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Foreword

This RECORD contains three papers from the Conference Session on Salt Stabilization. A summarization of informative references concerning stabilizer properties, mechanics of salt stabilization, properties of the stabilized soil, construction methods, field results, and use of secondary additives is presented by Thornburn and Mura. This review of the literature sets the stage for consideration of the place of salt stabilization in modern construction practices. The use of rock salt in the stabilization of base-course aggregates in Michigan is described by Mainfort. Nine years of field tests indicate optimum amounts and design requirements so that marginal aggregates with large amounts of fines may be successfully stabilized with concurrent savings in construction funds and improved performance. Wood, reporting on some basic research into the mechanism of salt stabilization, indicates that the apparent function of the salt is to disperse the clays and increase the densities. Migration apparently does occur during wetting and drying, but it is not necessary to overdose the mixture.

This RECORD will be of value to all of those interested in soil stabilization and to those who must utilize marginal materials in order to conserve the natural resources.

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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.

Salt is formed as the result of the neutralization of an acid by a base. Normal salts, such as NaCl (sodium chloride), Na₂SO₄ (sodium sulfate), KCl (potassium chloride), and CaSO₄ (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 NaHCO₃ (sodium bicarbonate) and NaH₂PO₄ (sodium orthophosphate), are called acid salts, while those containing excess hydroxyl ions are called basic salts.

Many salts (NaCl, CaCl₂, NaNO₃, NaHCO₃, NaH₂PO₄, Na₂CO₃, Na₂HPO₄, Na₃PO₄, Na₄P₂O₇, BaCl₂, MgCl₂, KCl, KMnO₄, Na₂SiO₃) 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 CaCl₂ 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 AASHTO 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. Slessor (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 concentration 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). Hilmy 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 dustproofing agent, 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 dustproofing agent 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 sheepfoot 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 $\frac{3}{4}$ 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 repulsive 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 dustproofing 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 dustproofing only on lightly traveled roads. Some county engineers, however, have stated that CaCl_2 acts as a complete dustproofing (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. Slessor (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 as barium 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 ($\text{NaMnO}_4 \cdot 3\text{H}_2\text{O}$), lithium sulfate ($\text{Li}_2\text{SO}_4 \cdot \text{A}_2\text{O}$), 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 ($\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$). 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 cementitious 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 CaCl₂ were tried first. Other trace chemicals were not evaluated until the middle 1950's. Lambe and Moh (39) used CaCl₂, NaCl, KCl, K₂Cr₂O₇, and Na₂CO₃ with two silts and one loess in cement-stabilized mixes. The additives had little effect on the loessial soil, but Na₂CO₃ and K₂Cr₂O₇ 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 CaSO₄, Na₂SO₄, CaCl₂, and Na₂CO₃ as trace chemicals with one silt, five clays, and two sandy soils. Na₂SO₄ 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, CaSO₄ and CaCl₂ 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 Na₂CO₃ + Ca(OH)₂ → 2NaOH + CaCO₃. 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 PROPERTIES 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 $\frac{1}{2}$ 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 south-eastern 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 deterrent 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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Binder soil is added to gravel at pit before going into crusher. Method of construction given.

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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.

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The equilibrium between NaCl, CaCl₂, 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 $2 \text{Na (adsorbed)} + \text{CaCO}_3 + \text{H}_2\text{O} \rightleftharpoons \text{Ca (adsorbed)} + 2 \text{Na}^+ + \text{HCO}_3^- + \text{OH}^-$ 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.

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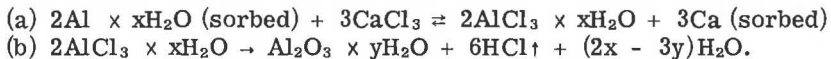
Design of plant and details of mix for preparing plant-mixed stabilized aggregate are given.

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-CaCl₂-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 H₂O. This suggests a reaction sequence of the sort:



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.

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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.

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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.

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The results of a series of tests on the chemical treatment of dirt roads for dust control are described. Chemicals tested were NaCl and CaCl₂ 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 Dust-proofing 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.

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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 because 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.

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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.

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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.
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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.

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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.

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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.

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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.

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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.

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

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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.

47. Mielenz, R. C., and King, M. E. Physical-Chemical Properties and Engineering Performance of Clays. Clays and Clay Technology, Dept. of Natl. Resources, State of California, Bull. 169, 1955, pp. 196-254.

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).

51. Pennsylvanian Township News. Check These Benefits of a Salt Stabilized Road. Apr. 1958.

Field results are discussed.

52. Pratt, P. F., Whitting, L. D., and Groerer, 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. Slessor, 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 $\text{Ca}^{++} > \text{Na}^+ > \text{Cl}^-$. 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.

Stabilization of Base Course Aggregates With Rock Salt

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This paper reports on test sections designed to determine the effectiveness of rock salt for stabilizing aggregate base course mixtures containing minus-200 material in amounts up to 12 percent. The test areas form a part of Michigan's trunkline system and carry about 1,300 vehicles per day. The test mixtures were prepared in a pug mill and placed on the roadway using normal construction methods. No construction problems were encountered with the use of salt. Results of the test program indicate that graded aggregates containing up to 12 percent fines can be successfully used when treated with rock salt. Rock salt treatment could be of benefit to highway programs where higher quality aggregates are not readily available.

●ALTHOUGH sodium chloride in the form of brine and rock salt has been used for many years in the construction of aggregate surfaces and base courses, the literature is meager concerning its use and performance under controlled construction conditions.

The Michigan Department of State Highways (MDSH) has used sodium chloride in the form of rock salt for stabilizing gravels since the mid-thirties. Originally, this treatment was used to stabilize surfacing aggregates containing approximately 16 percent of minus-200 material. For this type of construction, the admixture was applied in quantities of 10 lb per ton of aggregate and blended in place on the road. This mixture resulted in an excellent surface but eventually became so hard that blade maintenance was difficult. Michigan no longer constructs gravel-surfaced roads but does build many miles of aggregate base course to support higher type surfaces. Stabilization of such foundation material requires different methods from those used for the earlier gravel-surfaced roads.

During the past 20 years or so, sodium chloride has been specified for use in the base course of about 20 projects in accordance with standard MDSH specifications requiring 6 lb of sodium chloride per ton of aggregate. Results have been entirely satisfactory for all of these. To determine more fully the value of sodium chloride as an admixture to base course aggregates, the Michigan Department of State Highways and the Salt Producers Association (now the Salt Institute) formulated a cooperative study to determine the value of various amounts of rock salt for improving different soil-aggregate mixtures. In this study it was planned to investigate the performance of rock salt with soil-aggregate mixtures not only by maintaining the quantities in the present highway department specifications (6 lb of salt per ton of aggregate having a minus-200 fraction of less than 7 percent), but also by increasing the quantity of salt used and the limits of minus-200 material, referred to in this report as "fines". In this way, it was hoped to determine (a) the effect of different amounts of sodium chloride on the handling and field performance of soil-aggregate mixtures meeting present specifications; (b) if the addition of sodium chloride would permit larger quantities of fines in aggregate base course mixtures, thereby allowing the use of more economical aggregate sources; and (c) the effects of various quantities of sodium chloride treatment

on the amount of prime required and their subsequent influence on the performance of the asphalt cover.

This study was assigned to the Research Laboratory of the Testing and Research Division and was to include both field evaluation and supplementary laboratory investigation. The test areas were completed during 1959 and given a final surface in 1960. Their performance has been observed, evaluated, and reported on during the past nine years (1, 2).

SALT STABILIZATION

Long before sodium chloride was used for road construction, beginning shortly after 1900, there were indications from other sources of definite reactions between soil components and salt. In agriculture it was noted that the presence of salt increased the difficulties of cultivation, and in the ceramics industries it was found that the addition of salt to clay retarded moisture evaporation, allowing a longer period during which the clay was workable. In addition, salt strengthened the clay and reduced shrinkage. All of these are modifications of direct interest to those engaged in road construction.

