

Formation of New Minerals with Lime Stabilization as Proven by Field Experiments in Virginia

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In the fall of 1956 and the spring of 1957 subgrade soils on three projects in Virginia were stabilized with hydrated lime (Ca(OH)_2). The projects, located approximately 150 miles apart, were constructed on three different soil types. The clay fraction of each of the three soils was composed of different clay minerals; therefore, there was a considerable difference in the physical properties of the soils.

The three projects were sampled during 1960 for the purpose of studying the effects of addition of hydrated lime. X-ray diffraction data of the treated soils revealed that new minerals—calcium silicate-hydrates and calcium carbonate—had been formed. Petrographic analysis of thin sections prepared from the treated soils showed that the source of additional strength was a cementing material, hydrated calcium silicates, which now interlaces the soil grains.

• SINCE World War II much attention has been directed to the use of stabilizing agents to improve the engineering properties of cohesive soils. Lime (Ca(OH)_2), one of the many chemicals tried, has proven to be an effective and economical additive for improving many soils used in road construction. Although lime is generally used to stabilize clayey type soils, such soils as micaceous silts and loess have been stabilized by the addition of lime.

The beneficial effects of lime are generally attributed to the interaction of lime and the clay minerals in the soil. The reactions mentioned most often in the literature (1, 2) are (a) aggradation caused by flocculation of the clays, (b) cation exchange (that is, replacement of sodium, hydrogen or potassium ions by calcium), (c) cementing or bonding action of indefinite character, (d) reaction of the lime and CO_2 from the atmosphere to form calcium carbonate and thereby cement the soil particles together. It is believed that any or all of these phenomena may occur under the right conditions and with the right soil.

Although Eades and Grim (3) in 1960 reported the formation of calcium silicate-hydrates from pure clay minerals in the laboratory, many engineers have questioned whether or not this same reaction occurred in the field. Thus the question of permanency of lime stabilization still remained. It is for this reason, as well as others, that data are needed concerning the true nature of the reactions of lime and soil under field stabilization conditions.

The Virginia Council of Highway Investigation and Research, the research division of the Virginia Highway Department, in its soils laboratory added lime to its soil stabilization program in 1954. In the early fall of 1956 and the spring of 1957, field experiments involving use of lime, along with other additives, for treatment of sub-

grade materials were constructed. The objective of the subgrade stabilization phase of the experiment was to determine the feasibility of improving the bearing value of even the poorest subgrade soils to the extent that a minimum base thickness would prevent subgrade failure. The sections have been kept under surveillance since they were completed and periodic tests were made throughout the first year to determine strength characteristics and moisture-density changes.

During June 1960 the lime-treated sections of the two experimental projects, as well as a lime-stabilized project built in 1957 under regular construction, were sampled so that mineralogical studies could be made. The aim of the study was to note any mineralogical differences between the control and the lime-treated sections. The three projects studied were built in three different soil areas. The clay minerals were radically different, so the engineering characteristics were different.

DESCRIPTION OF FIELD EXPERIMENTS

The two experimental projects are located in the Piedmont Province of Virginia. One of the projects is located at the foot of the Blue Ridge Mountains in Patrick County on Route 58. The experimental sections, constructed with 3 percent and 5 percent lime, are 500 ft long. One group of sections was built in September 1956, a second group adjoining the first was completed in May 1957. The area is underlain by a deeply weathered micaceous schist, which seldom offers a clay horizon thicker than 24 in. Therefore, a good clay borrow material with which to cover the resilient micaceous material is scarce.

The second experimental project, also located in the Piedmont about 160 mi east of the experiments in Patrick County, is about 20 mi west of Petersburg on Route 460 in Dinwiddie County. The area is underlain by a deeply weathered granite, which has resulted in a micaceous silty clay. On this short project the soil varied from A-2-4 containing an appreciable percentage of coarse sand to the highly plastic A-7-5 (20) soil according to the AASHTO classification (4).

