The shrinkage rate increases greatly in the first 3 days. From 3 to 30 days, the shrinkage process becomes slow. The gel in air and in water kept stable after 30 days, but there exists a phenomenon of volume expansion of gel in the saline and acid conserving solutions, the most extent of expansion occurs in the acid solution, this can be explained by the reaction between the gel and the solution, the gel is eroded by the saline or acid solution.



Fig. 4. Shrinkage rate of pure gels of sodium silicate hardened by sodium aluminate.

The shrinkage of sodium silicate is much more than that of nanosilica. The maximum shrinkage rate arrives 40%, the gel volume can reduce to less than 2/3 of the original volume. This phenomenon is worthy for further study when used in situ because the porosity of the soil reinforced may largely change with time. With the increasing proportion of the sodium aluminate, the shrinkage rate is smaller.

For formulation (Sodium aluminate of 3% by volume), the gel trends to stop after 180 days, the more important shrinkage occurs in the water while the smallest shrinkage occurs in acid solution. For formulation (Sodium aluminate of 4% by volume), the gel trends to stop after 180 days for the humid environments, but for air environment, gel is not stable after 365 days. For formulation (Sodium aluminate of 5% by volume), it takes longer time for stability, and the maximum shrinkage occurs in acid solution which is different from the other two formulations.



Fig. 5. Shrinkage rate of pure gels in four environments.

*Note*: The series labels in Fig.5 : NN1-nanosilica+NaCl(75 kg/m<sup>3</sup>); NN2-nanosilica+NaCl(95 kg/m<sup>3</sup>); SA1-sodium silicate + sodium aluminate (3% by volume); SA2-sodium silicate + sodium aluminate (4% by volume); SA3-sodium silicate + sodium aluminate (5% by volume).

Fig. 5 shows the comparison of all formulations in each environment. It is obvious that the shrinkage of nanosilica gel is much smaller than sodium silicate, this means the stability and physical properties of nanosilica is much better than silicate sodium, which is very favorable for the porosity reducing of the soil.

For nanosilica, with increase of NaCl concentration, the shrinkage is slightly larger. For silicate, with the increase of the sodium aluminate, the shrinkage is smaller. Time for nanosilica gel to stabilize is much shorter than the silicate gel and the effect of different environment on the nanosilica is much smaller than silicate gel. The test was just measured by pure gel, the results can be a reference to learn more about the physical properties of the gel. After injection or mixing with soil, the phenomenon may different.

#### Porosity test sand-gel mixture

After learning the volume stability of pure gel, the porosity of sand-gel mixture was further measured to see if the syneresis phenomenon was the same as pure gel. This is a very important indicator to evaluate the soil combination effect and to estimate the anti-seepage effect after using the chemical material.

According to our sand-gel mixture characteristic, vacuum saturation method is adopted to measure the porosity.

#### Preparation of samples and test method

Firstly, samples with the same density of 1450 kg/m<sup>3</sup> and the same volume of 30 ml were prepared. The original porosity of FBS is 0.44. Five formulations which were studied in section 3.1 were used to reinforce FBS. The proportion of the pore filling is 25% by volume: 3.32 ml of gel mixed with 43.5 g of sand.

Then samples were conserved in four environments: Air, water, saline solution and acid solution (Fig. 6).



Fig. 6. Preparation of samples.

The porosity n is defined as the ratio of the volume of the pore space and the total volume of the soil, the total volume of all the samples were 30ml. The volume of the pore space was measured by vacuum saturation method (Fig. 7), and then porosity was calculated by (Verruijt 2004):

$$\mathbf{n} = \frac{V_p}{V_t} \tag{2}$$

Where  $V_p$  is the pore volume;  $V_t$  is the total volume.

For the samples conserved in the solutions, they were dried in the dryer at 80  $^{\circ}$  temperature during 48 hour (Fig. 7).



Fig.7. Drying chamber of  $80^{\circ}$  and vacuum pump.

### Results

The porosity of the same formulation in different environments was showed (Fig. 8 and Fig. 9). The porosity of all the formulations conserved in the same environment was also analyzed (Fig. 10).



Fig. 8. Porosity of sand samples mixed with nanosilica hardened by NaCl solution-(a):NaCl( 75 kg/m<sup>3</sup>); (b):NaCl( 95 kg/m<sup>3</sup>).

Firstly, the amount of gel is 25% of the pore volume, in fact the filling percentage is about 18-20% of the pore volume. Comparing the two formulations of nanosilica, when the concentration of the NaCl increases, the porosity is more stable and takes shorter time for stabilization.

After immersed 1 day, the porosity of sample in air increases a little, but the porosity in the liquid solutions increases significantly, this can be explained by the instability of gel, the gel has been rushed by the solution. After 7 days, the porosity is more stable. From 7 days to 15 days, the porosity increases slightly, that indicates the shrinkage of the gel. After 30 days, the porosity of formulas with amaller amount of aluminate decreases a little, this can be explained by the combination of gel and sand grains.



Fig. 9. Porosity of sand-silicate mixture.

