

# Chemical Soil Stabilization: Effect of Stabilizer Structure on Preparation and Properties of Stabilized Soil

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PROPERTIES of a solidified soil are dependent upon the reaction of the solidified matrix to the forces that operate upon it. The qualitative characteristics of the response depend essentially upon the chemical structure of this matrix whereas the actual values depend not only on the chemical structure but also on its geometrical structure (i.e., its distribution thru the soil mass). Alteration of this geometric structure can occur only when viscous flow within the matrix is possible. Thus, material in which viscous flow does not occur (i.e. cement) should be placed in as dense a state as possible since little self densification is possible. Materials which do possess viscous flow (i.e. calcium acrylate) can be placed at less than maximum density since the contractile forces of drying can cause self-densification. For this type of material to be suitable as a stabilizing agent, this property of viscous flow must eventually be removed either by chemical reaction or a phase change.

Experimental data are presented to demonstrate how the structure of various stabilizing agents affect the properties of solidified soil through the above mechanisms. It is shown that stabilizers can be classified into only a few groups each of which will possess type characteristics. The implications of these factors on the future of soil stabilization is discussed.

● THE greatest hope for the future of soil stabilization lies in its removal from the field of empiricism into the field of science. Due to the large number of factors that affect stabilization and to the complexities of their interactions it is hardly to be expected that a complete understanding of the mechanisms operating within stabilized soil can be developed at this time. Nevertheless sufficient data are becoming available to allow at least some preliminary theorizing. Since the requisite data for an all embracing theory is not yet available it would appear more fruitful to consider various aspects of the problem separately, leaving their synthesis for the future.

The importance of the colloidal aspects of the problem of soil stabilization has been emphasized by Winterkorn (1), of clay mineralogy by Hauser (2), and the interconnection of soil composition and engineering properties by Lambe and Martin (3). Important as these factors are they are still only part of the entire

problem. Another part is the effect of the structure of the stabilizing agent itself on the properties of solidified soil. This paper is an attempt to develop a fuller understanding of the role played by the stabilizing agent and to show how differences in the structure of the stabilizing agent affects the properties of the stabilized soil.

This paper will be restricted to those cases in which the stabilizing agent is present in large enough amounts to form a matrix between and/or with the individual soil particles. Furthermore the soil will be taken as an inert material and no attempt will be made to consider how it affects stabilization. A theoretical discussion of the role of the stabilizing agent will be presented first, followed by certain experimental data. Since unfortunately, if understandably, by far the greatest number of investigations have been carried out with the sole objective of producing a utilizable product, the author has been forced to rely on

data accumulated in the Soil Stabilization Laboratory at M.I.T. on new and unusual stabilizing agents.

#### THEORETICAL

##### 1. *The Matrix Structure*

A solidified soil must be held together by a three-dimensional network of forces supplied, at least in part, by the solidifying agent which forms some type of matrix between and/or with the soil itself. The properties of the solidified soil are dependent on how this matrix responds to the stresses that are imposed on it—whether these stresses are deliberately imposed as by traffic or are incidental such as drying or freezing.

The qualitative nature of the response (rigid, flexible, etc.) of a stabilized soil to stresses is dependent upon the chemical and molecular structure of the stabilizing agent. If the solidified soil consisted solely of soil plus stabilizing agent then the quantitative response would also depend primarily on the structure of the stabilizing material modified by the effect of interactions between the soil and the stabilizing agent. In all practical cases, however, the systems under consideration do not consist only of soil plus stabilizing agent but of soil plus stabilizing agent plus water or soil plus stabilizing agent plus air voids. Under such circumstances it is apparent that differences can occur in just how the stabilizing agent is distributed among the mass of soil particles. This distribution may be defined as the external or geometric structure of the matrix in contrast to the defined as the internal or molecular structure.

##### *a. The Internal or Molecular Structure*

The forces that hold the stabilizing agent itself into a coherent mass may be chemical (primary forces) or physical (secondary forces) or combinations of the two types. Table I presents a summary of these combinations with typical examples of materials possessing such structures.

With any one of these three classes a considerable range of properties can occur due to the strength of individual bonds (physical and chemical) and to the frequency of occurrence of the various types within a given volume. Since the exact quantitative values for these characteristics will depend on these inter- and intramolecular forces—matrices

TABLE I

Bond Type	Example
1. Three dimensional chemical	Cement, phenolic resins
2. Three dimensional physical	Asphalt
3. One dimensional chemical; two dimensional physical	Rubber, high molecular weight polymers

with a side spectrum of properties can be obtained.

##### *b. The External or Geometric Structure*

Since any actual stabilized soil system consists of soil + stabilizer + water (or air voids, or a combination of air voids and water) it is evident from a priori considerations that there can be no unique way in which the stabilizing agent extends from one soil particle to another through the intervening space. If this is the case then, as a corollary, it is probable that adventitious circumstances can affect this external geometric structure. Two of these factors are mixing and densification.

*i) Mixing.* If the soil and stabilizing agent are not uniformly mixed then there will be volumes of the stabilized soil that contain a greater amount of stabilizer than other volumes and hence be stronger, less permeable, etc. Thus, since the material is not uniform, failure (through these weak spots) may occur at lower values than if the material were uniform.

*ii) Density.* Since for a given percent treatment of soil both the soil and the stabilizing agent possess definite volumes, the density of the mixture will influence the shape or geometry of the matrix. The less dense the mixture the greater the linear distance (in all dimensions) the stabilizer has to cover to connect the soil particles. Thus within a given volume of the stabilized soil there will be less material the less dense the structure with the concomitant result that the structure will be weaker.

