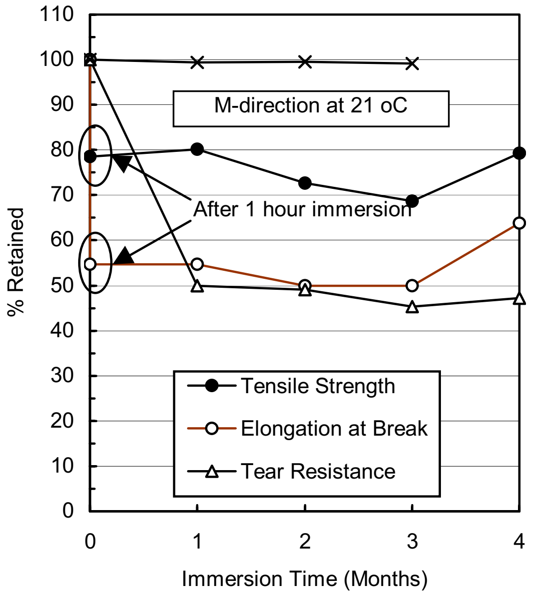

Figure 4. Evolution of the geotextile composite properties in machine direction at 21°C

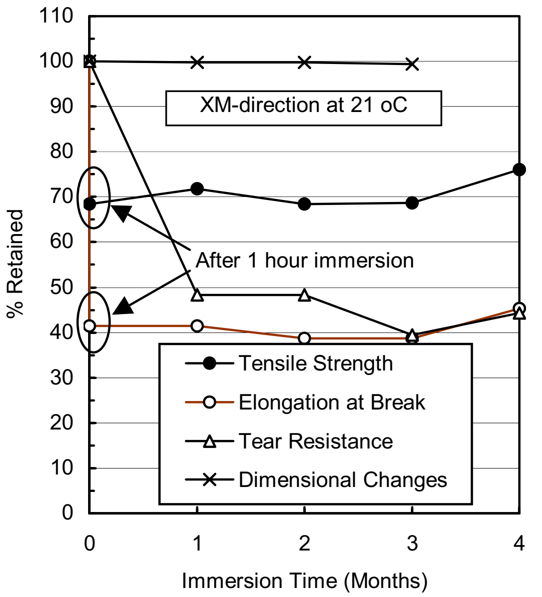

Figure 5. Evolution of the geotextile composite properties in cross-machine direction at 21°C

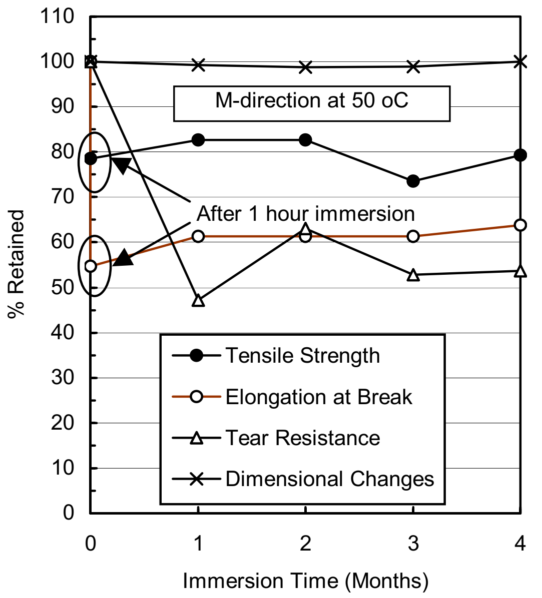

Figure 6. Evolution of the geotextile composite properties in machine direction at 50°C

