Stabilization of Soils With Inorganic Salts and Bases: A Review of the Literature

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This report consists of an annotated bibliography of the important literature on soil and aggregate stabilization with inorganic salts and bases published prior to 1965. In all, approximately 70 references of the 800 to 1,000 available have been reviewed, among which are several bibliographies providing additional references. From the more informative references, the authors have attempted to summarize information on stabilizer properties, mechanics of stabilization, properties of the stabilized soil, construction methods, field results, and the use of secondary additives. Particular attention is devoted to stabilization with sodium chloride, calcium chloride, and sodium hydroxide, which are the only salts and bases that had been evaluated sufficiently to draw meaningful conclusions.

•THIS REPORT is one of a series on the chemical stabilization of soils. It is limited to a review of existing literature pertaining to soil stabilization with inorganic salts and bases. No original or laboratory investigations were carried on. Similar reports on lime and phosphoric acid have been completed and published (see Herrin, M., and Mitchell, H.: Lime-Soil Mixtures, HRB Bull. 304, 1961; and Barenberg, E. J.: Phosphoric Acid Stabilization of Soils, Highway Research News 3, May 1963). The primary objectives of the report are to acquaint the highway engineer with the present state of the art and to suggest promising paths for future research.

The report deals first with soil stabilization with salts, primarily sodium and calcium chloride, and second with the use of inorganic bases. Within the limitations of available information it describes stabilizer properties, stabilization mechanisms, physical properties of stabilized mixtures, construction methods, and use of salts as secondary additives. The opinions expressed were arrived at from the study of the literature and personal knowledge and experience of the authors. Suggestions for future research are based on published suggestions and the authors' observations.

The annotated bibliography is not complete, but it represents the more important and informative references of the 800 to 1,000 available up to 1965. Because these stabilizers have been discussed in the literature for over 35 years, many of the articles are similar. Listing all those of a repetitive nature would be of little value. Reference is made to several other bibliographies that may be consulted if more references are desired on a particular subject.

The agricultural soil journals provided a vital source of information concerning the reactions of soil with chemicals. Although articles in these journals never dealt specifically with stabilization, the possible stabilizing effects of salts and bases could often be predicted or explained on the basis of knowledge of soil chemistry. These journals should be consulted frequently by soil engineers interested in stabilization with salt.

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Salt is formed as the result of the neutralization of an acid by a base. Normal salts, such as NaCl (sodium chloride), Na_2SO_4 (sodium sulfate), KCl (potassium chloride), and $CaSO_4$ (calcium sulfate), have been completely neutralized—that is, they contain no excess acidic hydrogen (A^+) ions nor excess basic hydroxyl (OH^-) ions. Salts that contain excess acidic hydrogen, such as $NaHCO_3$ (sodium bicarbonate) and NaH_2PO_4 (sodium orthophosphate), are called acid salts, while those containing excess hydroxyl ions are called basic salts.

Many salts (NaCl, $CaCl_2$, $NaNO_3$, $NaHCO_3$, NaH_2PO_4, Na_2CO_3, Na_2HPO_4, Na_3PO_4, $Na_4P_2O_7$, $BaCl_2$, $MgCl_2$, KCl, $KMnO_4$, Na_2SiO_3) have been tested as stabilizers in laboratory samples, but observed laboratory performance, economics, and limited availability dictated the use of only a few salts in the field. NaCl and $CaCl_2$ have been used extensively in highway construction for the last 35 to 40 years. Research on them has been carried on for more than 25 years (24). Since these two salts have been the subject of much of the literature they will be discussed separately and the other salts will be discussed as a group.

SODIUM CHLORIDE

There are three principal methods of producing sodium chloride. The oldest method is the solar process in which the sun is used to evaporate a salt-bearing water, leaving the salt in a crystalline form. The second oldest method is the mechanical mining of rock salt. A variation of the last method is the production of salt brine (from wells), which is then evaporated by artificial heat, often producing nearly 100 percent pure salt.

Sodium chloride is normally furnished in a dry form consisting of solid crystals that dissolve in the presence of moisture. The crystals are somewhat hygroscopic in nature. The predominant type of salt used today is the rock salt variety, which may be purchased in two grades, fine-grained (FC) or coarse-grained (CC), with a purity of at least 95 percent NaCl. Specifications for gradation are contained in ASTM and AASHO standards.

The freezing point of water is lowered as the concentration of dissolved salt is increased. Values for several molalities are given in Table 1. Slesser (68) obtained data indicating that 2 to 3 percent salt would lower the freezing point of soil to -22 C. An aqueous solution of 2 to 3 percent salt would show a freezing point lowering of only 6 to 11 C; thus, the salt concentration in the soil solute must have been considerably greater than 2 to 3 percent.

NaCl solutions have greater surface tension than pure water. One percent salt increases the surface tension of pure water by 1 to 2 dynes/cm. Surface tension for water at 20 C is 72.75 dynes/cm.

The vapor pressure of pure water is lowered by the addition of salt. One percent salt at 0 C lowers the vapor pressure by 4.4 mm of Hg, but at 38 C it lowers it by 50 mm of Hg. The critical humidity (lowest relative humidity at which moisture will be absorbed) is 80 percent for sodium chloride.

The freezing point, surface tension, and vapor pressure changes are all dependent on the solubility of the salt; that is, the greater the amount going into solution, the greater the change in these properties. Although it dissolves rapidly at low concentrations, sodium chloride is not extremely soluble. Only 35.7 g of salt are soluble in 100 cc of water at 0 C while 39.8 g are soluble at 100 C. The effect that these salt properties have on soil stabilization will be noted in the following sections.

TABLE 1

FREEZING POINT LOWERING OF SODIUM CHLORIDE SOLUTIONS

Molality	Grams Anhydrous Salt per 1,000 g Water	Freezing Point Lowering (C)
0.001	0.0585	0.004
0.01	0.5845	0.036
0.10	5.845	0.348
1.0	58.45	3.37
2.0	116.9	6.90
3.0	175.3	10.82
4.0	233.8	15.14
5.2	303.9	21.12

STABILIZATION MECHANISMS

Although there appears to be rather general agreement on the properties resulting

from the incorporation of salt into a soil-aggregate mix, there is some disagreement as to the mechanisms involved in producing these properties. Because salt stabilization probably takes place as a physicochemical reaction, both the physical and chemical aspects must be considered. Much of the basic research on soil-salt reactions has been carried out by mineralogists, agricultural scientists, and chemists.

Clay soil is usually considered the least desirable material for pavement subgrades and subbases. Thus, the effects of chloride on clay must be investigated and understood before salt stabilization can be used intelligently.

Particle Forces

An understanding of particle forces and ion exchange in fine-grained soils seems essential to understanding salt-soil stabilization. Grim (19, 20), Heagler (22), Slate and Yalcin (67), and Mielenz and King (47) all give excellent discussions on the basic properties of clay particles, and the treatment given in the following paragraphs is necessarily brief.

Most clay particles have an unbalanced charge on their surfaces, and therefore attract ions from a liquid phase that may surround them. A complex double layer of absorbed ions is formed through which the potential energy of the clay surface is dissipated to an amount equal to the potential of its liquid. This potential magnitude can be expressed by a quantity called the zeta potential, which is equal to $4Qd/AK$, where Q = charge quantity, d = diffuse layer thickness, K = dielectric constant, and A = surface area. The quantities A, K, and Q cannot be changed readily, but the thickness of the diffuse layer can. Its thickness can be changed by (a) increasing the con centration of electrolyte in the pore water, and (b) substituting higher valence for lower valence ions (Ca^{++} for Na^{+}). Since ions of like charges repel each other, increasing the concentration causes the ions in the diffuse layer to move closer to the clay particles. Decreasing the number of ions needed to neutralize the electrical charges on the clay by the substitution of the ions of higher valence will also result in a decrease of the diffuse layer thickness. From the formula it is apparent that a decrease in d decreases the zeta potential and in turn decreases the forces of repulsion between particles. Increasing d has the opposite effect.

Where particles are covered with charges of like sign they will repel each other, but if some of the particles (or some part of the particles) have opposite charges then an attractive force exists. If the environment is acidic with a surplus of H^{+} ions (low pH), the edges of the clay particles tend to become positively charged while the flat surfaces remain negatively charged. The resulting attraction causes edge-to-face flocculation of a clay suspension. In a basic environment with a surplus of OH^{-} ions (high pH), both edges and faces of the whole clay particles tend to be negative. This results in the formation of a dispersed (face-to-face) structure when the particles settle from suspension.

Another type of force that is related to the internal structure of atoms may be large enough to have some influence on the flocculation of fine clays. However, these forces, called Van der Waals forces, are overshadowed by more powerful forces in most instances and probably have no important influence on stabilization reactions.