Besides these adventitious circumstances that operate with all stabilizing materials the physico-chemical relationships between the stabilizing agent, the soil particle and any water present will have a controlling influence on the matrix geometry. No attempt will be made to discuss these factors in this paper but a couple of possibilities are illustrated in Figure 1.

## 2. The Action of Stresses

a) *The Forces.* The forces that stress a solidified soil may be divided into two types, those resulting from mechanical loads deliberately applied and those due to incidental conditions. The incidental forces are due primarily to the presence of water in the soil and comprise such stresses as those due to swelling and shrinking because of fluctuations in the water content and freezing and thawing due to changes in the ambient temperature. Whatever the source of the forces may be it is the primary duty of the solidified soil to support them.

b) *The Role of the Molecular Structure.* An applied stress to a solidified soil is going to be resisted and/or supported by the stabilizer matrix. The mechanisms by which the matrix responds to the stress is dependent upon its molecular structure which as has been stated above may be classified into three types. The problem of the response mechanisms of various materials to applied stresses has received considerable study and the following discussion will be based on Alfrey's (4) treatment of high molecular weight polymers.

Let us assume that the properties of any stabilizer matrix can be represented by a

combination of Maxwell elements such as shown in Figure 2.

In this figure the spring ( $\eta_1$ ) represents a purely elastic, and the dash-pot ( $G_1$ ) a purely viscous response to an applied stress. The combination of spring and dash-pot ( $G_2, \eta_2$ ) represents a delayed elastic response. The mechanism or combination of mechanisms through which a material responds to a stress is dependent on its molecular structure.

A primary chemical bond, which is the result of a transferral or sharing of electrons between atoms, requires a large quantity of energy for rupture and furthermore the mechanism of rupture is such that the bond is not available for recombination. Hence from our viewpoint the breaking of a chemical bond is an irreversible process. Secondary or physical bonds are of an electrostatic nature and are due to the existence of dipoles within the molecules. These bonds are much weaker than chemical ones and thus require much less energy to break. Furthermore since they are electrostatic they reform readily so from our viewpoint they are reversible. By which mechanism or mechanisms the stabilizer matrix will respond to an applied stress depends upon the type and distribution of bonds that hold it together.

If the stabilizer is held together by chemical bonds in all dimensions then, because of the large force required to break the bonds it will not flow under stress short of rupture of the bonds and is a rigid material. Because of the irreversible rupture the stabilizer cannot reknit once it has broken and the matrix is destroyed. With these properties an applied stress produces an elastic response up to the rupture point. Thus mechanisms 2 and 3 are frozen in and only mechanism 1 is operative. Furthermore the rate of loading would have little effect on the amount of stress the matrix could support. Such a material is exemplified by cement.

The properties of amorphous materials that possess a three dimensional isotropic distribution of physical bonds are such that an elastic, a viscous, or an elastic followed by a viscous response to a stress may occur. Just what will happen will depend upon the magnitude and rate of application of the load, upon the strength of the physical inter molecular bonds and since the strength of this type of bond is dependent on temperature, on

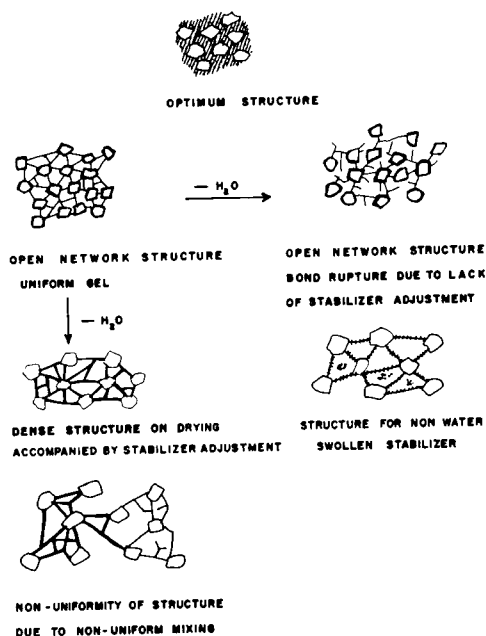


Figure 1. Possible matrix structures.

the temperature of the matrix. Such a material is exemplified by asphalt. At low temperature the bond strength and the viscosity are high so that the material gives an elastic response to the breaking point. At temperatures above the melting point of the asphalt the bond strength and the viscosity are low so that an applied stress results only in viscous flow. At intermediate temperatures these factors have intermediate values and both mechanisms can operate. Since an elastic response is rapid while a viscous response is slow the rate at which the stress is applied can have a significant effect on the response of the matrix. Applied and removed rapidly an elastic response would result while applied very slowly a viscous response would occur. Applied rapidly and maintained would result in an initial elastic response followed by a viscous flow.

Materials that do not have an isotropic bond strength distribution such as the high molecular weight polymers which have chemical bonds in one direction and physical bonds in the others (rubber, polystyrene, poly methyl methacrylate, etc.) can respond to an applied stress through an elastic, a viscous, or a delayed elastic mechanism depending upon various conditions. This delayed elastic response appears similar to mechanisms 1 + 3 on loading inasmuch as there is a rapid elastic response followed by an apparent slow flow. The difference occurs on removal of the load since with mechanism 2 an at least partial recovery of the creep occurs in contrast to 1 + 3 where no recovery occurs.