When first used in the highway field, salt was considered primarily as a dust palliative for open-surfaced aggregate roads. During the thirties its use for base and sub-base treatments began, and this application grew rapidly. In spite of increased use, however, the literature concerning the properties of salt-soil mixtures remained meager, and research and testing did not keep pace concerning evaluation and the establishment of optimum procedures for its use under field conditions.

One of the greatest problems encountered in trying to evaluate the effectiveness of sodium chloride is the lack of laboratory test procedures that reflect field performance of the material. Miles of satisfactory salt-stabilized roads have been built, yet the normally used laboratory soil tests do not correlate with field observations. These tests, in most cases, show no significant changes in engineering properties caused by the addition of salt.

The exact mechanism of the action between salt and the clay fraction of soil is quite complex and, even at the present time, is not fully understood. Normal soil tests involve only the physical features of the materials. Because the reactions between sodium chloride and soils involve both physical and chemical processes, special laboratory tests are required for proper evaluation. Until such special tests can be developed, however, the only satisfactory method for evaluating the properties of salt and soil mixtures is to construct field test areas. Such a method is empirical, of course, and the results are applicable only to the materials and conditions encountered in the particular test areas. It has been fairly well established, however, in Michigan and elsewhere, that salt performs best with aggregates containing from about 5 to 15 percent fines. Because this range includes all of our normally processed gravels, it is reasonable to assume that a successful treatment within this range would be generally applicable throughout the state.

When used in constructing a base course, salt behaves very much as it would on an open-surfaced road. Moisture is retained during placement and compaction, and subsequent evaporation results in crusting at the surface. However, when the prime and surface courses have been added, evaporation ceases substantially, and no crystallization takes place in the moist base. Any changes or benefits to the base stability under these conditions are thought to be caused by the following (3): (a) lubrication of particles permitting easier initial and continuing compaction; (b) moisture retention during construction allowing more uniform and easier compaction; (c) chemical action with the clay fraction of the aggregate; (d) depression of the freezing point of soil moisture, thereby inhibiting ice-lens formation and possibly reducing freeze-thaw cycles; and (e) flocculation of clay because of the presence of sodium ions, resulting in a change of grain-size distribution and possible reduction in plasticity index.

The amount and type of reaction taking place between sodium chloride and soil is dependent on the type of soil treated, particularly with regard to the kind of clay minerals present and the nature of the adsorbed ions present in the original soil.

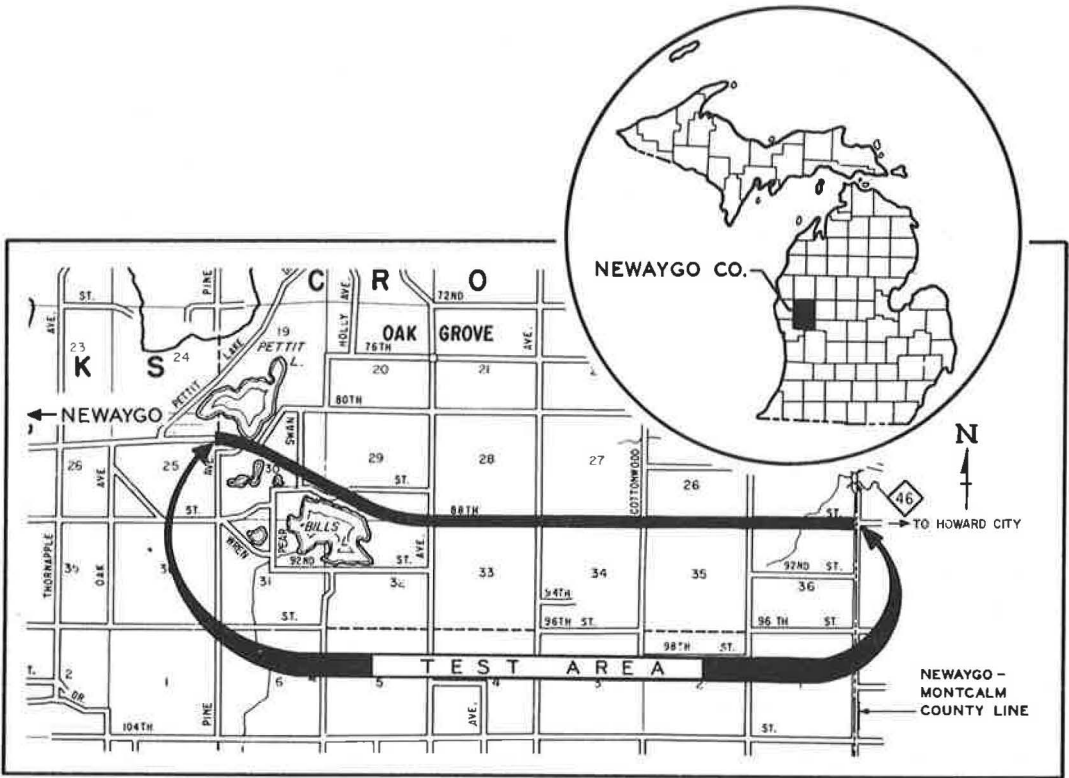
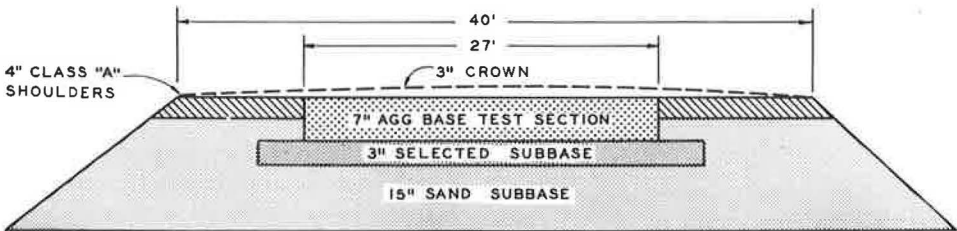


Figure 1. Location of test area.

THE NEWAYGO TEST PROJECT

The test areas for the salt stabilization project are located in Newaygo County and form a 5-mile portion of trunkline M-46 between Howard City and Newaygo (Fig. 1). This trunkline is one of Michigan's east-west highways and has an average daily traffic count that has increased from 400 to 1,300 vehicles per day during the life of this project. About 20 percent of the vehicles are commercial. Soil composition varies throughout the test area; about one-third of the test area is located on sand, and the remainder is on sandy loams and heavier textured materials. The soil types were not a significant factor in obtaining a uniform support for the test sections, however, because of the thickness and granular nature of the base and subbase support. At least 15 in. of sand



(NOT TO SCALE)

Figure 2. Cross section of roadway structure (surfacing not shown).

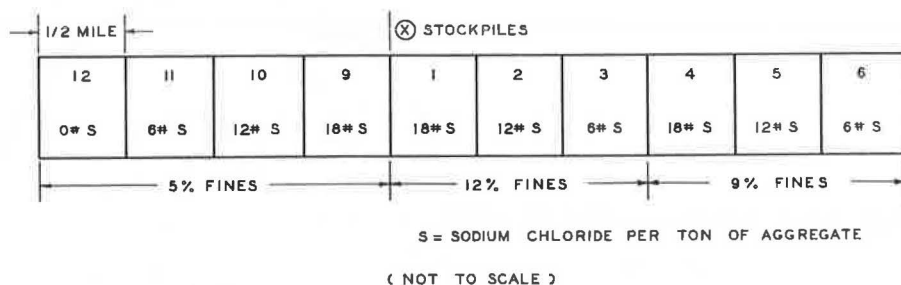


Figure 3. Arrangement of test sections.

subbase was placed under the selected aggregate bases. In the sandy areas, the existing material served this purpose. In other areas it was necessary to haul sand from a nearby pit. At no time during the life of this project has there been any indication of nonuniform subgrade support.