Ion Exchange

Ion exchange is the replacement of one ion adsorbed on the clay surface for another. Cation exchange (exchange of positively charged ions) is most important in soils since clay surfaces are usually negatively charged. Grim (19, 20) and Mielenz and King (47) state that the main sources of the negative charge on clay particles result from (a) broken bonds around the edges of the clay particle, and (b) substitution of cations in the crystalline lattice of the clay minerals. Mielenz and King (47) give an excellent discussion on the percent substitution compared to broken bonds for each clay mineral. Thus, the cation exchange capacity is influenced by the type of each clay mineral and its relative percentage in a soil.

The general order of replacement of adsorbed cations is $Li^{+} < Na^{+} < NH_4^{+} < K^{+} < Mg^{++} < Ca^{++} < H^{+}$; that is, at equal concentration any cation will tend to replace

those to its left in the series. Grim (19, 20) has suggested that this order might not be absolute, but rather may change among the clay minerals. If an excess of any one ion is present, it will be adsorbed to the largest extent. Thus, a clay may be made homoionic by leaching it several times with a solution of a single salt.

Soil organic matter also exhibits cation exchange reactions and thus may be important in soil stabilization. The cation exchange capacity of finely divided organic material is very high, usually several times that of clay minerals. Furthermore, organic cations tend to replace inorganic cations on the clay mineral surface and to produce a masking effect that reduces the clay mineral's exchange capacity.

Soil-Salt Reactions

Most unweathered soil materials have a high pH value with Ca^{++} and Mg^{++} as the primary adsorbed ions. It has been shown that Na^{+} will replace Ca^{++}, but to a limited extent (4, 25). Hilmay and Elgabaly (25) have shown that if 1 percent NaCl (dry weight of soil) is added to a Ca-soil, 10 to 12 percent Na^{+} will be adsorbed, and if 2 percent NaCl is added, 22 percent Na^{+} will be adsorbed. Sanborn (60) questions not only the ability of Na^{+} to replace Ca^{++}, K^{+}, Mg^{++}, etc., because of its low value on the scale of activity, but also its ability to be beneficial if adsorbed. Nevertheless, the majority of evidence points to Na^{+} being adsorbed and at least under some circumstances being effective in soil stabilization.

PHYSICAL PROPERTIES OF STABILIZED MIXTURES

It is generally believed that an increase in the density of a soil is usually accompanied by an increase in its strength. Thus, in soil stabilization, increased density is a condition to be achieved. Many investigators have claimed that the addition of NaCl has increased the density of a soil beyond that expected from the added weight of the crystals (18, 43, 46, 58). A completely opposite view is held by several others (49, 54, 61), who assert that the increase in density is numerically equal to the weight of NaCl added. Increased density is attributed to NaCl filling void spaces between soil particles or NaCl causing a dispersed soil structure that allows a closer particle orientation and thus greater density. Whether or not salt does increase density attained at the same compactive effort, in most cases maximum density occurs at a lower moisture content than in untreated samples.

Sodium chloride does reduce moisture content changes in soils, but the extent of the reduction and the process by which it is achieved are disputed. The most widely held belief is that evaporation of water is reduced by increasing the surface tension, which consequently reduces the moisture movement. Thus, the rate of supply to the surface is reduced below the rate of evaporation, and the surface begins to dry. Upon drying, the NaCl in solution is crystallized at the surface and in the voids. These two conditions further act as a barrier to movement of water in the liquid phase. Qayyum and Kemper (55) have stated that the rate of evaporation is inversely related to the thickness of the dry layer. Upon soaking of the dry surface, the salt is again taken into solution and carried down. This promotes swelling of the clay and retards the movement of water into the soil.

The effect of NaCl on the plastic and liquid limits of soils varies from no change to significant changes that seem to be dependent on the soil type (17, 18, 23, 30, 43, 49, 61, 74). In general, the effectiveness of salt treatment is greater and its durability is longer for a soil that has a higher liquid limit. Sodium chloride increases the shrinkage limit, and the volumetric or linear shrinkage is decreased (23, 41, 61, 74). This physical change, in conjunction with a hard surface and reduction in moisture variations, prevents dislodgment of the coarse aggregate and raveling of the surface under traffic (41, 43, 62).

Strength is also increased with the addition of NaCl, but the extent of the increase is again debatable (46, 49, 61, 74). Sanborn and Yoder (61) state that increased strength is realized only when increased density is obtained at lower moisture contents. Rosen-

quist (57) states that a marine quick clay formed by leaching of salt can show a strength gain up to eightfold from remolding and adding NaCl. As with changes in consistency, changes in soil strength are dependent on soil type.

A very desirable change in physical properties occurs in cold climates where frost heave is a problem. Slesser (68) states that frost heave is reduced or eliminated by lowering the freezing point of water-soil to -10 F and by decreasing the permeability of soil. Other authors (17, 18, 23, 54, 62) who mentioned the subject stated that the addition of NaCl definitely reduced frost heave.

Sodium chloride has long been used as a dustproofer, but here again its relative merits are debatable (17, 43, 54, 62). The degree of benefit is at least partly a function of soil type. Effective dustproofing is dependent on causing the particles in the soil to adhere to one another. One means of holding the particles together is to form cementing agents. Marley and Sheeler (43) felt that no cementation occurs between NaCl and the soil, but in a report of Purdue University (54) it was suggested that the soil particles were cemented together with flocculated colloids. Gow, Davidson, and Sheeler (18) mentioned a possible means of cementation within the mix based on the solubility of limestone and dolomite in chloride solutions, resulting in precipitation of cementitious carbonates. This type of cementation seems almost necessary in order to explain the high compressive strengths obtained by McLeland (46) on a salt-stabilized calcareous gravel. Without further knowledge of the cementing mechanism and the soil conditions under which it occurs, the effect of NaCl as a dustproofer or stabilizer is difficult to predict.

ROAD STABILIZATION

Construction Methods

The techniques used to incorporate salt into a stabilized mixture are generally the same as used for other dry additives, and are described in numerous texts and other publications. They range from a well-controlled plant mix to a rather poorly controlled in-place blade mix. Looker et al (41) in 1938 presented good descriptions of various methods, most of which are used today. A typical blade mix is prepared in the following steps: scarify the existing road material, pulverize it, add additional material to obtain desired thickness, spread the salt, add water and mix material by blading back and forth across the roadway, spread evenly, and compact with rollers. A typical plant mix is prepared in the following steps: feed hopper with material from pit or stockpiles in proportion to desired gradation, dissolve sodium chloride in water, mix material and water in a pug mill, load material into trucks, transport and spread evenly on roadway with a blade or spreading machine, and compact loose material with rollers.

Present trends favor a well-controlled plant mix. The essential features in satisfactory construction are accurate proportioning, thorough mixing, and adequate compaction (41). The plant mix can provide the most accurate proportioning and thorough mixing. With blade mixing, accurate proportioning is difficult to obtain, but thoroughness of mixing may be improved by using pulverizing mixers. The best compaction is usually obtained with a pneumatic roller followed by a finishing steel roller. Additional information is available in various publications of the Highway Research Board, the Salt Institute, etc. (23, 28, 41, 58, 61, 62).

Limitations

Sodium chloride is most beneficial in climates affected by frost (54) and in soils or aggregates that have sufficient fine-grained material to react. Soils high in organic matter do not react favorably with sodium chloride.

Thorough mixing of soil and sodium chloride is of the utmost importance if a well-stabilized product is to be obtained. The use of sheepsfoot rollers has generally proved to be ineffective in producing adequate compaction of stabilized mixtures.

Design

Every highway agency follows some type of specification for producing acceptable soil-aggregate mixtures. All specifications encompass two basic factors: (a) gradation of the mixture, and (b) plasticity of the fines. A gradation approximating Fuller's maximum density formula (61) is desirable for formulating the densest possible gradation. In general, the desirable range of maximum particle size is from ¾ to 1 in. and the fine fraction is limited to 5 to 15 percent passing the No. 200 sieve. The plasticity index commonly ranges from 5 to 10 percent for surface courses and 0 to 6 percent for base courses. The thickness of the compacted layer usually ranges from 4 to 10 in., depending on the gradation of the mixture and methods of compaction.

When the mixture is stabilized with NaCl, amounts ranging from 0.5 to 3.5 percent on the basis of dry weight have been used, but percentages of 0.5 to 1 percent are used most frequently. Further information on design and construction techniques are found in works by Huang (26), Looker et al (41), International Salt Co. (27), and Salt Institute (58).

CALCIUM CHLORIDE

Calcium chloride is produced as a by-product brine from several manufacturing processes and may also be found in some natural spring and well waters. The most common sources of $CaCl_2$ result from the manufacture of sodium carbonate by the ammonia-soda process and the production of bromine from natural brines. The material is available in the regular flake, concentrated flake, pellet, or other granular forms and except for the regular flake contains a minimum of 94 percent $CaCl_2$.

