Stabilization of peat by silica based solidification

D.A den Hamer, A.A.M. Venmans, W.H. van der Zon, J.J. Olie
Deltares, P.O. Box 177, 2600 MH Delft
Dianne.denhamer@deltares.nl
Arjan.Venmans@deltares.nl

ABSTRACT

Construction on peat soils has proven to be a challenging task as this soil is highly compressible, has a low strength and retains neither its form nor its strength after oxidation. Peat silicification is a novel soil stabilization concept, in which soil properties are modified *in situ* through encapsulating the peat fibers with a layer of silicate, which increases strength and some resistance to biological and chemical oxidation. The silicification process involves the addition of three components: a cationic surfactant, a binding agent (a sodium meta silicate solution), and molasses to stimulate microbial fermentation leading to the production of organic acids that will harden the geopolymer gel formed by the surfactant and binding agent. Using this process in the laboratory, strength up to 1 MPa (UCS) was achieved. Based on the preliminary results, peat silicification seems a promising technique for cost-effective and efficient soft soil improvement with a wide range of potential applications.

RÉSUMÉ

La construction sur des sols de tourbe s'est avérée être une tâche difficile compte tenu que le tourbe est fortement compressibles et ne garde ni sa forme ni sa résistance après oxydation. La silicification de la tourbe est une concept originale de stabilisation du sol qui est présentée et discutée dans cet article. Pendant la silicification de la tourbe, les propriétés du sol sont modifiées in situ par le renforcement des fibres présentes dans la tourbe. En plus de l'augmentation de la dureté, la tourbe devient quelque résistante à l'oxydation biologique et chimique par l'encapsulation physique des fibres. Le procédé de silicification nécessite l'addition de trois composants : un tensio-actif cationique, un agent liant (une solution de méta silicate de sodium), et de la mélasse pour stimuler la fermentation microbienne conduisant à la production d'acides organiques, qui durciront le gel de polymères formé par le tensio-actif et le liant. En laboratoire, des résistances de 1 MPa (UCS) ont pu être obtenues par cette technique. Des résultats préliminaires ont montré que la silicification de la tourbe est une technique prometteuse, rentable et efficace pour l'amélioration de sols mous avec un large éventail d'applications possibles.

Keywords : Peat, silicification, geopolymer, water glass, microbial fermentation

1 INTRODUCTION

Construction on peat soils has proven to be a challenging task to civil engineers as this soil is highly compressible. Moreover, peat retains neither its form nor its strength after oxidation and is therefore highly sensitive to oxygen invoked by fluctuating groundwater levels and drought. Layers of peat in the subsoil lead to differential settlements of roads, railways and foundations. Especially, in the densely populated area of Western Holland and throughout Ireland, construction on peat soils is frequently accompanied by high geotechnical risks and costs. In summary, modification of peat soils comprises (a) reducing its potential to oxidize and (b) strengthening of the highly compressible solid matrix.

Up till now, soil stabilization methods for engineering purposes have mostly been chemical. In these processes, known as grouting, cement (calcium-based minerals) or water glass are injected or mixed in soils to improve stability and or reduce soil permeability (Karol 2003).

The scope of this article is to evaluate conventional chemically induced stabilization techniques in peat soils and propose a new potential solution based on biochemically induced silicification (Van der Zon et al. 2007). A hypothesis regarding the underlying geochemical mechanisms of this new solution is presented. The concept of this process has been tested in small preliminary laboratory tests and the results are presented and discussed.

2 CONVENTIONAL PEAT SOIL STABILIZATION TECHNIQUES

Various techniques can be applied to reduce or to eliminate the adverse effects of construction on peaty and organic soils (Molendijk and Haan 1996; Nichol and Farmer 1998; Hebib and Farrell 2003; Karol 2003). Consolidation can be accelerated by the installation of vertical drains. Preloading, either by a temporary fill, or ground water table lowering or vacuum drainage, can reduce post construction settlements. The use of lightweight fill materials can reduce settlements both during and after construction: Embankments of Expanded Polystyrene (EP) foam are designed not to increase the effective stress at foundation level, thus eliminating settlements and allowing very fast construction. Another way of reducing settlements is stiffening of the subsoil, e.g. by inclusion of stiff elements. Various mix-in-place methods exist, and embankments placed on end bearing piles are becoming very popular in the Netherlands for the rapid construction of low-maintenance infrastructure on soft soil.

