Relative Effects of Chlorides, Lignosulfonates And Molasses on Properties of a Soil-Aggregate Mix

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Selection of the most economical stabilizing agent for a desired effect on the properties of a soil should be based on knowledge of relative effects of the agents rather than on personal prejudice or the publicity given to an agent. The objective of this paper is to provide a starting point for cost-effect comparisons by showing the effects of four agents on certain properties of a single soil-aggregate surface course mix.

Properties compared are (a) moisture-density relations as determined by standard Proctor density tests; (b) strength as determined from California Bearing Ratio studies; (c) moisture retention as determined by a non-standard test; and (d) the plastic properties of the mix as determined by the Atterberg limits tests. Additives, used in treatments of 0, 0.5, 1, 1.5 and 2 percent, are (a) Peladow calcium chloride pellets; (b) Sterling FC and CC salts; (c) Toranil A and Lignin Liquor spent sulphite liquors, and (d) a 79.5 Brix molasses.

The mechanism of stabilization with each agent is discussed to permit extrapolation of effectiveness to other soils. No selection of the "best" agent is made because this is a function of the desired effect on properties and available funds.

● SCARCITY AND COSTS of better grade road aggregates combined with ever increasing demands for low-cost secondary roads have focused the attention of highway engineers on the use of chemical additives to conserve available aggregate and to improve the performance of inferior materials. Despite the extensive research conducted relative to chemical stabilization, no record is available reflecting a direct comparison of the effects of the additives selected for this study on the properties of a specific soil.

Because logical selection of the most economical additive for a desired effect cannot be made without a basis for comparison, this study was initiated to provide a starting point for cost-effect comparisons. The objective of the paper is to compare the effects of calcium chloride, sodium chloride, lignosulfonates, and molasses on the moisture-density relationships, strength, moisture retention and plasticity characteristics of a soil-aggregate surface course mix.

MECHANISM OF STABILIZATION

The two main factors contributing to the stability (resistance to lateral flow) of a granular road are internal friction and cohesion (10). Internal friction in a soil-aggregate mix is attributed to the granular fraction, and is a partial function of density. Cohesion, on the other hand is a function of soil fines, moisture films, and cementing agents (8).

Chloride Stabilization

Davidson and Handy (5) attribute increased stability of granular road bases with the use of chlorides to the following seven effects:

Lubrication. — Based on the unctuous nature of a chloride solution, increased densities of 1 to 7 percent are cited in comparison with an untreated soil. This increase in density may logically be expected to increase internal friction and reduce the rate of moisture loss. Although this effect is less pronounced with sodium chloride than with calcium chloride, the deficiency may be negligible because sodium chloride contributes to dispersion of the binder preventing localized concentrations and thus eliminating soft spots.

Flocculation of Clays. — Presence of certain amounts of sodium or calcium ions in the mix will flocculate the binder into silt-sized particles. This amounts to changing the grain-size distribution and may have the effect of reducing the plasticity index. Other concentrations of ions (more or less) will cause electrical imbalances which will tend to disperse the clay. Crystallization of the salt or leaching by rainfall will change the concentration of ions, permitting dispersion of the clay, with consequent plugging of voids contributing to watertightness.

Moisture Retention. — Because of the deliquescence of calcium chloride and the hygroscopicity of sodium chloride, the rate of evaporation of soil moisture will be reduced. As a result, cohesion will be retained and the binder fraction will function as desired rather than being lost as dust.

Solubility of Road Aggregate. — This effect is mentioned as a possible means of cementation within the mix and is based on the solubility of limestone and dolomite in chloride solutions, resulting in precipitation of cementitious carbonates. The effectiveness of this reaction is unevaluated.

Freezing Point Depression. — By lowering the freezing point of the mixture, resistance to temperature effects is obtained with the use of chlorides. For complete freezing, road temperature must be -59.8 F with calcium chloride treatment or -6 F with sodium chloride treatment; thus the creation of ice lenses is inhibited.

Surface Tension. — The increase of this property due to the presence of chlorides results in strengthening water film bonds between soil grains, adding to apparent cohesion. With evaporation, the chloride concentration increases, causing a further increase in surface tension. The degree of increase may be such that increased densities will result.

Crystallization. — This effect is present only with sodium chloride and may compensate for the lesser effectiveness of salt altering other properties. Advantages which result from the formation of salt crystals are (a) the crystals plug voids thus retarding evaporation and shrinkage, (b) they act as a cement which prevents aggregate losses, and (c) they provide a hard, tightly knit traffic surface.

Lignosulfonate Stabilization

According to Davidson and Handy (5), the principal effects of lignosulfonates on a soil-aggregate mixture are those of cementation and dispersion of clay.

Cementation is derived from the fact that the lignosulfonates, being water soluble polymers, act in the soil similarly to a glue. Best results are obtained with mixes rich in binder soil, because open-type mixes permit rapid leaching of the lignosulfonate. Hygroscopicity of the wood sugars present may also contribute to strength by retarding evaporation, thus benefiting cohesion.

Dispersion of the clay fraction benefits stability of the soil-aggregate mix by: (a) plugging voids and consequently improving watertightness and reducing frost susceptibility, (b) eliminating soft spots caused by local concentrations of binder soil, (c) filling voids with fines thus increasing density, and (d) increasing the effective surface area of the binder fraction which results in a greater contribution to strength from cohesion.

Molasses Stabilization

Phillips (7) implies that the principal effects of molasses in a soil-aggregate mix

TABLE 1

MECHANICAL ANALYSES OF DRY MATERIALS USED IN STUDY

Sieve Size	Weight Percentage Retained on Sieve			
	Soil-Aggregate	CaCl₂ (Peladow)	NaCl (CC)	NaCl (FC)
¾ in.	0	_a	-	-
⅜ in.	-	Nil	0	-
No. 4	18.55	0.2	35.0	-
No. 8	-	37.0	48.0	0
No. 10	18.0	-	-	-
No. 12	-	-	-	5.0
No. 16	-	-	15.9	-
No. 20	-	62.8	-	42.0
No. 40	29.15	-	-	-
No. 80	-	-	-	43.0
No. 200	11.20	-	-	-
Pan	23.20	0.1	1.1	10.0

aSieve not used in analysis.

are increased moisture retention and cementation. Moisture retention effects may be attributed to the hygroscopicity of the molasses and to reduced vapor pressure. From his description of the cementation effect, it would appear that the actual effect is not cementation, which implies a rigid bond between particles, but rather an increase in surface tension with consequent increase in apparent cohesion. As with lignosulfonates, best results may be anticipated with a high percentage of binder soil owing to the ease with which molasses will enter solution and be leached from the mix.

INVESTIGATION

Materials Used

Soil-Aggregate Mix. — Three natural soils containing about 6 percent moisture, were blended in a 2-cu ft cement mixer to give a soil-aggregate mix conforming to Iowa State Highway Commission Specification 4111 (6) for stabilized surface course materials. The three soils used were (a) a pit-run gravel from a glacio-fluvial deposit north of Ames, Iowa; (b) a silty clay loam (Monona Series, C horizon) from Shelby County, Iowa; and (c) a C horizon oxidized Wisconsin-age (Cary) glacial till from near Ames, Iowa.