The solubility of calcium chloride is 59.5 g per 100 cc of water at 0 C and 159 g per 100 cc at 100 C. It is both deliquescent and hygroscopic. Although it does not greatly retard the rate of evaporation of moisture, it does replace lost moisture under favorable humidity conditions. The critical relative humidity at which $CaCl_2$ will absorb water is 30 percent. The vapor pressure of the $CaCl_2$ solution is also less than that of water at equal temperatures. Calcium chloride has the tendency to increase the surface tension of water between particles, thus helping to reduce evaporation. Calcium chloride also has the ability to lower the freezing point of a water solution by about 6 C for each percent addition.

STABILIZATION MECHANISMS

There is more agreement concerning the stabilizing mechanisms and the relative effects of calcium chloride on soils than there is for sodium chloride. The probable reason for this better agreement lies in the more extensive reasearch that has been conducted on calcium chloride.

Most sources (8, 18, 52, 67, 68) agree that ion exchange occurs on the clay, whereas only Sheeler and Hofer (63) suggest that "ion exchange is virtually absent." Slate and Yalcin (67) give an excellent dissertation on the theoretical aspects of stabilization and substantiate the fact that ion exchange does indeed occur by measuring the drop in pH after the addition of calcium chloride. Coleman, Ragland, and Craig (8) suggest that the unusual ion exchange of Ca^{++} for Al^{+++} occurs if HCl is produced in the reaction. This exchange causes a greater electrical attraction between particles because of the replacement of trivalent ions by divalent ions. The replusive forces acting between particles are reduced with the addition of calcium chloride. Furthermore, the water film bonds between soil grains are strengthened, adding to the apparent cohesion. The zeta potential is lowered when the Ca^{++} replaces lower valence ions, and this decreases the number of ions needed to satisfy the required electrical balance. The pH, although not a part of the stabilization mechanism, is consistently lowered when calcium chloride is added.

PHYSICAL PROPERTIES OF STABILIZED MIXTURES

Several references (18, 29, 63, 67, 73) have stated that density is increased with the use of calcium chloride, sometimes by as much as 11 percent (72). Some authors also

suggest that calcium chloride reduces the compactive effort needed to obtain a given density. The maximum density was usually obtained with mixtures having 0.5 to 3 percent $CaCl_2$ and seemed to vary with the soil type. Certain soil types, however, showed no tendency for increased density, and sometimes a reduction in density was noted (29, 72).

Gow, Davidson, and Sheeler (18) showed that 1 percent was the optimum calcium chloride content in a soil-aggregate mixture. Further additions of calcium chloride tended to decrease the density. They also suggested that the addition of small amounts of $CaCl_2$ brought clay particles closer together by first reducing the negative charges and then by producing valence bonds between neighboring clay particles. However, additional calcium ions change the negative particle charge to a positive charge and produce an increasing repulsive force, thus decreasing the density.

Calcium chloride will keep a soil-aggregate mixture at a fairly constant moisture content, but with time the $CaCl_2$ is leached. Because the swelling pressures and vapor pressures are reduced by $CaCl_2$, the rate of evaporation is reduced (72). Furthermore, $CaCl_2$ has the ability to absorb water equal to 4 to 10 times its own weight when the humidity is high enough (often at night) and to retain one-third to two-thirds of it through the heat of the day. These properties make the salt an acceptable dustproofer under favorable climatic conditions. On the other hand, it has little or no waterproofing action (16). The Corps of Engineers (34) suggested the use of $CaCl_2$ as a dustproofer only on lightly traveled roads. Some county engineers, however, have stated that $CaCl_2$ acts as a complete dustproofer (28). The stabilization of the water content helps to hold the aggregate in place and it has been claimed that $CaCl_2$ treated mixtures give 75 percent better service than non-treated, soil-aggregate mixtures (2). Usually, the strength of $CaCl_2$ stabilized mixtures has been determined by the California bearing ratio (CBR) tests. Slate and Yalcin (67), using a bank run gravel, found that, at a high compactive effort, the addition of $CaCl_2$ had no effect on CBR values. At a low compactive effort, $CaCl_2$ had an appreciable effect. Gow, Davidson, and Sheeler (18), using a soil-aggregate mixture at a single compactive effort, found that all samples increased in CBR with the addition of $CaCl_2$. They also observed an increase in strength of more than 600 percent. Yoder (73) tested 21 different fine-grained soils compacted with varying efforts and at varying $CaCl_2$ contents. The majority of the soils showed a decrease in CBR values even with an increased density, compared to the untreated sample. It seems apparent that the relative effect of $CaCl_2$ on strength varies with the material tested and the testing methods employed.

Data on the effects of $CaCl_2$ on the Atterberg limits are contradictory. Zolkov (74) showed that the liquid limit of a fat clay (PI of 43 to 55) is slightly affected, whereas the plastic limit is not affected. Gow, Davidson, and Sheeler (18) stated that changes in the Atterberg limits for a soil-aggregate mixture are not significant. Yoder (73), in his tests on 21 glacial soils, noted increases and decreases in the limit values. Thus, it appears that the Atterberg limits are generally changed only slightly by the addition of small amounts of $CaCl_2$ but that the kind of change that does occur is dependent on soil type.

Calcium chloride has been used for frost heave protection since the late 1920's. Slate (65) showed that 2 percent $CaCl_2$ will protect silt, 1 percent will protect clay, and only about 0.5 percent is needed to protect a soil-aggregate mixture from detrimental frost action. Slesser (68), in his excellent discussion on frost heave, states that 1 or 2 percent $CaCl_2$ is effective in reducing detrimental heaving in silt when subjected to temperatures as low as -15 F.

ROAD STABILIZATION

Construction Methods and Design

There have been many articles written on the subjects of construction and design, and the usual methods are those discussed previously in the sodium chloride section. The literature yields no design procedure that allows one to predict with certainty the amount of $CaCl_2$ needed to stabilize a given mixture or the length of time the $CaCl_2$ will

be retained against leaching. The amount of $CaCl_2$ used for stabilization is usually 1 percent or less of the weight of dry soil.

Limitations

Climatic conditions are a restriction for $CaCl_2$ uses. Because the ability of $CaCl_2$ to control moisture changes is dependent on its deliquescent properties, a climate furnishing at least 30 percent relative humidity is needed. Slate and Yalcin (67) stated that a soil-aggregate mixture must contain at least 5 percent passing the No. 200 sieve for $CaCl_2$ to be effective. A high water table should be avoided because $CaCl_2$ is easily leached or washed away when accumulated on the surface by evaporation.

OTHER SALTS

Salts such asbarium chloride, copper sulfate, barium sulfate, aluminum sulfate, and magnesium sulfate were evaluated by Massachusetts Institute of Technology during extensive research on soil stabilization, and generally found ineffective (34). Katti and Barve found some beneficial effects on properties of black cotton soils from small amounts of barium chloride, magnesium chloride, and potassium chloride (30).

To date, there is no good evidence that salts other than NaCl and $CaCl_2$ when used alone have stabilizing properties of sufficient magnitude to justify their economic use.

In some instances sodium and calcium chloride have been used in combination to stabilize soil-aggregate mixtures. The NaCl is mixed with the soil-aggregate and $CaCl_2$ is blended into the top 2 in. to take advantage of its deliquescent capabilities. The benefits to be derived from such mixtures seem reasonable but are difficult to demonstrate.

SALTS AS ADDITIVES IN TRACE AMOUNTS

Lime and Lime-Fly Ash

Considerable effort has been expended in determining the effects of various salts in trace amounts on lime, lime-fly ash, and cement stabilization. Davidson, Mateos, and Katti (11) investigated the effect of 47 trace chemicals on the unconfined strength of mixtures of Ottawa sand and lime-fly ash. Most basic salts greatly improved the early (7-day) strength, but did not improve long-term (4-month) strength to a proportionate degree. Sodium carbonate (Na_2CO_3) was considered the most promising of the basic salts. Most neutral salts tested provided good increases in strength, the most promising being potassium permanganate ($KMnO_4$), sodium permanganate ($NaMnO_4 \cdot 3H_2O$), lithium sulfate ($Li_2SO_4 \cdot A_2O$), lithium fluoride (LiF), lithium nitrate ($LINO_3$), and sodium nitrate ($NaNO_3$). Most acid salts did not appreciably improve strength, but of this group, the most promising were calcium chloride ($CaCl_2$) and manganese chloride ($MnCl_2 \cdot 4H_2O$). These trace chemicals were added in amounts of 0.5 or 1 percent. The authors present a rational explanation of the mechanism believed responsible for the strength increase noted.

