

# SODIUM SILICATE STABILIZATION OF SOILS: A REVIEW OF THE LITERATURE

Claude H. Hurley, Consulting Engineer; and  
Thomas H. Thornburn, University of Illinois

This report consists of an annotated bibliography and summary review of the important literature on the use of sodium silicates in soil stabilization processes. Annotations are given for approximately 90 articles published between 1931 and 1965. On the basis of these articles the authors have summarized pertinent information on stabilizer properties, reaction mechanisms, injection methods of soil solidification, properties of stabilizer-soil mixtures, and use of sodium silicates as dustproofers and water-proofers and as secondary additives with other stabilizers. There is some evidence that sodium-silicate stabilization can increase the strength and durability of sandy soils or even relatively nonplastic fine-grained soils under mild climatic conditions; however, there is almost no field evidence to justify its use when the stabilized material is subjected to the freezing and thawing cycles typical of temperate-to-cold climates. Sodium silicates with or without the addition of precipitants are of little value in dustproofing or waterproofing fine-grained soils. On the other hand, laboratory tests seem to indicate that sodium silicate used as an additive can improve the strength and durability of soils stabilized with portland cement, lime, or lime-fly ash.

•THIS REPORT is the final one of a series on the chemical stabilization of soils. It is limited to a review of existing literature on soil stabilization with sodium silicate compounds. No original or laboratory investigations were conducted. Similar reports on lime (1), phosphoric acid (2), and inorganic salts and bases (3) have been completed and published. The prime objectives are to acquaint the highway engineer with the present state of the art and to suggest whether the subject appears to hold promise as an area of future research.

Within the limitations of available information, the report describes stabilizer properties, stabilization mechanisms, physical properties of stabilized mixtures, construction methods, and use of sodium silicate as a secondary additive. The opinions expressed were arrived at primarily from the study of the literature. We believe that the annotated bibliography includes all articles that deal directly with sodium silicate stabilization from 1930 to January 1965. Most of the articles listed were published since 1940.

Practically all of the early articles and many of the later ones refer to the use of sodium silicate as a chemical grout to stabilize sands in place or to reduce their permeability. Although such techniques are important, there is no direct relationship between the results obtained (often temporary) and the requirements for highway usage where the stabilized material is exposed to repetitive loads and climatic variations. When articles of this type are eliminated from consideration, the useful literature is meager indeed.

The literature also includes some publications on the use of sodium silicates in the manufacture of bonded sand molds and cores for casting molten metals. A review of several of those indicated that the temperatures employed are above the range commonly

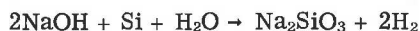
encountered in nature. Consequently, it was felt that those publications were not of particular value to the discussion of soil stabilization; thus, they were not thoroughly investigated.

## SODIUM SILICATES

Sodium silicates constitute a group of chemicals that possess a wide range of physical and chemical properties. They are used in industry as adhesives, cements, detergents, deflocculants, protective coatings, rust inhibitors, catalyst bases, cleaning compounds, and bleaching agents. Silicates are produced at various alkali,  $\text{Na}_2\text{O}$ , to silica,  $\text{SiO}_2$ , ratios, water contents, and particle sizes depending on their proposed use. They are usually derived from the relatively abundant raw materials of silica, sodium salts, and water. Manufacturers have widely distributed outlets for the products; therefore, sodium silicates are readily available and are easily obtained in various packages for commercial use. Vail has prepared what appears to be the most comprehensive treatise on the manufacture, properties, and uses of the soluble silicates (4).

### Manufacture

Sodium silicates may be prepared in a number of ways. Several so-called wet processes include the solution of infusorial or diatomaceous earth in the alkaline hydroxides with relatively poor quality and product control. The reaction between ferrosilicon, manganosilicon, or silico speigel and concentrated sodium hydroxide can be simply expressed as



and the reaction of sodium hydroxide and silicon carbide as



Both of these processes involve relatively high cost. The silicates have also been prepared by reactions of sodium hydroxide with residues of the extraction of metals such as aluminum, beryllium, and tungsten from their respective silicate minerals.

Most of the sodium silicate made in the United States is produced by fusing a specially selected sand,  $\text{SiO}_2$ , and soda ash,  $\text{Na}_2\text{CO}_3$ , at high temperatures in open-hearth furnaces. The resulting product is a molten glass that can be allowed to solidify and then ground into various particle sizes. It most commonly has a composition ( $\text{Na}_2\text{O}:\text{SiO}_2$ ) of 1:3.3. The molten glass may also be dissolved in steam under pressure to produce silicate solutions at various desired concentrations.

Other dry methods of preparing the silicates include the fusion of sodium nitrate, sodium hydroxide, or metallic carbonates with silica. In Europe the reaction of sodium sulfate, carbon, and silica when fused is most commonly employed.

### Types

Theoretically, alkali and silica may be combined in all proportions, but present products do not exceed a silica to alkali ratio of about 4 to 1 by weight because of the very low solubility of fused silicates above this ratio. The soluble silicates range physically from readily and highly soluble crystals to lumps of transparent glass that are sparingly soluble even in boiling water and from slightly sticky fluids of the consistency of maple syrup to heavy viscous materials that barely flow. The available commercial products marketed by any one company usually range from 15 to 30 silicate solutions and 5 to 15 anhydrous silicates.

The silicates of greater alkalinity than  $\text{SiO}_2:\text{Na}_2\text{O} = 1.60$  are definite crystalline salts of fixed composition and can be identified by specific chemical formulas, listed in order of decreasing alkalinity as follows:

<u>SiO<sub>2</sub>:Na<sub>2</sub>O</u>	<u>Name</u>	<u>Formula</u>
1:2	Sodium orthosilicate	Na <sub>4</sub> SiO <sub>4</sub>
2:3	Sodium sesquisilicate	Na <sub>6</sub> Si <sub>2</sub> O <sub>7</sub>
1:1	Sodium metasilicate	Na <sub>2</sub> SiO <sub>3</sub>
2:1	Sodium disilicate	Na <sub>2</sub> Si <sub>2</sub> O <sub>5</sub>

Silicates that are less alkaline than metasilicate form colloidal solutions. Because a molecule of Na<sub>2</sub>O weighs about the same as a molecule of SiO<sub>2</sub>, the molecular ratio and weight ratios are very nearly equal. Consequently, it has become standard practice to use weight ratios for sodium silicates that are more siliceous than metasilicate (1:1). The range in weight ratio, SiO<sub>2</sub>:Na<sub>2</sub>O, currently available is about 3.75 to 1.60. These solutions are obtainable in concentrations from 35 B to about 59 B at 68 F.

The silicate most commonly employed in the treatment of building materials is a solution known as water glass that has a silica:alkali ratio of about 3.22 and is sold at a density of about 41 B at 68 F or a specific gravity 1.394.

### Properties

Sodium silicate solutions are clear, colorless, and odorless. They are nonflammable and, in terms of a health hazard, act like a strong soap. Silicates in the eye are painful and should be flushed immediately with water. Although considered nontoxic, accidental swallowing may cause stomach upset. These are the significant hazards to be guarded against when the silicates are being used.

If kept in an airtight container, silicates will not deteriorate during extended periods of storage. The containers must be made of steel or other nonreactive materials. Aluminum, galvanized iron, or zinc containers must not be used because of the possibility of forming hydrogen gas that upon expansion could possibly burst the containers. Silicates react slowly with glass, absorb carbon dioxide from the air, and lose water by evaporation. These factors cause a considerable change in viscosity with time; therefore, a discard date accompanies those samples stored in glass containers (5).

The colloidal nature of the common liquid silicates is indicated by the fact that their boiling point is only slightly higher and their freezing point slightly lower than those of water. The 41-B silicate freezes at only 1 or 2 deg below the point that water freezes. In freezing there is a rapid growth of long crystalline masses that contain a high content of water. These crystals tend to float when the solution is warmed, and it often happens that drums or tank cars of sodium silicate when frozen and then thawed will contain highly concentrated silicate at the bottom and a relatively dilute solution on the top. Vigorous agitation or pumping will provide enough mixing action so that the solution will be identical in all characteristics to the original.

The concentration of solids in the liquid silicates and the SiO<sub>2</sub>:Na<sub>2</sub>O ratio greatly affect pertinent properties of the materials. As the solids concentration increases, the viscosity and the specific gravity of the solution increase. The more concentrated the solution is, the smaller the coefficient of expansion is. For a given total solids concentration, the solution with the greater alkali ratio has the higher specific gravity. The viscosity, however, shows a pronounced minimum at a ratio of about 1 Na<sub>2</sub>O:2 SiO<sub>2</sub> and tends to increase rapidly as the alkalinity increases or decreases from this ratio. In general, the density of the solutions decreases with increasing temperature.

The alkali activity of sodium silicate solutions is affected by several factors. The pH value of the available silicates lies in the range of about 11 to 13. The pH decreases with increasing silica content. As the solids concentration of a given alkali:silica ratio is increased, the pH increases rapidly at low concentration but levels off at concentrations above about 50 percent. The high pH of the solutions is maintained as acids are added until the alkali is almost completely neutralized. The buffer capacity of the solutions increases with increasing proportions of soluble silica. Hence, within limits the silicate solutions will maintain a fairly constant pH despite the addition of acid.

## REACTION MECHANISMS

In general, the physical properties of sodium silicates control their binding power. These properties may be altered with the use of physical or chemical or combined methods. The relative amounts of soda or silica in sodium silicate solutions may be changed by altering the basicity of the solution with additions of other chemicals. As a result a silica gel is usually formed. For instance, a sand-sodium silicate mixture is hardened in the ceramics industry as carbon dioxide gas is passed through it (6). Also, the viscosity of a solution may be increased by the application of heat or low pressure until gelation occurs and the silicate is essentially solid (7, 8).

The following discussion of the materials that cause precipitation of silica as silicic acid, the reactions that result in the formation of a complete gel, and the factors that control the character of the gel is based on the authors' interpretation of the information contained in numerous reports, especially those of Terzaghi (9), Vail (4), Iler (10), du Pont (11), and Philadelphia Quartz (5).

### Formation of Silica Gel

All sodium silicate is alkaline in reaction. When a silicate solution is mixed with a solution of an acidic material, the mixture becomes opalescent; and, if the silica concentration is above 1 or 2 percent, silicic acid is precipitated and gelation occurs. Solutions with a lower silica concentration form silica sols whose highly hydrated colloidal particles are negatively charged except in moderately concentrated solutions.

Several classes of materials react with sodium silicate to form sols or gels. All acids or acid-forming materials such as chlorine, sulfur dioxide, ammonium salts, bisulfates, sodium silicofluoride, and bicarbonates are examples. Precipitation or coacervation may be produced by various liquids that tend to dehydrate the silicate solution. For instance, alcohol, glycerin, salt brine, and strong ammonia solutions will precipitate concentrated solutions of sodium silicate. Such precipitates are soluble. Organic materials such as casein, rubber latex, cane or beet sugars, and starch as well as certain organic synthetic resins are compatible with sodium silicate and are combined for certain uses such as on adhesives or coatings.

Sodium aluminate, zincate, and plumbate solutions also form gels with soluble silicates. Sodium silicate is precipitated by most salts of the heavy metals such as calcium, magnesium, aluminum, titanium, copper, and lead. These precipitates are believed to contain silicic acid along with metallic silicate. The insoluble metallic silicates have bonding power that has been investigated and employed most extensively in the treatment of building materials.

### Character of Silica Gel

When a solution of a polyvalent metal salt is mixed with a solution of a soluble alkali metal silicate, such as sodium silicate, an insoluble metal silicate is usually precipitated as a gelatinous amorphous mass. Essentially all natural silicates are amorphous when precipitated from aqueous solution.

In a crystalline metal silicate, metal ions and silicate ions of uniform size and shape are arranged in a regular manner in a solid lattice or framework characteristic of the ionic sizes and charges. However, most solutions of soluble silicates do not contain silicate ions of uniform size. Instead they are a mixture of polysilicate ions. Even in the case of highly alkaline metasilicates, which are known to contain monomeric silicate ions, lowering of the pH upon addition of a solution of a metal salt causes rapid polymerization to polysilicate ions. Because the polysilicate ions are not of uniform size, they cannot arrange themselves along with the metal ions into a regular crystal lattice. Thus, when polysilicate ions combine with metal ions, the resulting insoluble precipitate is always amorphous.

Polymerization of basic metal ions is another factor that may interfere with crystallization. When the metal salt is mixed with silicate, the increase in pH in the environment of the metal ions at some point causes the formation of polymeric basic metal ions or colloidal metal hydroxide, which likewise cannot fit into the silicate lattice. Thus,



precipitation of a metal silicate from aqueous solution at ordinary temperatures does not yield crystalline silicates but instead usually results in a colloidal mixture. This may be visualized as an adsorption of metal ions on gelatinous silica or as a mutual coagulation of the positively charged colloidal metal hydroxide and negatively charged colloidal silica. In dilute solutions colloidal metal silicates are precipitated at a slightly lower pH than metal hydroxide alone would be precipitated. This suggests that no definite compounds are formed and that the hydroxides are precipitated along with silica by mutual coagulation. Thus "colloidal silicates" may vary from homogeneous colloidal aggregates of extremely small units of polysilicic acid and metal-hydroxide to heterogeneous masses in which either silica or the metal hydroxide is present as discrete colloidal units, held together by the other component.

Precipitated metal silicates are difficult to characterize physically because they are usually not homogeneous in nature. When one solution is added to the other, at the point of mixing there is no control of the ratios of silicate and metal ions that are brought together; yet the composition of the precipitate as it is formed depends on the ratio of the components in the reaction medium. Homogeneous gels can be formed by keeping the pH low until all the metal salt and silicate solution are mixed. However, when the pH is raised to induce gelation, the gel is still not truly homogeneous. The silica is polymerizing continuously in such a mixture, and the proportion of metal ions bound to the silica particles will vary depending on the degree of polymerization.

Structurally, the silica gel consists of 3-dimensional networks made up of chains of micelles or particles that may range in size from polysilicic acid units each containing only a few silicon atoms to colloidal  $\text{SiO}_2$  particles containing thousands of silicon atoms. The micelles are bonded together into chains, probably by hydrogen bonding. However, in view of the fact that the surface of particles of colloidal silica is composed of  $\text{SiOH}$  groups, it seems very likely that, when these particles come together, consolidation between these groups occurs and  $\text{Si-O-Si}$  bonds are formed between the particles.

From the preceding discussion it should be apparent that soluble sodium silicate is an unstable material and that mixing it with almost any other inorganic material is likely to cause the formation of a silica gel. However, the properties of the gel, such as strength, durability, and permeability, may vary greatly depending on factors such as concentration of the solution,  $\text{Na}_2\text{O}:\text{SiO}_2$  ratio, temperature, and the kind of salts, acids, or bases with which it reacts. Further discussions of the reaction mechanisms will therefore be undertaken in conjunction with the sections relating to its use in soil stabilization.

#### USES OF SODIUM SILICATE IN SOIL TREATMENT

Sodium silicate has been used to improve building materials for more than a century (12). Johann van Fuchs, a pioneer in the commercial development of soluble silicates, proposed in the early 19th century that soluble silicates could be used as a hardening agent for artificial stone. He also recognized the reaction of silicates with calcium compounds. During the 19th century several patents were issued for the manufacture of artificial stones from solutions of silicates mixed with solutions of calcium compounds.