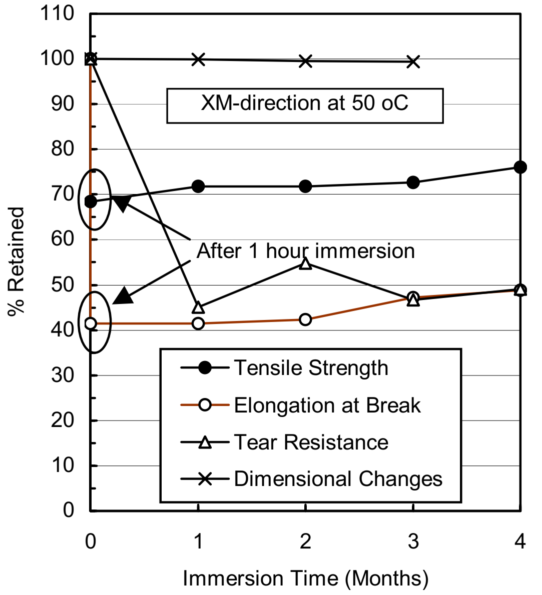

Figure 7. Evolution of the geotextile composite properties in cross-machine direction at 50°C

Surface condition of the fibres after 4 months immersion was investigated using a microscope and compared to the one of the virgin fibres. As indicated by the Figures 8 to 10, there is no tangible sign of superficial degradation of the fibres.

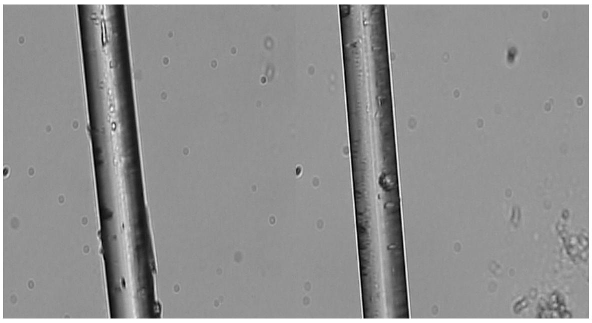

Figure 8. Surface condition of virgin PET fibres

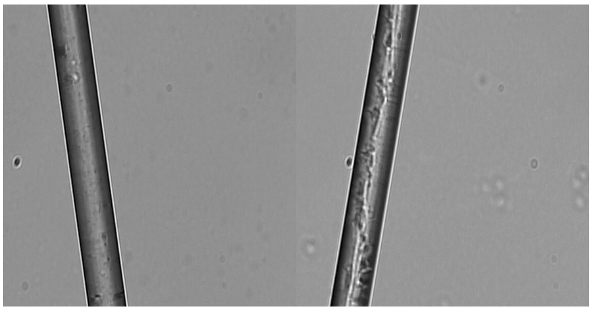

Figure 9. Surface condition of PET fibres after four (4) months immersion at 21 °C

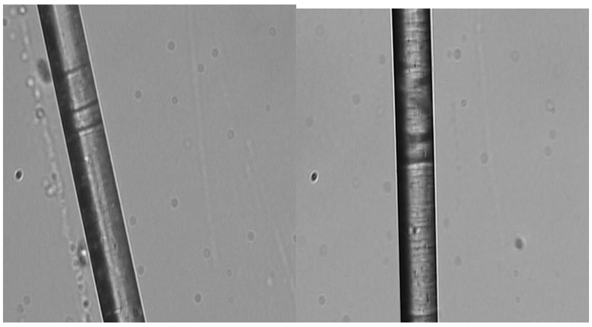

Figure 10. Surface condition of PET fibres after four (4) months immersion at 50 °C

According to the previous observations, it is obvious that the geotextile resistance (tensile strength, elongation at break, tear resistance) dropped significantly and nearly immediately after its immersion in the contaminated sediments slurry. However, after that drop, the mechanical behaviour of the geotextile remains stable throughout the four (4) months exposure. Moreover, the visual examination of the fibres does not reveal any visible sign of degradation. Based on this, it appears that the loss in the composite resistance could not be explained by a chemical degradation of the fibres.

It is believed that the presence of even small amounts of pyrite cinders particles (the test specimens were washed but residual contamination could not be completely eliminated) within test specimens could be sufficient to damage the fibres as they are rearranged by the induction of a tensile stress. As shown in Figure 11, the particles, acting as sharp knives, cause a premature failure of the fibres and an apparent decrease in the composite mechanical properties.