Mateos and Davidson (45) made further evaluation on Na_2CO_3 and NaCl as trace chemicals on five different soil-lime-fly ash mixtures. Na_2CO_3 proved very effective on the sandy soil- and friable loess-lime-fly ash mixtures, but proved detrimental in a montmorillonitic clay mixture. NaCl also proved beneficial for long-term strength on sand and friable loess mixtures. Ladd, Moh, and Lambe (36) also found that Na_2CO_3 as a trace chemical produced an increase in 28-day strength. They stated that most additives with soil-lime are promising, but the effectiveness varies widely with soil and lime type used.

Many trace additive chemicals apparently have the ability to increase strength or reduce the amount of lime used (lime content of 10 to 20 percent). Postulated mechanisms can be grouped as one or more of the following: (a) acceleration of the pozzolanic reaction, (b) production of secondary comentitious products, and (c) combination with the primary, or pozzolanic, cementitious products (45).

Cement

Trace chemicals were used to increase the strength of a soil-cement mixture as early as 1940. NaCl and $CaCl_2$ were tried first. Other trace chemicals were not evaluated until the middle 1950's. Lambe and Moh (39) used $CaCl_2$, NaCl, KCl, $K_2Cr_2O_7$, and Na_2CO_3 with two silts and one loess in cement-stabilized mixes. The additives had little effect on the loessial soil, but Na_2CO_3 and $K_2Cr_2O_7$ increased the strengths of both silts in excess of 150 percent. It was noted that increases in density did not occur with increases in strength. This result strongly suggests that additional cementitious compounds were produced.

Laguros and Davidson (37) evaluated $CaSO_4$, Na_2SO_4, $CaCl_2$, and Na_2CO_3 as trace chemicals with one silt, five clays, and two sandy soils. Na_2SO_4 was found to be beneficial in stabilizing organic topsoils that were acidic and low in clay content. With increasing clay content and in an alkaline environment, $CaSO_4$ and $CaCl_2$ generally gave high strengths. The clayey B and C horizon soils of near-neutral pH responded very favorably with most additives tested. As other papers have suggested, the relative effects of trace chemicals were found to be dependent on soil texture, clay mineral type, and soil acidity.

Additional data on the use of chemicals in trace amounts are given by Catton and Felt (7), Handy et al (21), and Lambe, Michaels, and Moh (38).

BASES

For stabilization purposes, only the inorganic bases—sodium hydroxide (NaOH), potassium hydroxide (KOH), and calcium hydroxide ($Ca(OH)_2$)—have been evaluated to any extent. Of these, sodium hydroxide has been tested most frequently. The majority of tests have been conducted with lime, lime-fly ash, and soil-cement mixtures using the inorganic bases as trace chemicals. Apparently no tests of inorganic bases were conducted before the early 1950's and to date no extensive field trials have been carried out. Because the data on potassium and calcium hydroxide are severely limited (11, 39), only sodium hydroxide will be discussed here.

Most sodium hydroxide is produced commercially by electrolysis of NaCl solution in electrolytic cells. In another process, the soda-lime method, the chemical reaction is $Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$. Sodium hydroxide is probably the most widely used alkaline material produced by the chemical industry. It is produced on a tonnage basis in both solid and liquid form. It is deliquescent, extremely corrosive, and must be handled with great care.

STABILIZATION MECHANISMS

Lime or Lime-Fly Ash

Davidson, Mateos, and Katti (11) suggest that NaOH may function as a catalyst as follows: "(a) it first reacts with the siliceous material to produce intermediate sodium silicates, (b) the over-all reaction goes to completion when the intermediate sodium silicates subsequently react with lime (calcium hydroxide) to form sodium hydroxide and cementitious insoluble calcium silicates, (c) the sodium hydroxide is then free for further reaction with unreacted siliceous material." Basically, NaOH increases the amount of hydroxyl (OH^-) ions and accelerates the pozzolanic reaction by increasing the solubility of the siliceous material.

Cement

Lambe, Michaels, and Moh (38) present a hypothesis on the mechanisms involved when NaOH acts as an additive in soil-cement mixtures. They suggest that lime, calcium silicate, and calcium aluminate are formed initially in the mixture of soil, cement, and water. The ultimate reaction products are hydrous alumina and a calcium silicate gel with rather low Ca:Si ratio. The formation of the cementitious silicate gel is confined to a narrow zone around each cement particle because lime forms an insoluble silicate upon contact with soil silica (or alumina). When NaOH is added to the mixture,

the calcium ion activity in solution is greatly depressed, the OH^- ion concentration is significantly elevated, and the pH is increased. The formation of the insoluble calcium silicate is retarded by suppression of the calcium ions, and the formation of soluble alkali silicates is accelerated by the increase in pH. Thus, the volume of hydrous silicate gel is increased and this cementitious material is free to diffuse through the pore fluid.

PHYSICAL PROPERITIES OF STABILIZED MIXTURES

Kozan and Fenwick (35) report that NaOH as an additive in lime-soil mixtures produces some changes in density. A slight increase in dry density seemed to occur in a lean mixture (PI = 15, LL = 39), while a small decrease was noted for a heavy clay (PI = 45, LL = 66). These authors, as well as Handy et al (21), present data for density changes in a soil-cement mixture. Both indicate that NaOH caused a slight increase in density, but no correlation with strength could be determined. It appears that the strength increases noted must be attributed at least in part to increased cementing action.

The addition of 0.5 percent sodium hydroxide caused fourfold increases in 7- and 28-day strengths of an Ottawa sand and lime-fly ash mixture. One to 2 percent NaOH increased the strength of three montmorillonitic clay soils stabilized with hydrated lime by as much as four times that of untreated samples (10). Mateos and Davidson (45) also found that soil-lime-fly ash mixtures prepared from Ottawa sand and a friable loess were greatly strengthened by small additions of NaOH. The 7-, 28-, and 90-day strengths were increased by amounts varying from 6 to 17 times.

Small additions of sodium hydroxide also favorably affected the strength of soil-cement mixtures but not to as great an extent as for soil-lime-fly ash. Tests reported by Laguros and Davidson (37) and by Lambe and Moh (39) showed a twofold to threefold increase in strength for a New Hampshire silt, Vicksburg loess, and several heavy clays. An Iowa silt and a Wisconsin sand showed no benefit, indicating that soil types and/or clay mineralogy must play a vital role in the stabilization process.

The durability of a soil-lime-fly ash mixture seems also to be dependent on the lime type. Dolomitic monohydrate lime gave adequate durability, but calcitic hydrated lime did not show consistent improvement. NaOH appeared to increase the durability of mixtures stabilized with calcitic hydrated lime (10).

Limitations

The curing temperatures to which lime-soil mixtures are exposed are quite critical, because sufficient strength must be developed to withstand the imposed stresses of the colder seasons. Mateos and Davidson (45) investigated the effect of chemical additives at low temperatures on a dune sand-lime-fly ash mixture. With NaOH the 28-day compressive strength was 300 psi when cured at 43 F, whereas curing at 70 F resulted in a 1500-psi compressive strength. It is apparent that late-season construction will result in weakly stabilized material. Davidson, Mateos, and Katti (11), on the basis of tests with natural monomineralic silica sand stabilized with lime-fly ash, suggest that the use of chemical additives in amounts greater than 1 percent may not be economical. Furthermore, some data indicate that chemical additives may be detrimental in larger amounts.

Lambe, Michaels, and Moh (38) investigated 11 soils stabilized with cement and reached these conclusions regarding sodium additives: (a) the strength development of soil-cement will be delayed by the presence of a high concentration of additive, but the full beneficial effect will be achieved after a longer time of cure; (b) optimum additive concentration observed at early cure times represents the minimum concentration required to obtain the maximum beneficial effect of the additive; (c) the optimum concentration of hydroxide is about the same for all fine-grained soils; and (d) the degree of effectiveness of additives decreases with increasing soil plasticity and/or organic matter content. Laguros and Davidson (37) further state that a low cation exchange capacity of the soil required the use of a low concentration of chemical additives to obtain optimum strength.

CONSTRUCTION METHODS

The basic procedure outlined in the sodium chloride section should be satisfactory for other salts but, because inorganic bases have not been tried in the field, one should proceed with caution and consider the use of alternate methods in advance. Davidson, Mateos, and Katti (11) found that the mixing of most chemicals in a powder form produced the best strength results. However, of necessity, the inorganic bases (NaOH and KOH) were applied in liquid form. The following reasons were suggested for superior results of powder form: (a) consumption of the chemical by side reactions takes place more rapidly in solution than in a semi-dry system, and (b) it is also possible that smaller amounts of chemicals than were studied are needed to obtain optimum benefits when the chemicals are added in water.

Sodium hydroxide has also been tried as a surface hardener for stabilized soil on the basis of laboratory tests. Handy et al (21) suggest that spraying with a 10 percent solution at the rate of about ½ gal per sq yd will increase the surface hardness of loess soil-cement as much as 50 percent. The effectiveness on other soils depends on their pozzolanic activity.