The subbase was topped by a 3-in. compacted granular base course meeting departmental 22A aggregate specifications and treated at the plant with 6 lb of salt per ton of aggregate. The special base courses forming the test sections were placed over this selected subbase and consisted of a standard 22A aggregate treated in the manner required for the individual test sections and compacted to a depth of 7 in. Figure 2 shows a typical cross section of the test areas. The shoulders were constructed of 23A aggregate treated with 6 lb of rock salt per ton, which was added at the pit, and stockpiled.

The arrangement and variations of each test section are shown in Figure 3. The sections were constructed in the order indicated. Sections 1, 2, and 3 contained 12 percent fines and were treated with 18, 12, and 6 lb of salt per ton of aggregate respectively. Sections 4, 5, and 6 contained 9 percent fines and were treated with salt in the same manner as the 12 percent fines areas. Sections 9, 10, 11, and 12 contained 5 percent fines treated with 18, 12, 6, and 0 lb of salt per ton respectively. Sections 7 and 8 were of standard construction and were not included in the test observations.

All of the experimental sections were built during the 1959 construction season in accordance with Michigan's Standard Specifications for Road and Bridge Construction, with special emphasis on uniformity of procedures and equipment throughout the project. The basic aggregate for the test sections was specified to be 22A with a maximum of 5 percent fines (minus-200). The average for the total amount produced was 4.7 percent. The additional fines required for sections 1 through 6 were obtained from natural ground near the test site. Table 1 gives the average characteristics of the 22A aggregate and the added fines. The fines were selected to be friable enough for easy and satisfactory mixing with the aggregate.

TABLE 1
CHARACTERISTICS OF AGGREGATE AND
ADDED FINES

Description	22A Aggregate	Added Fines
Sieve analysis (percent passing):		
1-in.	100	—
3/4-in.	98	—
3/8-in.	76	—
No. 4	56	—
No. 10	38	100
No. 40	12	88
No. 200	4.7	46
Atterberg limits:		
Liquid limit	—	21 percent
Plastic limit	—	13 percent
Plasticity index	NP	8

The sodium chloride used was in the form of rock salt that met department specifications, with 100 percent passing the 3/8-in. sieve. It was delivered and stored on the job in both bulk and bags. The aggregate, fines, and rock salt were all stored at the site of mixing and were proportioned as required for the individual test sections.

A Pioneer Stabilizer pug mill was used for processing the treated base materials for sections 1 through 6 (Fig. 4a). For sections 9 through 12, where no fines were added, the contractor requested, and obtained, permission to eliminate the pug mill and add the salt to the aggregate on a



Figure 4a. Pug mill for mixing aggregate, fines, and salt.



Figure 4b. Conveyor and baffle box for mixing aggregate, fines, and salt.

conveyor belt with the mixture passing through a special baffle box as it was loaded onto the truck (Fig. 4b). Both methods produced very uniform blends.

Because of the possibilities of segregation and loss of salt resulting from rainfall, none of the base course mixtures was stockpiled. All were fed into trucks as prepared and hauled directly to the grade for placement. Samples were taken for field and laboratory testing throughout the operation, both as construction controls and for recording the actual quantities and qualities of the different sections.

Prepared aggregates were placed and spread by aggregate spreaders and compacted with self-propelled, 5-ton, rubber-tired rollers, in accordance with normal construction procedures. The test base courses were placed in two layers with a final compacted depth of 7 in. Design densities were determined by the standard Proctor test (ASTM T 99) and controlled in the field by the highway department's Rainhart balloon compaction control method. In the low-fines section, field density control was supplemented by use of the Michigan cone test. Each section was completed before its adjacent section was begun.

The materials handled well during construction and compacted readily to higher than design density. Densification continued after compaction under the action of construction traffic. The rock salt dissolved readily in the moist aggregate so that no salt crystals remained in the mix the day following placement. In the higher salt areas, there was some surface hardening due to recrystallization of the salt, but this caused no construction difficulties. No rutting or shifting of the base was noted after final compaction.

It was found during the initial construction of section 1 that the moisture content was too high. The result was a spongy surface that was hard to compact. This was



Figure 5. Typical test sections prior to application of prime coat: (a) 12 percent fines; (b) 9 percent fines; (c) 5 percent fines.

corrected by cutting out the compacted area, blading it on the grade to allow drying, replacing, and compacting. Even though there had been surface hardening, this caused no difficulties and an excellent base was obtained after recompaction. The rest of the aggregates for the test areas were placed at moisture contents between 1 and 1½ percent below optimum, and no further problems were encountered.

Figure 5 shows typical conditions of the sections after compaction and shaping prior to priming. The higher fines areas appear more dense, a fact substantiated by subsequent

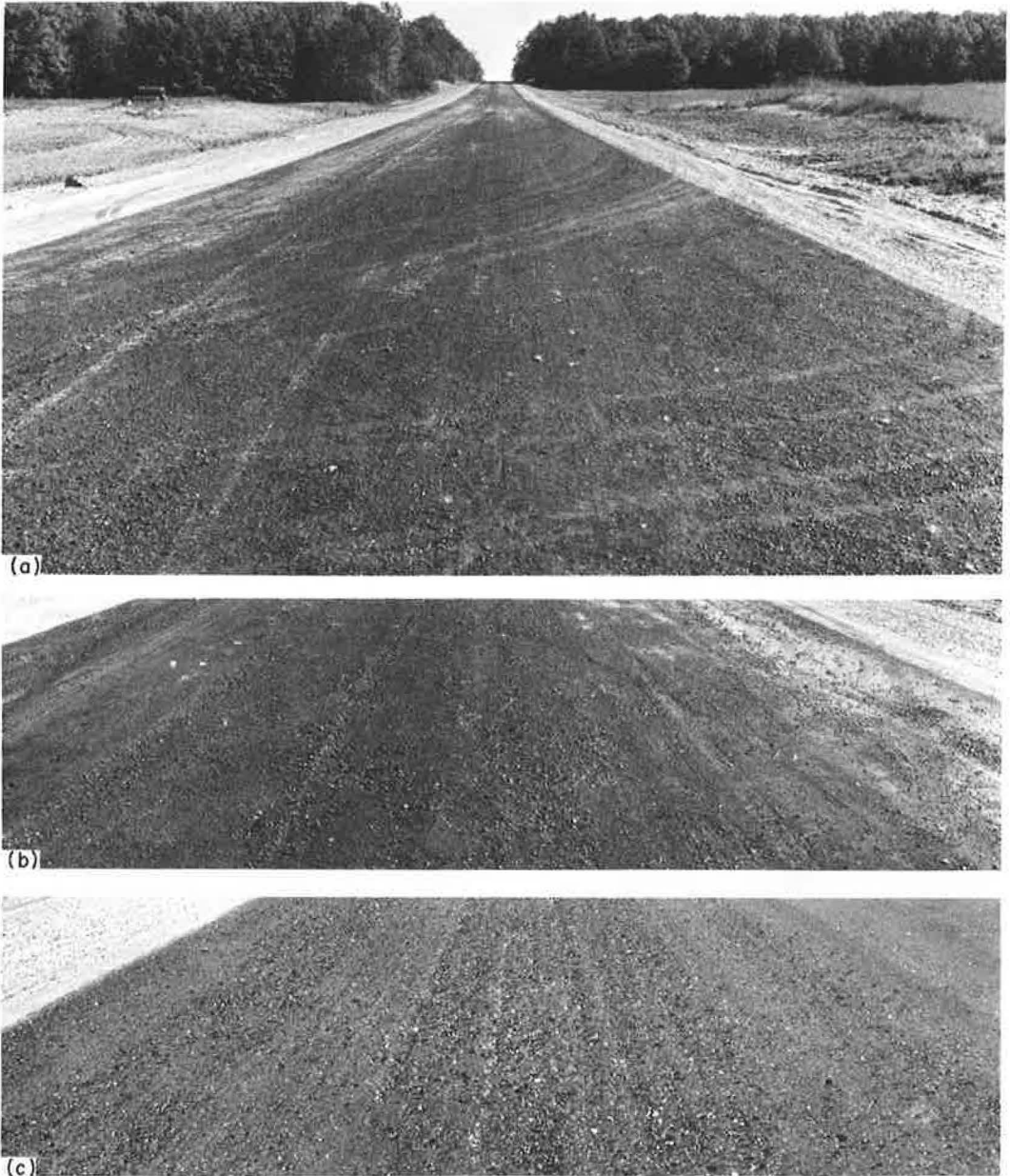


Figure 6. Typical test sections after priming: (a) 12 percent fines; (b) 9 percent fines; (c) 5 percent fines.

testing. Within the three fines areas (12, 9, and 5 percent) there were no noticeable differences resulting from the varying salt contents.

