



Long-Term Behavior of Colloidal Nano-silica Reinforced Sand in Different Environments

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Abstract. Colloidal nano-silica was firstly used for the injection of soil in the 1990s, which is relatively new compared with other materials. Nano-silica can be used into ground with low porosity. The aim is primarily to prevent or mitigate internal erosion. Since there are not any published data about the efficiency and the durability of nano-silica treated soil in different engineering environments, this paper focus on evaluating long-term improvement effect, including compressive strength and capacity to resist erosion. Nano-silica used in this paper is Levasil 300/30% hardened by NaCl of different concentration. Cylindrical specimens were prepared by mixing fine sand with nano-silica. The environments discussed in this paper include dry air, pure water, salt solution and acid solution. The test was carried out on specimens stored for 1, 7, 15, 30, 90, 180 and 365 days. The results show that, the colloidal nano-silica reinforced sand keeps stable in saturated environments (pure water, salt and acid) and becomes fragile in dry environment.

Keywords: Colloidal nano-silica · Internal erosion · Long-term behavior
Compressive strength · Capacity of resisting erosion

1 Introduction

Internal erosion (IE) is a complex phenomenon which causes major problems of levees, dikes and embankment dam stability. Several examples of failure of embankment dams have been reported in literature (Fry et al. 1997; Foster et al. 2000b) and most of them are related to this phenomenon.

It is very important to improve the erosion resistance of erodible soils using appropriate cost - effective techniques. Chemical stabilization is an effective technique for controlling erosion (Karol 2003). A great deal of research has been carried out on the engineering behavior of stabilized erodible and dispersive soils with traditional admixtures such as lime, cement, gypsum, slag, alum, and fly ash (Perry 1977; Rosewel 1977; Machan et al. 1997; Indraratna 1996; Indraratna et al. 2008a). However, traditional chemical stabilizers are not always readily acceptable due to stringent occupational health and safety issues. They also pose a threat to the environment by changing the soil pH, thus limiting the scope of vegetation and also affecting the quality of the ground water. Nanometric colloidal silica (also known as nano-silica), has shown promise at stabilizing some problematic soils. Nanosilica was firstly used in the 1990s in civil engineering, as

mineral addition in concrete; soil porosity reducer by the gel formation in the oil deposits to facilitate pumping through the holes; grout in fine soils to form waterproof barriers against the migration of pollutants (Noll 1992; Persoff et al. 1999) and grout for mitigating the risk of liquefaction of saturated soil (Gallagher 2000, 2007). Characterized by low (near water) viscosity and a nano-scale particle distribution, colloidal nano-silica can be considered as a grout injection for fine sand. These colloids are composed of SiO_2 and dispersed in aqueous solution by electrostatic repulsion. This suspension turns into hard frost in the presence of electrolyte (cation, polymer, etc.) for taking the product in the porosity of the soil and improving its properties. This chemical broth freeze time is perfectly adjustable depending on conditions of injection from a few minutes to a few hours (Guefrech 2010). Unlike other chemical grout such as sodium silicate, colloidal silica in gel form is physically stable and exhibits no shrinkage or withdrawal in a saturated environment. This silica is chemically composed of pure silicon dioxide SiO_2 which gives the product an “environmentally friendly character”.

The objective of this paper is to develop an experimental setup for the study of sustainability and durability of soil treated with nano-silica.

In addition, it is known that the reinforced structures are typically exposed to natural environments. They are permanently exposed to wind, rain, temperature changes, etc. They are also immersed in fresh water or sea water for a very long period. In short, they are affected by a variety of mechanical and chemical stresses. Therefore, the sustainability of soil chemical grout injected into its environment attracts a major concern of engineers.

In this paper, we focus on the durability of soil treated with nano-silica, depending on the time, the environment, etc.

2 Materials

Fontainebleau sand (FBS) (a fine material silica ($\text{SiO}_2 > 98\%$)) was adopted. The grain size is between 50 μm and 400 μm , it's the particle and bulk densities are respectively 2600 kg/m^3 and 1450 kg/m^3 , the cohesion is 70 Pa and the internal friction angle is 40°–45°.