As early as 1910, sodium silicate is mentioned as being used as a dust palliative. The application of a solution of sodium silicate followed by an application of a soluble aluminum or calcium salt causes the precipitation of an aluminum or calcium silicate in voids of the road stone. This led to the development of macadam roads in which the crushed stone was held in place by a cementitious matrix formed by a slurry of finely divided limestone and sodium silicate.

Around 1915, Albert Francois, a French engineer, found that the effectiveness of cement grout could be increased by preceding the grout with an injection of alum followed by sodium silicate. Apparently the resulting slippery gel coats the granular surfaces and causes greater penetration of the cement grout.

Later, a Dutch engineer, Hugo Joosten, injected sodium silicate as a grout into deep foundations and followed that with an injection of calcium chloride. The combination of these 2 chemicals forms an insoluble gel that fills the voids and prevents seepage of water or the continuance of any settlement. This injection method (with modifications)



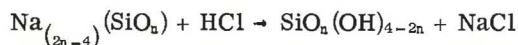
has been extensively used in foundation work and in controlling seepage, but the method is not practical in solidifying the soil within 3 ft of the surface (13). Another injection method, in which the precipitation reaction is much slower, uses a solution containing sodium silicate and sodium bicarbonate. The gel formed is not the insoluble calcium silicate and gradually deteriorates; it does not have the strength of the calcium silicate gel.

The earliest American papers on the use of sodium silicates as soil stabilizing agents appeared in 1945-46 and indicated that the method showed promise (14, 15).

### INJECTION METHODS OF SOIL SOLIDIFICATION

Of the nearly 100 references given in this paper, approximately 40 refer to the use of sodium silicate for the solidification of granular soils, usually at several tens of feet below the surface. Approximately 25 of these refer to the Joosten 2-step injection process or a modification of it and the remainder to the single injection process. One of the most useful bibliographies on chemical grouting was prepared by the ASCE Task Committee of the Soil Mechanics and Foundations Division (16).

The basic ingredient of nearly all silicate injection processes is a solution of sodium silicate in water, known as "water glass." This solution contains both free sodium hydroxide and colloidal silicic acid. The addition of salts or acids can cause the silicate solution to form a gel, for example,



If the acid is replaced by an acid salt, such as calcium or magnesium chloride, a complex metal hydroxide silica gel is formed.

As previously discussed, very little is known about the structure of silica gel. It gives very little or no pattern when exposed to X-rays and is, therefore, considered amorphous. It has a high specific surface (600 m<sup>2</sup>/gram, of the order of magnitude of montmorillonite) and is a very powerful and selective absorbent. On aging the gel shrinks (syneresis), becomes opalescent, and cracks; it dissolves readily in caustic. The life of silicate stabilization when the treated soil is exposed to air or to basic groundwater may be limited (16).

Numerous patents exist concerning variations of the silicate injection process, but the almost complete lack of published experimental and field data prevents even the beginning of the comparison of the many reactions. A single injection treatment has apparently a major advantage over the 2-shot, namely, the extent to which the separate solutions mix is never known. Also, the zone of mixing may in some cases be limited to the end of the injection pipe (16, 17).

On the other hand, the single injection silicate process is subject to many uncertainties. One of the most important of these is selecting the correct proportions in the mix to ensure that gel formation does not occur as the liquid is pumped into the soil but that it does set in a reasonable length of time after pumping is stopped. The appropriate setting time varies with the nature of the soil being injected. For highly pervious material containing groundwater in relatively rapid motion, a setting time as short as 15 min may be desirable. In moderately permeable sand, on the other hand, a longer setting time may be required in order to allow the solution to penetrate the ground to the desired distance from the injection hole (9).

#### Permanence

In general, 3 processes may lead to the deterioration of silica gel contained in the voids of a soil. These are shrinkage due to spontaneous expulsion of water (syneresis), shrinkage due to desiccation, and solution or erosion by groundwater. All types of silica gels undergo syneresis, and laboratory tests indicate the water loss may range from 20 to 60 percent by weight within 2 months. For some gels, shrinkage to nearly 25 percent of the original volume is possible depending on the type of agent and the concentration of silicate in the original solution. If a 1-shot sand-gel is subject to

desiccation, it loses its cohesion and its permeability may increase almost to the original permeability of the sand (9).

Laboratory permeability tests on impregnated uniform sand were conducted with several types of gel under a high hydraulic gradient. All systems showed an initial permeability of  $10^{-7}$  to  $10^{-6}$  cm/sec. With some types of gel the rate of discharge increased several hundredfold in 24 hours, and in most cases the rate of discharge increased with time of percolation. Although admittedly the tests were much more rigorous than field conditions, it can be concluded that gel-impregnated sand subject to a hydraulic gradient (as in a grout curtain) would deteriorate with time because of solution or erosion by groundwater, unless some other process intervened to prevent percolation through the grouted zone (9).

### Compressive Strength

Laboratory tests of impregnated sand indicated that acid gels with 16.5 percent water glass gave strengths 5 to 8 times that of an ultrabasic gel [produced with  $\text{Ca}(\text{OH})_2$ ] containing 45 percent water glass. Strength of the acid gel-sand ranged from about 1.5 to 2.5 ton/sq ft (approximately 25 to 28 psi) at times ranging up to 5 days (9). These values are only a fraction of those reported for samples solidified by the 2-step injection method, which gave strengths ranging from about 7 to 26 ton/sq ft (approximately 100 to 350 psi) shortly after injection (13).

### Limitations

Injection processes whether 1- or 2-stage are limited to soils in which the voids are large enough to allow penetration of the mass under reasonable pressures. Generally, this means that the lower limit is a fine sand substantially free of silt and clay; however, gravels with appreciable fines could probably be successfully injected.

Other environmental factors may influence the setting time of the gel and thus the success of the treatment. When the solution is injected into saturated sand, some dilution is inevitable; and, other factors being equal, dilution may lead to setting times 3 to 20 times those for undiluted materials. On the other hand, injection into dry sand may shorten the setting time as much as 30 percent. Soils or groundwater with appreciable salt contents, even  $\text{CaCO}_3$ , may also significantly decrease the setting time for silica gels, whereas there is some evidence that the presence of organic matter may prevent completely the setting of some gels (9).

Mainfort (17) points out that when 2-step processes are used there is a tendency for the second chemical to push the first chemical ahead of it and to prevent adequate mixing or at least mixing in the proper proportions.

## SODIUM SILICATE AS A SOIL STABILIZER

Since 1945, various researchers have reported on the effectiveness of sodium silicate as a soil-stabilizing admixture. Sometimes the silicate was used alone and sometimes in combination with various other chemicals. Sherwood concluded that sodium silicate, when used alone, is suitable only for the stabilization of sandy soils in a moderate climate (18). When the silicate is combined with soil and other chemicals, the results are mixed. Furthermore, there exist few or no field data to confirm the apparently beneficial results that have been obtained in the laboratory.

### Soil-Sodium Silicate Reaction Mechanism

Because the process of silicate gel formation is not completely understood, it is impossible to state exactly how sodium silicate reacts with soils. Laws and Page (15) found that sodium silicate reacted with various clay minerals commonly present in soil, but they did not make a detailed study of the nature or possible mechanism of the reactions.

Sodium silicate can be used in soil stabilization mainly because it reacts with soluble calcium salts in water solutions to form insoluble gelatinous calcium silicates. That hydrated calcium silicates are cementing agents has been fairly well established. The

exact nature of the bonding action of hydrated calcium silicates has been the subject of much investigation, but it has not been fully explained (12). Iler (10) believes that the silicate is in the form of polymeric chains of silicon-oxygen linkages, with sodium distributed along the chain on the oxygen. The addition of a polyvalent ion, such as  $\text{Ca}^{++}$  or  $\text{Mg}^{++}$ , results in the replacement of the  $\text{Na}^+$  by the divalent ion and permits bonding together of 2 chains to form an insoluble cross-linked gel structure. The effect of the addition of the silicate to appropriate soils is to increase water-stable aggregation and resistance to crushing and to decrease the plasticity index and swelling (15). On the basis of this evidence Wooltorton (19) postulates that the process involved is that of anionic exchange, resulting in the formation of insoluble silicate sheaths around the soil particles, accompanied by cementation effects. Murray (20) simply indicates that calcium silicate is precipitated as a continuous matrix in which a strong and rigid ionic polar bond is formed between the soil and stabilizer.

These concepts indicate that the important variables might be expected to be (a) the quantity of polymeric silica, which determines the amount of gel; (b) the frequency of sodium atoms along the chain, which determines the amount of cross-linking possible; and (c) the concentration of the precipitant, which determines the extent of cross-linking. In addition, it is believed that the elevation of the pH resulting from the presence of the sodium silicate solution would generate additional silicate by the solubilization of the already hydrated surface silica in the soil. Thus, the soil would be contributing additional stabilizing material to that added initially (21).

This might help to explain the highly favorable reaction that is usually obtained with silica sands. On the other hand, Laws and Page (15) found that, although clays of low activity, such as kaolinite, reacted favorably with sodium silicate, the stability of highly active clays, such as montmorillonite, might actually be impaired by the addition of the silicate. This lack of favorable reaction with many fine-grained soils was confirmed by Mainfort (14, 22) and to some extent by the studies at the Massachusetts Institute of Technology (21, 23).

### Properties of Stabilized Mixtures

Foundry Molding Sands—For many years sodium silicate, often mixed with various other materials both organic and inorganic, has been used for the bonding of foundry sands (4). Such materials must retain strength at relatively high temperatures but must also be porous enough to permit the escape of air and other gases during the casting processes. Several references are included as representative of investigations that have been carried out on the factors that determine the properties of the molded sand. Three of those refer to the process of hardening the silicate by treatment with carbon dioxide (6, 7, 24). Because the molds are usually baked at temperatures of more than 400 F, the results of these investigations are not directly applicable to soil stabilization work. Morey and Lange (24), however, do note that an increase in the  $\text{Na}_2\text{O}:\text{SiO}_2$  ratio caused a decrease in the strength of the material, and an increase in the percentage of sodium silicate (within limits) caused an increase in strength. (The amount of silicate usually ranges from approximately 2 to 10 percent of the weight of the sand.) It was also observed that an addition of 1 percent bentonite clay to the sodium silicate-sand mixture caused an increase in strength of about 10 percent more than that of the silicate mixture alone.

Jones and Kandic (8) discuss an investigation of a process for hardening silicate-bonded sand at low pressures. The silica sand was mixed with 2 to 6 percent sodium silicate and then hardened by pumping off 10 to 30 percent of the moisture at pressures below 10-mm Hg. Depending on the silicate composition and variations in time, pressure, and temperature, compressive strengths up to 800 psi were obtained. Although such a process could be impractical for field soil stabilization, it does indicate that under certain conditions high strengths may be obtained by treatments with silicate alone followed by dehydration.

Strength—Mainfort (14) reported on the results of a number of tests on sand, sandy loam, silt loam, and silty clay treated with various amounts of sodium silicate alone and in combination with other chemicals. The oven-dry strength of silicate-treated



sand was greatly increased by 8 percent sodium silicate applied as a 40 percent solution. The results with the fine-grained soils were not so spectacular but were "satisfactory." The treated specimens, however, were not resistant to immersion for 24 hours, and various additive combinations were tried to improve the resistance to wetting. Calcium chloride solution appeared to give the best strength results when the silicate-stabilized specimens were submerged in it for 15 min, then removed, and air-dried. These specimens, however, also showed low resistance to submergence. Subsequently, treatment with 4 percent sodium silicate and 2 percent sodium aluminate gave relatively high strengths for sands and also improved resistance to wetting.

Laws and Page (15) in tests with pure clay minerals and various soils also noted improvements in strength when a fine sandy loam was treated with various amounts of sodium silicate up to 3.5 percent. They stress the effect of the silicate treatment in aggregating even some fine-grained soils but conclude that the most beneficial results were obtained with coarse-grained soils.

Various authors mention the improvement in strength to be achieved by treating soils with sodium silicate (with and without other additives) but present few or no experimental data (25, 20, 26, 19, 27, 28, 18).

Dogra and Uppal (29) report that amounts of sodium silicate as low as 2.5 percent with sands and sandy soils produced strengths (1,500 psi) that exceeded those produced with the same soils at 10 percent cement (1,300 psi). They also found that long curing periods (6 months) at room conditions increased compressive strengths of sand-clay mixtures.

The studies of chemical soil stabilization conducted at M. I. T. (21) initially indicated that magnesium carbonate in combination with sodium silicate was one of the most effective tried. A 5 percent silicate treatment of Massachusetts clayey silt increased its strength more than fourfold to 400 psi. The optimum concentration of  $MgCO_3$  was 2 percent. Strength was found to increase with silica content, and the best results were found with sodium concentrations of 0.04 to 0.06 equivalents per 100 g of soil in combination with 0.75 equivalents of  $MgCO_3$  per equivalent of sodium. Various grades of soluble silicate with  $Na_2O:SiO_2$  ratios varying from 1:1.58 to 1:3.33 were used. Results obtained with solid silicates were generally not so satisfactory as with liquid silicates.

Later studies at M. I. T. (23) confirmed the effectiveness of the sodium silicate-magnesium carbonate combination with the Massachusetts clayey silt ( $L_w = 20$  percent,  $PI = 6$  percent) with wet strengths up to 600 psi at 6.4 percent total additive. The wet strength of New Hampshire silt ( $L_w = 28$  percent,  $PI = 8$  percent) was increased to 365 psi with 8.5 percent total additive and that of Vicksburg loess ( $L_w = 41$  percent,  $PI = 15$  percent) to 235 psi at 9.1 percent total additive. Attempts to stabilize Vicksburg buckshot clay ( $L_w = 65$  percent,  $PI = 37$  percent) were unsuccessful.

Winterkorn (30) reports on the field tests conducted by the U. S. Navy on beach sand stabilization with 1 to 3 percent sodium silicate by weight sprayed as a 40 percent sodium silicate solution. Although enough silicate was added to stabilize a 4- to 6-in. depth and the sand was compacted with rollers only, a hard brittle crust approximately  $\frac{1}{4}$  in. thick was formed. This crust could not withstand the weight of a jeep or a  $\frac{3}{4}$ -ton truck used as test vehicles.

Moisture-Density Relations—Very little information is available on the effect of sodium silicate (with or without precipitants) on the density of compacted soils. The M. I. T. studies (21, 23) were performed on samples prepared in a Harvard miniature mold by 2-end static compaction at about 900-psi pressure. Initial tests on Massachusetts clayey silt stabilized with 5 percent sodium silicate showed variations in dry density of from about 116 to 134  $lb/ft^3$  depending on the type and amount of precipitant used;  $MgO$  gave the highest as-molded densities, with  $MgCO_3$  about 3  $lb/ft^3$  less. Later tests with New Hampshire silt and Vicksburg loess indicated that the dry density after 1 day of humid curing varied with variations in silica, sodium, or magnesium content. The highest strengths were usually associated with the specimens having the highest densities. In the case of New Hampshire silt the densities varied from about 102 to 115  $lb/ft^3$ , whereas the Vicksburg loess specimens varied from 100 to 107  $lb/ft^3$ .