The surfaces were primed with MC-1 cutback asphalt at rates ranging from 0.12 to 0.25 gal per sq yd, depending on the fines content and density of the surface. Good penetration was obtained in all cases and there was no significant runoff once proper application rates were determined (Fig. 6).

After curing of the prime, a double seal coat was applied that served as the roadway surface until the following summer when a 250-lb bituminous concrete wearing course was placed. Figure 7 shows typical conditions of the sealed sections after the



(a)

Figure 7. Condition of seal coats after one winter in the 12 percent fines area: (a) 18 lb salt per ton; (b) 9 lb salt per ton; (c) 6 lb salt per ton.



(b)



(c)

first winter. These particular photographs are of the high-fines areas showing the three different salt contents. Although these represent only one winter, they indicate that the higher salt sections (18 and 12 lb per ton) performed the best with a double seal surface. This same trend was observed in the 9 percent fines area. No significant differences were found in the 5 percent fines area. All were in good condition.

EVALUATION OF THE NEWAYGO PROJECT

This project was set up on a long-term basis to obtain information concerning the performance of the sections over a significant period of use. It was estimated that at least five years would be required with additional studies to be made if warranted. The project is now in the ninth year of service, during which time continuing tests have been made to evaluate its performance through measurements of density, moisture content, quantity of salt, roughness, rutting, compressive strength of core samples, and observation. Figures 8, 9, and 10 show the results for the basic tests from the start of the project through the latest testing time. Results of special tests are shown separately.

Density Measurements

All field densities were measured by the highway department's conventional Rainhart balloon method. Although all passed minimum specification values, there were considerable differences in density within each test section. Results, therefore, represent trends rather than specific values. No attempts were made to control or test the areas by statistical control procedures.

After the surfacing was placed, density measurements of the base were made through holes cored through the asphalt. Densities in the high-fines areas were very high for all salt-treated areas. Densities obtained by the Rainhart method were periodically checked by measuring the density of cores. The two methods checked quite closely.

Densities increased under the action of traffic, mostly during the first year. After placement of the asphaltic concrete surface, there was a leveling-off of density and a slight decrease in density in the 5 percent fines area. All densities remain well above the design values, however. Some variations might be attributed to reasonable variation in the density of the material, and the difficulty of making precise measurements through the core holes. Each measurement represents the average of three Rainhart tests.

Moisture Content

Other than for some seasonal variations, the moisture content of the bases has remained constant after an initial moisture loss during the first year (Figs. 8, 9 and 10). At the end of 6 years (1965), the 5 percent fines area, as expected, had a slightly lower moisture content than did the higher fines areas. Values shown are the average of three oven-dried samples from different locations.

Salt Content

The amount of sodium chloride in the base course was determined by ASTM Designation D1411 56T in which, basically, the chemical is washed from the aggregate by agitation and the resultant solution is tested for chloride ion content. Control sampling indicated the method was accurate. Because sodium ions can combine with clay particles, it is possible that some sodium is not released by washing.

Field test data show that, during the first year, the salt content of the bases decreased rapidly from the design quantities (Figs. 8, 9, and 10). In the high-fines areas, the decrease has leveled off to from 2 to 5 percent, depending on the rate of initial treatment. In the low-fines areas, only a trace of salt remained in the base after 3 years, regardless of the quantity originally present. Testing of the subbase beneath the treated sections showed the salt to have leached into the subbase and beyond.

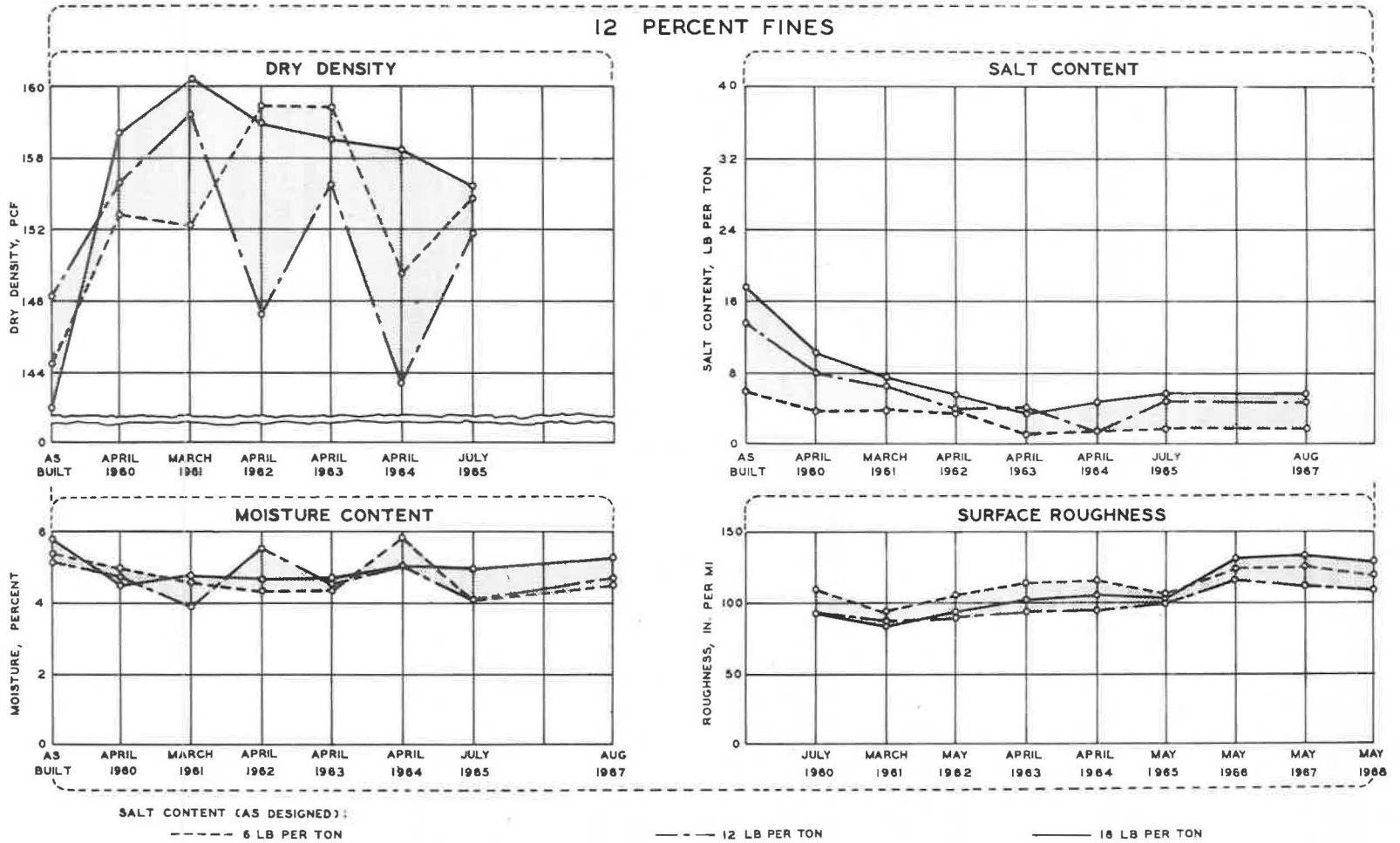
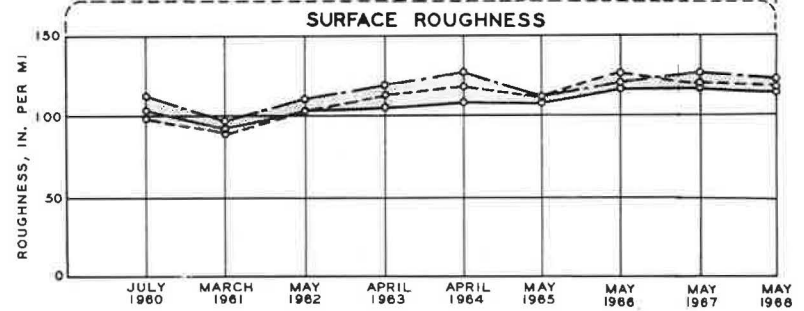
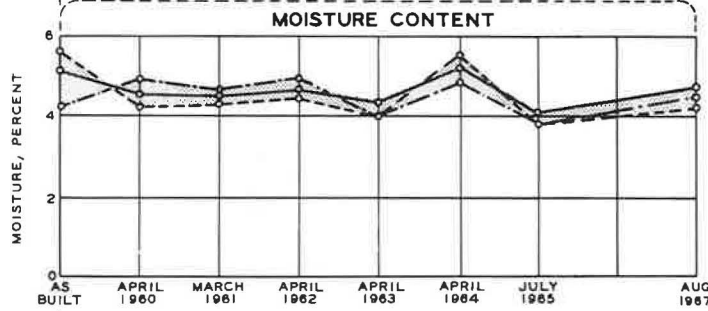
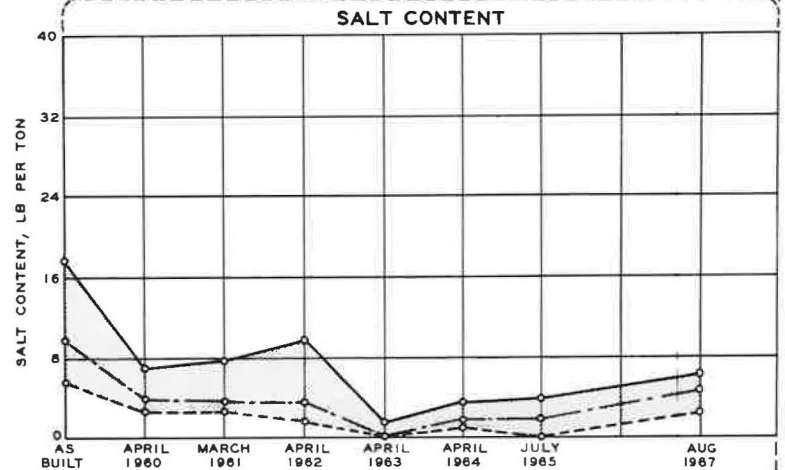
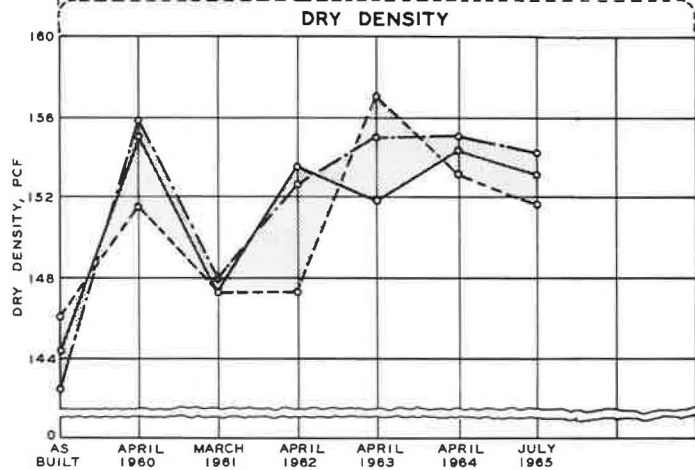


