

CHEMICAL STABILIZATION OF LOESS SOILS

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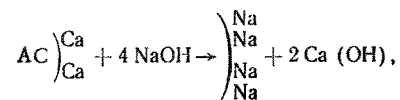
Construction of buildings and structures on collapsible soils, which is acquiring increasing importance in our country, is still an imperfectly solved problem. A chemical stabilization method for loess soils — silication — which speaks well for itself, is not fully suitable for solving the problem raised, since it calls for considerable quantities of sodium silicate, which is in short supply. In particular, the problem is complicated when it is necessary to silicate a loess soil throughout the entire collapsible mass if its depth exceeds 20 m.

From investigations carried out at the Scientific-Research Institute of Bases and Underground structures it was found that the bearing capacity of collapsible loess soils can be significantly increased by chemical stabilization by introducing into them, jointly with the wetting water, small quantities of cheap and readily available alkaline reagents capable of activating and mobilizing the loess soil's reserves of colloidal silicic acid, limes, and aluminum hydroxides with formation of time-stable cementing substances.

Because of their characteristics, the interaction reactions of an alkali with active alumina and silicic acid are similar to topochemical reactions. As is known, topochemical reactions take place in the solid phase, when the process is localized at the boundary of the starting solid material — the solid product of the reaction. Since the topochemical reactions take place within the limits of the interphase surface, the process rate is proportional to the magnitude of this surface at each instant of time. In many cases, the stabilization process depends not on the chemical reaction rate but on the rate of diffusion of the reacting atoms or ions through the layer of the new product formed.

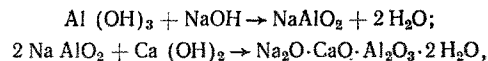
During the process of interaction of the alkaline solutions with the loess soil clay fraction the following basic reactions of formation of the complex binder which cements the soil take place.

1. Exchange reaction between absorbed calcium cation of loess soil and sodium or ammonium cation of introduced reagent:

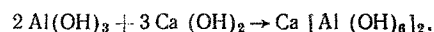


in which AC is the absorbing complex of the loess soil.

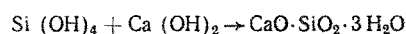
2. Interaction of hydrated alumina with liberated hydrate of calcium oxide:



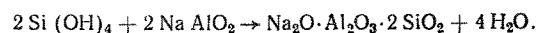
as well as



3. Interaction of hydrated silica with  $\text{Ca} (\text{OH})_2$



and with sodium aluminate:




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Scientific-Research Institute of Bases and Underground Structures. Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, No. 4, pp. 8-11, July-August, 1984.

TABLE 1

Soil designation	Absorption capacity in a 1 N solution of NaOH, mg-equiv., per 100 g of soil	Quantities of introduced components per 100 g of soil, mg		Quantities of absorbed components in mg per 100 g of loess soil					
		Na <sub>2</sub> O	SiO <sub>2</sub>	exposure time					
				7 days		28 days		3 months	
		Na <sub>2</sub> O	SiO <sub>2</sub>	Na <sub>2</sub> O	SiO <sub>2</sub>	Na <sub>2</sub> O	SiO <sub>2</sub>	Na <sub>2</sub> O	SiO <sub>2</sub>
Tashkent	12,5	194	582	109	450	113	462	122	470
Dushanbe	14,6	164	492	86	377	94	384	96	410
Kishinev	20	164	492	98	410	100	440	113	460

TABLE 2

Soil designation	Reagent designation	Conc., %	Strength (MPa) at stabilization time		
			28 days	6 months	24 months
Tashkent	Water Sodium silicate	2	0,07	0,09	0,09
		3	0,13	0,18	0,19
Dushanbe	Water Sodium silicate	2	0,08	0,09	0,10
		3	0,13	0,15	0,17
Kishinev	Water Sodium silicate	2	0,09	0,11	0,12
		3	0,13	0,15	0,17
Volgodonsk	Water Ammonia	3	0,08	0,11	0,13
		5	0,12	0,23	0,24
		7	0,18	0,31	0,46
			0,23	0,42	0,61

For interaction of the alkaline solution of the sodium silicate with the hydrated silica of the loess soil, depolymerization of the latter takes place. When the value of the pH in the alkaline medium is less than 10.5, there is active polymerization of the silicic acid with formation of a cementing gel, which develops on (takes upon) the hydrated silicic acid distributed on the clay particle surfaces.

Thus, in the complex of the presented reactions, as intermediate and end products cementing substances are formed which are capable of imparting to the soil a sufficiently high stability in water and of increasing its strength.

Laboratory tests were performed on stabilization of Tashkent, Dushanbe, and Kishinev loess soils by 2 and 3% solutions of sodium silicate, as well as on Volgodonsk loess soils by 5 and 7% water solutions of ammonia.