Ruff and Davidson (12) in their tests on Kansan till found that sodium sesquisilicate pentahydrate when added in the dry form had practically no effect on the as-molded



maximum dry density in amounts varying from 2 to 6 percent. Increasing the silicate contents did, however, result in a significant increase in the optimum moisture content.

**Durability**—Although the preceding discussion has indicated that sodium silicate alone or in combination with certain precipitants may increase the stability of coarse-grained or relatively nonplastic fine-grained soils, there is considerable doubt about the permanence of the improvement when the soils are exposed to normal climatic variations.

Mainfort (31) states, "Good bonding of sandy soils has been attained with treatments of 6 percent or more of sodium silicate, but such treatments will not withstand attacks by moisture. Very little effectiveness was obtained by the application of sodium silicate to fine-grained soils. Earlier studies indicated that the addition of sodium aluminate greatly increased the resistance of the soil-silicate sample to moisture attack but later tests, using a variety of soils and more severe exposure tests, have clearly shown this combination to be unsuitable as a soil stabilizing agent." He continues, "Unless a very successful additive should be found, sodium silicate cannot be considered a suitable soil stabilizing agent for paving purposes."

Dogra and Uppal (29) found that sodium silicate-treated specimens of sandy soils were more resistant to abrasion than cement-sand. They also conducted durability tests in which the specimens were immersed in water for 5 hours and then dried at 70 C for 42 hours. Specimens containing 10 percent clay and 90 percent sand when treated with 1 percent sodium silicate withstood 12 cycles of such a test and showed weight losses of only 3.5 to 4.0 percent. Higher percentages of sodium silicate in this mixture led to rapid disintegration upon immersion. Also specimens with higher percentages of clay did not give encouraging results. When pure sand specimens were tested, some improvement was noted even with 1 percent sodium silicate. At a sodium silicate content of 6 percent the pure sand withstood 12 wet-dry cycles with a 6 percent weight loss. Smaller amounts of silicate led to failure after 6 cycles, and larger amounts gave higher weight losses per cycle. They also showed that when specimens were aged for long periods before testing they developed greater resistance to the softening action of water.

The studies at M. I. T. (21) with Massachusetts clayey silt indicated that the stabilization reaction was not sufficiently rapid to provide stability upon water immersion immediately after compaction. However, after 24 hours of curing at 100 percent relative humidity and then 24 hours of immersion, the specimens retained at least 65 percent of the 24-hour, humid-cure strength. The most severe test reported to be performed on the M. I. T. specimens involved 24 hours of humid curing, followed by 24 hours of air-drying, followed by 24 hours of immersion. In these tests the Massachusetts clayey silt treated with 5 percent sodium silicate and varying percentages of magnesium carbonate retained about 40 to 80 percent of its 24-hour, humid-cure strength after immersion.

Tests conducted at M. I. T. on New Hampshire silt and Vicksburg loess (23) showed that certain specimens treated with sodium silicate and magnesium carbonate exhibited considerable strength increases after 7 days of humid curing and 24 hours of immersion as compared with 24 hours of humid curing. Optimum strengths and additive levels were 365 psi at 8.5 percent total additive for the silt and 235 psi at 9.1 percent total additive for the loess. No further tests for durability were conducted. Although the durability tests cited are meager, it appears that they do justify the conclusion of Sherwood (18) that sodium silicate as a chemical, when used alone, is suitable only for the stabilization of sandy soils in a moderate climate.

The long-time effectiveness of sodium silicate in combination with other chemicals when used as a stabilizing agent with nonplastic soils is unknown, but the information currently available does not inspire confidence in such treatments. Possibly the best summation of the utility of soil stabilization with sodium silicate in combination with magnesium carbonate and magnesium oxide precipitants is given by Kozan and Fenwick (32). Although only Vicksburg loess and Vicksburg buckshot (alluvial) clay were tested, these 2 soils represent a rather wide range of fine-grained soils that would be encountered in engineering practice. The form of the curing and testing was similar to that of tests conducted in the M. I. T. laboratories. They conclude, "... these materials did not produce any major strength improvement." On this basis they state, "The formulations

containing silicate compounds as the primary stabilizing agents were determined to be incapable of meeting the requirements established for the specified military road and airfield functions. On the basis of these findings, further investigation of these formulations for military use is not justified." Although the military requirements are more stringent than those for normal civilian highway use, it is apparent that no silicate-chemical combination has been found to successfully stabilize heavy clay soils. Furthermore, the amounts of additive required for slightly plastic, fine-grained soils approximate those of materials, such as portland cement, that are more readily available, easier to handle and mix (especially under field conditions), and are normally less expensive.

## DUSTROOFING AND WATERPROOFING

### Soils

Although sodium silicate, with or without chemical precipitants, has not proved to be an ideal additive for soil stabilization, there is some evidence that it might have value as a dustproofing or waterproofing agent. The Waterways Experiment Station (33) reported on a test conducted by the U. S. Army Corps of Engineers in the arid southwestern part of the United States. A fine-grained clayey silt soil, ML-CL, was treated to a depth of 1½ in. by penetration with 30 percent solution of sodium silicate. The surface withstood 200 coverages by a 2½-ton military cargo truck without evidence of stress, cracking, or surface abrasion. An attempt to stabilize a well-graded sand, SW, by similar means was not satisfactory unless the loose sand was first compacted and the penetration treatment applied subsequently.

The apparent success of this classified project led to further research on sodium silicate and other materials at the Waterways Experiment Station (34). It is stated that the qualifications of a waterproofing and dustproofing material are (a) it should be effective in a relatively thin layer, preferably not exceeding 6 in.; (b) it should be effective when applied in quantities of 5 percent (by weight of dry soil) or less; (c) it should retain its effectiveness under the expected traffic for at least 1 full cycle of seasonal change without additional treatment; and (d) although advantageous but not essential, it should have the capability of being applied as a penetration treatment.

A total of 13 materials were evaluated on a test section of Vicksburg loess ( $L_w = 38$ ,  $PI = 16$ , 97 percent < No. 200, 25 percent < 0.002 mm). Each material was incorporated with the soil by off-site mixing and placed in individual panels 12 by 6 ft to a 3-in. depth and compacted at optimum moisture content. A 16-in. untreated base (CBR = 36) was achieved by recompacting excavated loess in 4-in. lifts. Traffic tests were performed by a military truck loaded to produce 16,000 lb on each of 2 rear axles. Each test consisted of 40 passes at 5 to 7 mph with the truck wheels maintained on a path along the centerline of the panels. Seven such tests were conducted during a 13-month period. Data were collected to determine the resistance to traffic abrasion and amount of dust produced and the effectiveness of the surface in protecting the base from ingress of water.

For comparative purposes, the results of the sodium silicate treatment (14.5 percent of a 30 percent sodium silicate solution = 4.35 percent by dry weight of soil) will be compared to untreated control sections and a section treated with MC-O cutback asphalt (10 percent of 50 percent asphalt content = 5.0 percent by dry weight of soil). The results of the dustproofing tests expressed as weight in grams of dry material collected from an area 4 by 2.5 ft along the wheelpath in each panel are as follows:

Test	Control	NaSi	MC-O
1	1,148	905	185
2	3,481	1,237	284
3	2,783	2,012	262
4	3,058	2,730	368
5	1,969	2,242	606
6	7,824	5,479	722
7	3,970	3,164	516

The sodium silicate treatment produced some beneficial effect (as compared with the control) but was much less effective than MC-O, which rated 2 in effectiveness. Actually, the silicate treatment was rated 9 of the 13 materials tested.

The waterproofing characteristics of the treatments were based on the maximum moisture contents at 4- and 12-in. depths in the compacted base. The base was placed at an initial water content of 10.8 percent, and good waterprooferers were presumed to maintain this value or less throughout the tests. The base under the sodium silicate panel approached 20 percent water content throughout the tests and approximated that of the untreated panels. Of the 13 materials tested sodium silicate rated 10 in effectiveness; the MC-O treatment rated 1. Laboratory capillary rise rewet tests confirmed the ineffectiveness of sodium silicate as a waterproofer with water contents (25 percent) after 4 days of soaking approximating those of untreated specimens.

Subsequent laboratory tests conducted by the Waterways Experiment Station (35) on various sodium silicate systems (silicate plus magnesium carbonate or oxide precipitants) showed that they were totally ineffective as waterprooferers for Vicksburg loess and Vicksburg buckshot clay.

### Concrete

It has been stated (36) that treatment of concrete with sodium silicate is the cheapest, simplest, and most effective way of overcoming the concrete dusting problem. The proper penetration of the silicate into a porous concrete surface is obtained by 3 applications that should be made at about 24-hour intervals. For best results a silicate with a  $\text{Na}_2\text{O}:\text{SiO}_2$  ratio of about 1:3.3 and with a density of 41 to 43 B should be used. Various dilutions are suggested for each of the 3 applications with the estimate that 1 gal of silicate is sufficient to harden 200 to 350 sq ft of concrete surface. The article indicates a beneficial reaction between cement and sodium silicate, and that will be discussed more fully in the next section.

### SODIUM SILICATE AS A SECONDARY ADDITIVE

There are soils for which the requirements of common stabilizers, such as portland cement, lime, and lime-fly ash, are so high that it may be uneconomical to use them. Furthermore, these stabilizers when required in large quantities find limited military use because of the logistical problems involved. For these reasons some research has been carried out to determine whether minor amounts of other additives can reduce the requirements for the major stabilizer and still produce satisfactorily stabilized soil.

### Soil-Cement

**Mechanism of Reaction**—Lambe, Michaels, and Moh (37) and Moh (38) present the following hypothesis to explain the beneficial effects obtained by the treatment of soil-cement with various sodium salts and NaOH. The hypothesis is based on the results of tests carried on in the M. I. T. Soil Stabilization Laboratory.

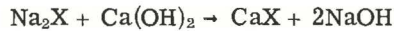
Most fine-grained soils contain large quantities of crystalline silica, feldspar, or colloidal clay minerals in a high degree of subdivision. These compounds are inherently acidic in nature and a small, but important, fraction of the silica and aluminosilicates present in soils is in a highly hydrous state on the particle surfaces. When exposed to strong alkalis, soils of this type function as powerful buffers. The surface silica and alumina react rapidly with the alkali to form silicate and aluminate salts, thereby reducing pH. The finer the particle size of the soil is, the greater will be the proportion of reactive silica and alumina available, and thus the more rapid and more extensive will be its buffering or alkali-consuming capacity.

When cement is admixed with soil and water, hydration of the cement leads initially to the formation of lime, calcium silicate, and calcium aluminate. However, reaction of the lime with reactive silica and alumina from the soil leads to formation of additional calcium silicate and aluminate, reduction of pH, and subsequent hydrolysis of the more basic calcium silicate and aluminate. The ultimate reaction products of soil and cement are summarized to be hydrous alumina and a calcium silicate gel of rather low



Ca:Si ratio. It is to be noted that, in soil-cement, nearly all the reactive calcium present initially in the cement is eventually available for production of cementitious silicate gel; hence, the quantity of cementitious material available for bonding in soil-cement is inherently greater than that in neat cement. Because, however, any lime that reacts with soil silica (or alumina) is immediately immobilized as insoluble silicate, and because cement particles are rather sparsely distributed between soil particles in typical soil-cement, the formation of cementitious silicate gel can be expected to be confined to a rather thin zone around each cement particle. Only when the cement concentration is high enough to permit these zones of gel formation to overlap will the soil become adequately stabilized.

When a sodium compound is added to soil-cement, the calcium ion concentration in solution is greatly depressed either by the common ion effect (with NaOH) or by the causticization reaction,



Simultaneously, the pH is significantly elevated. Suppression of the calcium concentration retards precipitation of insoluble calcium silicate gel, while elevation of pH accelerates attack of soil silica or alumina or both and formation of soluble alkali silicate or aluminate or both. Because the alkali silicate is free to diffuse through the pore fluid, there is opportunity for rather uniform distribution of silicate throughout the soil mass. Eventually, however, neutralization of the free alkali by reaction with the soil reduces the pH and permits the calcium ion to go into solution. Reaction of calcium with the uniformly distributed alkali silicate or aluminate in the pore fluid results in formation of mixed calcium-sodium silicate and gelation. Formation of an increased volume of well-distributed, hydrous silicate gel can thus account for the generally beneficial influence of alkali metal compounds on soil-cement.

In terms of this mechanism, it becomes rather simple to explain why different sodium compounds differ so widely in their effects on various soils. In coarse-grained soils, the amount of reactive silica present is small, and thus the amount of cementitious silicate gel that can be contributed by the soil is limited. If gel-forming material can be provided from an external source, however, the reactive silica deficiency of the soil can be compensated for; hence, sodium silicate or aluminate is more effective in sands than other sodium compounds. With heavy clays, on the other hand, there is present a large amount of reactive silica—so much in fact that neutralization of alkali by such a soil occurs with great rapidity. When the generation of free caustic soda must result from reaction with lime from the cement, the rate of generation of caustic is likely to be no faster than its consumption by reaction with the soil so that the pH never becomes greatly elevated. Because of this, the calcium solubility is but little depressed, and calcium silicate formation occurs promptly; hence, uniform distribution of cementitious gel will not occur. If caustic soda is used as the additive, however, the pH is immediately raised to a high level and the calcium concentration correspondingly reduced; rapid formation of sodium silicate and delayed gelation by calcium will thus contribute to more extensive and uniform cementation.

With soils of intermediate fineness, such as silts, it is likely that the supply of reactive silica is adequate and that the rate of reaction of the soil with alkali is sufficiently slow that the reaction with lime can proceed virtually to completion before the free caustic is consumed. Under these circumstances, it is of relatively little importance which sodium compound is employed, at least in terms of ultimate strength development.

Strength—Several reports (37, 18, 38, 39) indicate that sodium silicate (especially metasilicate) is most effective in increasing the strength of cement-stabilized clean sandy soils. Tests by Lambe, Michaels, and Moh (37) on a Wisconsin sand (approximately 20 percent < No. 200) stabilized with 10 percent cement showed an increase in wet compressive strength of 40 to 290 psi at 1 day and 230 to 440 psi at 7 days when 1 percent sodium metasilicate was added to the mixture. Of all the sodium additives tested, the silicate was most effective. Similar results were reported from tests on New Hampshire silt ( $L_w = 28$  percent,  $PI = 8$  percent, pass 200 > 95 percent) and Vicks-

burg loess ( $I_w = 41$  percent,  $PI = 15$  percent, pass 200  $> 90$  percent) when stabilized with 5 percent cement and 1 percent sodium metasilicate. The 7-day strengths with the silicate additive exceeded those for cement alone by 150 to 250 psi (increases of 100 to 200 percent). Further tests with the 5 percent cement-stabilized New Hampshire silt indicated that increasing the amount of silicate additive from about 0.6 to 2.7 percent had little effect on wet compressive strengths up to 28 days. At the 1 percent additive concentration the sodium metasilicate plus 5 percent cement produced strengths comparable to those obtained with the silt stabilized by 10 percent cement alone. Several cement-stabilized clay soils tested showed little or no improvement with silicate additive. Although some clays having high carbonate contents did show some improvement with the metasilicate, other sodium additives were somewhat more effective. It was concluded, however, that salts of weak acids are not effective as additives to cement-stabilized heavy clay soils.