Figure 8. Yearly variation in base and surface properties, sections 1, 2, and 3.

9 PERCENT FINES



SALT CONTENT (AS DESIGNED):
 - - - - - 6 LB PER TON - - - - - 12 LB PER TON ——— 18 LB PER TON

Figure 9. Yearly variation in base and surface properties, sections 4, 5, and 6.

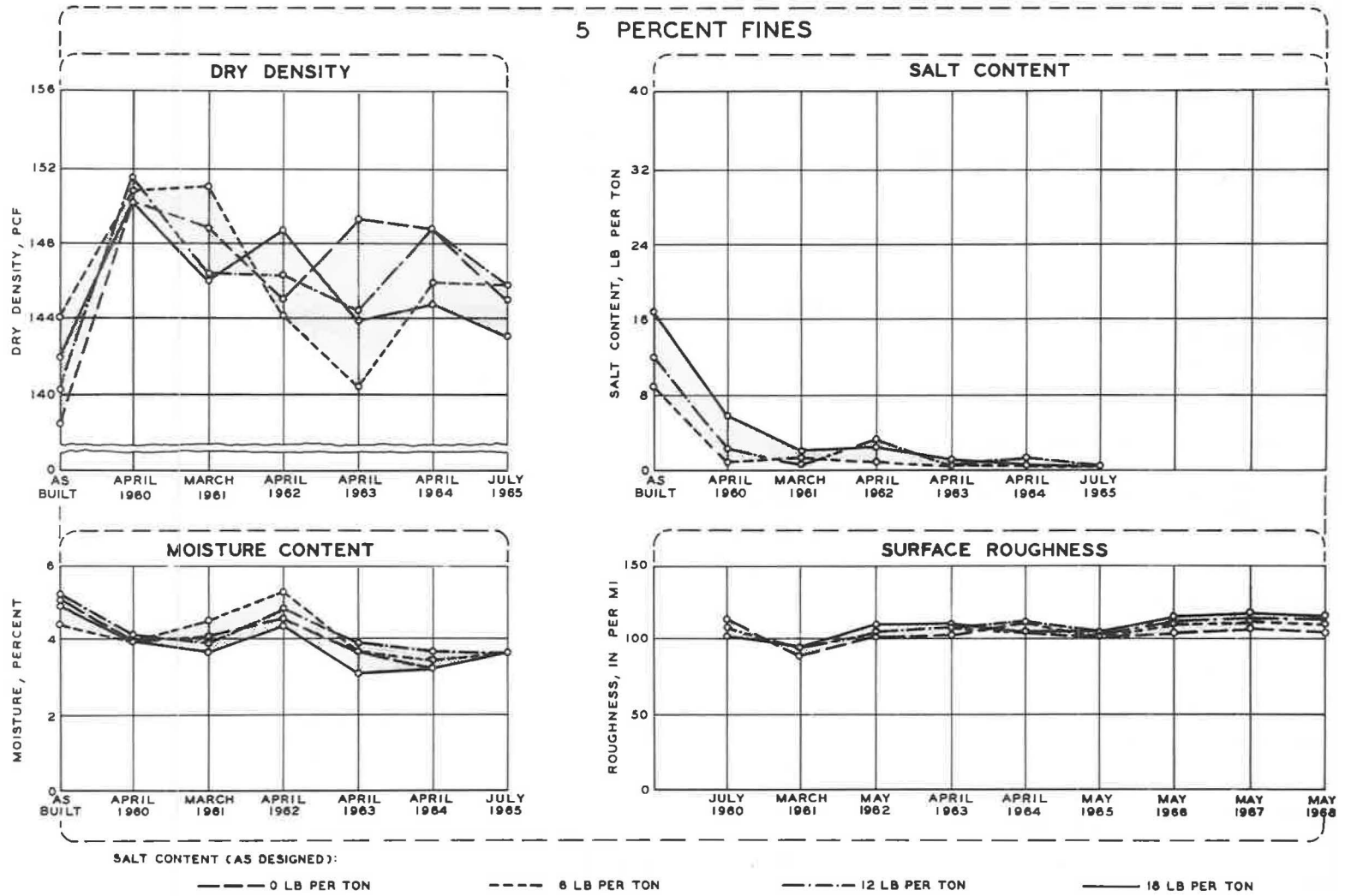


Figure 10. Yearly variation in base and surface properties, sections 9,10, 11, and 12.