The solution of colloidal silica is a kind of liquid composed of dispersed colloidal amorphous silica (SiO_2) diluted and mixed with a reagent. This reagent is generally a salt solution (NaCl solution used in this test) that causes irreversible solidification of solution. In our study, the nano-silica used is Levasil 300/30%. Density is 1300 kg/m^3 , particle size is 11 nm–40 nm, and pH is 10. (Iler 1975) proposed the hypothesis about the formation of bonds between silica particles through cations. In an aqueous solution, water molecules are adsorbed against sodium by their oxygen atoms (see Fig. 1).

A constant volume ratio of 1/4 between saline solution and nano-silica was kept. Two saline solutions with different concentrations were prepared to control the gelling time: 75 g/L and 95 g/L which were diluted by water. The choice of the two saline solutions with different concentrations was depending on the mechanic properties and the setting time. The setting time was 60 min ($C_{\text{NaCl}} = 75 \text{ g/L}$) and 30 min ($C_{\text{NaCl}} = 95 \text{ g/L}$) at 20° C, respectively. The LN (75 g/L) was noted for formula1: nano-silica + NaCl (75 g/L), while LN (95 g/L) for formula2: nano-silica + NaCl (95 g/L).

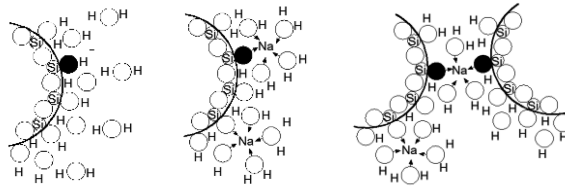


Fig. 1. Coagulation of silica particles in the presence of cations (large circles are oxygen atoms).

3 Laboratory Procedure

3.1 Environments Conditions

Four kinds of conservation environments were controlled (favorable or aggressive to the binders): for samples conserved in air, the relative humidity is 50%, and actually the dry atmosphere might be unfavorable to the stability of silica and silicate gel because of evaporation of water; for samples conserved in water, the samples were immersed in water after gelling, and this environment could be favorable due to humidity retention or unfavorable due to gel dissolves; for samples conserved in saline solution, NaCl solution concentration was 1 g/L, and this environment was studied in case that ground soil reinforced by chemical binders perhaps immersed in seawater, chloride ion could be aggressive to binders; for samples conserved in acid solution, pH was adjusted to 4 using sulfuric acid, and this case was for studying acid environments in contrast with the proprieties of alkaline gel. During these tests, the temperature of all the environments remains 20 °C, while the distilled water was adopted for water used in all solutions.

3.2 Unconfined Compressive Strength Test

Simple compression tests were performed on a T5K LLOYD, a kind of electric press with a capacity ranged from 500 N to 5 kN. An overview of the experimental device is shown in Fig. 2.

Compressive stress was measured through a force sensor placed on the upper base of the test piece and fixed to the press frame. It was considered that the deformation of the cylindrical samples corresponds to the displacement of the upper press plate.

The displacement and the force were recorded every 5 s. The test was controlled in movement at the velocity of 0.3 mm/min. The test was stopped when the force measured by the sensor decreased by at least 10% compared with the largest measured force. Throughout this test, the measured displacement was one of the high plateaus, so we would get an overall measurement of displacement.

Columns (5.2 cm in diameter and 10 cm in height) were filled with a mixture of FBS consolidated by Levasil 300/30%. The binders occupied 25% of the pore volume of the matrix of granular sand. In order to get reasonable time of IE and approach to the reality of consolidated soils, the columns were prepared by successive layers of 2 cm after compaction that was achieved by dropping a circular (256.5 g) so as to obtain a homogeneous density of $1.6 \text{ g}\cdot\text{cm}^{-3}$ at each level. Then the columns were stored in



Fig. 2. Coagulation of silica particles in the presence of cations (large circles are oxygen atoms).

four different environments: dry atmosphere (50% humidity), pure water, saline solution and acid solution. Preservation time was 1 day, 7 days, 15 days, 30 days, 90 days, 180 days and 365days.

3.3 Internal Erosion Test

The sample preparation was the same as compression test. In this study, erosion under constant head water was used to finish the erosion test (Figure 3).