Moh, Lambe, and Michaels (39) report on a series of tests with 5 percent cement-stabilized New Hampshire silt in which various sodium silicates were tested in additive ratios of 0.54 to 2.80 percent. It was concluded that there is an optimum  $Na_2O:SiO_2$  ratio of about 1:2 at the concentrations employed. At a given sodium concentration, higher ratios have higher early strength but lower ultimate strength. On the other hand, lower ratios (higher silica contents) tended to retard the cementing process. Generally, the other silicates tested gave even higher 28-day strengths than the metasilicate at equivalent additive concentrations.

Durability—Studies of the durability of soil-cement with silicate are few. In a discussion of some of the M. I. T. reports, Norling and Packard (40) briefly review some investigations carried out at the Portland Cement Association Laboratories. The Massachusetts clayey silt was subjected to the standard soil-cement freeze-thaw test at cement contents of 6 and 9 percent, with and without 1 percent sodium metasilicate as an additive. Soil-cement loss at 6 percent cement content was 32 percent with no additive and 7 percent with silicate; at 9 percent cement content the losses were approximately equal. It was concluded that the cement requirements for an allowable loss, not exceeding 10 percent, would be 8.5 percent for cement alone and less than 6 percent with the silicate additive. Although no tests with the silicate were made with New Hampshire silt, the results with other sodium additives indicated that sodium metasilicate would probably reduce the cement requirement 3 to 4 percent.

Moh, Lambe, and Michaels (39) also studied the effect of various additives on soil-cement exposed to sulfate attack. The soil-cement specimens were prepared as for the standard strength tests and then immersed in saturated calcium sulfate solution. Comparisons were made with companion specimens immersed in distilled water. Tests on clean Wisconsin sand (with 7 percent cement) showed that the sodium metasilicate additive greatly delayed or reduced the deteriorating effect of the sulfate. After 1 year, the strength of the metasilicate specimens immersed in sulfate solution was still higher than the early strength of the untreated soil-cement and exceeded the strength of the untreated specimens subjected to equal treatment by about 200 percent.

### Soil-Lime

Stabilization of soils with lime is thought to proceed by a mechanism similar in some respects to that of soil-cement. The high pH caused by the lime solubilizes part of the aluminosilicates in the soil, which in turn react with the calcium ions giving a cementitious calcium silicate (and perhaps aluminate) gel. Obviously, quicklime or hydrated lime will react with sodium silicate to produce gels. It might, therefore, be anticipated that the addition of sodium silicate to a lime-stabilized soil would provide more reactive silicate and thus speed up the cementing reaction.

Experience has shown that lime is especially attractive economically as a stabilizer for clay soils where cement requirements are high. Although sodium silicate alone or in combination with most precipitants is not useful for stabilizing clays, there is some reason to believe that as an additive to lime it could be beneficial.

Moisture-Density Relations—Practically all of the work on the use of silicates as additives to lime-stabilized soil was carried on at the Iowa State University Engineering

Experiment Station and has been reported by Ruff and Davidson (12). The soil tested was a plastic, calcareous, Kansan till ( $L_w = 39$ ,  $PI = 23$ ,  $<0.005$  mm = 40 percent). The predominant clay mineral is montmorillonite. Calcitic hydrated lime (about 70 percent available CaO) was used in all the tests in combination with 5 different powdered sodium silicates. These were 3 metasilicates in various stages of hydration ( $Na_2SiO_3$ ,  $Na_2SiO_3 \cdot 5H_2O$ , and  $Na_2SiO_3 \cdot 9H_2O$ ), a concentrated orthosilicate ( $Na_4SiO_4$ ), and the sesquisilicate pentahydrate ( $Na_3HSiO_4 \cdot 5H_2O$ ).

Because it was recognized that in the field some time would be required for mixing, a study of the effect of aging prior to compaction was undertaken. Times used were 9 min and 1, 2, 3, and 5 hours between final mixing and specimen molding. It was found that the dry densities and optimum water contents of the mixtures varied depending on the type of silicate used and the aging times.

In all of the soil-lime-sodium silicate mixtures, the highest dry densities were obtained at aging times near zero. As the aging time increased, the dry density of the specimens molded from all the mixtures decreased. It was also observed that the molding moisture content influenced dry density, but that the molding moisture content that gave the highest dry density at the shortest aging time did not usually give the highest dry density at the longest aging time.

One explanation for the dependence of maximum dry density and optimum moisture content on aging time is related to the chemical reaction between lime and sodium silicate. As water comes in contact with lime and sodium silicate, the chemicals dissolve and then react to form an insoluble calcium silicate gel. Inasmuch as lime is comparatively slowly soluble, the quantity of gel formed gradually increases as the reaction between the lime and sodium silicate continues. The gel absorbs water and at the same time begins to hydrate. As the gel hydrates, it hardens. The longer this process continues, the more gel is converted into a hydrated calcium silicate.

The processes of gel formation and hydration remove free water from the mixture, and as the gel hydrates the character of the soil changes because the hydrated gel is cementing the soil particles together. The loss of the free water lowers that amount available to act as a lubricant during compaction. The effective gradation of the soil is changed and its resistance to the constant compactive force is increased as the soil particles are cemented together. Thus, both the optimum moisture content and the maximum dry density are affected by the introduction of the lime-sodium silicate gel formation and hydration processes, and this effect is greater with increasing aging time.

Density and the amount of decrease in density with aging time are also a function of the type of sodium silicate used. Highest dry densities (106 to 110 lb/ft<sup>3</sup>) were obtained with anhydrous sodium metasilicate and sodium orthosilicate, but mixtures with these silicates had the greatest decrease in dry density (4 to 8 percent) with increase in aging time. Sodium metasilicate enneahydrate and sodium metasilicate pentahydrate gave the lowest dry densities (100 to 105 lb/ft<sup>3</sup>) and they had a smaller decrease in dry density (1 to 6 percent) with increase in aging time. Intermediate dry densities (102 to 107 lb/ft<sup>3</sup>) were obtained with sodium sesquisilicate pentahydrate mixtures, whereas the decrease in dry density with aging time was smallest (1 to 2 percent).

An explanation of this is related to the gel-forming ability of the different sodium silicates. In the previous explanation for the dependence of dry density on aging time, the controlling function of the amount of gel present was cited. A difference in the rate of gel formation by the different sodium silicates would produce different rates of change of dry density with aging time and might also account for the difference in dry densities obtained from the different sodium silicates.

**Strength**—A principal purpose of the Iowa tests was to determine the effect of aging time on the strength of the lime-stabilized soil when treated with various sodium silicates (12). Preliminary tests were made with the Kansan till combined with 6 percent calcitic lime and varying amounts of the silicates. Although the actual percentage of the silicates varied, the amounts were selected so that the anhydrous portion of each was equivalent to the anhydrous portion of 6 percent sodium metasilicate pentahydrate. The percentage reported, however, is on the basis of the weight of the sodium silicate in its normal state of hydration. The 6 percent metasilicate pentahydrate was selected on the basis of preliminary testing that showed this value to be optimum in stabilizing



the Kansan till. For the initial set of tests, an aging time of 5 hours was selected. On the basis of these initial tests, the sodium sesquisilicate pentahydrate was chosen for further testing because it showed the least overall decrease in strength between aging times of from  $\frac{1}{4}$  to 5 hours.

The data from the initial tests are given at the bottom of Table 1 and those from the second set at the top. All of the silicates except the orthosilicate produced 7-day wet strengths that were more than double those of the 6 percent lime alone even though the aging time for the silicate-treated specimens was 5 hours as compared to 2 hours for the lime-soil. The data given at the top

of the table also show that except for the 2 percent lime mixture the addition of 2 and 4 percent sodium sesquisilicate resulted in significant increases in 7-day compressive strengths. On the basis of those tests, Ruff and Davidson (12) reached the following conclusions:

1. The immersed strength (25-hour immersion) of Kansan till-lime-sodium silicate specimens decreased with increasing aging time. That decrease was comparatively slight and varied considerably with molding moisture content and type of sodium silicate. One explanation of the decrease in strength with increase in aging time is given along the same line as the explanation for the decrease in dry density. The amount of gel formed by the lime-sodium silicate reaction increases with time; thus as the aging time increases the amount of gel present at the time of molding increases. But the structure of this gel can be broken by compaction, and even though it reforms it does not form as strong a cementing agent.

2. Results of tests on this same soil to determine the optimum mix design for maximum strength indicated a mixture with 6 percent lime and 4 percent sodium sesquisilicate pentahydrate produced optimum results. It was also determined that, for amounts of lime greater than 2 percent, immersed strength increased with increasing sodium silicate concentration to a value of 4 percent.

3. The effect of curing time on Kansan till-lime-sodium sesquisilicate pentahydrate mixtures was such that as curing time increased the strength of the specimens increased. The average rate of strength gain for all 4 mixtures (6 percent lime and 1, 2, 3, and 4 percent sodium sesquisilicate pentahydrate) was greatest in the period of 3 to 7 days. The more sodium silicate added, the higher was the average rate of strength gain for this period. For the period of 7 to 28 days, the addition of 4 percent sodium silicate increased the average rate of strength gain over the 1, 2, and 3 percent sodium silicate mixtures. Further investigation of the reaction products formed by these combinations of Kansan till, lime, and sodium sesquisilicate pentahydrate were indicated before an explanation for this change rate of strength increase could be provided.

Katti and Kulkarni (41) also studied the effect of sodium silicate and other trace chemicals on the strength of lime-stabilized expansive black clay soil. Various percentages of lime were used with 0.5 and 1 percent sodium silicate. The optimum lime content for curing times up to 28 days was found to be 8 percent. At lime concentrations below 8 percent, sodium silicate increased the 7-day strengths roughly 100 percent. Sodium silicate also reduced absorption of water but had no consistent effect on swelling. Regardless of the lime content the addition of the silicate had little effect on the 28-day strength.

Table 1. Effect of silicates on strength of lime-stabilized Kansan till after 7 days of curing and 1 day of immersion.

Lime (percent)	Type of Silicate	Silicate (percent)	Aging Time (hour)	Strength (psi)
2	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	0	2	128
2	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	2	2	120
2	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	4	2	100
4	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	0	2	128
4	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	2	2	205
4	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	4	2	232
6	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	0	2	105
6	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	2	2	242
6	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	4	2	285
6	Na <sub>3</sub> HSiO <sub>4</sub> ·5H <sub>2</sub> O	5.3	5	267
6	Na <sub>2</sub> SiO <sub>3</sub> ·9H <sub>2</sub> O	8	5	231
6	Na <sub>2</sub> SiO <sub>3</sub>	3.4	5	225
6	Na <sub>2</sub> SiO <sub>3</sub> ·5H <sub>2</sub> O	6.0	5	240
6	Na <sub>2</sub> SiO <sub>4</sub>	3.8	5	167

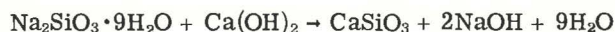


**Durability**—In the Iowa tests the 6 percent lime-stabilized Kansan till specimens with varying amounts of sodium sesquisilicate pentahydrate were subjected to 14 cycles of a modified British freeze-thaw test. A tentative criterion was that the freeze-thaw specimens must have an unconfined compressive strength of at least 250 psi after testing and also have at least 80 percent of the strength of specimens that have been immersed during the same time but not subjected to freezing. The tests showed that increasing the silicate content from 1 to 4 percent resulted in continued increases in final strength. However, the 4 percent treatment gave an average specimen strength of only 218 psi, which amounted to about 50 percent of the strength of the immersed specimens. No basis is given for comparison with specimens containing no silicate.

### Soil-Lime-Fly Ash

Studies of the effect of sodium metasilicate on soil-lime-fly ash mixtures were also conducted in Iowa (42). The 5 soils tested were Ottawa standard sand, dune sand, friable loess, alluvial clay, and Kansan gumbotil. Clay contents (< 0.002 mm) were about 0, 3, 14, 61, and 63 percent respectively. The predominant clay mineral in all soils was montmorillonite. The reaction of lime with soil and fly ash is similar to that with soil alone; however, the fly ash contains finely divided silicate and aluminate compounds that may be scarce or lacking in some soils, especially sands. The authors postulate that the effect of an alkaline additive, such as metasilicate, is probably as follows.

Alkaline additives increase the amount of available hydroxyl ions in the moistened Ottawa sand-lime-fly ash system, and as a result the pozzolanic reaction may be accelerated by the increased solubility of the siliceous material caused by the alkalinity. Sodium metasilicate,  $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$ , very likely reacts with lime,  $\text{Ca}(\text{OH})_2$ , or the moist Ottawa sand-lime-fly ash mixture to form highly cementitious calcium silicates and sodium hydroxide in the following way:



The sodium hydroxide presumably is then free for further reaction with unreacted siliceous material, thereby serving as a catalyst in the overall reaction processes.

**Strength**—The studies of Mateos and Davidson (42) illustrated the beneficial effects of small amounts of sodium metasilicate especially on sand-lime-fly ash mixtures.

Specimens prepared from a mixture of Ottawa sand, calcitic hydrated lime, and a medium quality fly ash (75:5:20 by weight) showed an increase in immersed compressive strength with increasing amounts of sodium metasilicate. In fact, the strength was increased greatly by the use of even small amounts of the chemical, and the increase was found to be more or less proportional to the amount of chemical used. The optimum was about 3 percent where a strength of 1,000 psi was found after 7 days of curing for specimens having that amount of sodium metasilicate. Sodium metasilicate in the amounts of 0.5 and 1.0 percent also increased the strength of the dune sand-lime-fly ash mixture.

Used in the amount of 1.0 percent, sodium metasilicate increased the strength of friable loess-lime-fly ash mixtures containing those fly ashes with relatively high percentages passing the No. 325 sieve (86 to 92) and possessing a relatively high specific surface (2,800 to 3,200  $\text{cm}^2/\text{g}$ ). It was suspected that the use of greater amounts of sodium metasilicate would improve greatly the strength of friable soils because of the previously mentioned 3 percent optimum concentration.

In general, the greater benefits were derived from the addition of chemicals, including sodium metasilicate, to the sandy soil-lime-fly ash mixtures. Benefits were seen to decrease with the increase in the amount of clay in the soil. At times the addition of chemicals to clayey soils was detrimental to the strength of the specimens. It was supposed that the decrease in strength in these soils was brought about by the excess sodium ions and high alkalinity present in the pore fluid of the soil-lime-fly ash mixtures. Both factors introduce disruptive forces in the clay structures that are not overcome by the cementitious bond of the pozzolanic reaction.

The strengths obtained with lime-fly ash mixtures depend greatly on curing temperatures. When soils are stabilized with lime and fly ash in the late part of the summer in temperate climates, they may not develop sufficient strength to withstand the imposed stresses of the colder seasons. A mixture of dune sand, calcitic hydrated lime, and a medium-quality fly ash without additive, cured for 7 days at 43 F, failed during a period of immersion in water. The addition of 1.0 percent sodium metasilicate gave 7-day immersed strengths of about 100 psi. After 28 days of curing, the mixture without additive showed an immersed strength of 41 psi. This strength was increased fivefold or sixfold by addition of 1.0 percent sodium metasilicate.