Figure 11. Rutting measurement device: (a) general view of unit and (b) depth indicator.

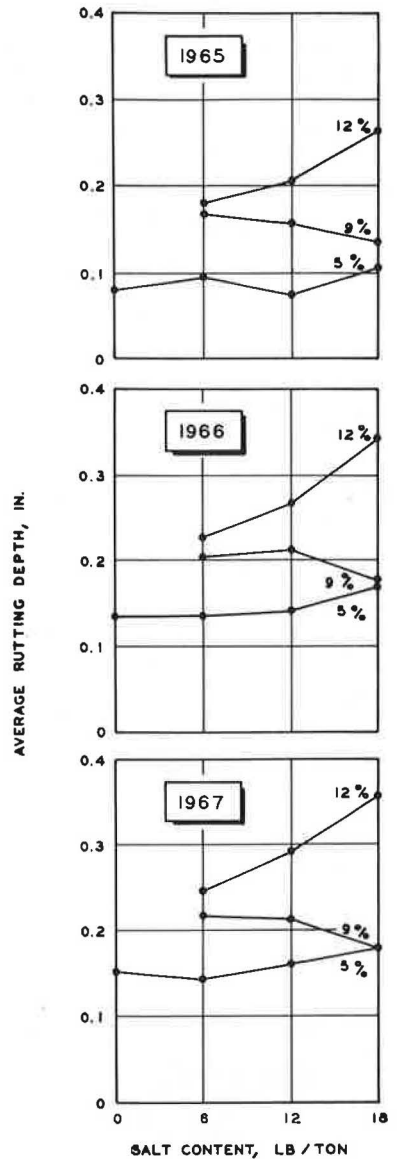


Figure 12. Periodic rutting values for the test areas.

Surface Roughness

Surface roughness measurements were begun in the summer of 1960, following application of the bituminous concrete surface, using the highway department's roughometer (U.S. Bureau of Public Roads type). Very little change in the riding quality or roughness of any of the test sections has been measured or otherwise noted. There appears to be a slight trend toward increased roughness during the past 3 years, but all values remain within the "good" riding category. The values show the average roughness of the four wheel tracks expressed in inches per mile (Figs. 8, 9, and 10).

Rutting Measurements

A new method of evaluating the pavement sections was begun in 1965 in which the maximum rutting of the wheel tracks was measured. The device used for this purpose (Fig. 11) was developed by E. C. Novak, Jr., of the MDSH Research Laboratory. In operation, the hand-held cable is unwound from the storage reel and stretched tightly across the roadway. One end of this cable is connected to a battery contained in the device. A calibrated wedge, also wired to the battery, is placed under the cable until contact is indicated by bell signal. The wedge, stepped in graduated readings of 0.025 in., is placed in the low point of each wheel track to obtain a depth measurement. The device is self-contained and has a counter for measuring the distance between reading sites. Three men are required to operate the equipment.

Figure 12 shows the rut-depth measurement values obtained since 1965. Each point represents the average of four wheel-track measurements taken every 100 ft within the test section. These results and testing procedures have been analyzed and found to be statistically meaningful.

Although none of the ruts was deep enough to cause concern at this time, the rut depths are noticeably greater in the higher (12 percent) fines areas and, generally, in the higher salt content sections. The least rutting is in the highway department's standard design section (6 lb salt per ton and 5 percent fines).

Core Samples

Attempts were made to core the test areas with the highway department's concrete coring device but this operation was not successful. The gravel broke up when both dry- and wet-coring methods were attempted. Short cores were obtained from the high-fines areas and the core-drill operator noticed that these areas also offered considerably more resistance to drilling than did the 5 percent area. The following year (1961) a new core drill developed by the International Salt Company was tried on the job and was successful in obtaining cores from the 12 and 9 percent fines areas but not from the 5 percent fines area. The cores obtained were in excellent condition, being well-bonded and very dense. Figure 13 shows such a core from section 5 (9 percent fines



Figure 13. Typical core from high-fines area in 1961 (section 5).



Figure 14. Best core obtained from low-fines area in 1961 (section 9).



Figure 15. Cores from high-fines areas obtained in 1967.

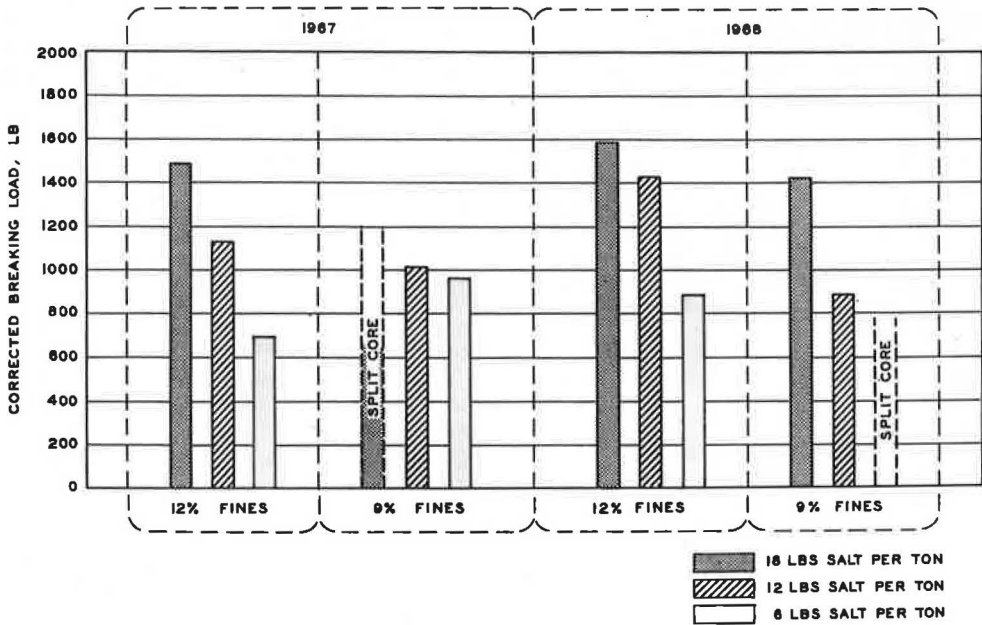


Figure 16. Breaking loads of cores.

and 12 lb salt per ton), which is typical of the other cores from the 12 and 9 percent fines areas. The best attempt at obtaining cores from the 5 percent fines area (section 9 containing 18 lb salt per ton) is shown in Figure 14. No core portions at all were obtainable from sections 10, 11, and 12.

Cores from the test areas were obtained again in 1967 and 1968. As before, no usable cores could be taken from the 5 percent fines area. Figure 15 shows the cores obtained in 1967. The core from section 4 was broken along the compaction plane of the two layers of compacted aggregate. The breaking loads (corrected to a 2:1 height-to-diameter ratio) for the 1967 and 1968 cores are plotted in Figure 16. The compressive strength increased with the percentage of salt for the test sections containing 12 percent and 9 percent fines. The cores were broken at field moisture conditions of about 4 to 5 percent. These cores again showed the salt-treated high-fines bases to be in excellent condition, well-bonded, and very dense.

Asphalt Surface Performance

Throughout this project there was no indication of any detrimental effects on the application and performance of the asphalt surfacing caused by salt content of the base. The adhesion of the prime and seal coat was, however, a definite function of the fines content. During testing, prior to applying the surface, it was necessary to remove the seal coat before measuring densities of the base. In the low-fines areas, this could be done easily by peeling back by hand a cut section. In the high-fines areas it was necessary to chip the seal coat from the base, a rather laborious operation (Fig. 17).

There was good adherence between the seal coat and base even in the low-fines areas, the separation taking place within the gravel itself. Examination of the cores also showed good adhesion of the asphalt to the salt surfaces, as has the performance of the pavement structure during the life of this project.