The gradation of the resultant mix is given in Table 1, other physical properties of the soil-aggregate mix are as follows:

Liquid limit — 25.5 percent
Plastic limit — 16.8 percent
Plasticity index — 8.7
Optimum moisture — 9 percent
Std. Proc. dens. — 129.2 pcf
Specific gravity — 2.69
Carbon content — 0.1 percent
Carbonate content — 21.2 percent
Cation exchange capacity — 7.5 mc/100 gm
Exchangeable cation — Ca^{++}
pH — 8

X-ray analysis of the fraction passing the No. 200 sieve revealed the presence of quartz, calcite, dolomite, and feldspars, as well as the clay minerals illite, kaolinite, montmorillonite and vermiculite, although recent work indicates that the latter may be

TABLE 2

PETROGRAPHIC ANALYSIS OF PORTION OF THE SOIL-AGGREGATE MIX COARSER
THAN THE NO. 200 SIEVE

Sieve Retaining Material	Weight Percentage				
	Quartz[a]	Feldspar	Heavy[b]	Carbonates[c]	Aggregate[d]
No. 4	0	2	0	51	47
No. 10	21	1	0	38	40
No. 40	~ 78	trace	0	~ 6	~16
No. 200	73	6	7	7	7

[a]Includes quartz and quartzite.
[b]Includes turmaline, augite, magnetite, and opaque minerals.
[c]Includes limestone and calcite.
[d]Includes all rock fragments; for example, granite, etc.

a non-expanding 14 angstrom montmorillonite (11). No quantitative analysis of these
minerals was attempted but the predomonant clay mineral was montmorillonite.

Results of a petrographic analysis (12) of the remaining portion of the soil-aggregate
mix are given in Table 2.

Calcium Chloride. — Calcium chloride for this study was provided in the form of
Peladow pellets by the Dow Chemical Company. In this form the chloride is anhydrous,
contains about 95 percent $CaCl_2$, and costs approximately $30 per ton undelivered.
Mechanical and chemical analyses of the material as given by the manufacturer (13)
are given in Tables 1 and 3.

Sodium Chloride. —Rock salt was provided by the International Salt Company in two
gradations. The larger size salt is designated by the manufacturer as Sterling CC, and
the smaller as Sterling FC. Identification in this paper will be by the letter designations
CC and FC, respectively. Costs at the mine for these salts vary from about $8 to $13
per ton depending on the size shipment and the packaging requirements. Typical me-
chanical and chemical analyses of the salts as provided by the producer (14) are given
in Tables 1 and 3.

TABLE 3

TYPICAL CHEMICAL ANALYSES OF CHLORIDES

Constituents	Weight Percentage		
	$CaCl_2$ (Peladow)	NaCl (CC)	NaCl (FC)
$CaCl_2$	95.2	0.053	0.071
NaCl	1.15	98.220	98.236
KCl	2.96	-[a]	-
$Ca(OH)_2$	0.068	-	-
$CaCO_3$	0.024	-	-
$CaSO_4$	-	0.643	0.651
$MgCl_2$	133[b]	0.052	0.085
Heavy metals as Pb	0.5	-	-
S as SO_4	0.009	-	-
Fe	16[b]	-	-
Water insolubles	-	1.041	0.957

[a]Not determined.
[b]Parts per million.

Lignosulfonates. — Two types of spent sulphite liquor were used in the study. The first, Toranil A, is a desugared calcium lignosulfonate which was provided in the concentrated form (50 percent solids) by the Lake States Yeast Corporation. The other, Lignin Liquor, is also a concentrate rich in calcium lignosulfonate, but contains a higher percentage of sugars. It was provided by the Appleton Division of the Consolidated Water Power and Paper Company. Table 4 gives a summary of the property analyses of the liquors as provided by the manufacturers (15, 16), costs are about 4.5 cents per gallon undelivered.

TABLE 4

PROPERTY ANALYSES OF SPENT SULPHITE LIQUORS AS GIVEN BY PRODUCERS

Property	Toranil A	Lignin Liquor
Total solids, %	50	52.4
Total sugar, %	0.6	11.5
Total sulfur, %	_a	3.21
Ash, %	8.65	8.58
Calcium oxide, %	3.75	3.40
Specific gravity	1.24	1.267
pH	4.55	4.0
Manufacturer	Lake States Yeast Corp., Rhinelander, Wis.	Consolidated Water Power & Paper Co., Wisconsin Rapids, Wis.

aNot determined.

Molasses. — The molasses used in the study was provided by the Inland Molasses Company. Although the Brix reading was 79.5, representing a sugar content of 79.5 percent, evaporation to constant weight at 70 C revealed a solids content of only 50 percent by weight. A typical analysis (17) of the molasses is given in Table 5. Current cost is $35 per ton in eastern Iowa.

TABLE 5

TYPICAL ANALYSIS OF 79.5 BRIX MOLASSES

Constituent	Weight Percentage
Minimum invert sugar	48
Reducing sugar	16-20
Sucrose	28-35
Nitrogen as crude protein	2-4
Ash	7-12

Method and Procedure

To permit direct comparison of effects, test specimens were prepared containing 0, 0.5, 1.0, 1.5, and 2.0 percent of each of the previously described additives. The percentages were based on the weight of solids contained in the additive, and the oven dry weight of the soil-aggregate mix. Duplicate specimens were prepared for each phase of testing.

Daily readings of temperature and relative humidity from a psychrometer located in the laboratory were recorded throughout the test periods to permit correlation with effects.

Mixing was accomplished in a model CC20 Blakeslee mixer in the sequence soil, additive, water. Materials were mixed mechanically for about 3 min, then transferred to a shallow pan where final mixing was done by hand. Next the mix was compacted to a depth of about 2 in. using a 5.5-lb rammer. Curing for about 5 min while covered with a damp cloth (to retard evaporation), permitted more uniform absorption of the moisture.

Standard Proctor Moisture-Density Relationships. — These tests were performed

in accordance with method D, ASTM tentative method of test D 698-57 T (2), except
that the height of the molded specimens was 5 in. instead of the specified $\overline{4}$. 584 in.

California Bearing Ratio. — These tests were performed in accordance with the pro-
cedures of the U.S. Corps of Engineers (9). For each percentage of additive, four
specimens were prepared at optimum moisture content and maximum density as de-
termined by moisture-density tests. Two specimens were tested immediately to de-
termine the CBR values. Then, after four days immersion using a 5-lb surcharge,
the soaked CBR values were obtained from the opposite ends of the specimens. The
second pair of specimens was permitted to air cure under room conditions for a week
prior to being subjected to the same tests. Expansion of the specimens during the
periods of immersion was also determined.

Moisture Retention. — This property was determined through a non-standard method
of testing. Two specimens, identical to those for the CBR tests, were prepared for
each percentage of the various additives. Specimens were extruded and stored on open
shelves under room conditions. The weight of the specimens was recorded after ex-
trusion and after lapses of 1, 2, 7, 15, 30, 60, and 90 days.

Atterberg Limits Tests. — These tests were performed in accordance with ASTM
tentative methods for test D 423-54 T (1) and D 424-54 T (3). Material for testing was
obtained from specimens used in the moisture retention tests.

RESULTS

Moisture-Density Relationships

Effect of Calcium Chloride. — Marked increases in density were realized with the
addition of calcium chloride to the mix. The dry densities obtained are shown in Fig-
ure 1. Of particular interest is the fact that maximum dry density was obtained at 1
percent calcium chloride, and that addition of more chloride tended to decrease the
density.