Also, embankment stability benefits from application of lightweight fill materials, mix-in-place (MIP) techniques (Karol 2003) or piled embankments. These techniques will allow an increase in embankment fill rate and require less space for stability berms. To increase the stability of river levees, other techniques have been applied in the Netherlands such as soil nailing, sheet pile walls, coffer dams, and diaphragm walls.

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Despite that these techniques are broadly applied in civil engineering and although extensive research has been performed (Hebib and Farrell 2003), still several serious concerns and disadvantages exist, resulting in elevated risks. Especially for mix-in-place techniques, the (homogeneous) quality is a permanent concern and the lifetime expectance in the soil cannot be guaranteed beyond 10-30 years (Sparks 2003; Kretzschmar 2004). In the peat, humic substances delay the hardening of the cement and severely reduce the obtained strength and durability of the formed mineral structure. (Sherwood 1993; Babean and Sevc 1997; Amjad et al. 1999) Besides the weakening mechanism of humic substances, other chemical properties of peaty soil lead to a reduced hardening in comparison to clay or sandy soils: due to the presence of puzzolanic minerals (even at low levels) and an elevated water content, more solids are required to form a solid matrix (Ahnberg and Holm 1999).

Apart from these quality and durability issues, mix-in-place and other traditional soil stabilization methods cannot be applied to improve the stability under already existing constructions on peat. However, corrective and preventative in-situ applications will become more important soon, because interruptions for maintenance or repairs are becoming less accepted.

In conclusion, the currently applied methods for stabilization of peat soils are far from ideal and their characteristics are expected to be less appropriate in modern civil engineering practice. Therefore, a general need exists for the development and use of in-situ stabilization techniques.

3 ALTERNATIVE PEAT STABILIZATION BY BIOCHEMICALLY INDUCED SILICIFICATION

Peat silicification is a novel soil stabilization concept, aiming at improving soil properties in situ. Through strengthening of the fiber itself rather than filling the pore space (as is the case during lime–cement stabilization of peat) not only the strength is increased, but the material also gains resistance against biological and chemical oxidation by physical encapsulation of the fibre. This process combines microbiological acidification and hardening of geopolymers. The process involves the addition of an alternative binding agent, a source of organic carbon and additional nutrients to facilitate a microbial fermentation reaction. The basic principle of the concept is a 3-step process.

The concept of peat silicification is based on the process of biologically induced carbonate precipitation, in which substrates are converted for soil stabilization, but using a different type of mineral: silica (Whiffin et al. 2007).

The intended process of fibre coating, is characterized by a low concentration of dissolved silicate in the pore water compared to the levels during traditional injections of water glass. Due to the lower silicate level in the biosilicification process spontaneous precipitation in the pore voids upon a decrease in pH (which is the governing method in chemical silicification methods) does not take place.

In order to initiate the formation of a geopolymer at these low concentrations, the ions need to be concentrated on a micro scale (Sparks 2003; Davidovits 2008). A positively charged template can be used to bind silicate ions (negatively charged ions) from solution, thereby initiating the first step in silicate solidification and polymerization (Coradin et al. 2003; Sparks 2003; Davidovits 2008).