Thus several inherently different responses to an applied load can be exhibited by a solidified soil depending upon the molecular structure of the stabilizing agent. The type and the magnitude of the response will depend on the absolute and relative values of  $G_1$  and  $G_2$  which are shear or tensile moduli and  $\eta_1$  and  $\eta_2$  which are viscosity coefficients.

c) *The External Structure.* If, as appears probable, the external structure of the stabilizer matrix depends partly on adventitious circumstances the question arises as to whether this geometric structure is capable of alteration short of destruction. The answer to this question is of importance since upon it hinges the problem as to whether a soil must be treated under optimum conditions or whether non-optimum conditions can be used without sac-

rificing some part of the optimum properties of the treated soil.

If the external overall geometric structure is going to be altered it must be accomplished by a change in the shape of the individual strands or particles that combine to form the stabilizer matrix. Changes occur because molecules and atoms shift their position relative to one another.

In materials that respond to a stress by a purely elastic mechanism this shift in molecular positions is quite small and remains only as long as the load is applied. On removal of the load the molecules return to their original positions. Thus the initial geometric matrix of stabilizing agents which respond by this mechanism can be distorted somewhat under a load but no permanent alteration of matrix geometry can occur. Such materials are those that possess an isotropic distribution of high strength bonds (usually chemical) and are exemplified by cement, phenol-formaldehyde resins, etc. Soil solidified with this type of stabilizing agent, then must be placed under optimum conditions since the matrix geometry cannot be altered after the matrix has been formed.

In materials that respond to a stress by a

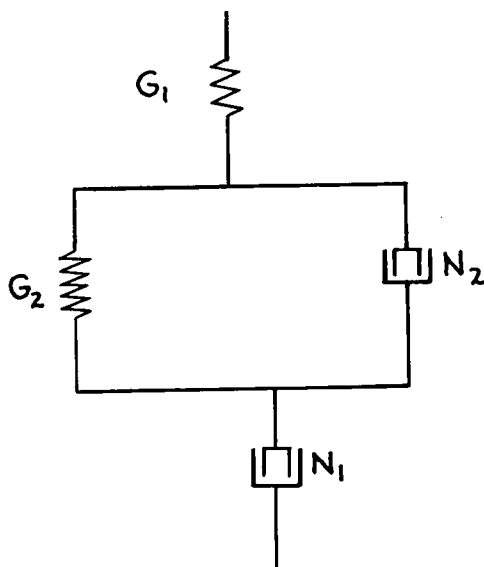


Figure 2  
(Mechanism 1)  
(Mechanism 2)  
(Mechanism 3)

viscous flow mechanism the molecules can alter their initial positions to any extent, the change in position continuing as long as the stress is applied. Furthermore once the stress is removed the molecules remain in the positions they had attained at that moment and have no tendency to revert to their initial locations. Hence the geometry of the matrix can alter very markedly under a stress. Such materials are asphalts at high temperature and highly plasticized resins.

In materials that can respond by a delayed elastic mechanism the molecules can alter their shape under stress but not their relative positions. Thus a greater degree of elasticity and a greater alteration of matrix shape under stress occurs than with a pure elastic response. Nevertheless this response is still of an elastic nature and once the stress is removed the molecules revert to their original shape and consequently the initial geometry of the matrix is restored. Thus permanent alteration of the initial geometry of the matrix cannot be accomplished with stabilizers of this type. Examples would be rubber and slightly cross-linked high polymers.

Thus it appears likely that unless a stabilizing agent possesses the ability to respond, at least partially, to an applied stress by a viscous flow mechanism the stabilized soil must be placed under optimum conditions. Furthermore it seems apparent that since the alternations occur within the individual particles this mechanism cannot overcome structure factors caused by uneven mixing. Thus if we wish to treat soils that are at nonoptimum conditions the use of a stabilizing agent with viscous flow characteristics would seem to be required. On the other hand if a material does possess a permanent flow mechanism it can hardly be considered as a stabilizer since it would deform permanently under each load application.

### 3. *Modification of Matrix Structure*

In the preceding sections we have discussed the effort of mechanical stresses as various matrix structures assuming that these matrices have certain definite structures. Since these matrices are held together by chemical and physical forces, we are quite at liberty to alter these forces by appropriate chemical and physical treatments. Thus by a judicious choice of conditions it is possible to use as a

stabilizing agent a material that does possess a flow mechanism and subsequently remove the flow properties by chemical or physical treatment to produce a suitable solidified soil.

In dealing with a problem of this type we must be concerned with the question of relative rates of various reactions. For example there would be the rate of shrinkage due to water loss thru the wet soil which is causing self-densification and the rate at which the viscous flow mechanism is to be removed by a chemical reaction. Obviously it would be desirable to have the maximum densification occur before the flow mechanism is eliminated.

### EXPERIMENTAL

If the above picture of the relationship between the structure of the stabilizing agent and the properties of solidified soil is to be of any value, it must be capable of correlating the many diverse empirical facts already known to form one intelligible whole. Even more it should be capable of predicting qualitatively how new stabilizing agents will act and place the search for new stabilizers on more than a purely empirical basis.

This section is an attempt to show how at least some of the experimental facts can be so correlated. Due to the lack of data of an appropriate nature available in the literature, the author has been forced to rely upon data accumulated in the Soil Stabilization Laboratory at M.I.T.