This phenomenon may be explained by reference to the diffuse double layer concept,
which considers that the clay particles have negative surface charges caused either by
isomorphous substitution of lower valence cations within the lattice or by adsorbed
hydroxyl ions due to broken valence bonds. These negative surface charges cause re-
pulsive forces between clay particles thus increasing the compactive effort required
for a given density, or conversely lessening the density which might be attained with
a given effort. Introduction of Ca^{++} ions will give two beneficial effects. First, the
negative surface charges may be neutralized, thus eliminating the repulsive forces,
and second, because the calcium ion carries a double positive charge, valence bonds
may be set up between neighboring clay micelles. Both of these effects will mean
greater densities with the given compactive effort.

Continued addition of calcium ions will give increased benefits only until the negative
surface charges are satisfied. Beyond this optimum point additional ions will be de-
trimental because the media will then assume a positive charge and repulsive forces
will be reinstituted. This, apparently, is the explanation of the lower densities ob-
tained in this study with the higher percentages of calcium chloride.

An additional point of interest in this phase of the investigation is the apparent in-
verse relationship between optimum moisture content and maximum dry density, indi-
cating the need for greater lubrication to assist in overcoming the repulsive forces.

Sodium Chloride. — As with calcium chloride, densities obtained with the addition
of sodium chloride exceeded the maximum obtained with the untreated soil-aggregate
mix. Unlike the specimens treated with calcium chloride, those treated with sodium
chloride were not restricted to a single optimum chloride content. Instead, as may
be seen in Figure 1, whether the salt used was CC or FC, a minimum dry density
(treated material) was observed at 1 percent salt.

Because the hydrated sodium ion is larger and more reactive than the calcium ion,
and because a gram of sodium chloride contains almost twice as many cations as does
a gram of calcium chloride, it is reasonable to expect an effective neutralization of
the negative surface charge of clay by a lower weight percentage of sodium chloride.
At 0.5 percent salt, a maximum density was attained probably because of an effective
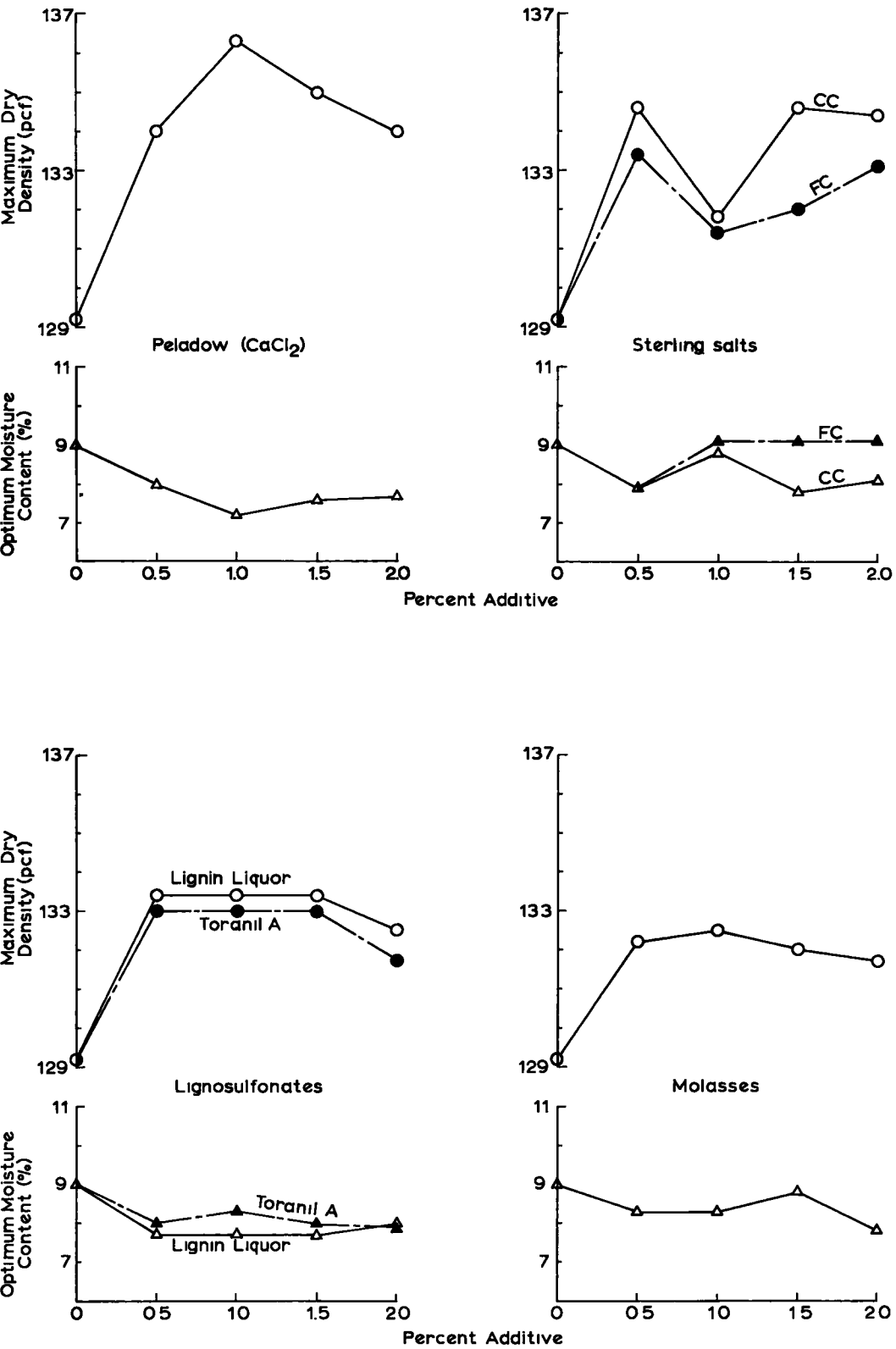
Figure 1. Variation of optimum moisture content and maximum dry density with percent treatment of indicated additives.

neutralization of negative surface charges on clay particles. This maximum density was not as great as that for 1 percent calcium chloride treatment because valence bonding of clay micelles is less probable, and because the size of the hydrated sodium ion precludes as close an approach of the neutral clay particles. At 1 percent sodium chloride content, the repulsive forces again were active because of the excess sodium cations, and lower densities resulted. Because the magnitudes of the repulsive forces are related inversely to the square of the distance between charges, and because of the imposition of aggregates and voids, a maximum effective value of repulsive forces is attained which is relatively unaffected by the addition of mere salt to the mixture. Thus, in effect, the increased densities which were observed at 1.5 and 2 percent sodium chloride may be partially attributed to the additional weight of salt contained within the specimens.

The fact that all densities resulting from FC salt treatment are less than those resulting from corresponding percentages of CC salt may be explained by the gradation differences. The FC salt, being finer grained, went into solution more rapidly than the coarser grained CC salt. Instances were noted where the CC salt crystals were not completely dissolved at the time of molding. Thus the number of active sodium ions was greater in the specimens prepared with FC salt.

The inverse relationship between moisture content and maximum dry density was again evident in the case of sodium chloride treatment, with the exception of samples containing 1.5 and 2 percent FC salt. This may have resulted from incomplete dissolution or from experimental error.