The fibre itself could theoretically function as such a template, but also biomass, or organic and synthetic surfactants are potential candidates for this function (Coradin et al. 2003; Staal et al. 2008; Davidovits 2008). It should be noted, that the mechanism of template bonding is comparable to aqueous silica – organic complex formation in order to control the solubility of silicate by inhibition of polymerisation and precipitation reactions. This method is common practice in wastewater treatment plants (Neofotistou and Demadis 2004) (Stumm and Morgan 1996). However, in this case, it concerns a solid template, which can be considered a backbone with functional groups attached. These functional groups should be able to form a chemical bond with the negatively charged silicic acid ions. In other words, the surface of the fibre should contain mainly positively charged functional groups in order to obtain attracting rather than repelling forces. Commonly, this is however not the case: an ‘activation step’ is required.

In ‘activation’ (step 1), a surfactant is added to the soil matrix: the surface of the peat fibre is activated by lowering its surface tension. The fibre is now susceptible to binding silicic acid through ionic bonding and complexation. In other words, the mainly negatively charged peat surface will become more positively charged due to the addition of this specific surfactant.

In ‘reaction’ (step 2), the water glass is introduced into the soil. Water glass is a silica solution that contains an alkali metal (monovalent ion of group one in the periodic table of elements, generally K^+ or Na^+) as counter ion. As mentioned before, the water glass solution is added in relatively low concentrations in order to prevent spontaneous precipitation and clogging of the soil matrix. Now, upon injection a first ‘primitive’ silica coating will be formed covering the peat fibre and interconnecting surfaces within the solid matrix.

In ‘hardening’ (step 3), microbially produced acids act as a hardening agent on the silicate and transform the polymer coating into a gel-like, amorphous structure, improving strength and stiffness and reducing the susceptibility to oxidation of the organic surfaces.

It should be noted, that the gelling of alkali silicates and the use of these gelled silicates for consolidating and stabilizing of soil are common practice. It is known that by adding a certain hardening agent to alkali metal silicates, solid silica gels can be obtained with similar characteristics as cement. Numerous of hardening reagents either organic or inorganic have been recommended for this purpose (fatty acids, phenols, ester, calcium chloride etc.). However, the time (gelation time) in which the ground is consolidated is generally short and is extremely variable within a small change of conditions like the ratio alkali to silicates in the solution. Since the gelation time can not be controlled sufficiently, the consolidation of ground by this method has been difficult. Organic-based hardening agents seem to be easier to control the gelation time. However, there is the issue of toxicity and contamination (Burkhardt et al. 1986).

In the biosilicification method, microbially produced acids act as a gelling agent. This gelling agent is released *locally* within the solid matrix itself and this therefore initiates condensation at a lower rate and specifically on those locations where microbial fermentation is stimulated. It is expected that the injection distances of the water glass solutions can thereby be extended.

On the long term, due to various natural soil processes the gel can dehydrate. The gel material hardens and shrinks in the process. The effects of these curing processes on the durability of the bulk material are subject for further research (Davidovits 2008).

4 MATERIALS AND METHODS

In the first part of the experimental program, a suitable recipe for peat silicification was defined. Several materials (including organic compounds with amino-groups, carbonic acid groups or hydroxyl-groups, mineral salts and complex organic materials like jelly proteins, sawdust, hay, and liquid manure) were evaluated on the ability of catching and binding of silicate to the organic molecule and/or how the organic compound initiates the jellification and even in crystallization of silicate. The effect of pH and concentration of silicate and organic compound determine how the silicate will interact and what type of gel will form: a gel (a network of polysilicates that will bind water) or a sol (a solution of ball-shaped silicate aggregates that move freely through the solution). Both types of aggregation were distinguished by phase contrast microscopy.

To test the concept of peat silicification as a whole, 1 kg of peat was mixed with 20 ml of a mixture of OMA-4 with hexadecyl trimethyl ammonium chloride solution in a mol ratio 1:1. After mixing (wing stirrer at 500 rpm), 50 ml of water glass was added. Peat from the Alblasserwaard (The Netherlands) was used for these preliminary tests. After addition of the water glass, the sample was incubated for 16 hours at a temperature of 20^{o}C. After that, the mixture was cast in a mold with 66 mm diameter and 100 mm length. After another 24 hours, the mold was flushed for 1 hour with a solution containing glucose (2 g/L). After that the sample was incubated for 48 hours at 20°C. The flushing and incubation was repeated 3 times, at similar intervals. After the third flush the samples were stored for 3 weeks at 20°C. Then samples were extracted to determine strength and analyze the sample using an environmental scanning electron microscope and determine the elementary composition with EDAX.