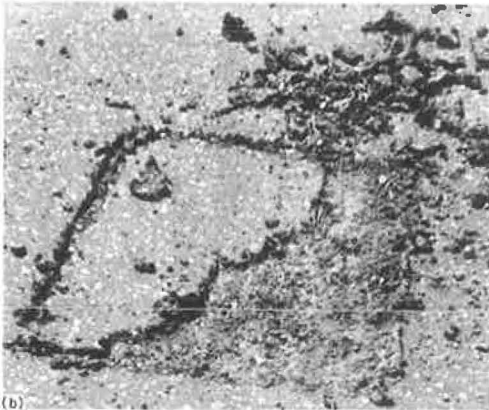


Figure 17. Removal of seal coat from (a) low-fines area and (b) high-fines area.

CONCLUSIONS

The 9-year evaluation of the Newaygo test sections indicates that aggregate containing up to 12 percent fines can be successfully used in base course construction when treated with rock salt. Densities, riding qualities, and rutting resistance were not functions of increased salt content but were better in all cases with the minimum (6 lb per ton) salt treatment. Michigan standard construction (in this project, 5 percent fines with 6 lb of salt per ton) performed as well as, or better than, any of the sections. Therefore, based on the results of this project there is no reason to change Michigan's current specifications for base course materials where such are economically available.

More specific conclusions include the following:

1. No construction problems were encountered using salt, and design densities were easily obtained. The salt dissolved readily in moist aggregate.

2. Salt-treated aggregate handled and compacted best when moisture contents were 1 to 2 percent below optimum moisture.
3. Densities of the sections increased under the action of traffic and were particularly high in the high-fines areas.
4. Salt content diminished with time to constant values in the high-fines sections. No significant amount of salt was found in the low-fines areas after about 3 years.
5. Excellent cores were obtained from the high-fines areas but none could be obtained from the 5 percent fines area. Core strengths from the 12 and 9 percent fines areas increased with salt content.
6. Excellent adhesion between asphalt and the salt-treated bases was obtained.
7. Sieve analyses of the bases during evaluation indicate that all of the test-section aggregates had degraded by about 2 percent so that the fines were higher than the design values.

APPLICATION OF FINDINGS

As a direct result of the Newaygo studies, rock salt has been used on two other special projects in Michigan. These are in addition to its use as an allowable specification item for base course aggregate treatment.

Ontonagon Project

Rock salt was used during 1967 in an effort to upgrade an aggregate that had degraded or become contaminated with fines during use as an open-surfaced road prior to the application of a seal coat. The area involved was an 8½-mile length of the relocation construction of M-64 just west of Ontonagon in the Upper Peninsula. Originally meeting 22A specifications, the aggregate when tested contained much higher amounts than the allowable 7 percent fines, varying up to 16 percent but averaging about 11 percent.

Because this gradation was similar to the aggregate that benefited by salt treatment in the Newaygo project, it was decided to try the same treatment on the M-64 construction. Although the 6-lb-per-ton salt treatment had proved satisfactory at Newaygo, it was felt that, because of possible nonuniformity of the in-place mixing required on the present job, the amount of treatment should be increased to 12 lb per ton.

The aggregate base was scarified and the salt spread on the surface and mixed to a full 8-in. depth with a Seaman Duo Stabilizer No. 642. The salt treatments were handled in approximately 3,000-ft long sections. Figure 18 shows the mixing operation and the appearance of a mixed section after passage of the Duo Stabilizer and the appearance of the salt-treated area prior to mixing. No problems were encountered in the salt application.

The stabilization and surfacing were completed during 1967 and the job has now gone through one winter. No detrimental effects of this exposure have been noted to date. Roughometer and rutting measurements are being made periodically, but it is too early to obtain any significant changes in physical characteristics. A nearby project constructed from the same aggregate source and in the same manner as the salt-stabilization project has been selected as a control section for comparative roughometer and rutting measurements.

Alpena Shoulder Project

Rock salt was one of several admixtures used by the highway department in an experimental project designed to evaluate the suitability of various stabilizing agents for upgrading open-surfaced aggregate shoulders. This project, located on US-23 just north of Alpena, was constructed in 1962 and includes—in addition to the salt treatment—sections treated with various quantities of asphalt and cement. The in-place aggregate was nonplastic and approximated Michigan's 23A shoulder gradation with about 13 percent passing the No. 200 sieve.

Two rock salt sections were constructed, one containing 6 lb, the other 12 lb of salt per ton of aggregate. Each section was 2 miles long, 4 ft wide, and 6 in. deep (compacted depth). The salt was incorporated into the aggregate by means of a Seaman



Figure 18a. In-place mixing of salt and aggregate on the Ontonagon project.



Figure 18b. Salt-treated base after mixing (unmixed salt in background).

Duo Stabilizer. Three passes of the mixer were required for satisfactorily mixing the salt, water, and aggregate. The test areas were surfaced with a single seal coat.

The salt sections were the easiest to construct and compact of all the test areas used in this study. With the exception of the untreated control section, the salt sections were the cheapest to construct. Periodic roughometer measurements have shown the salt sections to be among the smoothest riding of all the test areas. Throughout the project, the 6-lb-per-ton salt sections performed as well as or better than the 12-lb treatment, based on roughometer tests.

This study shows, as did the Newaygo project, that the highway department specification aggregates perform satisfactorily with or without rock salt treatment. As a construction aid, however, salt offers significant benefits when used with such aggregates. These benefits do not appear to be a function of the salt content, but are as readily obtainable with Michigan's recommended 6-lb-per-ton treatment as with higher amounts.

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Salt Stabilization Research

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●SALT stabilization has been practiced for many years, generally with success but occasionally with failures. This has brought about a need to know the conditions that favor salt stabilization and those to be avoided, so that we can predict the required conditions for optimum results. The most satisfactory place for determining these conditions would appear to be in the laboratory. We should then be able to translate these results to satisfactory practices in the field.

Previous research consisted of laboratory tests to find the types of soils most amenable to salt stabilization or field tests in which salt stabilization was tried without prior consideration being given to soil type. The efforts have yielded inconsistent results.

In our research, we decided to try a different approach. Instead of starting with soils and trying to stabilize them in the laboratory, we started with cores removed by a special coring machine from successfully salt-stabilized roads and tried to determine what conditions were present to yield the satisfactory results.

The cores studied came from successfully salt-stabilized roads in Monroe, Michigan (Fig. 1); Steuben County, Indiana (Fig. 2); Montpelier, Ohio (Fig. 3); roads composed of blast-furnace slag from South Gate, Michigan (Fig. 4); and roads composed of galena stone from Wisconsin (Fig. 5).

Our approach in investigating this subject was the scientific method consisting of (a) the observation and analysis of previous occurrences of the phenomenon, (b) the inference from the observations of a specific law or causation, and (c) the testing of this law by trying specific applications. Our observations were made on thin sections (approximately $\frac{3}{100}$ -mm thick) taken from the Monroe County, Michigan, core and studied under an optical microscope at magnifications between 10 \times and 160 \times using transmitted and polarized light, and under an electron microscope at 660 \times . The following observations were made from the microscope slides:

1. The cores are very dense, much denser than the original material.
2. Salt particles are observed at high magnification (660 \times) and evidently contribute to bonding.
3. Cracks are present. This could be evidence of cementation. Apparently the clay has been homogeneously dispersed throughout the matrix and has formed layers around the larger particles and cemented them together in one common mass. The evaporation of water from these clay layers would cause shrinkage and produce cracking.
4. There appear to be secondary growths of limestone and silica.
5. Some reduction in the size of some of the limestone particles appears to have taken place, thus indicating that this material has entered into a reaction.

The important result to be gleaned from these observations is the explanation of the cause. Some mass transfer has taken place, with secondary growths of limestone and silica also being present. Furthermore, clay particles appear to have surrounded the larger particles.

The inference we might draw from these observations is that migration of material has taken place. But migration under what conditions? Very possibly migration occurred under changing temperature and water conditions. We have thereby developed a possible explanation for the cause of this phenomenon. Laboratory samples were prepared for a test of this hypothesis.