TABLE 6

RESULTS OF CALIFORNIA BEARING RATIO TESTS

| Additive | | California Bearing Ratio, % | | | | Expansion, % | |
| | | Uncured Specimens | | Cured Specimens | | | |
Kind	%	Immediate	Immersed	Dry	Immersed	Uncured	Cured
Untreated	-	15.3	9.8	40.5	22.5	0.19	0.51
CaCl₂	0.5	42.0	35.0	129.0	67.0	0.20	0.31
(Peladow)	1.0	103.0	48.0	160.0	48.0	0.26	0.40
	1.5	51.0	43.0	82.0	53.0	0.21	0.19
	2.0	38.0	27.5	44.0	30.0	0.25	0.19
NaCl (CC)	0.5	56.5	45.0	90.0	52.5	0.33	0.11
	1.0	12.5	6.5	31.5	21.0	0.09	0.03
	1.5	51.0	36.0	120.0	57.0	0.05-	0.09
	2.0	34.0	25.0	54.5	43.5	0.10	0.09
NaCl (FC)	0.5	51.7	42.0	61.0	44.0	0.29	0.20
	1.0	16.8	10.3	21.0	17.7	0.22	0.16
	1.5	12.0	8.3	20.0	18.0	0.06	0.15
	2.0	8.6	6.4	14.5	10.0	0.05	0.08
Lignin	0.5	71.0	49.5	97.5	36.5	0.23	0.18
Liquor	1.0	53.0	35.5	76.0	42.0	0.21	0.26
	1.5	47.0	33.0	56.5	33.8	0.24	0.26
	2.0	16.0	12.0	24.0	13.5	0.04	0.32
Toranil	0.5	64.0	52.0	97.0	46.0	0.17	0.29
A	1.0	39.0	32.5	64.0	30.0	0.10	0.13
	1.5	42.0	29.0	56.0	28.0	0.14	0.24
	2.0	26.5	20.0	35.5	21.3	0.13	0.54
Molasses	0.5	32.0	24.5	48.0	30.0	1.07	0.39
	1.0	28.0	20.5	50.0	23.5	0.70	0.57
	1.5	12.0	11.5	25.0	19.0	0.52	0.61
	2.0	23.0	26.0	46.5	32.0	0.13	0.33

Lignosulfonates. — Densities obtained with the use of lignosulfonates as additives were higher than those obtained for the untreated soil-aggregate mix. The Lignin Liquor showed a slight advantage over Toranil A in all percentages. The maximum dry densities are shown in Figure 1.

With the lignosulfonates, constant maximum densities were obtained at 0.5, 1, and 1.5 percent additive, and a decrease in density was obtained with 2 percent additive.

Speculation as to the cause of density variations has lead to the conclusion that the initial density increase at 0.5 percent lignosulfonate treatment is caused by better lubrication derived from the decrease of surface tension. Because the lignosulfonates are assumed to coat the soil particles, the addition of further lignosulfonates should lead to thicker films and consequent separation of the soil grains. The specific gravity of the liquor is lower than that of the soil so that displacement of soil by lignin should lead to lower densities. Presumably, at 1 and 1.5 percent liquor, the beneficial effect of lubrication compensates for the thicker films and the over-all density remains constant. At 2 percent lignosulfonate, the effect of thicker films predominates and density decreases.

The difference in densities obtained with Lignin Liquor and with Toranil A is believed to be caused by the different specific gravities of the liquors. Lignin Liquor, having a slightly higher specific gravity, gave greater maximum dry densities. Other possible reasons for this difference might be found in the difference in lubricating properties because of the differing sugar contents, or in experimental error.

The inverse relationship between maximum dry density and optimum moisture content was again apparent with Lignin Liquor, but was not shown by the Toranil A treated specimens. A possible explanation is that the clay lumps may have been coated in aggregated masses with the higher percentages of Toranil A, preventing water intrusion, thus changing the effective gradation of the mix and lessening the moisture requirement for optimum lubrication.

Molasses. — Although density increases were appreciable with the addition of molasses to the soil-aggregate mix (Fig. 1), they were not as great as with any of the other additives. As with lignosulfonates, density increases are attributed to the lubricating effects accompanying reduced surface tension.

Optimum molasses content for maximum dry density occurred at 1 percent additive, with only slight deviation at contents of 0.5 and 1.5 percent. The same mechanism, as was proposed for the variation of density with lignosulfonates, is believed applicable to the molasses treated specimens; benefit from lubrication being overridden at higher percentages of additive by dispersion caused by thicker films.

The erratic nature of variation of optimum moisture with percent molasses is believed to be due to causes discussed for Toranil A.

California Bearing Ratio Study

Although CBR tests (as performed) included obtaining values for specimens permitted to air dry for seven days, direct comparison of these results would not be realistic inasmuch as all specimens were not subjected to similar conditions of relative humidity and temperature. For this reason the discussion of results will center on test values for specimens tested immediately, and after four days immersion, with only occasional mention of curing effects.

Effects of Calcium Chloride. — CBR values were increased in all cases by the addition of calcium chloride, the trend both in immediate and soaked values apparently correlating with the density of the specimen. As given in Table 6, the highest immediate CBR value was that with 1 percent calcium chloride. This value (103.0 percent) represents an increase in strength of more than 600 percent when compared to the value obtained for the untreated soil-aggregate mix. After four days immersion, the strength is 490 percent that of the untreated mix tested under the same circumstances.

After seven days curing, all of the calcium chloride treated specimens reflected an increase in unimmersed strength with only the 1 percent specimens failing to give higher immersed strengths than the corresponding uncured specimens. Expansion of the specimens during soaking was negligible (Table 6).

Effects of Sodium Chloride. — Marked increases in immediate CBR values were obtained with 0.5, 1.5, and 2 percent CC salt treatments, whereas only the 0.5 percent FC salt treatment gave values exceeding the untreated value. At 1 percent CC salt, and at both 1.5 and 2 percent FC salt, despite the fact that densities exceeded that of the untreated soil-aggregate mix, CBR values were lower than the untreated CBR. If one considers the 1.5 and 2 percent CC salt treated specimens to be not truly representative (because of incomplete dissolution of the salt), then the loss of strength may be attributed to loss of internal friction due to the lubricating properties of the chloride solutions, and to loss of cohesion due to repulsive forces caused by excess sodium ions. Loss of strength on immersion was less in the case of 0.5 percent sodium chloride treatment than in the case of 1 percent calcium chloride treatment, probably because of the lower percentage and the lesser hygroscopicity of the salt. Considering both the accuracy of the test, and the CBR curve corrections required, the best four day immersed CRB values (no curing) of the three chlorides tested (FC, CC, and Peladow) may be considered to be essentially equal.

As in the case of calcium chloride, the CBR values of rock salt treated specimens reflected strength gains after curing, both dry and immersed. Of note were the increases associated with 1.5 and 2 percent CC salt specimens, indicating rapid evaporation, and again supporting the assumption of incomplete dissolution of the salt. As given in Table 6, expansion of the salt treated specimens on immersion was negligible.

Effects of Lignosulfonates. — All percentages of lignosulfonates used in this study increased the strength of the specimens over the strength obtained with the untreated soil-aggregate mix. The greatest immediate gain was at 0.5 percent Lignin Liquor, with the greatest immersed strength (uncured and considering all additives) associated with 0.5 percent Toranil A. Immediate CBR values generally decreased with increase in lignosulfonate content, indicating the detrimental effects of increased lubrication. The exception in this trend was found at 1.0 percent Toranil A treatment. This may be attributed to the higher moisture content at molding and the consequent increase of lubrication.