5 RESULTS

5.1 *Recipe for silicification*

From the organic compounds tested, the detergent alkyl monoethanolamide ethoxylate (OMA-4, Akzo Nobel Surface Chemistry AB,Stenungsund, SWEDEN) and the hexadecyl trimethyl ammonium chloride (HTAC) produced bi-layer micelles (light quenching with phase contrast microscope) on contact with the water glass solution (sol). The samples from HTAC showed merging to large aggregates that showed enhanced light-emission with the phase contrast microscope, suggesting polymerization of a mono-layer of silicate on the aggregates in the sol. Gel formation was not observed during the first day for organics with any of the tested amides, organic polyols, and with humic acid. The last one is soluble in water glass (pH 13) but could not induce gel formation. The acetic and citric acids reduced the pH from 13 towards 4 and induced hard gel formation on direct contact. All mineral salts produced gels, the soft ones from aluminum chloride and a dilute calcium chloride solution. The mineral hematite was not able to induce gel formation as dissolved iron ions can do.

Complex organics like hay, saw dust and protein jellies were not able to adsorb silicates and to initiate gel formation at the surface. Using the liquid manure with pH 12 a soft gel was formed in the water phase on top of the settled sludge, probably initiated by dissolved ammonia.

Producing fatty acids from fermentation could initiate gel formation on the spot. The recipe of Ferris & Stehmeier (1992) with water glass at pH 7.3 showed in all samples that microbial activity was not inhibited by the water glass.

Table 2 Results of recipe study showing the effect on gel formation of different additives to a water glass reaction mixture

Test	Test agent	Agent Concentration	Final content of the reaction Mixture			Observed results (Type of gel, pH, remarks)
			Agent solution	Waterglass	Water	
Compounds		[%]	[ml]	[ml]	[ml]	
Organic amines	N-(2-hydroxyethyl)dodecanamide	1	50	3	47	Sol
	HTAC*	1	50	3	47	Sol
	Methylene blue	1	50	3	47	No gel
Organic acid	Humic acid	1 g		3	97	No gel
	Acetic acid	1	50	3	47	Hard gel , pH 4
	Citric acid	1	50	3	47	Hard gel , pH 4
Organic polyol	Guar gum	1 g		3	97	No gel
Mineral salts	Iron chloride $FeCl_3$	1	1	3	96	Hard gel
	Aluminum chloride $AlCl_3$	1	1	3	96	Soft gel
	Calcium chloride $CaCl_2$	5	16	64	20	Hard gel
	Calcium chloride $CaCl_2$	5	3	15	82	Soft gel
	Ammonium hydroxideNH_4OH	1	1	3	96	Hard gel
	Ammonium acetate	1	1	3	96	Hard gel
Minerals	Hematite Fe_2O_3	1 g		3	97	No gel
Organic materials	Sawdust	1 g	50	3	47	No gel
	Hay	1 g	50	3	47	No gel
	Gelatin	1 plate		3	1	No gel
	Liquid manure pH 12	5 ml	50	3	47	Soft gel, pH12
Fermentation**						
	Liquid (no soil)	-	-	17	233	Soft gel, pH 5, bacterial growth
	Sand	100 g		17	233	no gel, pH 7, sulfate reduction
	Mud	100 g		17	233	no gel, pH 6-7, sulfate reduction
	Peat	100 g		17	250	no gel, pH 7, fungal growth
Coatings						
	Sawdust; $FeCl_3$; wet & dry	-	-	4	-	Wet: hard gel; dry: no gel
	Sawdust; NH_4-acetate; wet & dry	-	-	4	-	Wet: hard gel; dry: no gel
	Sawdust; Methylene blue; wet & dry	-	-	5	-	no gel at both wet and dry
	Clay with OMA-4; wet	-	-	5	-	sol
	Sand with HTAC*; dry	-	-	5	-	hard gel at dry in 2 weeks