When a dolomitic monohydrate lime was used in place of the calcitic hydrated lime, stabilized dune sand showed about the same 7-day immersed strengths with or without the additive. However, at 28 days the untreated mixture had a strength of 111 psi as compared to more than 2 times that value for the mixture treated with sodium metasilicate. Thus, the beneficial effects of sodium metasilicate to the lime-fly ash pozzolanic reaction are important when low temperatures are expected during the curing period. These effects are seen to vary depending on the type of lime and probably also on the fly ashes used.

Addition of sodium metasilicate may lengthen the working season for stabilization of soils with lime and fly ash. Such salts also assist by lowering the freezing point of the free water in stabilized-soil mixtures. By depressing the temperature at which the soil water freezes, more time is allowed for strength gain; and the stabilized soil is exposed for shorter periods to the damaging effects caused by ice formation.

### CONCLUSIONS

On the basis of the literature review the following general conclusions seem to be warranted.

1. Injection processes utilizing sodium silicates and precipitants, such as calcium chloride, in 1- or 2-step procedures have been used successfully to harden and reduce the permeability of coarse-grained soils. There remains some doubt about the permanency of the beneficial effects over long time periods, especially when the soil is subjected to high hydraulic gradients.

2. Sodium silicate alone or in combination with certain chemical precipitants can stabilize sandy soils and produce a base or subbase that seems likely to retain the beneficial effects in mild climates.

3. Although there is some evidence that sodium silicate with precipitating chemicals can increase the strength and durability of relatively nonplastic fine-grained soils, there is almost no field evidence to justify its use when soils are subjected to the freezing and thawing cycles typical of temperate climates. Furthermore, the total cost of additives necessary to achieve stability is probably greater than that of stabilizers such as portland cement with which much more experience is available.

4. Sodium silicates with or without precipitants are of little value in dustproofing or waterproofing fine-grained soils.

5. On the basis of laboratory tests, various sodium silicates used as additives appear to improve the strength and durability of soils stabilized with portland cement, lime, or lime-fly ash. Best results have been obtained with sands or relatively nonplastic fine-grained soils. The sodium silicates, as well as other sodium salts, appear to be especially useful in increasing the resistance of cement-stabilized soils to sulfate attack. The addition of a small amount of sodium silicate can significantly reduce the cement requirement for clean sands. The early strength of a lime-stabilized clay soil can be increased by small amounts of sodium silicates, and the resistance of the stabilized soil to cool temperature and freeze-thaw effects can be increased.

### RESEARCH NEEDED

In view of the kinds of soils and the severity of climatic conditions that prevail in Illinois, it appears that further research on sodium silicates as soil stabilizers for highways is not warranted.



The only avenue that appears to hold promise for future research on silicates is in their use as minor additives to sand-cements in order to reduce overall costs by reducing cement requirements. However, in view of the additional difficulties of incorporating 2 admixtures when normal field stabilization techniques are used, there is some doubt as to whether research in this area can be justified.

#### ACKNOWLEDGMENT

This report was prepared as a part of the research under the Illinois Cooperative Highway Research Program. The research was conducted by the Department of Civil Engineering through the Engineering Experiment Station of the University of Illinois in cooperation with the Illinois Division of Highways and the Federal Highway Administration. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Illinois Division of Highways or of the Federal Highway Administration.

#### ANNOTATED REFERENCES

1. Herrin, M., and Mitchess, H. Lime-Soil Mixtures. HRB Bull. 304, 1961, pp. 99-138.
2. Barenberg, E. J. Phosphoric Acid Stabilization—Review of the Literature. Highway Research News, No. 3, May 1963, pp. 15-51.
3. Thornburn, T. H., and Mura, R. Stabilization of Soils With Inorganic Salts and Bases: A Review of the Literature. Highway Research Record 294, 1969, pp. 1-22.
4. Vail, J. G. Soluble Silicates, Their Properties and Uses. Vols. 1 and 2, Rheinhold, New York, 1952.

Volume 1 is a text on the types of soluble silicates, the principal sections of which deal with the methods employed in the manufacture of the silicates. Detailed descriptions of the reactions that occur between the silicates and various elements and compounds upon association are presented. Volume 2 is also a text on the types of soluble silicates, the pertinent sections of which discuss grouting techniques and results. Silicate reactions with soils and the results of projects conducted by various personnel are discussed.

5. Technical and Informational Bulletin. Philadelphia Quartz Company, 1964.
6. Lo Re, V. Areias de Fundicao Aglomeradas por Silicato de Sodio e Gas Carbonico. Boletim, Associacao Brasileira de Metais, Vol. 13, No. 47, 1957, pp. 129-137, in Portugese.

A study was made of the influence of humidity, time of mixing, proportion of sodium silicate, and time during which carbon dioxide is introduced to the properties of samples of molding sand agglomerated by means of sodium silicate and carbon dioxide.

7. Nield, F. W., and Epstein, D. Wasserglas als Bindemittel fuer Form-und Kernsande (Sodium Silicate as Binder for Molding Sands). Giesserei, Vol. 45, No. 9, 1958, pp. 567-575, in German.

This paper discusses the hardening of bonded molding sand after treatment with carbon dioxide. The effects of the silica to soda ratio, the silica plus soda content, and the temperature on the compressive strength of bonded sand are discussed.

8. Jones, R. A., and Kondic, V. Dehydration Hardening of Sodium Silicate Bonded Moulds. Foundry Trade Jour., Vol. 112, No. 2639, 1962, pp. 537-544.

Research work conducted on a compacted test piece of silica sand premixed with 2 to 6 percent sodium silicate as binder and hardened by holding it at pressures below 10-mm Hg and pumping off 10 to 30 percent of moisture from binder showed that tensile strength up to 180 psi and compressive strength of 800 psi can be obtained. Effects of binder and base compositions and of the process variables (time, pressure, and temperature) were studied in terms of the mechanical properties of the compact mixture.

9. Terzaghi, R. D. Report on the Significant Properties of Silica Gels. Personal communication, 1947.

This is a report on the properties of various types of silica gels resulting from single fluids containing water glass and various chemicals that cause the liquid as a whole to set at varying time intervals after mixing. The investigation was carried on to develop a suitable single-shot chemical grout for a permeable dam foundation. Data were obtained on setting times, deterioration, compressive strengths, and shrinkage for gels of varying composition.

10. Iler, R. K. The Colloid Chemistry of Silica and Silicates. Cornell Univ. Press, Ithaca, N. Y., 1955.

This text discusses the structure of the various forms of commercial sodium silicates. The basic gel-forming reactions that occur between polyvalent metal salts and sodium silicates are interpreted, and the structure of the resulting gel, as well as the nature of the bond formed between particles, is discussed.

11. Technical and Informational Bulletin. E. I. du Pont de Nemours and Company, 1964.

12. Ruff, C. G., and Davidson, D. T. Lime and Sodium Silicate Stabilization of Montmorillonite Clay Soil. HRB Bull. 304, 1961, pp. 76-92.

The results and interpretations of a laboratory soil-stabilization investigation of combination lime and sodium silicate treatments of a montmorillonite-rich clay soil are presented. Five kinds of powdered sodium silicate were evaluated in mixtures with the soil and a calcitic hydrated lime. Mixtures with sodium sesquisilicate pentahydrate appeared least affected in strength, density, and durability by elapsed time between mixing and compaction. Hence, this sodium silicate was selected for studies of the effect of lime and sodium silicate mix proportions on immersed strength versus curing time and on freeze-thaw resistance. Results of these studies indicate that a soil-lime-sodium silicate mixture with 6 percent calcitic hydrated lime and 4 percent sodium sesquisilicate pentahydrate produces specimens that possess optimum immersed strength and maximum durability properties.

13. Riedel, C. M. Chemical Soil Solidification Work in Construction and Emergencies. Proc., Conf. on Soil Stabilization, M. I. T., Cambridge, 1952, pp. 68-80.

This paper reviews the basic principles involved in soil solidification with the Joosten injection method. A brief discussion is given of the durability, permeability, and resistance to acid action of groundwater of the stabilized soil. An extensive list of practical applications of the process is provided.

14. Mainfort, R. C. A Laboratory Study of the Effectiveness of Various Chemicals as Soil Stabilizing Agents. Technical Development Note 40, U. S. Civil Aeronautics Administration, Oct. 1945, 20 pp.

The results of early phases of the study indicated that a 40 percent solution of sodium silicate combined with a solution of sodium aluminate as a waterproofing agent was the most promising of several chemicals. This combination when used with the more sandy soils gave high compressive strengths and resisted the action of water with time. The 2 chemicals reacted and set immediately upon contact. Consequently the control of mixing and compacting was difficult. No practical means of adding the materials to soil comparable to normal construction methods were found.

15. Laws, W. D., and Page, J. B. Silicate of Soda as a Soil Stabilization Agent. HRB Bull. 1, 1946; Jour. of American Society of Agronomy, Vol. 38, 1946, pp. 95-97.

Results of investigation conducted on specimens of 3 clay minerals (kaolinite, illite, and montmorillonite) and specimens of soils whose constituents were the 3 minerals and varying amounts of sand and silt. Tests were conducted to determine the effect of sodium silicate solution on the degree of aggregation, liquid limit, plastic limit, volume shrinkage, crushing resistance, exchange capacity, and colloidal content of the minerals and soils. In general, beneficial results were noted when kaolinitic and illitic soils were treated with sodium silicate and detrimental



effects resulted from the treatment of montmorillonitic soils. The mechanical makeup of the soil, i.e., the proportions of sand, silt, and clay, also affected the properties of the treated soil. The coarser grained soils were benefited more than clays or clayey silts.

16. Chemical Grouting. Jour. Soil Mech. and Found. Div., Proc., ASCE, Vol. 83, Nov. 1957, pp. 1426-1-1426-106.

This paper summarizes the state of knowledge on chemical grouting up to 1957. A brief description is presented of the various injection processes employed and of the chemical reactions applicable to each. The processes include dissolution, ion exchange, soil structure alteration, cooling of thermoplastic or molten materials, and pore-water freezing. Others discussed are polymers, emulsions, breaking, suspension, separation, and metathetical precipitation. The most common grouting process is reported to be one that employs the injection of chemicals in fluid form to react in the soil to produce an insoluble gel. This process may be classified as being 1 of 2 types: polymerization or metathetical precipitation. The authors divide the many metathetical precipitation reactions into those that do not involve a soluble silicate and those that do employ a soluble silicate, primarily sodium silicate. References include more than 200 papers.

17. Mainfort, R. C. Discussion, Chemical Soil Solidification Work in Construction and Emergencies. Proc., Conf. on Soil Stabilization, M. I. T., Cambridge, 1952, pp. 78-79.

The limitations of injection of sodium silicate-calcium chloride solutions into nonporous materials are discussed. Studies indicated that the amount of penetration depends on the permeability of the soil, the affinity of the internal soil surface to the injection fluid, the viscosity and wetting characteristics of the injection fluid, and the pressure applied. Blowups occurred if too high pressures were used near the surface of the deposits. The second solution tended to force the first ahead of it in the 2-stage injection process. Special laboratory mixing methods were needed to obtain a satisfactory stabilizing reaction between sodium silicate and calcium chloride. These were impractical for field construction. Very hard samples were obtained by treating sandy soils with sodium silicate alone and sodium silicate-sodium aluminate, but sodium silicate treatments were unsatisfactory with fine-grained soils. Most suitable form of sodium silicate was a 40 percent solution with a  $\text{Na}_2\text{O}:\text{SiO}_2$  ratio of 1:3.22. Sodium silicate was effective in reducing the plasticity of clay soils.

18. Sherwood, P. T. Soil Stabilization by the Use of Chemical Admixtures: A Review of the Present Position. Roads and Road Construction, Vol. 39, No. 460, 1961, pp. 102-110.

This paper reviews the state of knowledge (through April 1961) concerning the application of chemical techniques to the modification of the properties of soil for road engineering. The general principles of soil stabilization are discussed, including the methods of stabilization, the mechanisms of stabilization, and the properties required of stabilizing agents. Sodium silicate is cited as a chemical suitable, when used alone, only for the stabilization of sandy soils in a moderate climate. It is noted, however, that the use of sodium silicate as a secondary additive in soil-cement reduced the amount of cement required for stabilization by as much as 50 percent. Forty-six references are listed.

19. Wooltorton, F. L. D. Engineering Pedology and Soil Stabilization, Use of Electrolytes in Stabilization. HRB Bull 108, 1955, pp. 55-56.

Sodium silicate as one of the electrolytes important in soil stabilization is discussed. The effect of the addition of a suitable percentage of sodium silicate to appropriate soils is to increase water-stable aggregation and resistance to crushing and to decrease the plastic limit, plasticity index, and swelling. The process involved is apparently that of anionic exchange resulting in the formation of insoluble silicate sheaths around the soil particles and accompanied by cementation effects. Because silicates are electronegatively charged, they are not expected to stabilize active clays. The efficiency of the additive increases with decrease in clay activity, i.e., with decrease in the

silica:sesquioxide ratio. It is most likely to be most efficient with those soils of an electropositive character or with those active clays that have had imposed on them an electropositive nature by virtue of coatings of iron compounds.

20. Murray, G. E. Soil Stabilization by Chemical Means. Proc., Conf. on Soil Stabilization, M. I. T., Cambridge, 1952, pp. 107-121.

The various aspects of soil stabilization by chemical means are explained by analyzing the forces operating in a soil system and noting how they can be altered by the introduction of a stabilizing agent. The possible mechanisms through which the stabilizing agents can act to alter soil properties and the effect of both the soil and stabilizer composition on the properties of the treated soil are discussed. The methods by which stabilizing agents form on or around soil particles, i.e., precipitation of calcium silicate from sodium silicate and calcium chloride, are analyzed. The modes of application of the basic concepts to present and potential stabilization methods are given. Discussion of the paper indicates the practical problems that must be solved if any stabilization method is to be employed successfully.

21. Chemical Modification of Soil-Cement. M. I. T., Cambridge, Soil Stabilization Res. Rept., Phase 11, 1959.

This reports (1) the effect of sodium compounds as additives to cement-stabilized soils of widely different origin, fineness, and mineralogical composition; (2) investigation of reactions between cement, lime, sodium compounds, and soil minerals; (3) study of the effect of soda-to-silica ratio in sodium silicates as additives on strength; (4) study of the effect of additives on the resistance of soil-cement to sulfate attack. Results of durability tests (wet-dry, freeze-thaw cycles) indicate the strength test is a good measure of the effectiveness of sodium additives. Observation of test data indicates the effects of sodium additives in soil-lime are similar to those in soil-cement.