#### 1. *The Effect of Structure on Initial Properties*

a) *The Internal Structure.* That the internal structure of the stabilizing agent can have a considerable effect on the properties of a solidified soil is, of course, already recognized in a qualitative fashion—soil cement is rigid whereas soil-asphalt is a more flexible material. However to develop a more quantitative viewpoint by comparison of such widely different stabilizers is beset by difficulties inasmuch as what is actually compared is not the stabilizing agents but the stabilizing agents plus water and water can affect the various stabilizing agents in different ways. Fortunately by the technique of in situ polymerization of water soluble monomers a series of solidified soils can be prepared in which the type and number of cross-links, and hence the degree of rigidity of the stabilizer can be

controlled while the influence of water on the remainder of the stabilizing agent remains essentially the same. The effect of such changes in stabilizing structure is shown in Table II.

It is apparent that at high water contents the type of cross linking can be quite important as can be seen by comparing the results from different acrylate salts. That the number of cross-links has a very appreciable effect can be seen by comparing the various divalent acrylate salts in which part of the divalent ions have been replaced by monovalent ions and even more clearly by the acrylic acid/methylene-bis-acrylamide series where the tensile strength and elongation are both seen to decrease steadily as the amount of cross-links (i.e. amount of MBA) increases. At lower water contents these differences become smaller since there is not enough water to overcome the ionic and polar bonds so that a more rigid material is formed. At sufficiently low water contents relatively minor differences would be expected between the compounds listed.

b) *The External Structure.* How variation in the external structure of the stabilizing agent effects the properties of the solidified soil is also of great importance. What little quantitative data that are available on this subject has come from mixing studies in which the strength of a stabilized soil is compared to

TABLE II  
EFFECT OF STABILIZER STRUCTURE ON  
TENSILE STRENGTH AND ELONGATION

Stabilizer*	Water, %			
	50		20	
	TS†	E	TS	E
Magnesium acrylate	17	58	150	5
Calcium acrylate	22	30	150	7
Zinc acrylate	43	5	200	2
Calcium acrylate + Ca <sup>++</sup> (1:1)	37	9	—	—
Calcium + sodium acrylates (4:6)	14	73	—	—
Zinc + sodium acrylates (4:6)	23	101	160	2
Acrylic acid + MBA‡				
10:0	0	—	—	—
9.9:0.1	93+	225+	—	—
9.5:0.5	60	75	200	15
9.0:1.0	24	18	—	—
8.0:2.0	19	8	—	—

\* Equivalent molar quantities—calcium acrylate 10 weight percent in dry soil.

† Tensile strength calculated on cross-section at time of rupture.

‡ Increasing amounts of MBA (methylene-bis-acrylamide) means increasing amounts of cross-linking and hence a more rigid material.

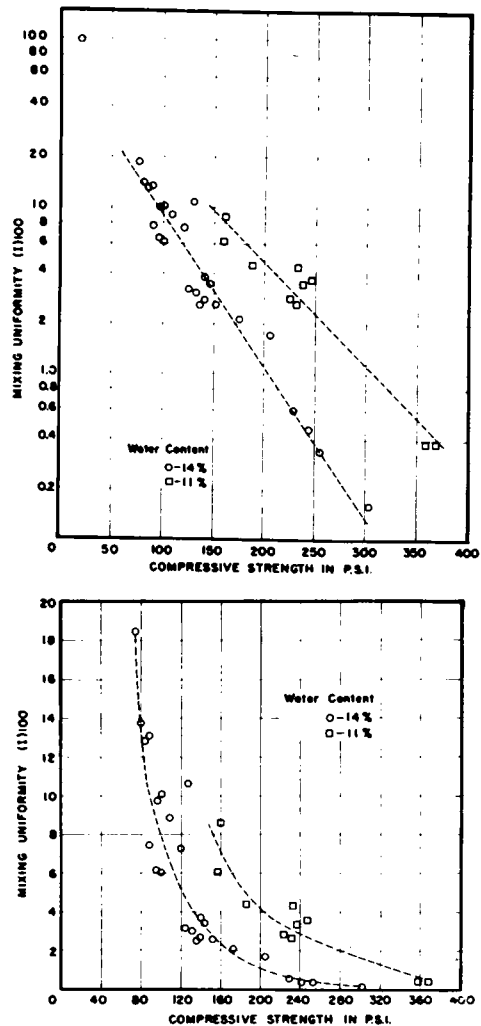


Figure 3. Unconfined compressive strength of silt soil-cement vs. the log of the Mixing Uniformity Index I of the soil and cement mixture.

TABLE III  
MIXING UNIFORMITY VS. STRENGTH FOR  
CALCIUM ACRYLATE SOLIDIFIED  
KAOLINITE

Mixing Time	Uniform. Index	Average TS	TS Range
min.	100 I	psi	psi
0.5	4.8	37.3	19.2-58.0
1.5	2.5	50.0	30.0-69.0
2.5	1.6	54.5	40.0-66.5
4.5	1.0	48.5	45.0-56.3
7.5	0.96	46.8	41.5-50.7

Water/clay ratio 0.40.