Strength loss on immersion of the Toranil A treated specimens was generally less than that of the specimens treated with Lignin Liquor possibly due to the lesser hygroscopicity of Toranil A. Another factor which may account for the strength loss associated with immersion of Lignin Liquor treated specimens was the fact that fungal consumption of the lignin was indicated by the presence of a mold on the surface of the specimens.
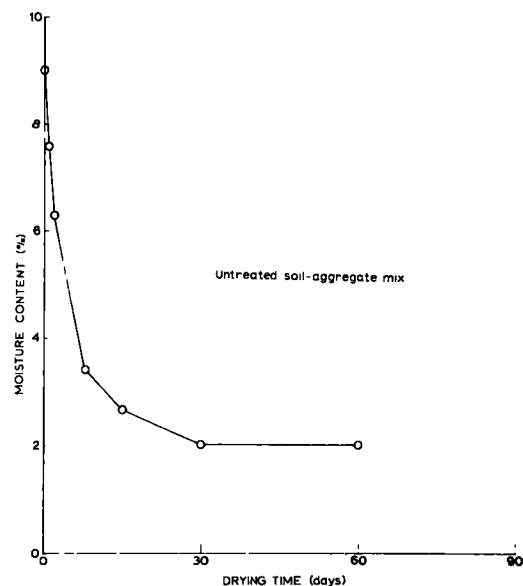

Figure 2. Variation of moisture content with drying time, untreated soil-aggregate specimens.

Curing either benefited immersed strength or left it unchanged except in the case of 0.5 percent Lignin Liquor. This loss may have been caused by lower waterproofing potential at this content or may have been caused by loss of lignin due to fungal consumption. Expansion on immersion was negligible.

Effects of Molasses. — With CBR strength as a criterion, molasses was the least beneficial of the additives tested. Maximum immediate strength gain was with 0.5 percent molasses treatment, which, as given in Table 6, gave approximately a twofold increase over the untreated soil-aggregate mix strength. At 1.5 percent molasses content, a loss of strength was apparent.

Results of this phase of the investigation are not considered to be very reliable because the treated specimens were subject to rapid fungal action, becoming moldy both during the curing and immersion periods. This factor, combined with the degree of
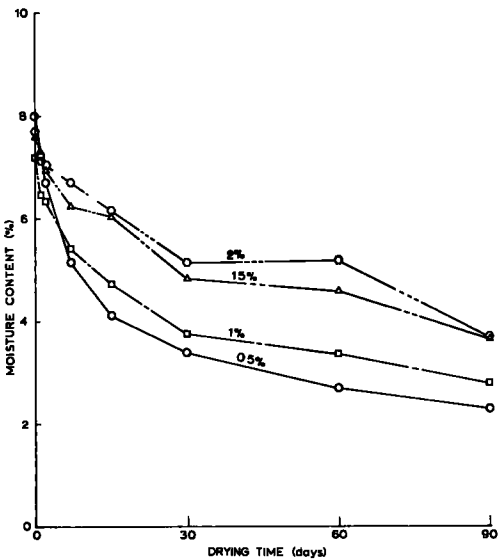

Figure 3. Variation of moisture content with drying time, calcium chloride treated specimens.
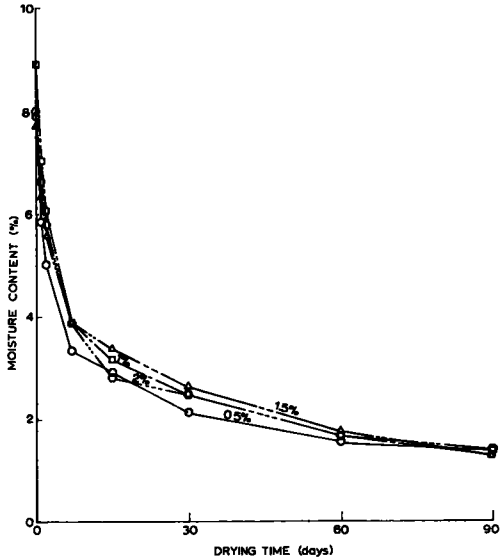

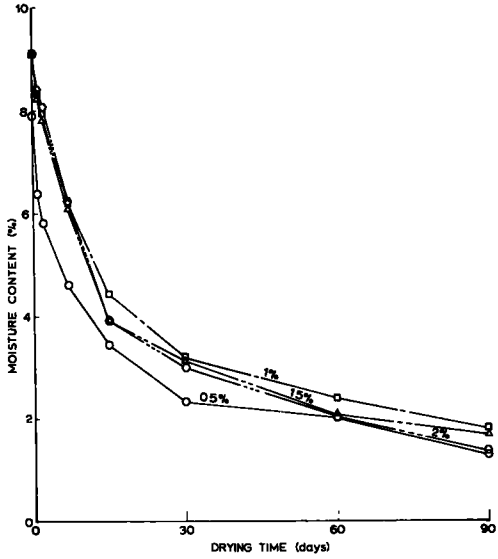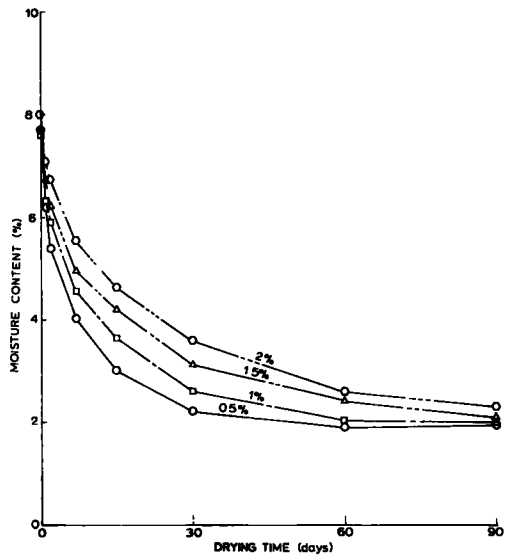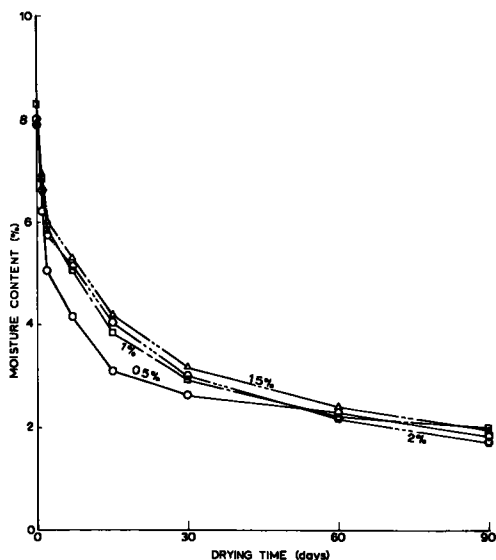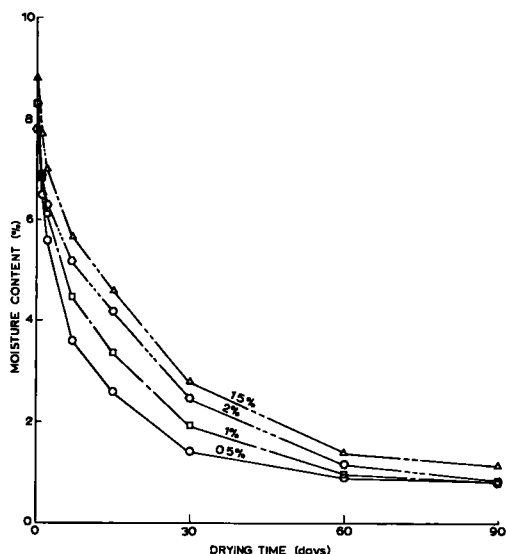Figure 4. Variation of moisture content with drying time, CC salt treated specimens.