A third project, built by contract in a privately owned subdivision called Birchwood Gardens, was located north of Route 58 in Princess Anne County, in the Coastal Plains Province of Virginia. The area is underlain by a heavy clay which classified as A-7-6 (12). A 6-in. 5 percent lime-stabilized subgrade with a 6-in. base was used in place of 12 in. of select borrow with a 6-in. base.

LABORATORY AND FIELD TEST RESULTS

The California Bearing Ratio test, made on the subgrade soil, is used to aid in determining the design of Virginia pavements. Therefore, early evaluation of the success of lime for subgrade stabilization was obtained from CBR tests of the soil-lime mixtures, both in the laboratory and in the field.

The laboratory samples were compacted into standard CBR molds which had tight fitting lids with rubber gaskets to prevent moisture loss. This permitted the specimens to be given an accelerated oven cure at 140 F, usually for 7 days, after which the lids were removed and the specimens were given the usual 4-day soaking period prior to testing. Later some of the samples were tested after only a 3-day oven cure, inasmuch as this seemed to produce better correlation between laboratory CBR and field CBR after 1 year. Table 1 presents data on laboratory CBR values for one typical sample from each of the three field projects.

During and for some time after construction of the lime-treated subgrades, in-place CBR tests were made in the field to record the progressive effects of the lime.

The field CBR test is known to have distinct limitations. Attempts to correlate it with the standard laboratory CBR test have generally proven unsuccessful. Field test values may vary unpredictably with variations in moisture content and percentage of coarse aggregate in the soils. However, this much can be said of CBR values of untreated subgrade soils: experience gained from testing a number of projects in Virginia has indicated generally that the field CBR value tends to go down as the moisture content of the soil reaches equilibrium. For a good many soils, this in-place value a year or two after construction has been found to be lower than the laboratory soaked value for the same soil.

TABLE 1
RESULTS OF LABORATORY CBR TESTS

Source	Soil Class.	CBR (%)			
		Raw Soil	Soil + 3% Lime ¹	Soil + 5% Lime ¹	Soil + 5% Lime ²
Dinwiddie Co.	A-5-(2)	2.5	-	99.0	-
Patrick Co.	A-4-1	8.8	39.0	110.0	66.0
Princess Anne Co.	A-7-6 (12)	6.0	42.0	87.0	58.0

¹Cured 7 days at 140 F.

²Cured 3 days at 140 F.

For those field CBR tests made on the lime treated subgrades, however, the indications are that the treated soils tend, rather, to gain strength with age. Figures 1 and 2 show the strength gained over periods up to 1 year on the experimental projects on Routes 58 and 460.

Crude attempts were made to secure a later series of field CBR data as late as 1960, but the results were of questionable value because only 6-in. auger holes were available through which the tests might be made, and the CBR piston could not be assured a positive and uniform contact with the subgrade. In spite of this, the average field CBR values remained in approximately the same neighborhood as those determined earlier from test pits and shown in Figures 1 and 2.

X-RAY DIFFRACTION ANALYSIS

Samples were taken from each of the auger holes made in 1960 for mineral analysis. As the samples were taken from the subgrade they were sealed in plastic bags to protect any unreacted lime from carbonating until they could be transported to the laboratory.

Portions of the samples were ground to pass a 200-mesh screen and were analyzed by X-ray diffraction. When the diffraction tracings of the treated soils were compared with those from the control sections it was evident that a reaction had taken place forming new compounds. Closer analysis showed that calcium carbonate was present and also some additional lines. The next step was to identify the compounds causing these lines, and to determine the percentage of carbonate present.

The soils from the projects prior to stabilization did not contain calcium carbonate; therefore, it was a simple matter to determine how much of the lime had carbonated. Chemical analysis showed that the samples from the 5 percent treated sections now contained about 2.5 percent calcium carbonate.

To better determine the reaction products of the soil and lime, samples of the soil from the control sections were treated with 20 percent lime and the mixtures were cured at 140 F for 60 days in sealed containers.