The syneresis rate of sand-silicate is as much as sand-nanosilica, which is very different from pure gel. That means that when the gel of nanosilica and silicate sodium mixed with sand, the pore filling effect is similar. This can be explained by the fine grains of SFB, the pores of fine grain soil make the gel discontinuous, which obstructs the development of gel syneresis.

With the increasing proportion of the sodium aluminate, the increase rate of porosity is bigger, which is contrary with pure gel. On the whole, after 30 days, the porosity trends to be stable.



Fig. 10. Porosity of samples in four environments.

The gel is more stable when mixed with sand, after a great increase in the first day, the porosity changes very slightly. For samples conserved in dry air, the porosity increases slowly and gradually. For samples conserved in liquid solutions, the porosity increases significantly in the first day and then changes slowly.

#### CONCLUSIONS

In this work, usual techniques are adopted to provide practical and direct information on the effect of the reinforcement of sand with new material-nanosilica and traditional material-silicate binder.

Compared with silicate sodium, nanosilica is much more stable, which means that this new material is very effective for reducing the soil pore and have a very good long-term anti-seepage effect.

For pure gel, nanosilica has much smaller syneresis than silicate sodium. When the gel is mixed with sand, the difference becomes smaller, but nanosilica is also a little more stable than silicate sodium, and the stability time is shorter.

For samples stored in solutions, after long time, the gel can be eroded, the erosion rate of nanosilica in acid and saline solution is more important than in water. For silicate, the effect of water is much bigger.

At first, the amount of gel is 25% of the pore volume, but the actual filling rate is about 18-20% of the pore volume, this result can be a reference for practical use of this material.

The physical & chemical properties of the soil mixed with nanosilica are stable after 15 days, when those of soil mixed with silicate are stable after 30 days.

### REFERENCES

- Bolisetti, T., Reitsma, S., Balachandar, R. (2009). "Experimental investigations of colloidal silica grouting in porous media". *Journal of Geotechnical and Geoenvironmental. Eng.* 135(5), 697-700.
- Guefrech, A. (2010). "Injection et pérennité des coulis à base de silices colloïdales nanométrique". *Thèse de doctorat à l'Ecole Centrale de nantes*, Nantes, France, 23-64.
- Iler, R.K. (1975). "Coagulation silica by calcium ions mechanism and effect of particles size." *Journal of Colloidal and Interface Science*, 53(3), 476-488.
- Karol, R.H. (2003). "Chemical grouting and soil stabilization." *Engineering & Technology, 3rd edition CRC Press*, New York, 122-148.
- Muresan, B., Saiyouri, N. (2011). Internal erosion of chemically reinforced granular materials: A granulometric approach. *Journal of Hydrology*. 411(3-4), 178-184.
- Noll, M.R. (1992). "In situ permeability reduction and chemical fixation using colloidal silica." *Proceedings of 6th National Outdoor Action Conference*, Les Vegas, 443-457.
- Oka, F. (2003). "Deformation and strength characteristics of improved sand by a grouting materials and its application to liquefaction analysis of man made island." *Proceeding of 13th ICSMGE*, 861-866.
- Verruijt, A., Van Baars, S. (2007). "Soil mechanics." VSSD, 19-25.

# Experimental Study of the Electro-osmosis Consolidation of Soft Clay under Anode Follow-up

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**ABSTRACT:** Electro-osmotic consolidation is an effective method for soft ground improvement. A novel technique called anode follow-up for electro-osmotic consolidation of soft clay is proposed. A series of electro-osmotic consolidation experiments with different anode follow-up programs were carried out to investigate the influence of anode follow-up to electro-osmotic consolidation. In the electro-osmotic process, the electric current, shear strength, volume of drained flow, water content, soil conductivity were monitored. Test results show that anode follow-up can promote the effectiveness of electro-osmotic consolidation and reduce the resistance of anodic region obviously in the circuit. The effect is the best when anode follow-up is applied for the first time. When the current density is relatively low, anode follow-up will promote the electro-osmotic process. Soil conductivity decreases in cathodic region is due to the electro-chemical reaction.

#### INTRODUCTION

Electro-osmotic consolidation is a vital stabilization technique for soft ground. Compared with some other traditional methods, electro-osmosis has a fast rate in consolidation and drainage of the dredged soil and soft clay which are characterized by their low bearing capacity, high compressibility and significant change in volume. Esrig (1968) studied the electro-osmotic consolidation theory and provided one dimensional theoretical solution for electro-osmosis. Shang (1998) developed a two-dimensional consolidation theory of planar electrode. Guy Lefebvre and Fabien Burnotte (2002) studied the effectiveness of electro-osmotic consolidation by means of minimizing power loss at the electrodes. Su et al. (2003) put forward the two dimensional electro-osmotic consolidation theories on the basis of the Esrig's one dimensional consolidation theory. Glendining et al. (2005, 2007, 2008) investigated the electrokinetic geosynthetics (EKG) in electroosmosis and indicated that EKG belt presses could offer a cost effective solution to improve dewatering of sewage sludge. Zhuang et al. (2007) analyzed the problem of interface resistance in the process of electro-osmosis. Li et al. (2011) investigated the influence of salinity on soft clay electro-osmotic drainage and the influence of voltage on the one dimensional electro-osmotic drainage. Stalin, V. et al. (2011) made an attempt to study the influence of initial water content, voltage and spacing on the behavior of prepared soft clay subjected to electrical field .They found that in case of lower initial water content and lesser spacing, the current flow decreased drastically while the propagation of cracks was sharply increasing. Gong et al. (2011) proved that intermittent current technology played a good role in promoting the electro-osmotic process. Li (2012) carried out a laboratory test to investigate the effect of electrode space on electro-osmosis and showed that decreasing the electrode spacing while keeping the voltage gradient could effectively improve the efficiency of electro-osmotic consolidation.