Figure 5. Variation of moisture content with drying time, FC salt treated specimens.

Figure 6. Variation of moisture content with drying time, Lignin Liquor treated specimens.

Figure 7. Variation of moisture content with drying time, Toranil A treated specimens.

Figure 8. Variation of moisture content with drying time, molasses treated specimens.

expansion (particularly at 0.5 percent molasses content), indicates that the use of molasses as a stabilizing agent should be limited to areas with extremely dry climates.

Moisture Retention

A direct comparison of the moisture contents of the various specimens as a function of time of curing proved inadequate as a means of determining the relative effectiveness of the additives. Figures 2 through 8 reflect the inadequacy of direct comparison because they show inconsistencies even among various percentages of the same additive, as well as showing higher equilibrium moisture contents for the untreated soil-aggregate mix than for specimens containing hygroscopic additives. The reason for this apparent discrepancy is that the conditions under which samples dried varied; therefore a more complete analysis is required to compare the effectiveness of the additives.

The process of drying may be divided into four phases during which the rates of drying will differ because of changes in the governing properties. The phases of drying, and the governing properties during each phase are given by Brown et al (4) as:

Phase 1.— During this phase of drying, the water content of the specimen is at a maximum (near saturation) and thus evaporation may be considered as essentially that from a free water surface. The area of escape for water vapor can be considered to be the exposed surface area of the specimen. This period is one of instability because the specimen is adjusting to the temperature of the drying medium.

Phase 2. — This is a period of steady rate drying which, owing to the lower moisture content, is governed by the rate of capillary movement of moisture and the rate of flow of air into the soil voids. During this phase the area of escape is some portion of the exposed area of voids.

Phase 3. — This period of drying is characterized by a constantly decreasing rate of evaporation more or less proportional to the moisture content of the specimen. Because of the low water availability, the rate of evaporation is governed by the rate of diffusion within the specimen. The area of escape is essentially the exposed surface area of the voids.

Phase 4. — The final phase of drying again is characterized by a decreasing rate of moisture loss. During this period, the rate of loss is governed by the water retention
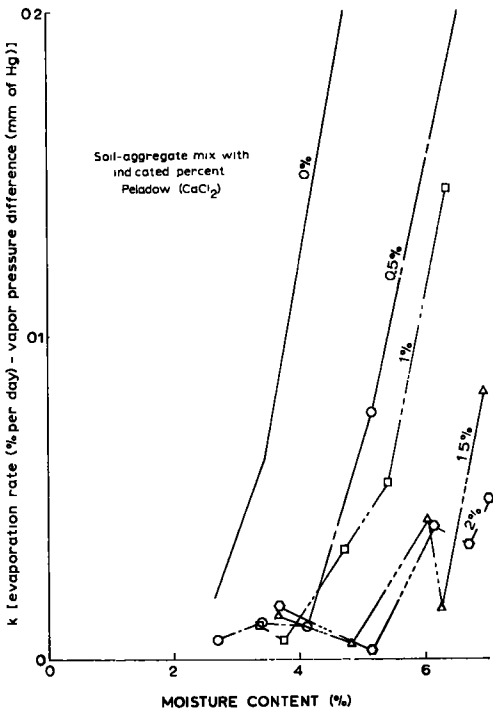
Figure 9. Index of moisture retention effectiveness for calcium chloride treated specimens.
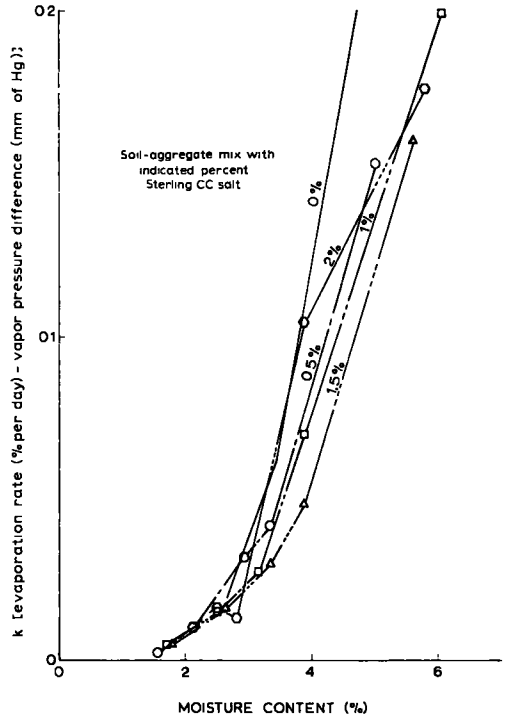

Figure 10. Index of moisture retention effectiveness for CC salt treated specimens.
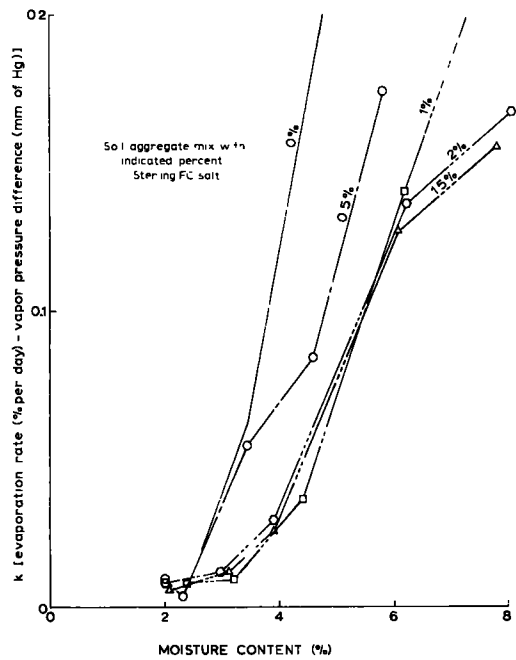

Figure 11. Index of moisture retention effectiveness for FC salt treated specimens.

forces of the soil, vapor pressure of water on clay, with the area of escape remaining unchanged.