Finally, it must be emphasized that sodium hydroxide is dangerous to handle and special precautions must be observed by personnel exposed to it. It is also extremely corrosive, and it may be necessary to develop special modifications of conventional field equipment before it will find much use in the field.

EFFECT OF SOIL TYPE

Although a variety of soil types has been mentioned in conjunction with the preceding discussions, no attempt has been made to suggest soil types best suited for inorganic salt and base stabilization. Actually, no engineering soil classification system is very useful in grouping soils for appropriate chemical stabilization, because such systems do not consider clay mineralogy, pH, or other soil chemical properties that are of the utmost importance in these reactions. However, an analysis of the available literature does suggest soil types that are most amenable to stabilization with chemicals. Most of the soils of Illinois have been derived from Wisconsinan drift, Illinoian drift, loess, and/or a combination of drift and loess. Several north-central states exhibit similar soil conditions. The local soil variations can usually be determined more or less precisely from publications of state university engineering and agricultural experiment stations and state geological surveys.

Sixty-seven percent of the surficial soils of Illinois are loess-derived. In the western half of the state the loess is generally 4 to 8 ft thick and may be thicker. This material is typically calcareous and has a textural composition of 1 to 3 percent sand, 80 to 88 percent silt, and 10 to 18 percent clay. The principal clay mineral is montmorillonite. The physical and chemical characteristics are also a function of age of the deposit, local topography, and the native vegetation under which soil development occurred. Wisconsinan till-derived soils are concentrated in the northeastern section of the state and compose approximately 13 percent of the surficial soils. The basic deposit is calcareous, and illite is the principal clay mineral with Ca^{++} and Mg^{++} as the absorbed ions. A thin loess layer covers large areas of Illinoian drift in southeastern and south-central Illinois. Data on the underlying drift are still relatively scarce but below the depth of leaching it seems to contain 20 to 30 percent carbonates, with illite being the predominant clay mineral. The unweathered gravel deposits in all areas appear to be predominantly calcareous.

Possible reactions between salts and calcareous material have been suggested in the engineering literature. Gow, Davidson, and Sheeler (18) postulate that limestone and dolomite are soluble in some salt solutions and that cementitious carbonates are subsequently precipitated in the stabilization process. Handy et al (21) suggest that calcite forms weak and relatively soluble bonds compared to most silicates. Cementation bond strength tends to develop rapidly but shows little increase at high curing temperatures. Hilmay and Elgabaly (25) present laboratory data to show that Na^{+} is adsorbed in greater quantities if calcareous material is present in the soil.

Thus, a calcareous soil would react with sodium salt in a very favorable manner if no deterent factors such as high organic or montmorillonite contents were present. Sodium hydroxide behaves similarly and, where evaluated against sodium salts, generally produced higher compressive strengths. Both sodium salts and bases react favorably with loessial soils if the montmorillonite content is low enough; however, reactions with clays are too erratic to be generalized.

Calcium chloride does not seem to be as effective in soils with calcium as the adsorbed ion as in noncalcareous soils.

CONCLUSIONS

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

1. The type and exact percentage of chemicals most beneficial to strength are unique for each soil and depend on its physical, chemical, and mineralogical composition;
2. The addition of inorganic salts or bases permits lime-treated soil to cure at lower temperatures;
3. Sodium additives considerably increase the resistance of cement-stabilized soil to sulfate attack;
4. Optimum moisture contents are usually lowered by the addition of salts;
5. Leaching of the additive will occur unless a protective cover is applied but, because of the type of reactions that occur, such leaching may not be detrimental; and
6. Detrimental freeze-thaw effects are probably reduced.

RESEARCH NEEDED

More than half of the articles reviewed indicated the need for further research on chemical stabilizers. One of the biggest needs is for laboratory tests that more closely simulate field conditions. For example, stabilization with sodium and calcium chloride has been carried on successfully in the field for many years, but attempts to utilize laboratory tests to predict field behavior have generally been unsuccessful. This is probably because laboratory curing procedures have not usually involved wet-dry cycles, which may be necessary to produce the required strength. Several investigations have touched upon this problem but a great deal of work remains to be accomplished (8, 12, 38, 61, 67).

Once a suitable laboratory curing and testing procedure is developed, further investigations can then be conducted to determine more specifically the reactions of various salts, especially chlorides, as influenced by such soil properties as texture, pH, clay mineral composition, carbonate content, adsorbed cations, and organic matter content.

At the same time, basic information is needed on the manner in which inorganic salts and bases act to stabilize soils or improve the stabilizing qualities of other cementing materials. Such information can most likely be obtained from detailed chemical and mineralogical studies, especially through the use of electron microscopy.

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ANNOTATED REFERENCES

1. Amstutz, M.E. Stabilized Bases Mixed at Pit. Better Roads, Vol. 12, No. 9, 1942.

   Binder soil is added to gravel at pit before going into crusher. Method of construction given.

2. Baylard, E.M. Performance Study of Calcium-Chloride-Treated Roads. HRB Proc., Vol. 31, 1952, pp. 336-348.

   The results of studies of stabilized gravel roads in Onondaga County, New York, are given. Performance studies were devoted principally to measurements of gravel loss due to the effect of climate and traffic. This 16-year study of calcium chloride-treated gravel roads showed a gravel loss of only 23.5 cu yd per mile per year for roads carrying from 41 to 216 vehicles per day. Comparing the loss with those reported by the University of Michigan and others for untreated gravel roads, it appears logical to assume a saving of at least 50 cu yd of gravel per mile per year by maintenance with calcium chloride.

3. Belcher, D.J. A Field Investigation of Low Cost Stabilized Roads. Purdue Univ. Bull. 81, Res. Series, 1941.

   Details are reported of the construction, maintenance, and behavior of a test road built near West Lafayette, Indiana. For various sections of stabilized road, tests were made for temperature at various depths, moisture content at various depths, position of water tables, and performance of sections stabilized by mechanical methods, portland cement, calcium chloride, sodium chloride, and bituminous materials. Contingent laboratory studies were made involving photoelasticity, triaxial testing, permeability, drainage, frost action, and optimum bitumen content.

4. Bolt, G.H. Ion Adsorption by Clays. Soil Science, Vol. 79, 1955. pp. 267-276.

   The equilibrium between NaCl, $CaCl_2$, and a Na-Ca-illite indicates that the distribution of ions can be predicted on the basis of existing double-layer theory without involving the use of arbitrary constants. The difference in amount of Na and Ca held can be explained almost entirely as a result of the valence of the ions. The limitation of the double-layer theory is discussed and its results are compared with other existing theories on ion exchange equilibrium. The corrected double-layer theory suggested should accurately describe the ratio of cations held on the clay surface.

5. Bower, C.A., and Goertzen, J.O. Replacement of Adsorbed Sodium in Soils by Hydrolysis of Calcium Carbonate. Soil Science Soc. Amer. Proc., Vol. 22, 1958, pp. 33-35.

   The reaction 2 Na (adsorbed) + $CaCO_3$ + $H_2O \rightleftarrows$ Ca (adsorbed) + 2 Na^+ + HCO_3^- + OH^- was studied from the standpoint of describing the replacement of adsorbed Na in calcareous soils subjected to leaching by rainfall. This reaction can be expressed by the Langmuir equation which shows the equilibrium between solution and adsorbed Na at various water contents. Simplified approximate solutions of equations have been suggested.

6. Calcium Chloride Association. Plant Mixing Stabilized Aggregate for Low-Cost Roads. Bull. 24, 1936.

   Design of plant and details of mix for preparing plant-mixed stabilized aggregate are given.

7. Catton, M. D., and Felt, E. J. Effect of Soil and Calcium Admixtures on Soil-Cement Mixtures. HRB Proc., Vol. 23, 1943, pp. 497-529.

This report shows that some sandy surface soils that react poorly with cement, and therefore require high cement contents for hardening, can be improved to react in a normal manner by adding clayey soil, or a small quantity of calcium chloride. Compressive strength, wet-dry, and freeze-thaw test data are given showing the effect of the soil and calcium chloride admixtures on a number of poorly reacting sandy soils. Practical application in field construction of the methods developed in the laboratory for economically treating these poorly reacting sandy soils is also discussed. Construction costs are analyzed for poorly reacting sandy soils with indications that the costs may be excessive when cement alone is used.

8. Coleman, N. T., Ragland, J. L., and Craig, D. An Unexpected Reaction Between Al-Clay or Al-Soil and Calcium Chloride. Soil Science Soc. Amer. Proc., Vol. 24, 1960, pp. 419-420.