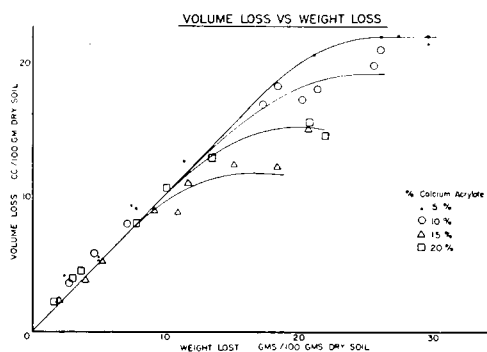


Figure 4

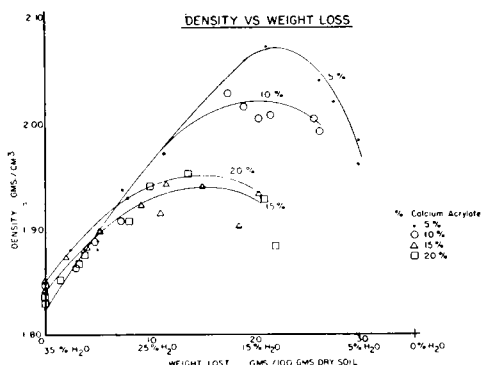


Figure 5

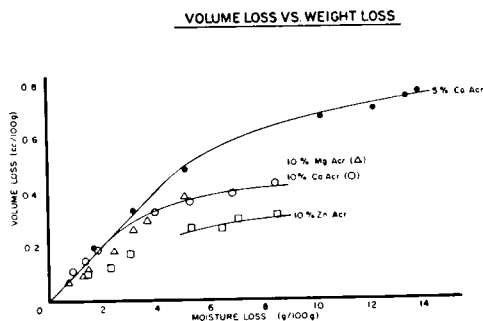


Figure 6

the uniformity of the mixture. Figure 3 shows the results obtained by Baker (5) on soil-cement mixtures and Table III shows the results obtained at M.I.T. with calcium acrylate on kaolinite. It is interesting to note that whereas with cement the strength increased with improved mixing uniformity, with calcium acrylate the average strength did not increase appreciably but the variation of

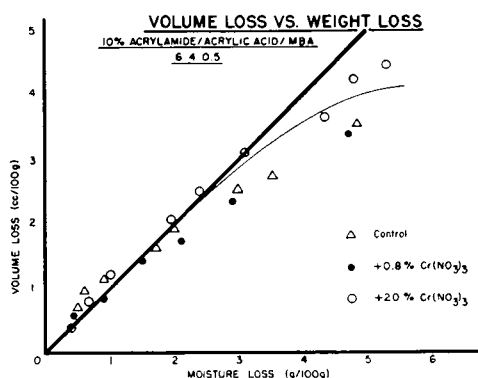


Figure 7

strength decreased. These two experiments, however, were carried out under different sets of conditions—i.e., with cement compressive strength, were measured on samples that required most of the material on the mixer whereas with calcium acrylate tensile strengths were measured on several samples from the same mix. While more research is required along these lines, the present data do clearly show that differences external structure caused in these cases by mixing differences, does have a significant effect on the initial properties of solidified soil.

## 2. The Effect of Molecular Structure on Drying Phenomena

The loss of water from a stabilized soil produces a stress in the system, probably caused by surface tension forces, and as a result of this stress a strain pattern is developed in the stabilizing matrix. How the stabilizer reacts to this stress controls the overall properties of the stabilized soil. If the stabilizer can only give an elastic response as would be the case with highly rigid materials such as cement then very little shrinkage would be expected. If however the stabilizer could give a viscous response then shrinkage of the entire system would be expected. As a corollary if no shrinkage occurred void formation would be expected whereas when shrinkage took place void formation would not occur.

How molecular structure of the stabilizing agent affect drying phenomena is discussed below. Figures 4 to 9 show the weight, volume and density changes on drying for samples of sandy clay solidified with various acrylate polymers.

Figure 4 shows the relation between volume loss and weight loss and Figure 5 shows the relation between density and water loss for samples of sandy clay solidified with various amounts of calcium acrylate at 35% water. These curves show that initially there is a 1:1 correspondence between volume loss and weight loss with a steady increase in density during this period. This can be explained on the basis that there is a viscous flow mechanism operating within the matrix so that the drying stresses cause shrinkage. At various water percentages depending on the amount of calcium acrylate the curve of volume vs. weight loss breaks and continued weight loss is not accompanied by an equivalent volume loss. At the same point the density curves reach maxima and then start to decrease which can only signify that voids are starting to form in the system. On the basis of our model this means that the viscous response mechanism of the system is no longer operating and the system must be strained.

Figure 6 and 7, and 8 and 9 show similar data for the same soil solidified with 10% of

various acrylate polymers at approximately 16% water. Magnesium acrylate and acrylamide/acrylic acid/methylene-bis-acrylamide (A/AA/MBA) show straight lines approximately 1:1 ratio, for the duration of the test whereas zinc acrylate does not show the 1:1