The investigations were carried out on samples of artificial structure which were prepared from loess soil powdered and sifted through a sieve with 1-mm openings. The samples, which had the same water content and density, were soaked with the reagents and placed in a chamber with an air-wetted medium and, after specified periods of time, when they were brought to a specified water content (0.22), their strength was tested, compression tests were performed on them, and their overall composition was determined by the sieve method in water.

The samples, soaked with a sodium silicate solution having a density of 1.02 g/cm<sup>3</sup>, were subjected to investigations intended to determine their absorption of sodium silicate solution with time. The investigations showed that the silicic acid introduced into the loess soils as part of the sodium silicate solution is absorbed by them in the amount of 80-94%, a process in which it passes into an irreversible form, while the Na<sub>2</sub>O is absorbed within the limits from 55 to 70%. The quantitative absorption of sodium silicate solution is determined

TABLE 3

Soaking reagent	Strength (MPa) at indicated water content		Modulus of deformation (MPa) at indicated water content		Cohesion (MPa) for indicated plate diam. m		Rel. collapsibility at indicated sampling depth, m	
	0,15	0,22	0,15	0,22	0,012	0,049	4	6
Water	0,321	0,193	28,0	14,0	0,038	0,049	0,042	0,040
Sodium silicate, $\rho = 1,02 \text{ g/cm}^3$	0,480	0,289	38,0	19,0	0,097	0,097	0,0025	0,0026

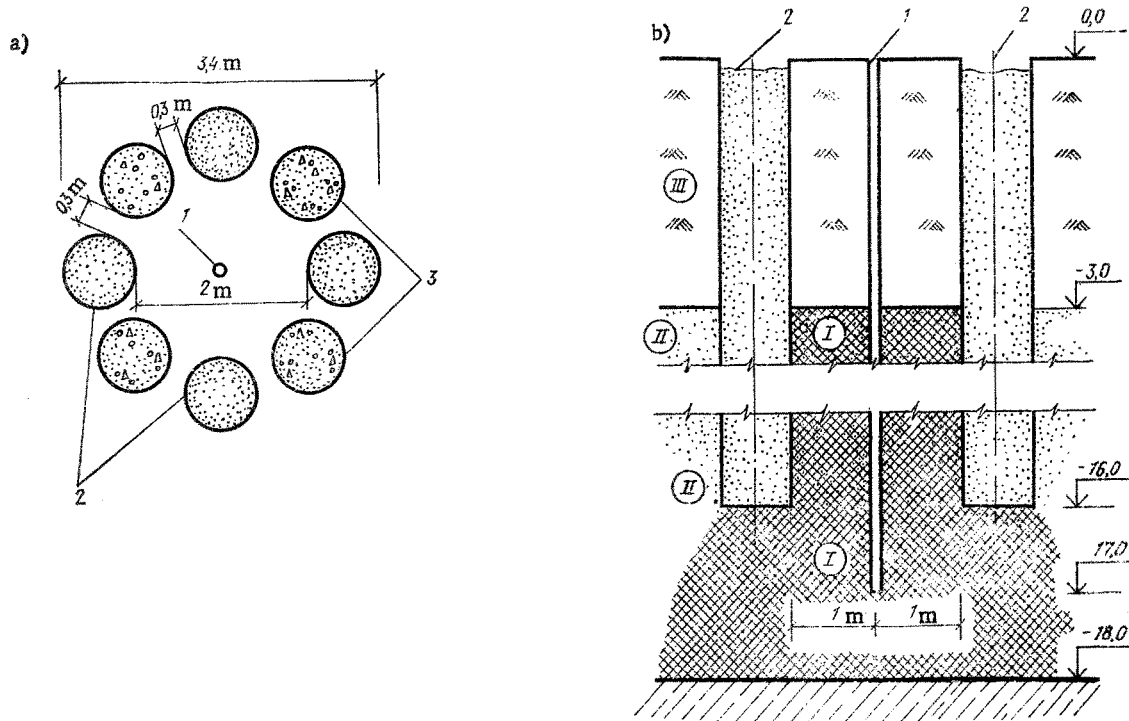


Fig. 1. Trench arrangement. a) Plan; b) section. 1) 127-mm-diameter grout hole) 2, 3) 700-mm-diameter holes filled with loam and sand respectively. I) Loess loam layer soaked with solution or water; II) loess soil having natural water content; III) surcharge soil layer.

by the loess activity and the absorption capacity in the alkaline medium. The absorption of silicic acid and alkali by the loess soils with time increases (Table 1).