Soil stabilization with sodium silicates and salts of divalent metals was investigated. Preliminary gelation tests run in the absence of soil indicated that magnesium carbonate,  $MgCO_3$ , calcium hydroxide,  $Ca(OH)_2$ , and calcium sulfate,  $CaSO_4$ , would be most promising for testing with silicates in soil. At 5 percent treatment by weight of Massachusetts clayey silt, sodium silicates with  $MgCO_3$  as precipitant are effective stabilizers, increasing strength to more than 400 psi. The curing reaction is essentially complete within 5 hours. An optimum concentration of 0.75 equivalents of  $MgCO_3$  (2 percent by dry soil weight) per equivalent of sodium was found. The stabilization reaction is not sufficiently rapid to give stability upon water immersion immediately after compaction. At least 65 percent of 24-hour, humid-curing strength is retained upon 24-hour curing followed by 24-hour immersion.

Study was made of effect of major variables—silica, sodium, and magnesium content—on soil stabilization. Strength increases with silica content; however, for best results the sodium concentration is confined to a range between 0.04 and 0.06 equivalents per 100 g of dry soil. Below this, strength development is slow. Above 0.06 equivalents per 100 g of dry soil and a corresponding amount of precipitant,  $MgCO_3$ , crystallization of sodium carbonate,  $Na_2CO_3$ , with resultant expansion cause deterioration of the stabilized soil. At high sodium levels (high pH) and low magnesium concentration, removal of the magnesium prevents any significant strength development. Solid silicates are not so effective as the corresponding silicate solutions when applied in the same manner. Attempts to increase effectiveness of solid-silicates through heating or increasing particle fineness have been unsuccessful. Some stabilization was achieved with metasilicate and orthosilicate (more soluble silicates).

22. Mainfort, R. C. Soil Stabilization With Resins and Chemicals. HRB Bull. 108, 1955, pp. 112-120.

Sodium silicate is effective as a stabilizer of sandy soils when used at a concentration of 6 percent by dry weight of soil but is ineffective when used with fine-grained materials. It develops a strong bond between soil particles but does not withstand action of water. The most effective form of sodium silicate is a 40 per-



cent solution, 40 to 42 B, with a ratio of 1 part  $\text{Na}_2\text{O}$  to 3.25 parts  $\text{SiO}_2$ . The injection process employed in practice is discussed and projects are cited.

23. Soil Stabilization With Sodium Silicates. M. I. T., Cambridge, Soil Stabilization Res. Rept., Phase 12, 1960, pp. 29-46.

It was found that New Hampshire silt [ $L_w = 28$  percent,  $PI = 8$  percent, A-4(8)], Vicksburg loess [ $L_w = 41$  percent,  $PI = 15$  percent, A-7-6(10)], and Massachusetts clayey silt [ $L_w = 20$  percent,  $PI = 6$  percent, A-4(4)] can be stabilized with sodium silicates and basic magnesium carbonate. The best results obtained after 7 days of humid curing and 1 day of immersion are 365 psi wet strength in NHS at 8.5 percent total additive, 235 psi in VL at 9.1 percent, and 610 psi in MCS at 6.4 percent. Unsuccessful attempts were made to stabilize Vicksburg buckshot clay [ $L_w = 65$  percent,  $PI = 37$  percent, A-7-6(20)] with sodium silicate and magnesium carbonate. The effect of silica, magnesium, and sodium contents on each of the soils was studied. An explanation of the observations was advanced in terms of the formation of a strong, cementitious gel that results from the presence of polyvalent gel-forming cations in the inorganic salts and in the soils. Several inorganic salts were reacted with sodium silicate in the absence of soil to investigate their gel-forming characteristics. Magnesium oxide formed a gel that is as strong as that of the magnesium carbonate, but stabilization was considerably slower than stabilization with the carbonate. Calcium hydroxide was found to be a much less successful precipitating agent than magnesium carbonate.

24. Morey, R. E., and Lange, E. A. Factors Affecting Sodium Silicate-Bonded Sands. Foundry, April 1959, pp. 188-198.

Tests conducted and reported on were a part of an investigation of the carbon dioxide process for hardening molds and cores. The temperature range (400+ F) in which the tests were performed is unrealistic with respect to soil stabilization in general, but several significant aspects of the results should be noted. An increase in the  $\text{Na}_2\text{O}:\text{SiO}_2$  ratio caused a decrease in strength, and an increase in percentage of sodium silicate used caused an increase in strength. Also, it was observed that an addition of 1 percent bentonite clay to the sodium silicate-sand mixture caused an increase in strength (about 10 percent) over the sodium silicate-sand alone.

25. Buchanan, S. J. Military Application of Soil Stabilization. Proc., Conf. on Soil Stabilization, M. I. T., Cambridge, 1952, p. 295.

The author outlines the methods of soil stabilization applicable to the difficult problems encountered in the development of air force installations in forward areas. The use of sodium silicate is indicated as a possible solution to some of these problems.

26. Murray, G. E. Chemical Soil Stabilization: Effect of Stabilizer Structure on Preparation and Properties of Stabilized Soil. HRB Proc., Vol. 34, 1955, pp. 602-613.

The effect that the structure of a stabilization agent, i.e., magnesium, calcium, zinc, and sodium acrylates, has on the characteristics of a treated soil is discussed. The response of the treated mass to load depends on chemical structure of the admixture and distribution of the agent throughout the mass. Results indicate that a stabilizing agent that forms an initially rigid 3-dimensional matrix should be placed under optimum conditions because it cannot adjust to applied stresses to provide uniform distribution needed for effective stabilization. Cement and sodium silicate are cited as examples of such a nonviscous mixture. A stabilizing agent that can undergo viscous flow can be placed at less than maximum density because drying stresses cause it to densify. This type of stabilizer has lower initial strength.

27. Zhuravko, N. M., Drozd, P. A., and Ioseleva, M. A. Resistance to Frost of Sands Stabilized by Chemical Methods. Sbornik Nauch. Rabot. Beloruss. Politekh. Inst., No. 54, 1966, pp. 57-62, in Russian.

Aqueous solutions of mixtures of sodium silicate and of salts of bivalent and trivalent metals (e.g.,  $\text{MgSO}_4$ ) on introduction into sandy ground make the latter mechanically stable (temporary compressive strength of 115 psi).



28. Zhmako, N. M., and Ioseleva, M. A. The Consolidation of Sand by the Introduction of Mixed Salts in the Reaction With Sodium Silicate. Belorus. Politekh. Inst. Im. I. V. Staline. Sbornik Nauch. Trudov, No. 78, 1960, pp. 162-167, in Russian.

Soil stabilization was studied. Sulfates, chlorides, and acetates of calcium, strontium, barium, magnesium, and cadmium were mixed singly with sand and the mixtures were treated with a solution of sodium silicate. The compressive strengths of the specimens were determined after time intervals up to 270 days. Sulfates and chlorides of calcium and magnesium were combined and, after being mixed with sand, were also treated with sodium silicate solutions. Mixtures containing calcium salts have the highest strength, up to 162 psi, because of the formation of hydrated calcium silicate.

29. Dogra, R. N., and Uppal, I. S. Chemical Stabilization of Sand and Sandy Soils, Laboratory Experiments With Sodium Silicate as Stabilizer. Jour., Indian Roads Congress, Vol. 23, No. 1, 1958, pp. 161-172.

Investigations compared the properties of sodium silicate-sand and sodium silicate-sandy soils with the properties of cement-sand and cement-sandy soils. Strengths of pure sand and nonplastic soil specimens were greater at even low quantities of sodium silicate concentrations (1,500 psi at 2.5 percent on dry soil basis) than strengths of samples with higher concentrations of cement additive (1,300 psi at 10 percent). Sodium silicate-treated specimens of sandy soils were more resistant to abrasion than cement-sand. Durability test results (immersed 5 hours and dried 70 C for 42 hours) on specimens of 10 percent clay, 90 percent sand, and 1 percent sodium silicate showed loss of 3.5 to 4.0 percent in 12 cycles. However, larger additive concentration caused rapid disintegration of the specimens upon immersion. Use of sodium silicate with soils of higher clay content produced specimens with poor durability.

30. Winterkorn, H. F. Final Report on Beach Sand Stabilization Research. Bureau of Yards and Docks, Dept. of Navy NOy-15087, 1949, 564 pp.

Pertinent statements are made concerning the use of sodium silicates as dust preventives and road binders, soil stabilizers, and soil solidifiers. Data are presented that show the results of field tests with aqueous solutions of sodium silicate used as a stabilizer of beach sand. Strips 10 ft long by 50 ft wide were stabilized to depths of 4 to 6 in. by loosening the sand, spraying an application of 40 percent solution sodium silicate at concentrations of 1 to 3 percent on dry weight basis of treated depth of sand, and compacting with pneumatic and flat rollers. Tests indicated the sections had a hard brittle crust about  $\frac{1}{4}$  in. thick that did not withstand the weight of a jeep or  $\frac{3}{4}$ -ton truck used as test vehicles.

31. Soil Stabilization by the Use of Chemical Admixtures. Roads and Engineering Construction, Vol. 89, No. 10, 1951, p. 112; Mainfort, R. C. A Summary Report on Soil Stabilization by the Use of Chemical Admixtures. U. S. Civil Aeronautics Administration, Tech. Development Rept. 136, Feb. 1951.

This article presents a summary of the results obtained from laboratory and field investigations of the soil-stabilizing properties of numerous chemicals with respect to their applicability for road and airport construction. Sodium silicate was among the most commonly available materials found to be unsuitable stabilizing materials. However, small quantities of sodium silicate were effective in reducing the plasticity of fine-grained soils.

32. Kozan, G. R., and Fenwick, W. B. Soil Stabilization. U. S. Army Engineer Waterways Exp. Station, Tech. Rept. 3-455-7, Feb. 1965.

A laboratory investigation was made to examine the relative effectiveness of several primary additives in stabilizing Vicksburg loess and buckshot clay. Included as additives were sodium silicate solution and anhydrous orthosilicate and metasilicate. Magnesium carbonate and magnesium oxide were examined as precipitating agents. These materials produced very little improvement in strength (40 psi maximum). Although they were small, the strengths developed by using sodium orthosilicate in the loess (lean clay) during humid cure were effectively re-

tained upon soaking. Specimens of the heavy clay treated with sodium orthosilicate disintegrated during soaking.

33. Review of Materials and Methods for Dustproofing and Waterproofing Soils. Corps of Engineers Research and Development Report, U. S. Army Engineer Waterways Exp. Station, Misc. Paper 3-176, July 1956, pp. 6-7.

The review includes a discussion of applicability of sodium silicate for dustproofing and waterproofing. A fine-grained clayey silt (ML-CL) was satisfactorily dustproofed with treatment of 3 gal/sq yd of a 30 percent solution of sodium silicate in an arid, southwestern area of the United States. Depth of penetration was  $1\frac{1}{2}$  in. The surface withstood 200 coverages of  $2\frac{1}{2}$ -ton cargo truck without evidence of stress, cracking, or surface abrasion. Attempt to stabilize a well-graded sand (SW) by similar means was unsuccessful because of the deeper penetration of sodium silicate in the more pervious material. However, satisfactory penetration was obtained by first compacting the loose sand then applying the sodium silicate.

34. Freitag, D. R., and Kozan, G. R. An Investigation of Soil Waterproofing and Dustproofing Materials. HRB Bull. 282, 1961, pp. 13-27.

The capabilities of a number of materials to waterproof and dustproof a lean clay ( $L_w = 38$  percent,  $PI = 16$  percent, A-6) were evaluated by means of field and laboratory studies. Traffic was applied at intervals during a 13-month period of exposure to weather to a test section consisting of panels treated with 13 selected materials. The amount of material abraded by the traffic was measured to determine dustproofing effectiveness, and observations of moisture changes in the compacted soil under each surface were made to provide an indication of the degree of waterproofing supplied by the various treatments. A 30 percent solution of sodium silicate was used and was found to be a relatively ineffective water dustproofing material.

35. Dustproofing and Waterproofing of Soils. Laboratory Studies of Soil Waterproofing Materials, U. S. Army Engineer Waterways Exp. Station, Tech. Rept. 3-530-2, July 1963, 40 pp.

Results of tests on specimens, prepared by using the Harvard miniature compaction apparatus with a compacting effort of 20 tamps of a 40-lb spring tamper on each of 5 layers per specimen, indicated various sodium silicate systems were totally ineffective as waterproofers for either of the 2 test soils: Vicksburg loess (CL,  $PI = 15$  percent,  $L_w = 39$  percent) and buckshot clay (CH,  $PI = 40$  percent,  $L_w = 63$  percent). Anhydrous silicates (sodium orthosilicate,  $Na_4SiO_4$ , and sodium metasilicate,  $Na_2SiO_3$ ) were premixed with a modifier, either magnesium carbonate or magnesium oxide, before being added to the soil; whereas the silicate solution,  $Na_2O:SiO_2$ , was incorporated after mixing of the soil and modifier.

36. The Dust-Proofing of Concrete With Sodium Silicate. Indian Concrete Journal, Vol. 29, No. 9, 1955, p. 291.

The article discusses the relative merits of using sodium silicate as a dustproofing material for concrete surfaces. It indicates that sodium silicate is cheaper than alternative dustproofing materials, can be stored indefinitely in a closed container without deterioration, is nontoxic and nonflammable, and is very effective in penetrating and hardening a relatively porous concrete surface.

37. Lambe, T. W., Michaels, A. S., and Moh, Z. C. Improvement of Soil-Cement With Alkali Metal Compounds. HRB Bull. 241, 1960, pp. 67-103.

A large number of soils of widely different geographical origin, fineness, and mineralogical composition have been tested to determine their response to stabilization by cement in the absence and presence of a selected group of alkali metal compounds at low concentration. The soaked compressive strength of nearly all cement-soils tested was substantially improved (twofold to tenfold) by the use of relatively small quantities of sodium compounds that form insoluble compounds with calcium. Optimum additive concentration was found to correspond very nearly to a sodium ion concentration in the molding water of 1.0 N, that is, between 0.5 and



2.5 percent by weight, depending on soil and additive. Five percent cement and 1 percent sodium silicate-silt gave strengths comparable to those of 10 percent cement-silt, but sodium silicate was the most beneficial additive in clean sands where it doubled early and ultimate strength of sand-cement specimens. Economics of additive treatment is discussed, and it is shown that considerable financial saving can be realized by the use of the sodium additives. A hypothesis to explain the action of the additives is proposed. It attributes the beneficial action to enhanced participation of soil-derived silica in the cement-hydration process. Alkali metal compounds exert their major influence on cementation in soils at the earliest stages of the cure process by promoting silica solubilization and retarding calcium silicate precipitation; they have relatively little effect on the composition of the final cementing components.

38. Moh, Z. C. Soil Stabilization With Cement and Sodium Additives. American Society of Civil Engineers, Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 88, SM6, Paper 3356, 1962, pp. 81-105.

This is a report of an investigation of improvement in the effectiveness of portland cement as a stabilizer by use of chemical additives. Tests showed that, with all types of soils studied, from nonplastic sands to heavy clays, cement stabilization can be substantially improved by incorporation of relatively small quantities of sodium compounds. Strength improvements varied from 15 to 250 percent. The degree of effectiveness of the sodium additives depends largely on the characteristics of the soil involved; sodium metasilicate is most effective in clean sands and least effective in plastic clays.

39. Moh, Z. C., Lambe, T. W., and Michaels, A. S. Improvement of Soil-Cement With Chemical Additives. HRB Bull. 309, 1962, pp. 57-76.