From comparison of natural evaporation formulas and constant condition drying formulas, it is apparent that the rate of evaporation is proportional to the vapor pressure difference between the vapor pressure of the moisture in the soil and the partial pressure exerted by the air. This is expressed: $d\lambda/dt = -k \Delta p$ in which

λ = moisture content
t = time
Δp = vapor pressure differential
k = a constant of proportionality for any given moisture content

Based on the foregoing equation Figures 9 through 14 were prepared to permit evaluation of the effectiveness of the additives. The figures show a plot of k versus moisture content. In preparing the figures, several approximations were required. First, data for the early periods were discarded because of the unstable nature of this phase of drying and because the temperature of the
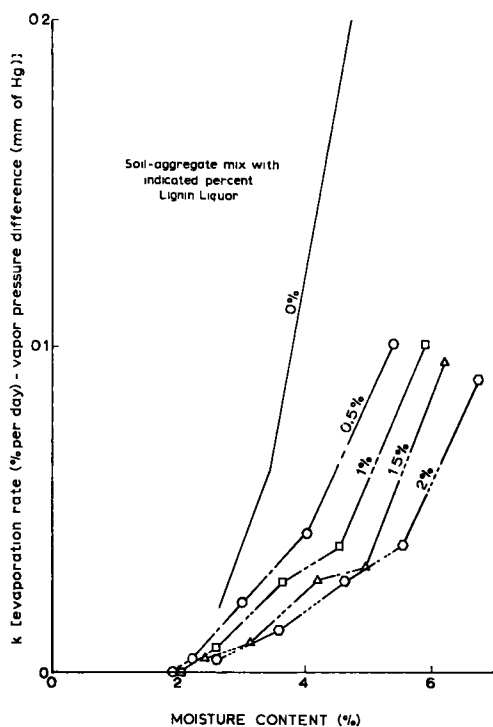
Figure 12. Index of moisture retention effectiveness for Lignin Liquor treated specimens.
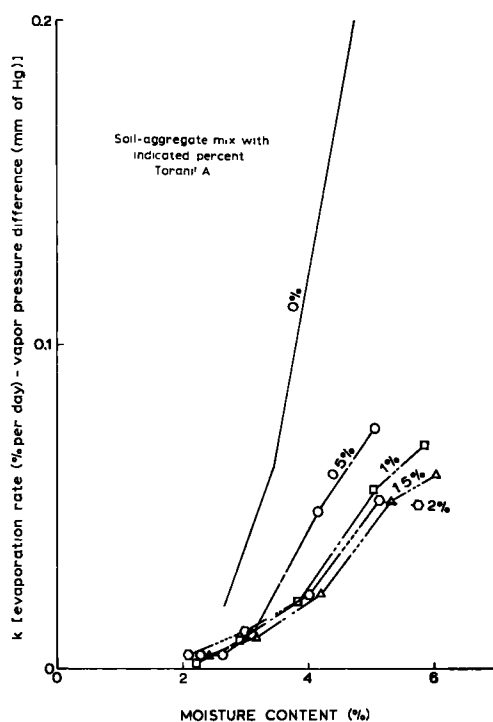

Figure 13. Index of moisture retention effectiveness for Toranil A treated specimens.
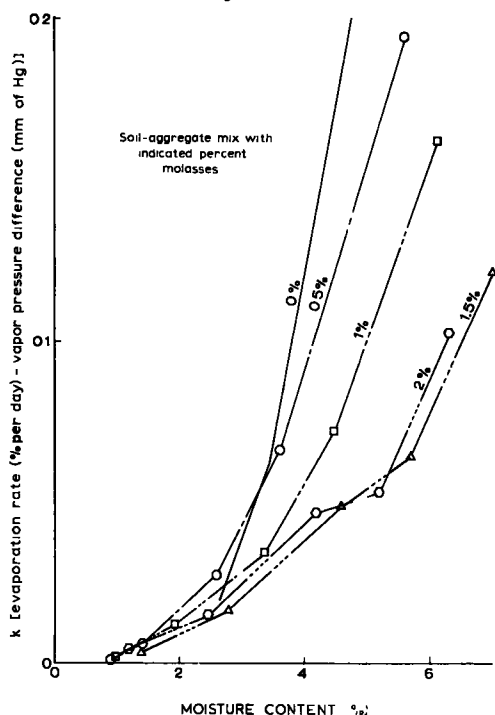

Figure 14. Index of moisture retention effectiveness for molasses treated specimens.

specimens could not logically be estimated as air temperature. Next, inasmuch as the vapor pressure differential was not constant throughout the drying periods, the assumption was made that the average of differences for the day of weighing and the two previous days would be representative of the conditions for the entire period. In this respect, the vapor pressure of moisture in the specimen was based on pure water because there was no knowledge of the concentration of chemicals in the solution. By doing this no serious error is introduced, because the net result is that of reflecting the vapor pressure effects of the chemicals in the calculated values of "k".

Based on these assumption, the formula was solved for k, and the resultant values were plotted against the moisture content of the specimen at the start of the time period associated with the incremental loss of moisture. Although certain irregularities appear in the curves as a result of the approximations, sufficient consistency exists to permit comparison.
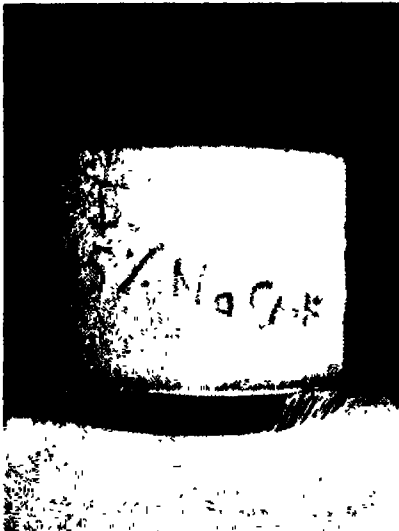
Relative moisture retention capacity of the additives may be determined from the curves by comparing the value of k for the various additives at a given moisture content; the greater the value, the less effective the additive.   Less credence should be given
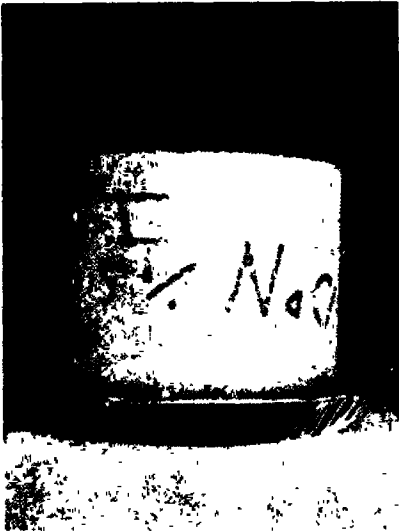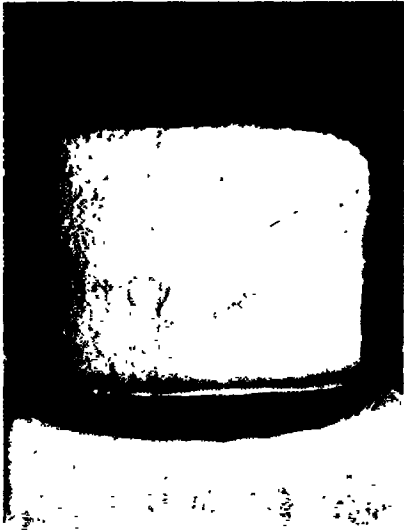

0.5% FC salt
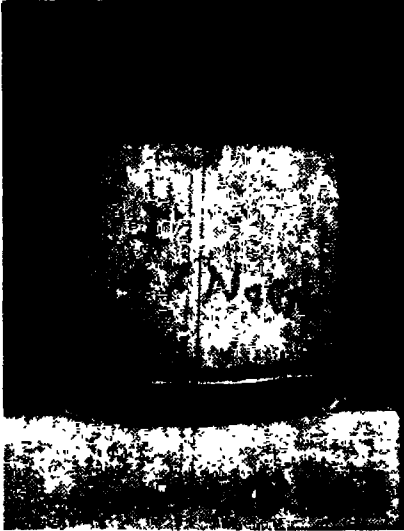
1.0% FC salt

1.5% FC salt

2.0% FC salt

Figure 15.   Crystal growth on Sterling FC salt treated specimens.

to the lower ends of the curves because weighing errors would have greater effects in this range, and because specimens may have reached equilibrium moisture content before lapse of the time increment used.