When these laboratory-treated soils were analyzed it was learned that calcium silicate-hydrates had formed. By comparing the X-ray tracings of the laboratory-treated material with tracings of the samples from the field it was evident that calcium silicate-hydrates had also formed in the field.

These phenomena can best be demonstrated by calling attention to Figures 3, 4, and 5, in which the X-ray tracings are arranged one above the other so that a comparison can be made of the untreated, laboratory-treated, and field-treated soil. Tracing A of each of the three figures represents a dry mixture of soil plus 20 percent lime. Of course, the soil sample is diluted by 20 percent lime; therefore, the peak heights of the soil minerals are reduced. Tracing B of each of the figures represents the material from Tracing A after water was added and it was heat cured in the laboratory. Tracing C is of the treated soil from the subgrade, which was stabilized in 1956 and 1957.

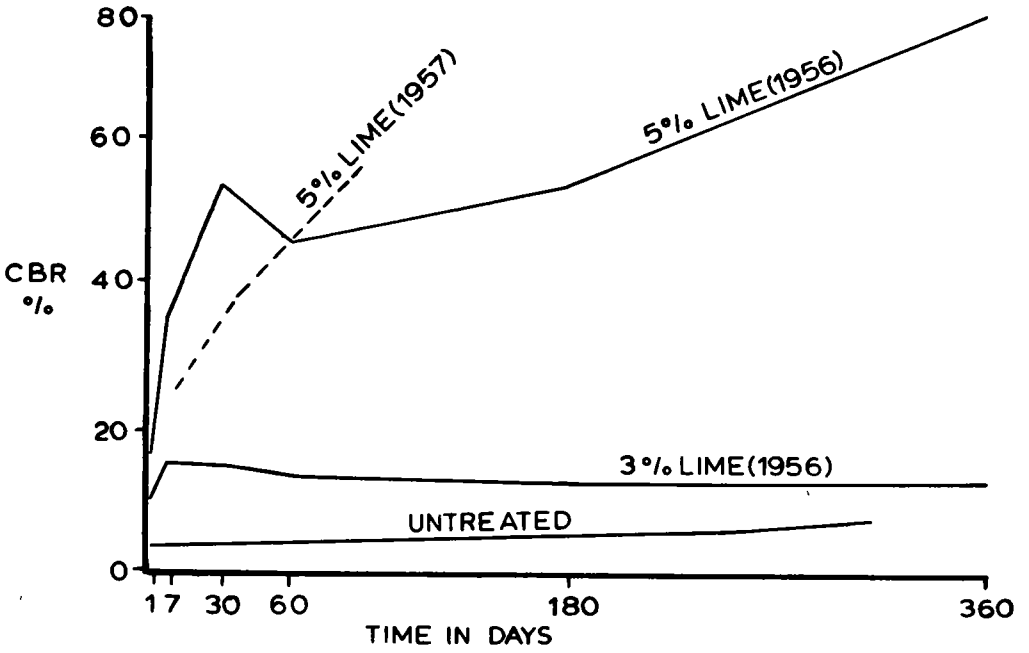


Figure 1. Field CBR results, Rt. 58, Patrick County.