This paper summarizes the results obtained from detailed study on the use of alkali additives in soil-cement. Study of the long-term effects of immersion in sulfate solution of a cement-stabilized sand indicates that sodium metasilicate greatly delays or reduces the deteriorating effects of the sulfate, thereby prolonging the life of the soil-cement. Examination of the effect of the soda-to-silica ratio in sodium silicate showed a 1:2 ratio to be about optimum for improving strength of New Hampshire silt with 5 percent cement. A higher soda-to-silica ratio in sodium silicate tended to give higher early strength but lower ultimate strength, while a lower ratio retarded the cementing process.

40. Norling, L. T., and Packard, R. G. Discussion of Improvement of Soil-Cement With Alkali Metal Compounds. HRB Bull. 241, 1960, pp. 103-108.

The effect of alkali metal compounds on the durability of soil-cement was studied. The results of tests on 4 soils show that the effect of chemical additives on durability, as measured by freeze-thaw and wet-dry tests, is similar to that of the additive on compressive strength. The addition of 1.0 percent sodium metasilicate reduced the cement required to satisfy durability specifications of Massachusetts clayey silt [ $L_w = 20$  percent,  $PI = 6$  percent,  $A-4(4)$ ] from 8.5 percent to 6.0 percent.

41. Katti, R. K., and Kulkarni, K. R. Effect of Trace Organic Chemicals on Lime Stabilization of an Expansive Soil. Jour., Indian Roads Congress, Vol. 27, 1962, pp. 215-230.

The effect of lime,  $CaO$ , and lime plus 0.5 and 1 percent sodium silicate,  $Na_2SiO_3$ , and other inorganic chemicals on strength, water absorption, and swelling of a black soil was studied. Maximum strength, after 7, 14, and 28 days of curing the mixtures, was obtained when 8 percent lime was used. Sodium silicate increased strength, about 100 percent after 7 days of curing, at lime concentrations below 8 percent, reduced absorption, and had no consistent effect on swelling. Mixtures containing sodium silicate did not have maximum strengths significantly different from those containing lime alone when tested at 28 days.



42. Mateos, M., and Davidson, D. T. Further Evaluation of Promising Chemical Additives for Accelerating Hardening of Soil-Lime-Fly Ash Mixtures. HRB Bull. 304, 1961, pp. 32-50.

The results of an investigation on the effect of various amounts of 12 chemicals on the strength of a mixture of Ottawa sand-lime-fly ash are presented. The effects of 4 selected chemical additives, including sodium metasilicate, on the strength of soil-lime-fly ash mixes, including 4 natural soils (dune sand, friable loess, alluvial clay, and Kansan gumbotil), calcitic hydrated and dolomitic monohydrate lime, and 3 fly ashes, are also presented. The evaluation showed sodium metasilicate to be very beneficial to sandy soil-lime-fly ash and friable loess-lime-fly ash mixtures. In general the benefits decreased with increasing clay content (montmorillonitic mineral content) of the soils tested.

43. Jorgensen, L. R. Solidifying Gravel, Sand and Weak Rock. Western Construction News, Vol. 6, No. 21, 1931, pp. 591-593.

The process invented by Joosten for binding loose material to obtain a solid watertight mass by successively injecting solutions of sodium silicate and salt into gravel, sand, weak rock, masonry, or concrete is discussed. Compressive strengths range from 300 to 1,200 psi. The magnitude of the strength depends on the relative quantities of siliceous material present in the materials and the relative grain size of the treated materials. Applications also include waterproofing masonry shaft linings by reducing water flow from 150 gpm to a negligible amount.

44. Pohl, K. A. The Chemical Solidification of Loose Soils. Engineering Progress, Vol. 13, No. 4, 1932, pp. 85-88.

The author discusses the characteristics of the chemical solidifying process using successive injections of silicic acid and salty solutions. The procedures of solidifying practice are outlined. The principal soil property changes, including increased compressive strength, reduced permeability, and increased resistance to chemical attack, are enumerated. An example of the process application is given.

45. Japp, H. New Methods of Excavating Quicksands, No. 11. The Engineer, Vol. 156, No. 4060, 1933, pp. 422-425.

This paper discusses the Joosten soil consolidation process and presents examples of practical applications to engineering projects. Included are examples of the successful uniform consolidation of sandy soils containing patches of fine-grained soils, the adherence of clay layers and concrete structures to chemically solidified coarse-grained water-bearing strata, and the development of a 15-*tsf* compressive strength in a ballast containing about 25 percent silt and clay.

46. Harding, H. J. B. Groundwater Lowering and Chemical Consolidation of Foundations. Concrete and Constructional Engineering, Vol. 30, No. 1, 1935, pp. 3-12.

The Joosten consolidation process was employed to strengthen existing foundation materials prior to adjacent excavation for a rebuilding project in Kingston, England. Waterlogged ballast and sand foundation soils were solidified into a form of artificial sandstone with a crushing strength of 30 *tsf*.

47. Gutmann, I. The Moscow Subway. Engineering News-Record, Vol. 116, 1936, p. 515.

Solidification of quicksand by injecting sodium silicate and calcium chloride solutions under 70- to 90-*psi* pressure is discussed. Compressive strength of the solidified material was from 280 to 850 *psi* and up to 3,600 *psi* in quartz-abundant material. About 90 gal of chemicals were required to solidify 1 *yd*<sup>3</sup> of material. Solidification occurred in 15 to 20 min. Poor pervious concrete lining was waterproofed by chemical grouting.

48. Joosten, H. Chemical Solidification of Loose Soils. The Constructor, Vol. 19, No. 8, 1937, pp. 23-24.

The author discusses the method of sealing and reinforcing porous material underground by chemical solidification. A presentation of the techniques employed, the limitations of the process, and some of its possible uses is given.

49. Karghin, V. A. Interaction Between Concentrated Solutions of Sodium Silicate and Calcium Chloride. *Prikladnoi Chimyi*, 1937, pp. 93-98, in Russian.
50. Bodascher, I. O. Strengthening and Sealing in the Building of Rumanian Wells by Chemical Processes. *Die Bautechnik*, Book 10, March 10, 1959, pp. 139-140, in German.

This describes the processes employed to reduce the flow of water into the Mihar well, drilled on the grounds of the salt mines of Vioara, Rumania. A sodium silicate-calcium chloride 2-step injection technique used with cement reduced the flow of water through a gravel layer connected to a nearby water-bearing strata.

51. Lewin, J. D. Grouting With Chemicals. *Engineering News-Record*, Vol. 123, No. 7, 1939, pp. 61-62.

The use of sodium silicate with calcium chloride, aluminum sulfate, and other metallic salts in the consolidation of soils is discussed. Chemical grouting is said to be applicable to soils possessing permeabilities of  $10^{-1}$  to  $10^{-4}$  cm/sec. The most commonly used sodium silicate solution has a density not less than  $42.25^\circ$  B and a sodium oxide,  $\text{Na}_2\text{O}$ , to silica,  $\text{SiO}_2$ , ratio of 1:3.22. Examples of applications include the reduction of the permeability of sand from 40 to 0.15 gpm and the increase of the bearing capacity of sand to 1,300 psi.

52. Consolidating Loose Soils. *Roads and Road Construction*, Vol. 22, No. 256, 1944, pp. 103-104.

The method of stabilizing granular soils by injecting solutions of sodium silicate and common salt into a deposit is discussed. The compressive strength of the treated soil can be increased by 140 to 570 psi. The major drawback of the process is stated as its limitation to application in cohesionless soils.

53. Riedel, C. M. Chemical Soil Solidification and Chemical Sealing of Leaking Concrete. *Jour. of American Water Works Assn.*, Sept. 1945, pp. 849-862.

The underlying principles of Joosten's injection method of chemical soil solidification and sealing of leaking concrete are outlined. The uses of the process in water works and other public utilities construction are discussed. Examples are listed.

54. Chemical Injections Solidify Soil to Stop Foundation Settlement. *Construction Methods*, Vol. 27, No. 12, Dec. 1945, p. 78.

Silicate of soda and calcium chloride were used to solidify a wet, medium fine sand under the heavy foundation of a mill-engine and crusher at the Clewiston, Florida, sugar mill of the U. S. Sugar Corporation. Injection pressures used were about 400 psi; after solidification, injection pipes could be driven into the deposit only with great difficulty.

55. Injected Fluid Stops Running Sand. *Western Construction News*, Vol. 23, No. 9, 1948, pp. 89 and 101.

Free-running sand in a cable tunnel was solidified by pumping a dilute solution of sodium silicate and sodium bicarbonate (1-shot system) at 200-psi gauge pressure to the face of the tunnel. The treatment made the sand into a soft sandstone (80- to 100-psi compressive strength), made it possible to place the liner plates without breast boards or piling and without danger of losing ground, and developed an arch of solid sand above the tunnel that diminished the pressure on the liner plates.

56. Bristow, T. Footings Dug Without Shoring in Chemically Solidified Sand. *Engineering News-Record*, Vol. 143, No. 19, 1949, p. 48.

A sodium silicate solution was used to solidify a free-running sand foundation soil. Solidification was accomplished by introducing 500 gal of the solution under 200-psi pressure for each footing. Compressive strength of the solidified sand was about 75 psi.

57. Debecq, A. The Silicatization of Soils. Rev. Tech, Luxembourg, Vol. 41, 1949, pp. 29-30.  
 Methods of densifying soil and increasing its resistance to load are discussed. When the Gayard process is used, sodium silicate is injected with 3 to 15 percent sodium or potassium bicarbonate, 3 to 15 percent sodium chloride, and 0.3 to 1.0 percent sodium or potassium hypochlorite of the weight of sodium silicate,  $\text{Na}_2\text{OSiO}_3$ , used. The injection techniques are described.
58. Riedel, C. M. Latest Developments in Soil Solidification. Midwest Engineer, Vol. 1, No. 6, 1949, pp. 6-8.  
 This is a discussion of the chemical solidification of loose, sandy soils, based on the Joosten Process. The characteristics of the solidified material are presented, including 250- to 1,100-psi compressive strength, 160-psi tensile strength, and very low acid solubility. Limitations of the process are comparative economics and soil grain size. Examples of practical applications are listed.
59. Wright, R. E. Chemical Stabilization of Sand Speeds Driving of 10-ft Tunnel. Engineering News-Record, Vol. 143, No. 5, 1949, pp. 42-43.  
 A storm water tunnel in San Francisco, 2,700 ft long with a 10-ft horseshoe section, had to be driven through dry sand that came through cracks between lagging and breast boards more rapidly than it could be removed. Remedy was injection of sodium silicate with reacting agent in the form of sodium bicarbonate. The amount of combined solution required for stabilization varied from 30 to 45 gal/yd<sup>3</sup> of solidified soil.
60. Chemical Treatment Cures Sick Tunnel. Construction Methods and Equipment, Vol. 31, No. 9, 1949, pp. 66-73.  
 Injections of 8,400 gal of silicate of soda and 5,100 gal of calcium chloride were used to stop excessive flow (250 gpm) of water under a 50-ft hydraulic head through a 4-ft medium fine sand strata so that a tunnel could be advanced 62 ft through the strata.
61. Askalonov, V. V., Korablinov, A. M., and Koltunovskaya, B. M. Application of Silicate Treatment to Loess Soils. Stroitel. Prom., Vol. 28, No. 4, 1950, pp. 10-12.  
 Equipment and procedures are described for impregnation of loess soils with sodium silicate for purposes of mechanical fixation of the soil. The treated surfaces, bound apparently by cementation with partly hydrated  $\text{SiO}_2$ , are satisfactory in respect to strength, hardness, and water resistance.
62. Gershoy, E. C., and Mueller, C. Soil Stabilization for Transmission Tower Footings. Electric World, Vol. 135, No. 3, 1951, pp. 60-61.  
 Tower footings in loose sand can be strengthened and solidified with the aid of a mixture of sodium silicate,  $\text{Na}_2\text{SiO}_3$ , and sodium bicarbonate,  $\text{NaHCO}_3$ . The mixture forms a silica,  $\text{SiO}_2$ , gel that holds the grains of sand together in a stable semi-permanent mass that can be excavated with a conventional auger without sloughing or caving. Concrete can be poured directly into the bored hole without need of forms. A mixture of 12 parts by volume of sodium silicate (1:3.22, 41 B) 60 parts of water, and 28 parts of a solution containing 6.6 lb  $\text{NaHCO}_3$  per 100 lb gels in 45 to 60 min.
63. Riedel, C. M. Chemicals Stop Cofferdam Leaks. Civil Engineering, April 1951, pp. 23-24.  
 The method of using sodium silicate-calcium chloride solutions to reduce the permeability and increase the strength of granular materials is illustrated. The strength developed depends on the silica content of the natural soil. The injection process is limited to soils containing less than 25 percent clay, silt, or minus No. 140 sieve (0.105 mm) sand. The bearing strength of the stabilized soil approaches 700 psi, and the strata is impervious to water even under considerable hydrostatic head.



64. Keil, K. The Densification and Strengthening of Bonding Soils (Adhering Loose Rocks). Bautechnik, Vol. 29, 1952, pp. 42-46, in German.

Binding soils can be stabilized by chemical or electrolytic treatment based on the physical change that the soil undergoes by elimination of the decisive influence of the water. This is made possible by the limitation of the exchangeability of ions and the capacity of water molecules to be adsorbed at the unsaturated border areas of the clay minerals. The action of this chemical strengthening is always limited to the chemical sphere of influence. Although sodium chloride was formerly used, especially in America, for the electrolytic treatment, Keil uses labile water glasses,  $\text{Na}_2\text{SiO}_3$ . The mutual actions between chemicals and soils are discussed.

65. Soil Stabilizing Permits Sand Augering. Electrical West, Vol. 110, No. 5, 1953, pp. 82-83.

To overcome the difficulty of caving holes in sandy areas, it was necessary to develop a process of stabilizing the sand long enough to permit augering the hole, setting the template and reinforcing steel, and pouring the concrete. The soil was stabilized by injection of a chemical solution into the alluvial deposit at 100-psi pressure.

66. Lambe, T. W., and Michaels, A. S. Altering Soil Properties With Chemicals. Chemical and Engineering News, Vol. 32, No. 6, 1954, pp. 488-492.

The authors present a thorough discussion of the soil-stabilization problem. The various factors that influence the type and amount of stabilization agent needed to produce a satisfactorily stabilized mass are noted. These include the soil properties; the use for which the agent is intended, i.e., a true additive, a trace chemical, a waterproofer, or an aggregation or flocculation agent; and the means by which the soil is chemically treated. The future of chemical stabilization is also discussed.

67. Gnaedinger, J. P. Soil Stabilization by Injection Techniques. Industrial and Engineering Chemistry, Vol. 47, Nov. 1955, pp. 2249-2253.

Problems pertaining to the injection process of stabilization of subsurface soils are discussed. A comparison is drawn between AM-955, a product of the American Cyanamid Company, and sodium silicate when used in stabilizing sands. It is noted that AM-955 generally provides more satisfactory results but is more expensive. Principal civil engineering problems that can be solved effectively by injecting chemicals into the soil are discussed. These include the prevention of seepage into underground structures, construction of caissons and tunnels, prevention of seepage beneath dam foundations, and sealing pervious strata in water and oil wells.