Figure 1. Salt-stabilized core from Monroe, Michigan.

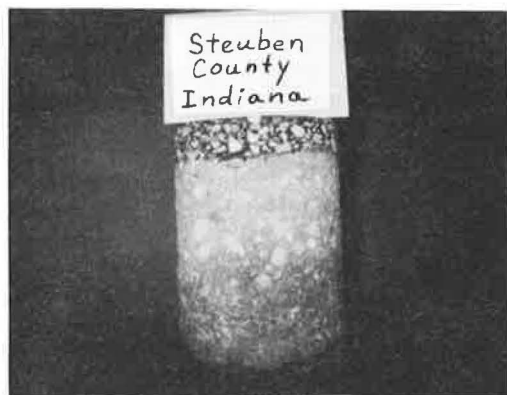


Figure 2. Salt-stabilized core from Steuben County, Indiana.



Figure 3. Salt-stabilized core from Montpelier, Ohio.



Figure 4. Salt-stabilized core composed of blast-furnace slag from South Gate, Michigan.



Figure 5. Salt-stabilized core of galena stone from Wisconsin.

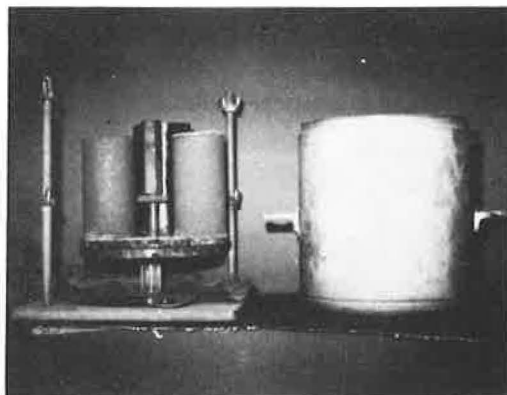


Figure 6. Extruded synthetic cores before curing, mounted on an elevated and perforated base that rests on a rubber gasket and large baseplate; mold is at the right.

The formula for the mixture used for these tests is as follows: 10 percent clay (Grundite), 30 percent calcium carbonate, 60 percent sand, and 1 to 2 percent sodium chloride. This formula is a first approximation of the ingredients and percentages of ingredients that should produce the desired effect.

Grundite is a trade name for an illitic clay from Grundy County, Illinois. It was selected as being typical of a glaciated clay of intermediate plasticity, which is characteristic of the northeastern United States. The amount was limited to 10 percent in the samples used because, if higher percentages were used, the plasticity in the presence of sodium ions could increase to the point where the initial formula would be unstable.

Calcium carbonate was included in the mixture because secondary calcium carbonate appeared to be present in the sections observed. A sufficient amount was used to give contact between limestone particles in the final mixture. Sand was included because secondary silica also appeared to be involved in some of the growth between particles. The amount selected was sufficient to make up the remainder of the formulation.

The quantity of sodium chloride was selected on the basis of the amount commonly used in salt stabilization.

The equipment used for preparing the compacted core consisted of a standard Proctor mold, baseplate, and collar. Optimum moisture was first determined, the samples were blended with water at optimum moisture, and then compacted to optimum density. The synthesized core was extruded from the mold after compaction. The cores were quite fragile at this point and considerable care was required to transfer them.

A large mold was set in place on a correspondingly large baseplate using a rubber gasket between the baseplate and the mold. A perforated and elevated base was placed over the baseplate and the extruded samples were then placed on the perforated base. A small amount of water was added to the bottom of the container. A second baseplate with gasket was then placed on top of the container, and the bolts were drawn onto the studs until a tight seal was obtained (Fig. 6).

The samples were then cycled according to the following procedure: (a) the mold was first placed in an oven at 120 F for 48 hours; (b) it was allowed to stand at room temperature for 24 hours; (c) the cover was removed, and the mold was placed in the oven without a cover at 120 F for an additional 48 hours; (d) the sample was then allowed to stand at room temperature for 24 hours. This procedure was repeated 30 times. This number of cycles was chosen because it was believed to be in excess of any number of natural cycles of this type that might be encountered.

Well-hardened synthesized cores resulted from applying this procedure (Fig. 7). No salt was observed on the outside of the core to which 1 percent salt had been added.

Salt was seen on the outside and at the top of the core containing 2 percent salt. These cores were oriented to be in the same position as they were before being removed from the cycling apparatus. It is interesting to note that the salt remaining on the outside of the core had migrated to the top. One conclusion that appears valid from this observation is that the required amount of sodium chloride is between 1 and 2 percent.

Thin sections taken from the synthetic cores were examined with an electron microscope at high magnification (7,200 \times). It was observed that the limestone particles were fused together and that some unreacted salt was present in the voids. The indistinct appearance of the particles indicated that the clay had been uniformly dispersed.

Is this the end of our research? No, we are quite frank about admitting that it



Figure 7. Two synthetic cores, one containing 1 percent salt and the other containing 2 percent salt, after being subjected to 30 cycles in the cycling apparatus.

is just the beginning. We are very pleased with the results, but we realize that there is still much to be done.

Future avenues of research that should be pursued include the following:

1. The minimum number of cycles should be determined. It is proposed that this be done with a density pycnometer and surface-area measurements. We believe that maximum bridging between the particles should be indicated by the number of cycles required to obtain minimum surface area and maximum density.
2. The formulation should be optimized. This should include determination of the optimum amount of salt required as well as varying the amount of calcium carbonate. One experiment would completely eliminate calcium carbonate to determine if this is an ingredient that enters into the stabilization reaction.
3. Various types of clays should be substituted. The grundite clay, as mentioned before, has been chosen as a typical example of glaciated clay of intermediate plasticity that is typical of the northeastern United States. It is proposed that kaolinite clays, which are typical of the southern United States, and montmorillonite clays, which are typical of the central United States, should be substituted to determine the limitations of these clays in other areas of the country.
4. The function of the clay and the function of the salt should also be determined. The tool for determining this appears to be the electron microprobe. With this tool, an attempt will be made to find the location of sodium ions in the thin sections. It is believed that these will be found in the clay areas, indicating that the sodium ion has served as a means of dispersing the clay particles.

In summary, thin sections removed from cores taken from successfully salt-stabilized roads and observed under the microscope show the cores to be more dense than would be expected of untreated material. Furthermore, none of the original salt has been observed to be present in these sections, and cracks are present, possibly indicating cemented areas. Secondary growths of limestone and silica also appear to be present, and erosion of these materials from other locations in the sample seems evident. We infer from this that migration has taken place, and we attribute the cause to cycling moisture and temperature conditions.

We have tested this theory in the laboratory using materials of the approximate composition to be found in the field. They were cycled under moisture and temperature conditions much more severe than believed to be encountered in the field. We are pleased to report that cores of good quality have been obtained. We fully realize that much future work remains to be accomplished before the results of this research can be applied in the field.

DISCUSSION AND SUGGESTIONS

Dr. John B. Sheeler of the University of Iowa suggested that consideration be given to coating the thin sections removed from cores taken from successfully salt-stabilized roads with a solution of zinc uranyl acetate. Exposure of the sections to ultraviolet light, instead of using the electron microprobe, could then be used to determine the location of sodium ions.

It was also suggested that a control synthesized core containing no salt be included in plans for subsequent research, and plans have been made to include synthesized cores of this type.

In response to a question, the author confirmed that water is added to the cycling apparatus at the beginning of each cycle.

A representative believed to be from Ottawa, Canada, suggested that foreign material in the cracks should be identified as secondary calcium carbonate, etc. This identification is necessary because it is possible to introduce impurities into these areas during the preparation and mounting of the thin section.

It was further suggested by a representative from the U. S. Bureau of Public Roads that toy samples, i. e., samples prepared from absolutely pure materials, could be prepared to make sure that the ions identified by the electron microprobe are the result of migration and not impurities present in the materials used to prepare the synthesized materials.