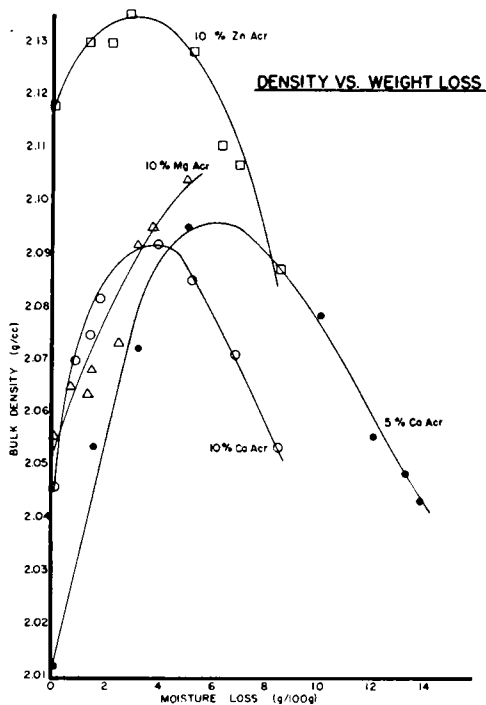


Figure 8

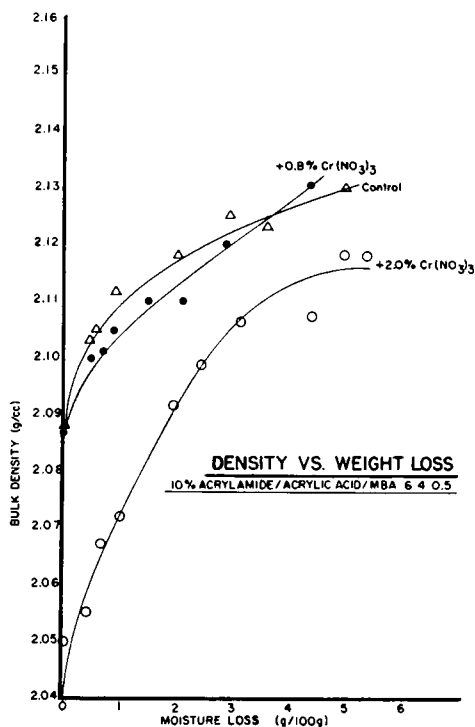


Figure 9

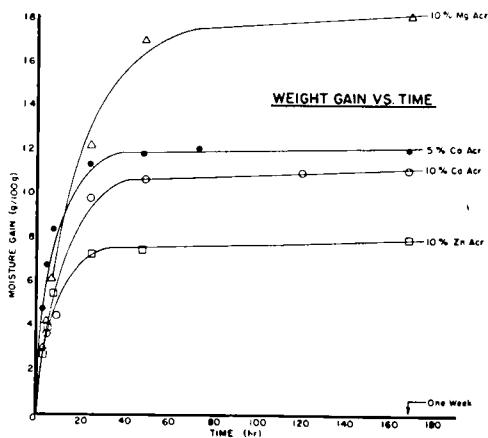


Figure 10



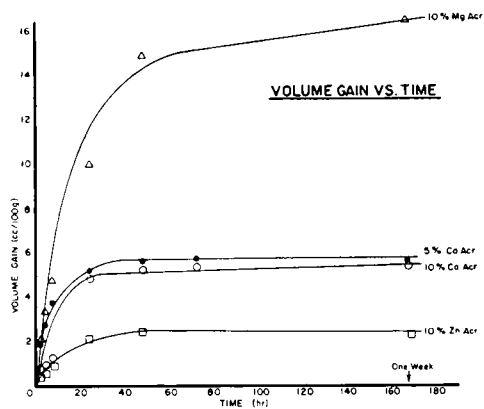


Figure 11

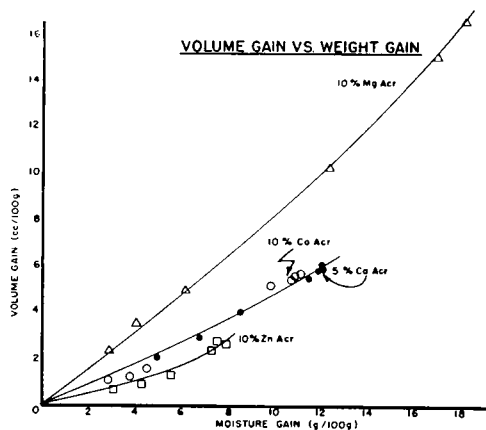


Figure 12

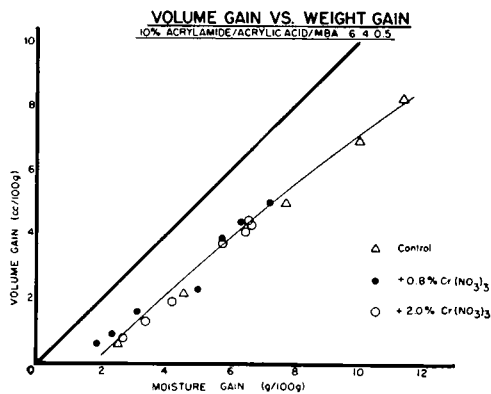


Figure 13

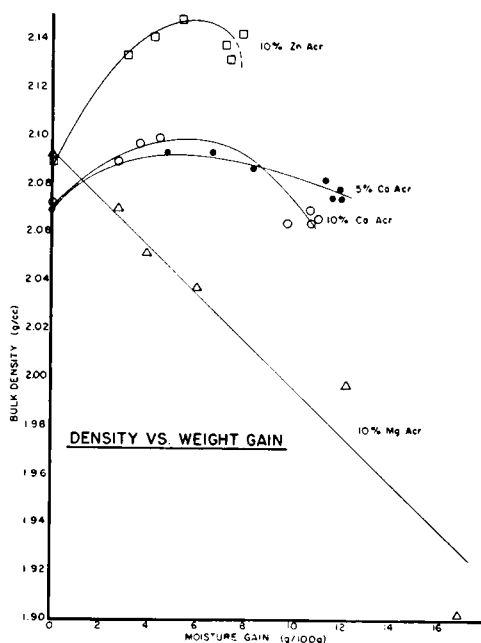


Figure 14

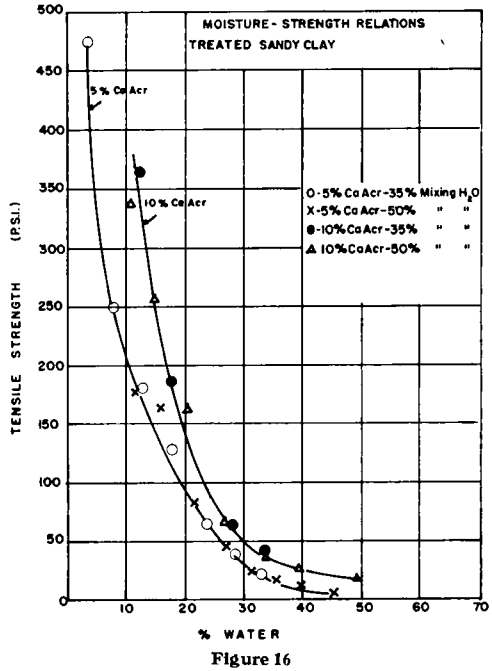
ratio even from the beginning and calcium acrylate is intermediate. Similarly neither the magnesium acrylate nor the A/AA/MBA had reached peak density at the end of the experiment whereas both the calcium and zinc acrylate had passed their maxima. The density increase for calcium acrylate was considerably greater than for zinc acrylate. It should also be pointed out here that curves do not show anything about the differences in rate of drying that actually existed. These tests were run for one week and at the end of this time all samples had reached an equilibrium point except magnesium acrylate.

### 3. The Effect of Stabilizer Structure on Re-wetting

As solidified soils lose water under drying conditions they can absorb water under wet conditions on the soil properties is of major importance. The result of a study on the connection between water absorption and wet volume and density changes are shown in Figures 10 to 15, for the same series of samples on which the drying studies were conducted.

Figures 10 and 11 shows the water absorp-

tion and volume gain of these air dry solidified soils with time, Figures 12 and 13 show the relationship between weight and volume gain, and Figures 14 and 15 show the connection between weight gain and density. As with the drying curves the effect of changing the stabilizer structure by changing the divalent ion is clearly evident. With calcium and zinc acrylates there is an initial rapid water absorption without