68. Golder, H. Q. Use of Chemical Injection Processes in Underpinning and Tunnelling. Der Ingenieur, Vol. 67, No. 49, 1955, pp. B173-176, in German, and discussion, pp. B176-177, in English.

This paper discusses the injection processes and lists types, limitations, and uses. Chemical processes are divided into 2 groups, the single-solution and the 2-solution processes. Single solution is cheaper when a large volume of material is treated, but placing of chemical is difficult to control. Therefore, it is used for impermeabilizing strata. The 2-solution is more adaptable to situations where strength and stability are prime considerations. Numerous applications in British construction are described.

69. Hauser, E. A. Composition and Structure of Siliceous Compounds. Silicic Compounds, 1955, pp. 7-20.

70. Hauser, E. A. Soil Stabilization. Silicic Science, 1955, p. 141.

This and the preceding report discuss the basic reactions that occur when sodium silicate is used with a calcium salt for stabilizing a soil deposit. It is stated that, soon after the soluble calcium salt is injected, an ion exchange reaction occurs that causes the formation of calcium silicate and releases sodium ions. The calcium silicate forms a gel that solidifies quite rapidly.

71. Lambe, T. W. Chemical Stabilization Can Make Construction Materials of Weak Soils. *Engineering News-Record*, Vol. 155, No. 3, 1955, pp. 41-42, 44, 46, 48.  
By a minor change in physical characteristics, discarded soils can be converted into usable highway construction soils. The importance of and new uses for conventional stabilizers as construction materials are discussed. Aids to soil mixing, information on methods of obtaining greater density, and a discussion of antistripping agents, aggregants, and dispersants are presented.
72. Numata, M., Marugasu, T., and Kurosaki, T. A New Method of Chemical Grouting to Solidify Loose Ground. *Trans., Japan Society of Civil Engineers*, No. 12, 1956.  
The use of sodium aluminate plus sodium silicate plus sodium hydroxide in grouting is discussed. With a coagulation period varying from 1 min to 1 hour, the compressive strength of treated sand approached 20 to 30 kg/cm<sup>2</sup>. Field testing disclosed a reduction of permeability from 10<sup>-3</sup> to 10<sup>-5</sup> cm/sec.
73. Riedel, C. M. Chemicals Dry Up Pump Pit Job. *Engineering News-Record*, Vol. 157, No. 14, Oct. 4, 1956, pp. 49-50.  
The 2-shot Joosten method of soil solidification was employed to alleviate a water problem in the modernizing of Chicago's old pumping stations. The process consisted of first injecting a solution of silicate of soda, followed immediately by a strong calcium chloride solution, into the wet fine sand present at the job sites. As the chemicals met in the ground, a rapidly formed silicic gel of high surface tension bound the loose sand particles together into an insoluble sandstone-like mass of hardness varying from 150 to 900 psi, depending on the character of the loose material. After being properly solidified, the soil was watertight and withstood groundwater and saltwater acidic action. Its hardness generally increased with time, and it possessed a bond comparable to that of concrete.
74. Rozgaj, S. Chemical Injections Based on Waterglass Solutions. *Tečnicki Pregled*, Vol. 8, 1956, pp. 67-75, in Russian.  
Mechanical and chemical properties of water-glass solutions and precipitation and control of reactions for use in soil consolidation are discussed.
75. Ingenuity Needed for Bell Caissons in Loose Sand. *Western Construction*, Vol. 31, No. 5, 1956, pp. 36-37.  
Foundation soils vary from loose sand to clay beneath a proposed 13-story building. Soil was stabilized with sodium silicate and bicarbonate of soda injections, but the variable nature of deposits and high moisture content reduced the length of flow from the injection nozzles and prohibited effective solidification.
76. Chemical Stabilization Cuts Excavation Cost. *Pacific Builder and Engineer*, Vol. 62, No. 7, 1956, p. 105.  
The construction of a swimming pool built in sandy and gravelly soil under an existing building, adjacent to footings and columns of the building and adjacent also to a concrete slab floor, is discussed. Commercial sodium silicate, certain metallic salts including calcium chloride, and certain dispersing gases were used to stabilize the soil. Excavation costs were reduced by 30 percent. Solidification cost was about \$25/yd<sup>3</sup>. The capabilities of chemical soil stabilization are outlined.
77. Cambell, C. W. Chemicals Seal Foundation for New York Building. *Civil Engineering*, Vol. 27, No. 10, 1957, pp. 47-51.  
Chemical grouting, using the Joosten 2-shot injection process with sodium silicate followed by an intrusion of calcium chloride, was used successfully as an aid in constructing foundations for the Chase Manhattan Bank building in New York City. The grouting effectively sealed off the excavation site so that the flow of water through water-bearing strata into the excavation was negligible, and the loss of ground to adjacent structures was minimized.



78. Polivka, M., Witte, L. P., and Gnaedinger, J. P. Field Experiences With Chemical Grouting. *Jour. Soil Mech. and Found. Div., Proc. ASCE*, Vol. 83, April 1957, pp. 1204-1-1204-31.

This paper cites many examples of the use of chemical grouts, either for improving the stability of sandy soils or for sealing porous strata to prevent water movement. The examples given include the use of sodium silicate grouts as an aid in the construction of tunnels and foundations in free-flowing sand. Laboratory control, composition of grouts, and methods of grouting are discussed. First sodium silicate,  $\text{Na}_2\text{SiO}_3$ , and then a reagent, such as calcium chloride,  $\text{CaCl}_2$ , are injected into a subsurface soil to form a precipitated insoluble crystal-like solid that fills the voids in the soil and cements together the loose grains. When sodium bicarbonate,  $\text{NaHCO}_3$ , replaces the calcium chloride, the resulting gel is weak. When sodium silicate and the reagent are injected simultaneously, the gel deteriorates in a few months. A permanent gel may be formed with dilute sodium silicate mixed with hydrochloric acid,  $\text{HCl}$ , and copper sulfate,  $\text{CuSO}_4$ .

79. Van Heerde, J. A., and Golder, H. Q. Solving a Problem in Soil Stabilization. *Consulting Engineer*, Vol. 9, May 1957, pp. 80-81.

The settlement of adjacent buildings was prevented by injecting a solution of sodium silicate-sodium carbonate followed by calcium chloride into sandy soil before excavation was begun for a new post office at The Hague, Netherlands. Samples of the injected soil showed a compressive strength of from 250 to 700 psi, depending on the origin of the sample and the pressure on the sides of the test cubes (0 to 140 psi). The results indicated a shear strength of about 70 psi. No measurable settlement of adjacent buildings was noted.

80. Chemically Made Rock Seals Foundation Pit. *Construction Methods and Equipment*, Vol. 39, No. 9, 1957, pp. 95-97.

Injection of sodium silicate and calcium chloride solutions under pressures of 160 to 600 psi made a subterranean cutoff wall in a wet sand-gravel stratum.

81. Pynnonen, R. O., and Look, A. D. Chemical Solidification of Soil in Tunneling at Minnesota Iron-Ore Mine. U. S. Bureau of Mines, Information Cir. 7846, 1958, 8 pp.

Construction of a conveyor tunnel at an iron ore mine was stopped when a 22-ft bed of saturated fine gray sand was encountered. Solutions of sodium silicate and calcium chloride were forced into the water-bearing sand, consolidating it and removing the water problem. Excavation was done with pneumatic spades.

82. Zhmako, N. M., and Ioseleva, M. A. Effect of Various Sulfates on the Strength of Fixation of Sandy Soil During Silicatization. *Belorus. Politekh. Inst. Im. I. V. Stalina. Sbornik Nauch. Rabot.*, No. 59, 1958, pp. 149-153, in Russian.

Test cubes of sand were treated with 50 cc of 2 N water glass solution and from 6- to 12-g portions of hydrated sulfates of Be, Mg, Zn, Cd, Mn, Fe, Co, Ni, Al, Cr, Cu, and a Ca-Mg mixture. The strength of the cube (maximum  $10 \text{ kg/cm}^2$ ) is greater the lower the atomic weight of the metal is.

83. Chemical Modification of Soil-Cement. *Soil Stabilization Res. Rept.*, Phase 10, M. I. T., Cambridge, 1958, pp. 22-42.

Sodium metasilicate is one of a group of sodium compounds found to be effective additives for improving the properties of soil-cement. Use of 7 percent cement and 1 percent sodium metasilicate in a clean sand resulted in higher early strength and comparable 28-day strength when compared with 10 percent cement alone. With a silt of low plasticity ( $\text{PI} = 8$ ), 5 percent cement and 1 percent sodium metasilicate gave strengths comparable to those with 10 percent cement. With 2 heavy textured soils ( $\text{PI} = 30$ ), 1 percent sodium metasilicate improved the 7-day strength of 10 percent cement by 50 percent. Sodium metasilicate was most effective in sandy soils that are deficient in reactive silica. The effectiveness of sodium compounds decreases with increasing plasticity or organic matter content of the soil or both.



84. Handy, R. L., Jordan, J. L., Manfre, L. E., and Davidson, D. T. Chemical Treatments for Surface Hardening of Soil-Cement and Soil-Lime-Fly Ash. HRB Bull. 241, 1960, pp. 49-66.

Laboratory experiments were conducted to determine the effectiveness of surface applications of chemical solutions on specimens of lime-fly ash and cement-stabilized friable loess [PI = 6 percent,  $L_w$  = 34 percent, A-4(8)] and a 75:25 sand:loess mixture [PI = 3 percent,  $L_w$  = 19 percent, A-4(1)]. Soil-lime-fly ash was benefited most by application of sodium silicate solutions. The sodium silicate penetrates into the soil and reacts with calcium and magnesium ions from the lime to produce insoluble calcium and magnesium silicates. Ratios of  $\text{Na}_2\text{O}:\text{SiO}_2$  and lime to fly ash were not critical, and the treatment was only moderately sensitive to kind of lime. A single application of sodium silicate followed by continual moist curing approximately doubled the bearing strength, and sodium silicate treatment followed by daily applications of water increased bearing capacity in the surface layer about 4 times. The silicate crust also forms an effective seal against entry of surface water and loss of soil moisture due to drying. Laboratory data indicate that a road surface treatment of 1 gal/sq yd of 20 percent solution gives a threefold to eightfold increase in bearing strength. One gal/sq yd of 20 percent sodium silicate raised the bearing value of silt-cement about 35 to 50 percent. However, sodium silicate was most beneficial to sand-cement and, when used in a 5 percent solution in the amount of  $\frac{1}{2}$  gal/sq yd, doubled the bearing value.

85. Herzog, A. The Use of Additives in the Stabilization of Poorly Reacting Soils With Cement. Constructional Review, Vol. 33, No. 9, 1960, pp. 35-36.

The compressive strength of soil-cement mixtures made from poorly reacting soils was greatly increased by chemical additives. Calcium chloride was most effective on sand and soils of low plasticity; sodium metasilicate and, to a lesser extent, ferric chloride were effective on plastic soils that responded least to calcium chloride. Additive concentrations used were 0.5 and 1.0 percent based on dry weight of treated soil.

86. Vaisfel'd, G. B. A New Formula for a Single-Solution Method for the Silicate Stabilization of Loose Ground Masses. Sb. Nauchn.-Issleda. Institute Osnovanli i Podzem, Sooruzhenii, Akad. Stroit. i Arkitekt. SSSR, No. 39, 1960, pp. 14-27, in Russian.

Sandy and loose ground soils, unsafe for the support of buildings, are stabilized by injecting into them solutions that interact to form cementing materials of sufficient strength to consolidate the granular mass into a monolithic structure. Solutions possessing the necessary qualities, such as low viscosities, easily regulated setting times, good cementing properties, and adequate final strength, and usually made up by mixing dilute acids or acid salts with dilute water glass set into solid gels at pH 3.7 to 7.0. A new formula in which phosphoric acid,  $\text{H}_3\text{PO}_4$ , is replaced with sulfuric acid,  $\text{H}_2\text{SO}_4$ , with considerable reduction in cost calls for a solution 1.32 to 1.40 N with respect to sulfuric acid and 0.36 to 0.38 N with respect to aluminum sulfate,  $\text{Al}_2(\text{SO}_4)_3$ , to which is added a solution of water glass of density 1.19 to 1.20 in the ratio of acid solution:water glass of 1.3 to 1.4. Its viscosity is 1.7 cp; its setting time is 10 to 16 hours. Structures so hardened have a crushing strength of about 45 psi.

87. Volkova, V. L. A Single-Solution Method of Claying. Uch. Zap. Vses. Zachn. Institute Inzh. Zhelezno-Dorozhn. Transp., No. 6, 1960, pp. 190-195, in Russian.

Stabilizers and coagulators for clay solutions used for stabilizing weak soils and rocks were selected. When water glass was introduced as a stabilizer and, at the same time ferric chloride,  $\text{FeCl}_3$ , was introduced as a coagulator into the clay suspensions, it was possible to get clay mixtures fulfilling all requirements for performing the claying with 1 solution. The described claying method in which ferric chloride,  $\text{FeCl}_3$ , was used as a coagulator can be recommended for anchoring acid soils.

88. Cunningham, L. J. Use of Chemicals in Mine Grouting. Canadian Mining and Metallurgical Bulletin, Vol. 55, No. 603, 1962, pp. 480-483.

Use of sodium silicate, chrome lignin, and AM-9 chemical grouts is discussed. The procedure for surveying and determining the mine water problem and the methods of sodium silicate application (used as a primer or lubricant), properties, and equipment requirements are presented. A comparison of chemical grouts with cement is made.

89. Higuchi, Y. Studies on Admixtures of Cement Grout for Filling Fine Voids. Trans., Japan Society of Civil Engineers, No. 81, 1962, pp. 27-50, in Japanese with English abstract.

A survey of the history of cement and chemical grouting is presented. The successful treatment of cracks larger than 0.01 mm or voids among soil particles larger than 0.1 mm by combining cement and sodium silicate is reported, and recommendations for using quick-setting cement and expansive grout are provided.

90. Katti, R. K., and Brave, A. G. Effect of Inorganic Chemicals on the Consistency Properties of an Expansive Soil Sample, HRB Bull. 349, 1962, pp. 1-8.

This paper reports the results of the effect of 20 inorganic chemicals on the consistency properties of an expansive soil. The soil was treated with amounts of the inorganic chemicals ranging from 0.1 to 10 percent to take into consideration both practical and academic interests. The data indicate that sodium silicate brings about dispersion of the soil mass. For chemical concentrations below 3 percent, the liquid limit and plasticity index of the soil increase greatly with increasing concentration, whereas the plastic limit and the shrinkage limit of the soil are only slightly affected. Beyond 3 percent, because of the high dispersive action of the chemical, it was not possible to run the liquid limit and plastic limit tests properly; but it was determined that the shrinkage limit was increased threefold over that of the control soil when the chemical concentration was 10 percent.

91. Manvelyan, M. G., Babayan, G. G., Galstyan, V. P., Gevorkyan, S. V., and Aslanyan, D. G. Reaction of Aqueous Solutions of Lithium and Potassium Carbonate With Calcium Metasilicate. Izvestiya Akademii Nauk Armyanskoi S. S. R. Khimicheskie Nauki, Vol. 16, 1963, pp. 437-441, in Russian.