The compression tests of the samples soaked with sodium silicate solution showed that their settlement under a load of 0.15 MPa is smaller by a factor of 2-3 than in nonstabilized samples made from the same soils, whereas when they are soaked with ammonia solutions the corresponding settlement is smaller by a factor of 2-5. For further loading the settlements of the stabilized samples are smaller by a factor of 2-10 than in nonstabilized samples.

In the water-sieve analysis, the nonstabilized samples fully disintegrate to particles whose diameter is less than 0.25 mm. In stabilized samples, the quantity of water-stable particles larger than 0.25 mm in diameter for soaking with sodium silicate solutions amounted to 20-77%, whereas for soaking with ammonia solutions it amounted to 89-96%.

The processes of increase, with time, of the compressive strength of samples stabilized with sodium silicate and ammoniacal water solutions differ appreciably. From Table 2 it follows that the soil samples stabilized with sodium silicate solutions after just one month gathered more than 50% of the strength of the samples subjected to 2-yr exposure, whereas the soil samples stabilized with water solutions of ammonia had after 1 month following soaking 10-15% of the strength only after 6 months. The strength of nonstabilized soils (wetted with

TABLE 4

Loess soil state	Sampling depth, m	Distance from injector	Rel. collapse for indicated pressure, MPa				Initial collapse pressure, MPa	Modulus of deformation soil, MPa		Shear strength (MPa) for indicated pressure (MPa)		
								at natural water content	water-saturated	0,1	0,2	0,3
			0,1	0,2	0,3	0,4						
Before stabilization	2		0,001	0,012	0,020	0,018	19,1	5,6	0,060	0,070	0,100	
	3		0,012	0,025	0,041	0,053	34,0	5,6	0,070	0,100	0,150	
After stabilization	2	0,33	0,000	0,000	0,000	0,001	97,5	54,2	0,070	0,100	0,146	
	2	0,66	0,001	0,001	0,001	0,001	46,4	28,3	0,080	0,110	0,150	
	2	1,33	0,002	0,003	0,005	0,005	65,0	30,5	0,080	0,110	0,160	
	3	0,33	0,000	0,000	0,001	0,001	115,8	86,2	0,100	0,100	0,140	
	3	0,66	0,001	0,001	0,000	0,000	99,0	42,5	—	—	—	
	3	1,33	0,003	0,006	0,008	0,010	119,8	45,9	—	—	—	

water) was lower by a factor of 1.5-4 than the strength of the stabilized soils (Table 2).

To determine the effectiveness of stabilization of loess soils by soaking them with water containing small amounts of sodium silicate solution, tests were performed at a site in Volgodonsk.

From the site surface to a depth of 23 m there are loesslike yellow-brown loams of deluvial origin with a cellar topsoil level, underlain by a mass of alluvial sand-clay deposits. The area falls into type II collapsibility soil conditions with a collapse of up to 0.32 m of the soils under their dead weight when wetted. Groundwater occurs at a depth of 16-17 m.

At a depth of 4-6 m, the loess soil contains about 2.5% of gypsum concentrations, by volume. In the gypsum concretions, from 37 to 44% of gypsum and from 7.6 to 8.2% of calcium carbonates are contained. The gypsum content in the soil itself does not exceed 2%, amounting most commonly to 1.8%, and the calcium carbonate content is 11.6%.

The absorption capacity in a 1 N solution of caustic soda corresponds to 30 mg-equiv. per 100 g of dry soil. The soil contains 1.13% of active alumina and 3.48% of silica. Because of its absorption capacity and quantity of active alumina and silica, the loess soil from the site is highly active with regard to silication and chemical stabilization.

Field test work was carried out in accordance with an accelerated method of determination of the collapsibility of loess soils by wetting trenches of small area, worked out at the Scientific-Research Institute of Bases and Underground Structures by V. I. Krutov and I. K. Popsuenko.

At the site, two trenches 5 m<sup>2</sup> in area each were equipped: the first for accelerated soaking with sodium silicate solution 1.02 g/cm<sup>3</sup> in density, and the second for soaking with water. For partial cutting of the trenches from the surrounding soil having natural water content, outline holes 0.7 m in diameter and 16 m deep were drilled along their perimeters at spacings of 1.0 m (Fig. 1). The cutting area amounted to 68%. Every other hole was filled with well-rounded fine sand, and the other holes were filled with local dried loam having a plasticity index equal to 9.

To force the solution of sodium silicate and water at the trench center, drainage holes, 0.127 m in diameter and 17 m deep, were drilled which were equipped with pneumatic plugs designed by the Rostov Promstroiniproekt Institute. For observations on the soil collapse within the limits of the trenches and in the area surrounding them, surface marks were installed.