No discussion of the actual results obtained is deemed necessary because the relative effectiveness may be readily observed from the curves. However, the poor showing of the salt treated specimens does merit some discussion. Factors which should be considered because they are not reflected in the curves are (a) salt crystals grew out from the surface of the specimens (Fig. 15), (b) under traffic these crystals would be packed into void spaces, and (c) the exposed surface area per unit volume of the specimens was greater than for comparable material in a road; thus the crystallization was less dense at the surface and moisture retention was therefore less.

Atterberg Limits Tests

The Atterberg limits give an indication of the plastic and cohesive properties of soils. Specifically, these tests give: (a) the liquid limit of the soil, or the minimum moisture content at which the soil-water mixture reacts as a viscous liquid; (b) the plastic limit, or the minimum moisture content at which the mixture acts as a plastic solid; and (c) the plasticity index, which is the range of moisture content through which the mixture exhibits plastic behavior (8). From this it is possible to assume that improved lubrication will tend to decrease both the plastic and liquid limit. Increased viscosity would have the opposite effect.

Effect of Chlorides. — Because of the amount of individual judgment involved in these tests, the degree of change in limits caused by incorporation of chlorides in the mix is

TABLE 7
RESULTS OF ATTERBERG LIMITS TESTS

Additive Kind	%	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index
Untreated	-	16.8	25.5	8.7
CaCl₂	0.5	15.6	26.1	10.5
	1.0	16.0	26.3	10.3
	1.5	16.5	24.9	8.4
	2.0	15.0	25.5	10.5
NaCl (CC)	0.5	16.2	24.7	8.5
	1.0	16.5	26.1	9.6
	1.5	17.0	25.3	8.3
	2.0	16.3	26.1	9.8
NaCl (FC)	0.5	17.2	26.2	9.0
	1.0	17.3	25.4	8.1
	1.5	17.5	24.9	7.4
	2.0	16.7	24.7	8.0
Lignin Liquor	0.5	16.4	26.5	10.0
	1.0	15.7	29.0	13.3
	1.5	14.6	28.4	13.8
	2.0	14.2	27.5	13.3
Toranil A	0.5	15.8	28.9	13.1
	1.0	16.2	30.1	13.9
	1.5	15.3	27.2	11.9
	2.0	14.9	29.0	14.1
Molasses	0.5	17.0	32.5	15.5
	1.0	16.4	31.7	15.3
	1.5	17.5	31.6	14.1
	2.0	17.9	31.2	13.3

not significant. Results, (Table 7) are erratic and establish no definite trend. One contributing factor in the case of sodium chloride treated specimens evolves from the fact that the salt migrated to the surface of the specimens (Fig. 15) thus causing changes in salt concentration in the material tested.

Effect of Lignosulfonates. — A consistent decrease of plastic limit coupled with consistent increase in liquid limit was observed with increased lignosulfonate treatment. This trend lead to the natural consequence of increasing the plasticity index, irrespective of the spent sulphite liquor involved. Table 7 gives the results of the Atterberg limits tests, and inasmuch as it can be observed that no consistent significant difference exists between decrease in plastic limit and increase in liquid limit, the increased plasticity index cannot be attributed to either lubrication or viscosity changes alone, but must be considered as a combination of both effects.

Effect of Molasses. — Results given in Table 7 indicate that, of the additives tested, molasses had the greatest effect on the plasticity index of the mixture. Because significant changes were not noted in the plastic limits, but marked increases were noted in the liquid limits, the increased range of plasticity is attributed to higher viscosity because of the presence of molasses.

CONCLUSIONS

Conclusions are based on the use of additives of Peladow calcium chloride pellets, Sterling FC and CC salts, Toranil A and Lignin Liquor spent sulphite liquors, and a 79.5 Brix molasses with a single soil-aggregate surface course mix.

Using standard Proctor compactive effort the value of maximum density is increased by use of any of the additives. An inverse relationship exists between maximum dry density and optimum moisture content when the additives are used. Density is sensitive to the amount of additive in the case of chloride stabilization.

Calcium chloride is the most effective agent for densification. In order of decreasing effectiveness, the other additives evaluate as Sterling CC salt, Sterling FC salt, Lignin Liquor, Toranil A, and molasses.

Strength of the soil-aggregate mix can be improved by any of the additives. Immersed strengths with optimum amount of additives are approximately equal for all additives except molasses. Molasses is subject to fungal action and only improves strength about one-half as much as the other additives.

Calcium chloride is the most effective of the additives for moisture retention. Lignosulfonates and molasses have moderate effects, whereas rock salt is relatively ineffective.

Chlorides have little effect on the plastic properties of the mix; lignosulfonates and molasses raise the plasticity index.

RECOMMENDATIONS

Recommendations based on the results of this study are that: (a) additional studies of the effect of these additives be initiated to provide a basis for comparison applicable to other soils; (b) investigation of the effects of the additives on moisture retention be carried out in a controlled humidity room to permit immediate comparison of results; and (c) curing of specimens for CBR tests be conducted under controlled conditions of relative humidity and temperature to permit equitable comparison of results.

ACKNOWLEDGMENTS

REFERENCES

1. American Society for Testing Materials, "Tentative Method of Test for Liquid Limit of Soils." ASTM Designation: D 423-54 T (1954).
2. American Society for Testing Materials, "Tentative Method of Test for Moisture-Density Relations of Soils." ASTM Designation D 698-57 T (1957).
3. American Society for Testing Materials, "Tentative Method for Test for Plastic Limit and Plasticity Index of Soils." ASTM Designation: D 424-54 T (1954).
4. Brown, G. G., et al, "Unit Operations." John Wiley and Sons (1953).
5. Davidson, D. T., and Handy, R.L., "Highway Engineering Handbook." Section 21, "Soil Stabilization." McGraw-Hill (1960).
6. Iowa State Highway Commission, "Standard Specifications for Construction on Primary, Farm to Market, and Secondary Roads and Maintanance Work on the Primary Road Systems." (1956).
7. Phillips, E., Jr., "Soil Stabilization Methods." Soil Research Lab., Eng. Exp. Sta., Iowa State University (Unpub. mimeo report) (1956).
8. Spangler, M. G., "Soil Engineering." International Textbook Co. (1951).
9. U.S. Army, Corps of Engineers, "Suggested Method of Test for California Bearing Ratios of Soils." ASTM Comm. D-18, "Procedures for Testing Soils." p. 386-397 (July 1950).
10. Wilford, H.D., Downey, B.R., Briggs, G.F., Hogentogler, C.A., Jr., Knight, J.A., Elleman, J., and Burggraf, F., "Use of Calcium Chloride in Road Stabilization." HRB Proc., 18, Pt. 2:209-256 (1938).
11. Handy, R.L., "Information on Non-Expanding 14 Angstrom Mineral." Private communication (1959).
12. Rosauer, E.A., "Petrographic Analysis of Soil-Aggregate Mix." Private communication (1959).
13. Sauers, R.C., "Information on Peladow." Private communication (1958).
14. Duncan, S.J., "Information on Rock Salt." Private communication (1959).
15. Pecore, R.J., "Information on Toranil A." Private communication (1957).
16. Lausman, H.J., "Information on Lignin Liquor." Private communication (1958).
17. Greenstein, S., "Information on Molasses." Private communication (1958).