Studies relating to the aluminum concentrations of exchange sites and the solutions phase in acid soil-$CaCl_2$-water mixtures were conducted. After carrying such mixtures through wetting-drying cycles the following alterations were observed: (a) the change from Al to Ca-saturation of the soil; (b) the loss of Ca from the solution phase; and (c) the loss of Cl from the solution phase. Acid soils or clays containing exchangeable Al were used, and subjected to drying temperatures of 80 C and wetting with deionized H_2O. This suggests a reaction sequence of the sort:

(a) $2Al \times xH_2O$ (sorbed) + $3CaCl_3 \rightleftarrows 2AlCl_3 \times xH_2O + 3Ca$ (sorbed)
(b) $2AlCl_3 \times xH_2O \rightarrow Al_2O_3 \times yH_2O + 6HCl\uparrow + (2x - 3y)H_2O$.

There the chloride was lost, presumably through volatilization as HCl. The reaction was observed to occur in a "dry" soil.

9. Cuthbert, F. L. Use of Calcium Chloride in Granular Stabilization of Roads—A Review of Available Literature. HRB Research Rept. 2F, 1945.

A critical review and analysis of available literature on the use of calcium chloride in granular stabilization of roads is presented (from Slate and Johnson, 66).

10. Davidson, D. T., Mateos, M., and Barnes, H. F. Improvement of Lime Stabilization of Montmorillonitic Clay Soils With Chemical Additives. HRB Bull. 262, 1960, pp. 33-50.

Three Iowa soils ranging in clay content from 35 to 74 percent were studied in combination with varying amounts of both hydrated calcitic and hydrated dolomitic limes and three inorganic chemicals—sodium phosphate, sodium carbonate, and sodium hydroxide. Additions of 1 to 3 percent sodium hydroxide doubled the strength of soil-lime mixtures while sodium phosphate actually decreased the strength. Additions of sodium carbonate gave inconsistent results. A study of the effects of curing temperature and the freeze-thaw resistance of the soil-lime and soil-lime-chemical mixtures is also reported.

11. Davidson, D. T., Mateos, M., and Katti, R. K. Activation of the Lime-Flyash Reaction by Trace Chemicals. HRB Bull. 231, 1959, pp. 67-81.

The results of an investigation of the effect of small amounts of 47 different chemicals on the strength of Ottawa sand-lime-fly ash are presented. An explanation is offered for the mechanism of strength improvement by the different groups of chemicals studied.

12. Duncan, S.J. Salt Stabilization of Soils. No. Ohio Geol. Soc. Inc., Second Symposium on Salt, Vol. 1, 1966, pp. 352-355.

The advantages of salt stabilization are discussed. The addition of salt to aggregates containing a quantity of material passing No. 200 mesh has proved advantageous in increasing density, load-bearing values, resistance to penetration of moisture, and transforming otherwise frost-susceptible material into frost-resistant all-weather road material. The quantity of fines required varies with different types of aggregate-limestone, gravel, slag, or cherts—but the salt required remains at 1 percent by weight of the mass to be stabilized or upgraded.

13. Earth Movers. Stabilized Road Construction in Minnesota. Vol. 23, No. 10, 1936.

Three methods for preparing stabilized material are described—road mixing by blading, machine mixing on the road, and plant mixing. Calcium chloride was used as a stabilizing agent.

14. Fiedelman, H.W. Evaluation of Sodium Chloride-Calcium Chloride Mixture for Dust Control. No. Ohio Geol. Soc. Inc., Second Symposium on Salt, Vol. 1, 1966, pp. 348-351.

The results of a series of tests on the chemical treatment of dirt roads for dust control are described. Chemicals tested were NaCl and $CaCl_2$ and mixtures of the two. Both gravel and limestone-based roads were included.

15. Frank, N.H. Salt-Filled Vertical Drains for Highway Improvement. Public Works, Vol. 88, No. 6, 1957, pp. 104-106.

Vertical drains were constructed in existing roads by boring 2-in. holes to a depth below the frost line and filling them with salt. The drains were installed at various spacings from 10 to 100 ft. The drains were used to relieve trapped water that accumulated in low areas. After three years of observation, spring heave damages have been arrested in drilled sections.

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

Controlled field tests of 13 selected materials commonly used for maintenance of low-cost roads are reported.

17. Funada, S., Ogura, Y., and Sakurai, T. On the Effectiveness and Cost of Soil Stabilization by Addition of Salt. Bull. Soc. Salt Science, Japan, Vol. 17, 1963, pp. 7-18.

A large number of field tests were conducted to determine effectiveness of salt treatment, durability, salt migration, results of repairs, and cost of construction. Tests conducted on playgrounds revealed remarkable effectiveness for preventing damage from freezing and positive suppression of weed growth and dusting. The road test did not produce the same excellent results becuase the roads were subjected to use immediately after rains. It was shown that without exception the effectiveness of salt treatment is greater and its durability longer for the soil that has a higher liquid limit.

18. Gow, A.J., Davidson, D.T., and Sheeler, J.B. Relative Effects of Chlorides, Lignosulfonates and Molasses on Properties of a Soil-Aggregate Mix. HRB Bull. 282, 1961, pp. 66-83.

This article provides a starting point for cost-effect comparisons by showing the effects of 0, 0.5, 1.0, 1.5, and 2 percent of Peladow calcium chloride pellets, Sterling FC and CC salts, Foranil A and Lignin Liquor spent sulphite liquors

and 79.5 Brix molasses on certain properties of a single soil-aggregate mixture. The mechanism of stabilization with each agent is discussed to permit extrapolation of effectiveness to other soils.

19. Grim, R.E. Applied Clay Mineralogy. McGraw-Hill Book Co., New York, 1962.

    Data on the effect of various cations on the properties of clays are presented.

20. Grim, R.E. Clay Mineralogy. McGraw-Hill Book Co., New York, 1953.

    The basic structure of clay minerals is discussed. Data on physical and chemical properties of clays are presented.

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

    Calcium chloride, sodium hydroxide, sodium carbonate, and sodium silicate were investigated in the laboratory for surface treatments. Measured amounts of these solutions were sprinkled on the surface of molded 2-in. by 2-in. specimens confined in their molds. Specimens were tested for bearing capacity by the Iowa Bearing Value, essentially a miniature CBR. Soil-lime-fly ash was benefited most by application of sodium silicate solution, while sodium carbonate gave little or no benefits. Sodium silicate again produced the best results with a soil-cement mix while sodium hydroxide gave satisfactory results. Calcium chloride and sodium carbonate gave erratic results.

22. Heagler, J.B. Clay Mineralogy and Soil Stabilization. 15th Highway Geology Symposium, Missouri Geol. Surv. and Water Resources, 1964, pp. 133-137.

    The nature of the clay minerals and the importance of surface energy concepts are presented with emphasis on their relation to the physical properties of the bulk system.

23. Highway Research Board. Report of Subcommittee on Treatment With Sodium Chloride, Part 5, 1936.

    A complete review of the history, theory, design, construction, and maintenance of salt-stabilized roads is presented.

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25. Hilmay, A.K., and Elgabaly, M.M. Exchange Reactions Between Sodium Salts and Calcium Saturated Soils. Alexandria Journal Agricultural Research, Vol. 2, No. 1, 1954, pp. 42-57.

    Sodium adsorption from different sodium salts at varying concentrations by Ca-soil has been studied under equilibrium conditions. The results obtained indicate that Na^+ adsorption is generally low except in the case where the Ca-salt produced as a result of exchange is of limited solubility. Na^+ adsorption increased as the concentration of sodium salt was increased. $CaCO_3$ had the tendency to allow more Na^+ adsorption.

26. Huang, E.Y. Manual of Current Practice for Design, Construction and Maintenance of Soil-Aggregate Roads. Univ. of Illinois, Engineering Experiment Station, Circ. 67, 1959.

    Title is self-explanatory.

27. International Salt Co. Road Stabilization With Sterling Salt.

    Reasons for stabilizing with salt are given. Construction methods and maintenance information are given.

28. International Salt Company. Road Stabilization Reprints, 1961.

This booklet contains stabilization reprints from road magazines dating back to 1955. The 19 articles describe field experience, construction methods, and field results of municipal, county, and state engineers with sodium chloride.

29. Johnson, A.M. The Role of Calcium Chloride in Compaction of Some Granular Soils. HRB Proc., Vol. 26, 1946, pp. 594-602.

Results of 90 compaction tests on six typical A-2 soils—one plastic and one friable from each of 3 states (Alabama, North Carolina, and Virginia)—are described. A substantial saving in the compaction effort required to obtain a specific density is effected by addition of $CaCl_2$. For some soils the maximum density obtained without admixture was reproduced with about 50 percent of the compactive effort when 3 percent admixture was used. Penetration curves indicate a noticeable increase in workability with successive additions of the chemical.