volume increase but accompanied by a density increase caused a rapid filling of the voids in the system with water. Since these phenomena hardly occur with magnesium acrylate it is probably that on drying no voids had formed in this case (probably because under the conditions of the drying tests the rate of loss of water for magnesium acrylate had been too slow for this stage to have been reached). After the initial water absorption further absorption is accompanied by swelling and density decreases. Here the zinc acrylate absorbs very little further water and swells only slightly never reaching a 1:1 correspondence between weight and volume increase. Magnesium acrylate on the other hand ab-

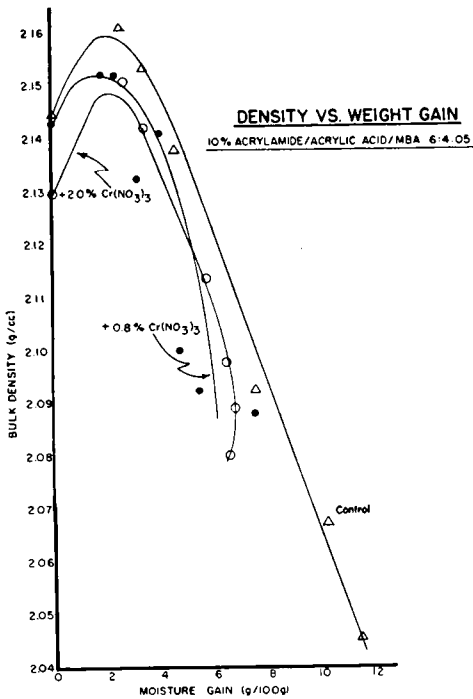


sorbs considerable quantities of water and swells in an almost 1:1 correspondence while again calcium acrylate shows intermediate properties.

#### 4. The Effect of Structure on Strength and Flexibility

The effect of structure of the stabilizing agent or the initial strength and flexibility of solidified sandy clay is shown in Table II. Since the structure of the stabilizing agent has important effects in density and volume on drying and rewetting it is interesting to see how these differences are reflected in the strength of the treated soil. Figures 16 to 18 show the connection between water content and strength for calcium acrylate, zinc acrylate and acrylic acid/methylene-bis-acrylamide (AA/MBA). It is apparent that the curves for calcium acrylate and AA/MBA, which possess similar shrinkage characteristics, are similar in shape whereas zinc acrylate is different.

Table IV gives the results of drying these variously treated soil samples to different water contents and then rewetting to equilibrium water content. It is evident that as long as the solidified soil is not dried below some particular water content the strength of