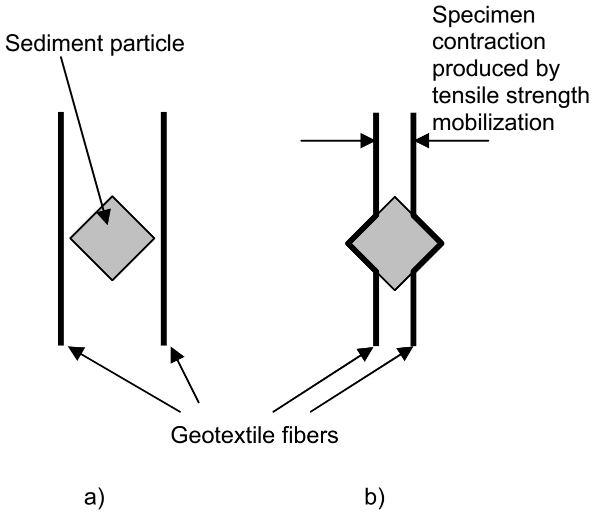

Figure 11. Sediment / fibre interaction causing the geotextile composite reduction of its mechanical properties: a) particle trapped between fibres under no tensile stress; b) damage initiation of the fibres by the sediment particles as the fibres are rearranged by the induction of a tensile stress.

5. DISCUSSION

Chemical degradation, like installation damage or creep, is taken into account in the calculation of the allowable tensile strength by mean of a reduction factor, such as (Holtz, Christopher & Berg, 1997):

$$T_{allowable} = \frac{T_{ultimate}}{RF_{ID} \bullet RF_{CR} \bullet RF_{CD} \bullet RF_{BD}} \qquad [1]$$

where:

RF_{ID} = installation damage reduction factor;
RF_{CR} = creep reduction factor;
RF_{CD} = chemical degradation reduction factor;
RF_{BD} = biological degradation reduction factor.

There is no general agreement on whether or not immersion tests are suitable for determining RF_{CD}. According to Elias (2000), these tests do not provide a sound basis for such purpose, especially due to their relatively short duration (usually 120 days) compared to the polymer degradation mechanisms kinetic. On the opposite, Geosynthetic Research Institute standard practices GRI-GT7 and GG4(a) clearly established a methodology for determining RF_{CD} based on the strength reduction measured from specimens immersed in a solution at a temperature of 50°C after 120 days. Nevertheless, chemical compatibility testing gives good indication on whether or not the geosynthetic might degrade.

According to the previous definition, a RF_{CD} of 1 is obtained for the geogrid composite. However, based on the minimal reduction factor values recommended by Elias (2000), the RF_{CD} of the geogrid composite should not be less than 1.1.

By considering the minimal % retained tensile strength of both immersion temperature and material direction, a RF_{CD} of at least 1.4 should be considered for the woven / non-woven geotextile composite. As it was mentioned in section 4.2, this strength reduction does not appear to be linked to a chemical degradation but rather the reflection of a pyrite cinders – fibres physical interaction.

At first glance, such a high safety factor produces a noticeable decrease in the allowable tensile resistance of the geotextile composite and may involve the use of expensive high strength materials to overcome the pyrite cinders – fibres interaction. However, PET fibres higher creep resistance over HDPE geogrids should not be neglected. Other factors such as geosynthetic's unit cost, ease of installation are also very important elements in the final decision.

6. CONCLUSION

This paper deals with the evaluation of the chemical compatibility of two (2) geosynthetics that have been selected as part of the reinforcement element of a cap structure for *in situ* remediation of contaminated sediments with pyrite cinders.

Two (2) geosynthetics were selected for this investigation, namely:

- A HDPE geogrid / PET geotextile composite;
- A woven / non woven PET geotextile composite

Analyses of the chemical compatibility test results have demonstrated that the HDPE geogrid composite has no apparent chemical incompatibility with the pyrite cinders.

This same conclusion is applicable to the PET geotextile composite, even if it underwent noticeable strength reduction after being immersed in the contaminated sediments. This could be explained by the physical interaction between the sediment particles and the PET fibres.

7. ACKNOWLEDGEMENTS

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