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

Results are reported of the effect of 20 inorganic chemicals in varying amounts on the consistency properties of an expansive soil sample from Poona, India. Certain soluble and insoluble hydroxides make the soil friable. KCl and NaCl are also found effective in improving the shrinkage characteristic of the soil. $FeCl_3$ and $(NH_4)_2HPO_4$ make the soil mass porous.

31. Kaufmann, D.W. Sodium Chloride. American Chemical Society Monograph Series No. 145, Reinhold, New York, 1960.

This complete book gives history, methods of production, physical properties, chemical properties, and uses of NaCl.

32. Kelly, F.G. Gravel Roads Stabilized by Rock Salt. Contractors and Engineering Monthly, Vol. 50, No. 5, 1953, pp. 33.

The use of salt in Perry, New York, for construction and maintenance cost reduction is described. Emphasis is placed on proper portions of clay, aggregate, and salt; thin, well-compacted layers; and a 24-hour curing period.

33. Kozan, G.R. Review of Materials and Methods for Dustproofing and Waterproofing Soils. U.S. Army Corps of Engineers Waterways Experiment Station, Misc. Paper No. 3-176, 1956.

This paper attempts to narrow the range of promising additives for future study.

34. Kozan, G.R., and Pimental, R.A. Guide Manual for Selection and Use of Dust Palliatives and Soil Waterproofers in the Theater of Operations. U.S. Army Corps of Engineers Waterways Experiment Station, Misc. Paper 4-756, 1965.

This is a guide for military engineers in selecting and using additives. It discusses the problems, methods of application, and application criteria for bituminous, cementing, resin, and salt materials.

35. Kozan, G.R., and Fenwick, W.B. Soil Stabilization. U.S. Army Corps of Engineers Waterways Experiment Station, Tech. Rept. 3-455, Rept. 7, 1965.

Laboratory investigations of "problem" soils were conducted to determine relative effectiveness and ability of stabilizer to meet established strength requirements. Portland cement, lime, phosphoric acid, and sodium silicate were used on two different fine-grained soils, a lean clay and a heavy clay. Five percent cement was most effective in meeting the established strength criteria. Several secondary or modifying additives were evaluated with only 1 percent magnesium sulfate combined with 4 percent quicklime producing beneficial strength.

36. Ladd, C.C., Moh, Z.C., and Lambe, T.W. Recent Soil-Lime Research at the Massachusetts Institute of Technology. HRB Bull. 262, 1960, pp. 64-85.

Results of research on soil-lime stabilization conducted at MIT are summarized. The effects of the following tests are discussed: varying percentages of lime on compaction and strength of four soils ranging from clayey sand to organic clay; varying percentage of quicklime with four very wet soils; and using secondary additives at different concentrations.

37. Laguros, J.G., and Davidson, D.T. Effect of Chemicals on Soil-Cement Stabilization. Highway Research Record 36, 1963, pp. 172-203.

The effects of compounds of sodium, calcium, magnesium, and commercial lime on soil-cement mixtures were quantitatively measured. Unconfined compressive strength, triaxial compressive strength, and Iowa freeze-thaw and wet-dry durability were the parameters evaluated. Eight soils varying widely in physical and chemical properties were tested.

38. Lambe, T.W., Michaels, A.S., and Moh, Z.C. Improvement of Soil-Cement With Alkali Metal Compounds. HRB Bull. 241, 1960, pp. 67-108.

A large number of soils of widely differing geographical origin, fineness, and mineralogical composition were tested to determine their response to stabilization by portland cement in the presence of a selected group of alkali metal compounds. A hypothesis to explain the action of these additives is proposed. Results indicate that chemically modified soil-cement offers considerable promise as a low-cost soil stabilization method.

39. Lambe, T.W., and Moh, Z.C. Improvement of Strength of Soil-Cement With Additives. HRB Bull. 183, 1958, pp. 38-47.

A search at MIT for additives to improve the strength of soil treated with portland cement is described. Three soils with 29 additives, including dispersants, synthetic resins, waterproofing agents, and several salts and alkalis were investigated.

40. Lee, C.H. Sealing the Lagoon Lining at Treasure Island With Salt. Trans. ASCE, Vol. 106, 1941, pp. 577-607.

A method is described by which a 10-in. clay lining of the bottom of the 7-acre fresh-water lagoon was sealed by a treatment of salt water pumped in from the bay. Initial seepage loss from fresh water was 1.00 in. per day, but the salt treatment reduced this to 0.10 in. per day.

41. Looker, C.D., Spencer, W.T., Kushing, J.W., and Allen, H. Use of Sodium Chloride in Road Stabilization. HRB Proc., Vol. 18, Pt. 2, 1938, pp. 257-274.

The theory, design, construction, and maintenance of soil-sodium chloride roads are discussed. Salt water aids in dissolving calcium carbonate and limestone. Canada, New York, and Maryland use limestone dust.

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Private communication.

43. Marley, J.J., and Sheeler, J.B. Studies on Soil-Aggregate-Sodium Chloride-Stabilized Roads in Franklin County, Iowa. Highway Research Record 7, 1963, pp. 47-62.

Field tests on four sodium chloride-treated roads were compared with four untreated roads. Thickness of the soil-aggregate surface and the amount of loose or float material on the surface was measured in the field. Laboratory tests included Atterberg limit and X-ray diffraction analyses.

44. Massachusetts Institute of Technology. Soil Solidification by Chemical Methods. Phase X Report, Nov. 1958.

Results of laboratory investigations on carbonates, sulfates, and other sodium compound-cement-soil mixtures are given.

45. 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 effects of different amounts of 12 chemicals on the strength of a mixture of Ottawa sand-lime-fly ash are presented. The effects of four selected chemical additives on the strength of soil-lime-fly ash mixes—including four soils, two limes, and three fly ashes—are also presented. An evaluation of competitive mixes of soil-lime-fly ash was made, including freeze-and-thaw studies.

46. McLeland, C. J. Sodium Chloride Stabilization Work in Steuben County, Indiana. ARBA Tech. Bull. 254, 1964.

Field results, construction methods, and laboratory tests of sodium chloride stabilization are discussed. One hundred miles of road have been stabilized in an 8-year period. Excellent results have been observed with dry densities of 150-152 pcf and unconfined strengths as high as 1,960 psi.

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This report states that texture, structure, and mineralogical composition determine the response of clays and shales to events occurring during construction and operation of engineering works. It also discusses surface chemical phenomena.

48. Moh, Z. C. Soil Stabilization With Cement and Sodium Additives. Proc. ASCE, Jour. Soil Mech. and Found. Div., Vol. 88, No. SM-6, 1962, pp. 81-105.

An experimental investigation aimed at elucidating the mechanisms by which a group of alkali metal compounds improves the stability of cement- or lime-stabilized soils is described. X-ray diffraction, differential thermal analysis, flame-photometry, and colorimetry were used during the curing period.

49. Ogawa, T., Funada, S., Nakamura, T., Hashimoto, S., and Masui, N. Studies on the Limitation of Soil Stabilization by the Addition of Sodium Chloride. Bull. Soc. Salt Science, Japan, Vol. 17, 1963, pp. 3-7.

A further investigation of the relationship between soil properties, moisture, and sodium chloride is evaluated. Thirty samples of soil—5 from roads and 25 from playgrounds—were tested with 1 and 3 percent sodium chloride added. Analysis suggests the sphere of free moisture in the soil was slightly expanded by the addition of NaCl. The liquid limit is reduced in all samples. The reduction is more striking for the addition of 3 percent salt. The initial moisture conditions will determine if addition of salt will decrease or increase density and compressive strength. The degree of exchange for adsorbed Na^+ ions is about 20-30 percent.

50. Olmstead, F. R. Plant Mixed Stabilized Aggregate for the Michigan Secondary Road System. Better Roads, Vol. 10, No. 1, 1940.

Methods used to assure the uniform production of stabilized materials are reviewed (from Cuthbert, 9).

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Field results are discussed.

52. Pratt, P. F., Whitting, L. D., and Grorer, B. L. Effects of pH on Sodium-Calcium Exchange Equilibrium in Soils. Soil Science Soc. Amer. Proc., Vol. 26, 1962, pp. 227-230.

The Na-Ca exchange equilibria in 10 acid soils were measured at pH values of 5, 6, 7, and 8 and the results related to a theoretical ion exchange equation based on the Poisson-Boltzman differential equation of the electrical double-layer. The relative change in the ratio of adsorbed Na^+ to adsorbed Ca showed a decrease when the pH increased. The ratio varied from 1.0 to 2.0.

53. Proceedings, Conference on Soil Stabilization, June 18-20, 1952, Massachusetts Institute of Technology.

This work contains a series of papers on many phases of soil stabilization, including state of the art at the time of writing.

54. Purdue University. Road Stabilization With Sodium Chloride. Progress Report on Research Project No. 16, Dec. 28, 1955.