**HTAC: Hexadecyltrimethylammoniumchloride*

*** Using recipe of Ferris and Stehmeier (1992) to induce microbial activity: 3 g yeast extract; 20 g glucose and citric acid and pH adjusted to 7.3*

Only the blank with just the recipe produced a soft gel at a pH of 5 after 4 weeks. In sand and mud, addition of HCl solution produced a H_2S smell, suggesting sulphate reduction (Ferris and Stehmeier 1992).

Coating of wet saw dust containing iron chloride or ammonium acetate induced directly hard gel formation. That was not the case with dry coatings. Methylene blue did not induce gel formation in any condition. Clay with OMA in the hang water produced a sol on contact with the water glass solution. Sand, coated with HTAC in dry condition, produced an opal layer in a water glass solution during 2 weeks in a Petri dish without lid. Water vaporization induced silicate polymerization.

5.2 *Mixed in place column test*

The following density of the peat was determined: 1280 kg/m^3. The relatively high density, indicates a high content of mineral matter, predominantly clay.

The unconfined compressive strength of the obtained test sample (after curing for 3 weeks) was 640 kPa. At the moment of testing, the density of the mixture was 1340 kg/m^3.

The electron microscope image shows that the silicate gels are adsorbed onto the fiber and that they enclose this fiber partially (Figure 1). Element analysis of the product further show elevated concentrations of silicate as expected, but also the elevated presence of calcium. This could not be explained from the origin of the peat, since the Alblasserwaard is located at the edge of the perimarien area[1]. Probably this is related to the current groundwater composition. Besides, the analysis reveals the incorporation of aluminum, iron and magnesium into the silicate encapsulation.

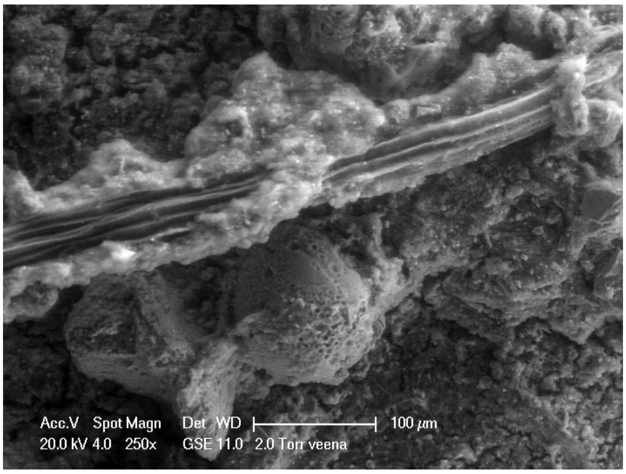

Figure 1: ESEM image of a partly silicificated peat fiber.

6 CONCLUSIONS

A new soil stabilization method is introduced, which involves a three step procedure in which fibers are coated with hardened silicate coatings, which strengthens the peat fibers and partly reduces their oxidation potential. Recipe studies identified the effect of a number of additives on the gel formation of a water glass solution. These studies resulted in a procedure, producing a strength of 640 kPa (UCS) using a mix-in-place approach. Testing the hypothesis that the material gains resistance against biological and chemical oxidation by physical encapsulation of the fibre, is a subject of future research. Nevertheless these preliminary results already show a promising method to reduce risks and costs when constructing on very soft grounds.

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[1] Perimarien indicates an influence of the tides on the groundwater levels although there is no infiltration of saline water. Historical events have changed the chemical composition of peat layers post deposition: flooding of a low moor peat by the marine sea probably generates a flux of calcium carbonate and consequently results in the relatively high pH.