To eliminate the soil seepage irregularity along the horizontal, and also to accelerate the soaking, forcing of the solution was performed at a pressure of 0.15 MPa in two runs of 7 m each, by the "upward" method with simultaneous wetting from the trench and the outline holes.

Before pumping of the upper run, the lower was filled with sand mixed with local loam. In each run, 36 m<sup>3</sup> of reagent was pumped in 5 h. Through the trench and the outline holes, 80 m<sup>3</sup> of reagent was caused to seep. For soaking the first trench, 152 m<sup>3</sup> of sodium silicate solution having a density of 1.02 g/cm<sup>3</sup> was used, and for the second trench 152 m<sup>3</sup> of water (taking into account the evaporation losses) was used, which is significantly greater than the volume required for wetting and full development of collapse under the soil dead weight.

The observations showed that in the area adjoining the trench no collapse occurred. The collapse of the outline holes filled with sand was 1-1.5 m, and the collapse of the holes filled with loam was 0.2-0.5 m. This collapse took place during the first days of soaking of the trenches. Along the perimeter of the trench filled with water, small steps 0.1 m high were formed. The cracks were ring-shaped.

The greater part of the collapse in the trenches occurred during the first week after soaking and amounted to 0.002-0.033 m in the first trench and 0.064 to 0.163 m in the second, that is, it was greater by a factor of several orders of magnitude in the latter than in the former.

The results of the physicomechanical tests of samples taken from the soil masses soaked with the solution of sodium silicate and water are presented in Table 3

The strength of the soil stabilized by the sodium silicate solution was higher by a factor of 1.5 than the strength of the soil soaked with water, the modulus of deformation

being higher by 30-35%, and the soil cohesion, determined by N. A. Tsytovich's spherical plate method, being higher by a factor of two. The relative collapsibility of the stabilized soil decreased by a factor of more than 15.

In the stabilized soil, the amount of water-stable particles of diameter larger than 7 mm increased by a factor of 3.5, and the content of the fraction of size smaller than 1 mm decreased by a factor of 6.

The stabilization of collapsible loess soils by water solutions of ammonia was carried out by the Zaporozhpromstroï Trust at the construction site of a cattle-breeding complex in Zaporozhe, with the participation of V. A. Gubkin (KhIMÉSKh). The construction site falls into type II collapsibility soil conditions. Collapsible loess soils occur to a depth of more than 15 m and have the following characteristics: liquid limit, from 0.29 to 0.39; plastic limit, from 0.22 to 0.24; plasticity index, from 0.09 to 0.13; natural water content, 0.12-0.18; density, 1.56-1.69 g/cm<sup>3</sup>; specific gravity, 2.69-2.72; dry density, 1.36-1.45 g/cm<sup>3</sup>; porosity, 0.49-0.69; void ratio, 0.80-0.96.

To soak the soil, holes 0.127 m in diameter and 4 m deep were drilled in which injector plugs were installed. Through these holes, an 8% ammonia solution was pumped at a pressure of less than 0.1 MPa in the amount of 0.33 m<sup>3</sup> of solution per 1 m<sup>3</sup> of soil to be stabilized.

Six months after soaking the soil mass, a test pit was driven and samples of the stabilized soil were taken which were tested at the laboratory of the Zaporozhe branch of the "Ukrvostok-GIINTIZa." The test results, presented in Table 4, indicate the high quality of the soil stabilization. Thus, the grout propagation radius reached 1.5 m. Collapse of the stabilized soil under a pressure of 0.4 MPa at a distance of 0.66 m from the injector did not occur and only at a distance of 1.33 m it reached 0.010 m, which is lower by a factor of 5.3 than in nonstabilized soil. After stabilization, the modulus of deformation of soil having natural water content increased significantly: at a distance of 0.33 m from the injector by a factor of 3-5, at a distance of 0.66 m by a factor of 2-2.5, and at a distance of 1.33 m by a factor of more than 2. On the other hand, for water-saturated soil at the same distances from the injector, the modulus of deformation increased by factors of more than 10, 7, and 6, respectively.

The stabilization work was carried out using standard soil silication equipment: an installation for drilling holes 60-130 mm in diameter to a depth of 30 m or machines for driving and extracting injectors, and pumps for pumping the solutions at a pressure of up to 5 atm and with a discharge of up to 30 m<sup>3</sup>/h.

The cost of stabilization of 1 m<sup>3</sup> of soil at the test sites was less than 4 rubles.

#### CONCLUSIONS

The theoretical investigations, laboratory experiments, and test control under field conditions showed that loess soils can be effectively stabilized without introducing a binder into the soil, on account of drawing-in, into the exchange reactions in the alkaline medium, of calcium from the absorbing complex of the soil, as well as active silicic acid and alumina from the clay minerals contained in the loesses, with formation of a cementing binder.