In the system of constant head, the water level was set from which an injection pressure was constant. The maximum water flow rate entering the cell mortar was regulated by the valve at the top. A tank was used to collect and lead water discharged to the water discharge system in the lab. The effluent samples (40 ml) were collected regularly to monitor the permeability distribution of nano-scale particles, the mass eroded, conductivity and pH after erosion over time.

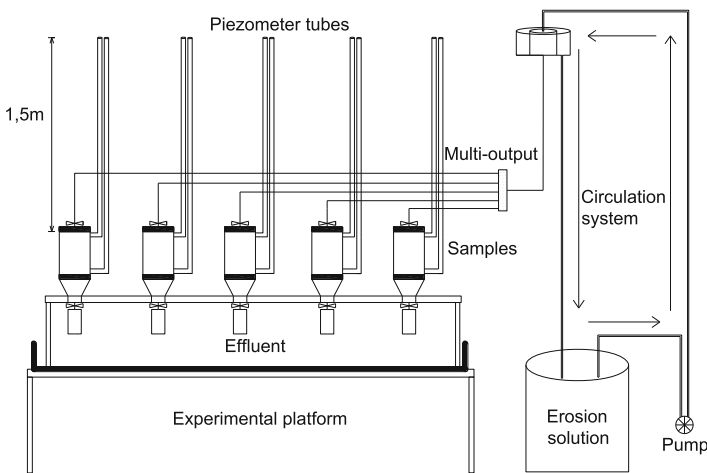


Fig. 3. Schematic diagram of erosion test under constant head

Before test, it was important to decide the experimental conditions that serve the objective. Preliminary tests were carried on to define the imposed pressure, the maximum flowing entering the device and the preservation time. An average pressure of no more than 0.15 bar was obtained to avoid liquefaction. The suitable entering flow of 30 ml/min was proved to make the mortar erodible and non-self-locking. The preservation time was set as 1 day to 365 days. The duration of erosion was tested for one week from the beginning to the collapse of mortar.

4 Results and Discussion

4.1 Unconfined Compressive Strength

Figure 4 shows unconfined compressive strength of two formulas in different environments.

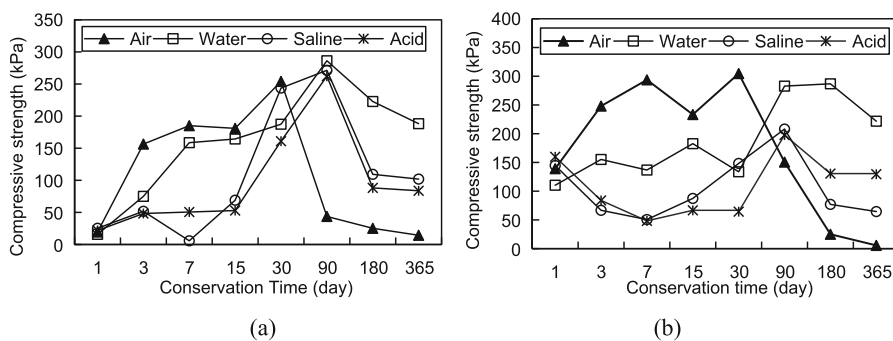


Fig. 4. Compressive strength of LN (75 g/L) and LN (95 g/L)

The maximum compressive strength of LN was 300 kPa for one year. This nano-silica reinforced has no strong resistance, thus it is suitable for filling the pores of sand but not suitable for enhancing mechanical property.

With the increase of NaCl concentration, the resistance does not change a lot. After 1 day of storage, the mortars of LN (95 g/L) have a greater resistance than those of LN (75 g/L). After 1 year of conservation, two formulations have almost the same resistance.

For both formulations stored in air, the resistance increases enormously during the first 3 days, then shows a slight increase from 3 days to 30 days. After 30 days, two formulations show a drop in mechanical strength.

For both formulations stored in water, the resistance increases gradually during the first 90 days, and it decreases gradually after that.

In salty and acid environments, the resistance of LN (75 g/L) increases gradually during the first 90 days, then a drop appears in the mechanical performance. The resistance of LN (95 g/L) decreases in both environments during the first 7 days, then increases from 7 days to 90 days, and a drop in mechanical strength is observed after 90 days.