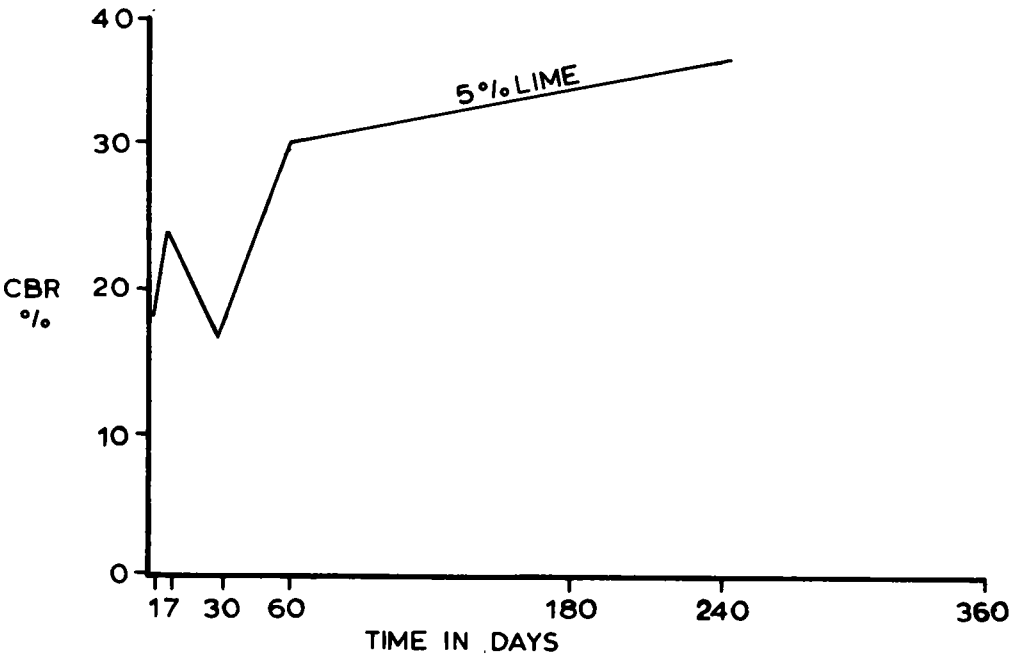


Figure 2. Field CBR results, Rt. 460, Dinwiddie County.

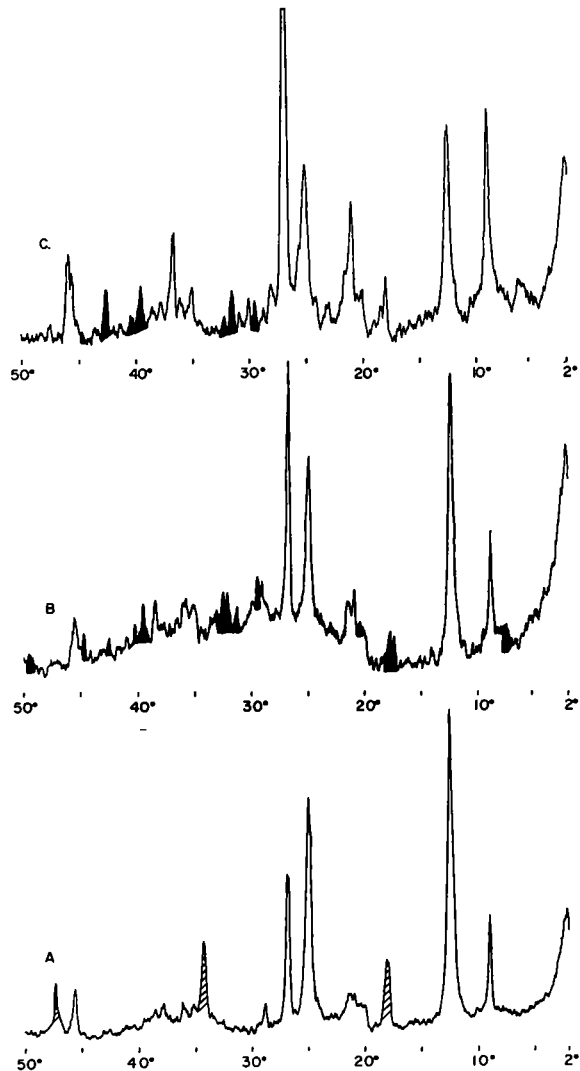


Figure 3. X-ray diffraction tracings for micaeous soil from Rt. 58, Patrick County, Va.