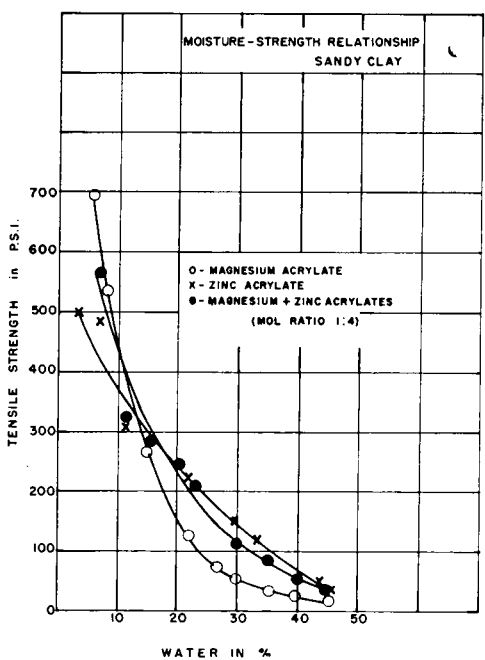


Figure 17

**MOISTURE-STRENGTH SANDY CLAY**  
**ACRYLIC ACID : MBA : 9.50 : 0.50**

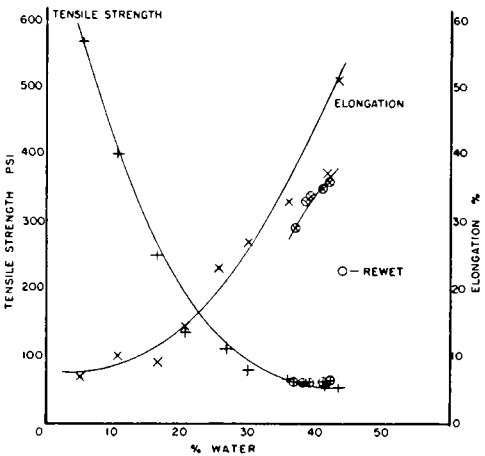


Figure 18

TABLE IV  
MOISTURE-STRENGTH DATA FOR DIVALENT ACRYLATES

Drying			Rewetting		
Water, %	Tensile strength, psi	Elongation, %	Water, air dry %	Water, rewet %	Tensile strength, rewet psi
Magnesium Acrylate					
45.0(3)*	14.9	28			
39.5(3)	23.7	17			
35.1(4)	30.6	14			
29.8(3)	54.4	9	28.9(4)*	41.5	33.2(20)†
26.5(6)	72.9	7	23.6(4)	39.9	32.4(20)
21.6(15)	127.0	5	21.6(4)	38.1	37.7(25)
14.6(8)	267.2	3	14.2(4)	38.4	27.0(25)
8.0(6)	538.0	4	9.4(4)	35.5	18.4(30)
5.7(9)	693.0	4			
Zinc Acrylate					
45.2(5)*	33.2	6			
43.3(3)	48.4	6			
33.1(5)	119.4	3			
29.6(7)	148.8	3			
21.7(7)	219.2	1.5	23.4(4)*	31.0	93.4(140)†
15.7(4)	280.8	2	16.4(4)	28.6	74.2(153)
11.2(6)	303.8	1.5	14.1(4)	29.2	109.4(150)
6.8(8)	479.4	3	8.8(4)	28.2	57.7(160)
3.3(6)	493.5	3	6.6(4)	30.6	50.6(140)
10% Calcium Acrylate—35% Water—AP/ST					
35(2)	43.1	27	27(2)	32	50.5(45)
33(6)	41.4	25	25(2)	30	55.5(55)
28(7)	64.3	16	21(2)	27	64.3(65)
25(3)	88.5	11	15(4)	25	82.2(80)
22(6)	106.4	11	10(7)	24	50.5(85)
18(8)	187.0	5	7(11)	24	18.0(85)
10(1)					

\* Number of bars averaged.  
† Theoretical tensile strength at this water content from drying curve.

the rewet material is the same as obtained on drying to this value from a higher water content, whereas drying below this value produces relatively weaker materials on rewetting. Again there are very noticeable differences between the various solidifying agents. Zinc acrylate, which shrinks very little, cannot be dried very far without relative strength loss or rewetting, whereas AA/MBA, which can shrink very considerably, can be dried to low water contents with equivalent strength retention, and calcium acrylate, which has an intermediate shrinkage, can be dried to an intermediate value. While the data are not too precise, it seems that this point of no return for calcium acrylate is about 15% water, which is the point where the 1:1 weight to volume

loss ratio breaks and the density reaches its maximum. The similar point for zinc acrylate for high water solidified soil is about 25% but for AA/MBA is less than 5%. On the theoretical basis it is evident that calcium acrylate and AA/A/MBA possess viscous flow mechanisms which are controlled by the amount of water present (by ionization with calcium acrylate and reduction of polar forces with AA/MBA) whereas zinc acrylate does not possess this mechanism. Again calcium acrylate possess high elongation and low strength compared to zinc acrylate which is what would be expected for material containing a viscous flow mechanism compared to one that does not have such a mechanism. Furthermore, it is evident that the drying stresses can be high enough to rupture the matrix when the viscous flow mechanism can no longer relieve the stresses.

Space limitations prevent the further application of these concepts to the explanation of the action of other stabilization agents at this time but it is hoped to devote future papers to other materials.

#### CONCLUSIONS

If these theoretical concepts are valid then a number of conclusions of extreme importance for soil stabilization can be declared.

1. Any stabilizing agent that forms an initial rigid three-dimensional matrix should be placed under optimum conditions since it can not adjust to applied stresses.

2. A stabilizing agent that can undergo viscous flow can be placed at less than maximum density since drying stresses can cause it to undergo self densification. However, this type of material would be expected to have a rather low initial strength.

3. To be suitable as a stabilizing agent the molecular structure that permits viscous flow

in a material must be eliminated by physical or chemical means at the proper time.

4. By altering the relative quantitative values of the elasticity, delayed elasticity and viscosity, stabilizing agents with a wide range of properties are possible.

5. By proper choice of starting materials and conditions and by appropriate physical and chemical reactions it will eventually be possible to produce solidified soils with a wide range of properties.

6. There will always remain certain limitations inasmuch as some sets of desired characteristics would require the stabilizing agent to possess opposite characteristics at the same time.

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