By summarizing the above, the conservation condition seems the most important parameter for the mechanical strength of mortars made in our experimental study, the air is the most aggressive environmental conservation, the salt and acid environments have less effect on this type of nano-silica, and the environment of pure water has the least effect on this type of nano-silica.

4.2 Internal Erosion Test Under Constant Head Water

Erosion time was measured from the beginning of water injection till the collapse of mortar, which is varied from a few minutes for more fragile samples to a few weeks for more consolidated samples. The result of erosion time of LN (75 g/L) and LN (95 g/L) is shown in Fig. 5.

From Fig. 5, it can be seen that the longest erosion time of LN (75 g/L) was 400 h for 1 year’s conservation, while the longest erosion time of LN (95 g/L) was 510 h for 1 year’s conservation. With the increase of NaCl concentration, the samples have a better capacity to resist erosion.

For both formulations stored in water, the erosion time increases gradually during the first 90 days, and then decreases gradually after that.

For samples conserved in pure water, the erosion time of LN (75 g/L) increases gradually with the increase of conservation time from 1 to 90 days. After 90 days, the erosion time of LN (75 g/L) tends to be stable. From 1 to 30 days, the erosion time of LN (95 g/L) increases gradually with the increase of conservation time. After 30 days, the erosion time of LN (95 g/L) tends to be stable, which indicates that both formulations have a good ability to resist erosion after 1 year of conservation; and the erosion time tends to be stable earlier for LN (95 g/L).

For samples conserved in saline solution, the erosion time of LN (75 g/L) increases gradually with the increase of conservation time from 1 to 365 days. From 1 to 30 days, the erosion time of LN (95 g/L) increases gradually with the increase of conservation time. After 30 days, the erosion time of LN (95 g/L) tends to be stable, which indicates that both formulations have a good ability to resist erosion after 1 year of conservation; The erosion time tends to be stable earlier for LN (95 g/L), we have got the same conclusion in cases of dry environment and pure - water environment.

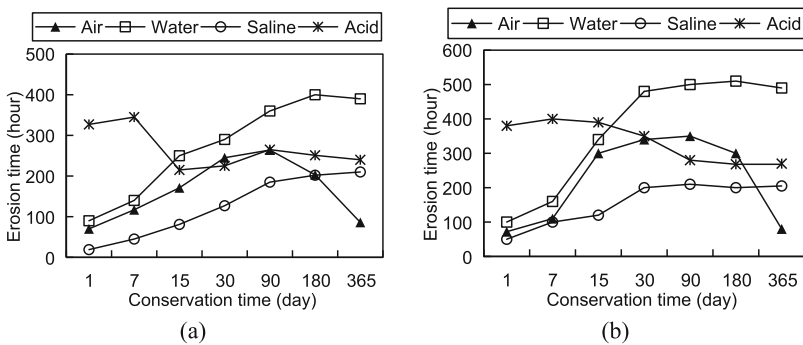


Fig. 5. Erosion time of LN (75 g/L) and LN (95 g/L)

For samples conserved in acid solution, the erosion time decreases with the increase of conservation time. Generally speaking, the capacity of insist erosion of LN in acid environment is good.

Through summarizing the above, the ranking of favorable degree of the four environments is: Pure water > Saline > Acid > Dry air.

5 Conclusions

By analyzing the results of compressive strength and capacity of resist erosion respectively, we have gotten the influence of environments on LN during long time and some same conclusions from two tests: conservation condition seems the most important parameter for the mechanical strength of mortars made in our experimental study. Air is the most aggressive environment, salt and acid environments have less effect on this type of nano-silica, and pure water is the most favorable for this type of nano-silica.

It is worth noting that the influences of long time on compressive strength and capacity of erosion are not completely consistent. In dry air, the compressive strength and capacity of erosion are basically consistent over time, and the values increase first then decrease. In pure water and saline solution, the compressive strength increase first then decrease, while the capacity of erosion is better over time. In acid environment, the compressive strength increases first then decreases, while the capacity of erosion becomes worse over time.

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