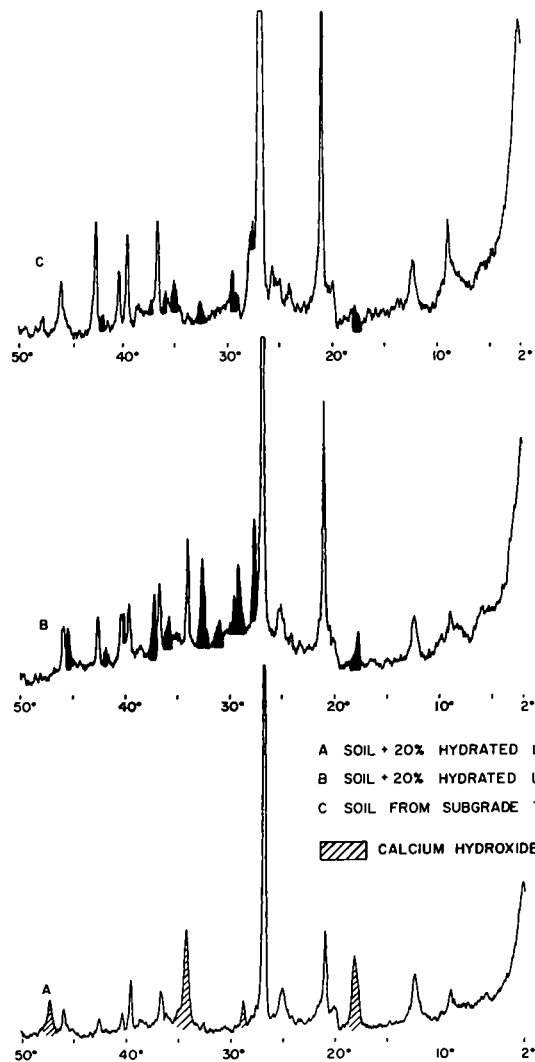


Figure 4. X-ray diffraction tracings for micaeous soil from Rt. 460, Dinwiddie County, Va.

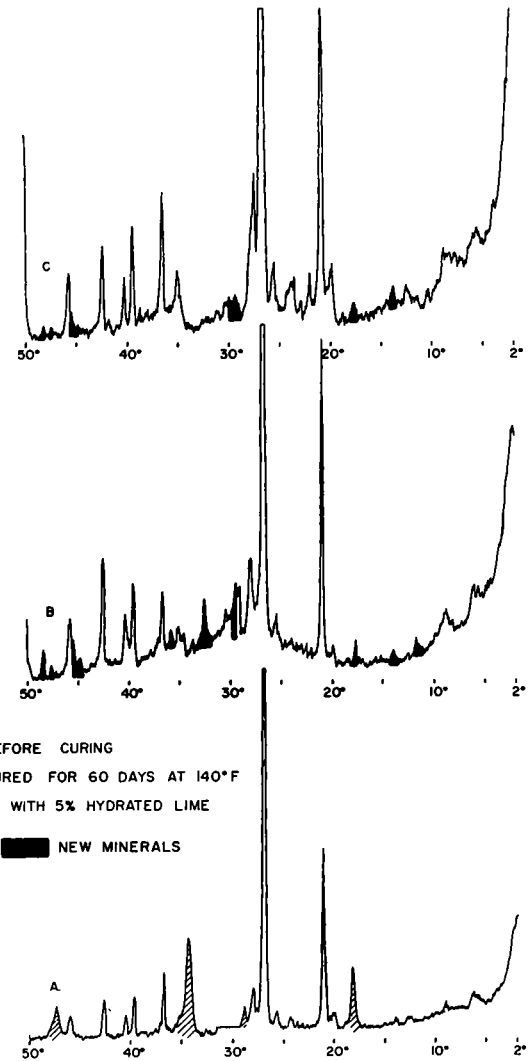


Figure 5. X-ray diffraction tracings for marine gumbo clay from Princess Anne County, Va.