Research conducted for International Salt Company is discussed, including a brief review of literature and the purpose and scope of project.

55. Qayyum, M. A., and Kemper, W. D. Salt-Concentration Gradients in Soils and Their Effects on Moisture Movement and Evaporation. Soil Science, Vol. 93, No. 5, 1962, pp. 333-342.

This paper reports research on the effects of salt-concentration gradients formed by the upward movement and evaporation of water on rate and amount of water moving in the soil and on water lost from the surface. NaCl and $CaCl_2$ were used at five different moisture contents. There was greater evaporation from soils with low salt levels compared with those with no salt. At high salt levels the salt formed a white crust at the top and the rate of evaporation was lower.

56. Report on Road Stabilization With Sodium Chloride, 1955.

This private communication concerns field uses of sodium chloride.

57. Rosenquist, I. T. Considerations on the Sensitivity of Norwegian Quick-Clays. Geotechnique, Vol. 3, pp. 195-200, 1953.

Marine quick clays formed by loss of moisture and salt can be strengthened by remolding and adding sodium chloride. In one case after 10 days the clay strength was increased eightfold. Salt helps to transform quick clays into very stiff clays and increases the liquid limit.

58. Salt Institute. Salt for Road Stabilization.

This booklet discusses aspects of salt stabilization including design, materials, and construction procedure. Some case histories are given.

59. Salt-Soil Stabilization, 1954.

This private communication concerns title subject for 1954.

60. Sanborn, A. F. An Annotated Bibliography on Soil Stabilization With Sodium Chloride—Including a Review of the Literature. Purdue University, 1956.

Title is self-explanatory.

61. Sanborn, A. F., and Yoder, E. J. Stabilization of Soil-Aggregate Mixtures With Sodium Chloride. Progress Report No. 1, Purdue University, 1956.

This report covers the first phase of a laboratory program to study the effects of sodium chloride on compaction and strength characteristics of soil-aggregate mixtures. Moisture adsorption and plasticity were also determined.

62. Sheeler, J. B. Sodium Chloride Stabilized Roads in Iowa. HRB Bull. 282, 1961, pp. 59-65.

This paper reports a summary of interviews with Iowa county engineers. The composition and dimensions of the various salt-stabilized roads are given together with maintenance practices, present physical conditions of surface, and effects of winter climate.

63. Sheeler, J. B., and Hofer, D. W. Density-Compactive Energy-Calcium Chloride Content Relationships for an Iowa Dolomite. HRB Bull. 309, 1962, pp. 1-8.

Laboratory experiments were used to determine effects of calcium chloride content and the amount of compaction effort on the density of a crushed limestone. The data were analyzed on the basis of energy cost or savings due to the presence of calcium chloride.

64. Sheeler, J. B. A Method for In-Place Mix Control in Reconstruction of Soil-Aggregate Roads. HRB Bull. 357, 1962, pp. 69-78.

This report gives the design method for the specific case where old aggregate surfaces are scarified and incorporated into the new surface while binder material is taken from the roadbed.

65. Slate, F. O. Use of Calcium Chloride in Subgrade Soils for Frost Prevention. HRB Proc., Vol. 22, 1942, pp. 422-441.

$CaCl_2$ will diffuse through the subgrade when applied through pockets. Information is presented on the soil and application factors governing the spacing of the pockets to secure uniform distribution of the salt. The effects of groundwater level and the movements of water through soil on $CaCl_2$ migration were checked by laboratory tests. The rate of migration is faster with higher groundwater levels supplying water to the migration zone. Movement of water through silt will carry the salt with it. In laboratory tests of heaving of soil specimens due to freezing of capillary water, 2 percent $CaCl_2$ protected the specimens from damaging frost heave.

66. Slate, F. O., and Johnson, A. W. Stabilization of Soil With Calcium Chloride. HRB Bibliography 24, 1958.

This is an excellent annotated bibliography on the subject arranged according to useful subject matter divisions.

67. Slate, F. O., and Yalcin, A. S. Stabilization of Bank-Run Gravel by Calcium Chloride. HRB Bull. 98, 1955, pp. 21-32.

Specimens of different moisture contents were prepared without calcium chloride and with varying percentages of added calcium chloride. Data are given on the effect of calcium chloride on optimum density, density obtained with various compactive efforts, and CBR values of both washed and unwashed gravel. Calcium chloride is most effective on gravels containing an appreciable amount of material passing No. 200 mesh. The effect is minor when the fines content is below 5 percent.

68. Slesser, C. The Migration and Effect on Frost Heave of Calcium Chloride and Sodium Chloride in Soil. Purdue Univ., Bulletin 89, Research Series, 1943, 168 pp.

The action of chemicals in contributing to soil stabilization and preventing frost heave is discussed from a theoretical standpoint. Results are given of extensive field tests on the migration of $CaCl_2$ and NaCl in soils of different types under different exposures of nearly 5 years. Laboratory studies of migration and frost heave were also made. NaCl shows greater tendency than $CaCl_2$ to move and crystallize on the surface of an unpaved road. Lateral movement proceeds primarily by washing from the top to side ditches. Important factors

in migration are: evaporation, soil texture, percolating water, soil cover, and temperature. Both bituminous and gravel coatings tend to conserve NaCl. In sandy clay the order of permanence of ions is $Ca^{++} > Na^{+} > Cl^{-}$. Frost heave can be eliminated by addition of water-soluble chemicals to the soil, the amount required depending on the texture. Several percent entirely prevented heave in coarse-textured soils and greatly reduced it on fine-textured soils.

69. Spencer, W. Base Stabilization. Proc. Kentucky Highway Conf., Feb. 1962, Univ. of Kentucky College of Engineering, Bull. 64, 1962, pp. 61-73.

General discussions are given of soil stabilization with asphalt, asphalt emulsion, tar, cement, lime, calcium chloride, and sodium chloride.

70. Stewart, L. C. Design and Operation of Plants for Producing Stabilized Soil-Bound Road Material. HRB Proc., Vol. 16, 1936, pp. 369-379.

Title is self-explanatory.

71. Strong, F. C. A Study of Calcium Chloride Injury to Roadside Trees. Mich. Agricultural Experimental Sta. Quart. Bull., Vol. 27, No. 2, 1944, pp. 209-224.

A survey of untreated and $CaCl_2$-treated roads showed that in some cases trees bordering the road were killed by $CaCl_2$ concentrated in impounded runoff water from the highway. The symptoms were similar to leaf scorch caused by drought. Experimental studies showed that trees can be killed by applications of $CaCl_2$ to the soil and that tree species vary in their tolerance. NaCl was 5 to 10 times as toxic as $CaCl_2$. When moderately large concentrations of $CaCl_2$ were used, leaves and needles of trees turned a pale green, became dry and brittle, and were soon shed (in the case of hardwoods). The roots were not apparently injured as much as tissues where the salt accumulated. Applications of $CaCl_2$ and dust mixtures to leaves did not produce symptoms of leaf scorch but caused a characteristic brown spotting of the leaves.

72. Wilford, H. D., Downey, B. R., Briggs, G. F., Hogentogler, C. A., Knight, J. A., Elleman, J., and Burggraf, F. Use of Calcium Chloride in Road Stabilization. HRR Proc., Vol. 18, Pt. 2, 1938, pp. 209-256.

Abstracts for symposium papers are arranged according to subject matter and cover principles of stabilization; mixture design specifications; computing quantities; properties of calcium chloride and its function in road stabilization; moisture attraction; vapor pressure; surface tension of water; freezing point of water; binding properties; effect of density; calcium chloride stabilization types; surface consolidation by maintenance types; construction of designed stabilized roads; road mixing; plant mixing; compaction and seasoning; crown; construction costs; maintenance; utility of calcium chloride-stabilized roads as future bases; and research.

73. Yoder, E. J. The Effect of Calcium Chloride on the Compactive Effort and Water Retention Characteristics of Soils. HRB Proc., Vol. 27, 1947, pp. 490-509.

The compactive effort required to produce a given density in fine-grained glacial drift soils was usually decreased by the use of $CaCl_2$. It is most effective at low compactive efforts. The pH of the soil-$CaCl_2$ mixture is less than that of the same soils without $CaCl_2$. $CaCl_2$ lowers both the liquid and plastic limits of some of the soils. The results of drying and rewetting tests show that the moisture contents of the specimens containing $CaCl_2$ are lower after the drying and wetting cycle than those without $CaCl_2$.

74. Zolkov, Elias. Influence of Chlorides and Hydroxides of Calcium and Sodium on Consistency Limits of a Fat Clay. HRB Bull. 309, 1962, pp. 109-115.

This paper discusses relative effects of various quantities of sodium chloride, calcium chloride, sodium hydroxide, and calcium hydroxide on the liquid limit, plastic limit, shrinkage limit, and pH value of a highly plastic fat clay.