However, some problems confined the application of electro-osmosis, such as the reduction of the electric permeability coefficient in electro-osmotic process, the rapid increase of interface resistance in later stage, non-uniform consolidation and so on. In order to solve these problems, a new method called anode follow-up is proposed. In the process of electro-osmosis, cracks develop in the anode-soil interface (cracks could bring about a sharp increase to the anode-soil interface resistance) when water moves towards cathode by direct current. The anode will be pulled out and re-inserted into the position close to cathode and the water content is high. The anode could be tightly bounded to the soil again and the interface resistance will be greatly reduced. Then, the soil near the cathode will be further consolidated, resulting in an improvement for electro-osmotic consolidation.

#### **EXPERIMENTAL PROGRAMME**

#### **Soil Specimen**

The typical properties of the soft clay are listed in table 1. The soil sample in the experiments was collected from Longwan hydraulic fill field in Wenzhou.

Table 1. Typical properties of Soft Clay											
Water	Gs	γ	ø	Sr	Wp	Wı	Soil conductivity	nH			
content (%)	Us	$(kN/m^3)$	C	(%)	(%)	(%)	( <b>S</b> ⋅ <b>m</b> <sup>-1</sup> )	hII			
65	2.75	16.9	1.54	99.7	26	56.5	4.96	8.16			

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#### **General Experimental Procedure**

An electro-osmotic cell made of glass with internal dimensions of L:B:H =280: 100:100mm was selected in the tests, as shown in Figure 1. The rectangular box is hollow, transparent, and it has openings on both sides so that the water can be discharged. Slits or grooves are provided at 40, 240 mm from left end of the box for fixing the electrodes. The electrodes are all made up of iron plates. The cathode is perforated to keep the water flowing (see Figure 2) and it is wrapped with geotextile filter to prevent the loss of soil particle while the water is passing through the cathode. The follow-up anode is a stainless steel mesh which is less than 1mm thick.



FIG. 1. Electro-osmotic cell FIG.2. Electrode used in the experiment

The schematic diagram of experimental cell is shown in Figure 3. The electrodes were fixed in the slits to create a uniform electric field in the tests. The drainage hole near the cathode was free to drain off water which would be collected by a graduate. Multimeter and potential measuring needles were used to measure the soil potential. The potential measuring needles were vertically inserted 40cm in depth into the soil. Model installation of the tests is shown in Figure 4.



FIG. 3. Schematic diagram of experimental cell (top view and side view)



FIG. 4. Full test set-up (overall view and experimental cell)

Table 2 is the summary of the test programs. Test E1 and E2 were the reference tests without anode follow-up and polarity reversal. Test E3 was conducted with the polarity reversal. Tests E4-8 were conducted with the anode follow-up. The voltage gradient (1V/cm) was constant in all the tests.

Test No.	Test methods	Schematic diagram of anodic follow-up	Voltage (V)	Total testing time (h)	Polarity reversal
E1	none	A   C	20	24	
E2	Pre-inserted follow-up anode	A   * <sup>24h</sup> *  C	20	24	
E3	Polarity reversal	A (C) 24h C (A)	20	24	Yes
E4	Start in 6h, conduct three times	$A \mid \stackrel{6h}{\longrightarrow}_A \stackrel{6h}{\longrightarrow}_A \stackrel{6h}{\longrightarrow}_A \stackrel{6h}{\longrightarrow}_A \mid C$	20/15 /10/5	24	
E5	Start in 6h, conduct one time	A   <sup>6h</sup> × 18h C	20/15	24	
E6	Start in 6h, conduct twice	$A \mid \stackrel{6h}{\longrightarrow}_{A} \stackrel{6h}{\longrightarrow}_{A} \stackrel{12h}{\longrightarrow} C$	20/15 /10	24	
E7	Start in 6h, conduct twice	A $  \overset{6h}{\prec}_{A} \overset{12h}{\prec}_{A} \overset{6h}{\leftarrow}   C$	20/15 /10	24	
E8	Start in 6h, conduct twice	$A \mid \stackrel{6h}{\swarrow}_{A} \stackrel{12h}{\longrightarrow}_{A} \stackrel{6h}{\longleftarrow} C$	20/15 /5	24	

### **Table 2. Summary of Test Programs**