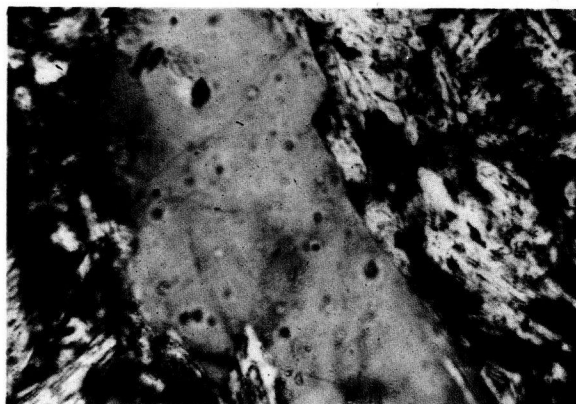


Figure 6. Photomicrograph of untreated soil from Rt. 58, Patrick County, Va.

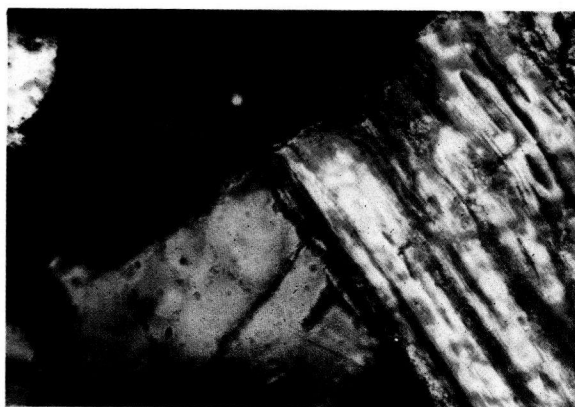


Figure 7. Photomicrograph of field-treated soil from Rt. 58, Patrick County, Va.



Figure 8. Photomicrograph of field-treated soil from Rt. 58, Patrick County, Va.



Figure 9. Photomicrograph of laboratory-treated soil from Rt. 58, Patrick County, Va.

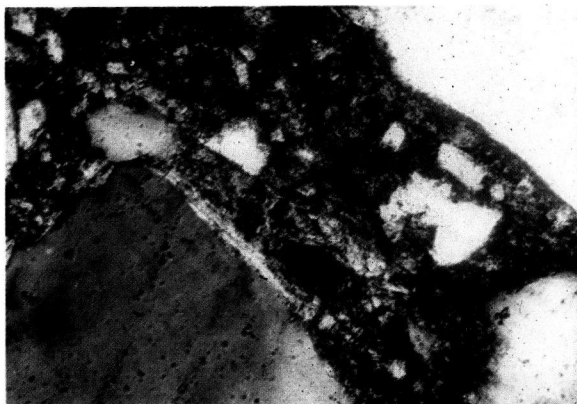


Figure 10. Photomicrograph of untreated soil from Rt. 460, Dinwiddie County, Va.

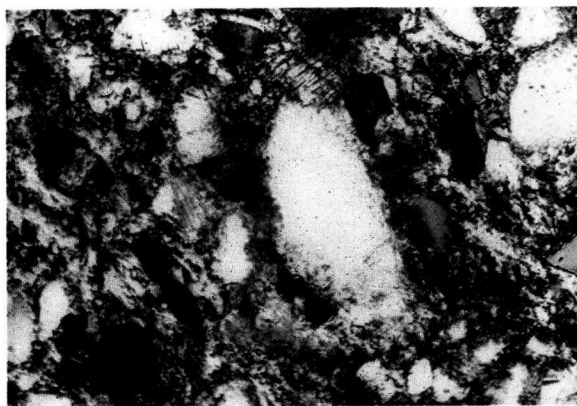


Figure 11. Photomicrograph of field-treated soil from Rt. 460, Dinwiddie County, Va.

A comparison of Tracing A with Tracing B shows that all of the lines representing the lime disappear, which is puzzling because no reaction product appears in abundance adequate to account for the lime. Observing Tracing B further, one will notice additional lines that did not exist before the lime reacted. These lines check with the "d" spacings for calcium silicate-hydrates which Eades and Grim (3) found after treating pure kaolinite with lime.

By comparing Tracing C with Tracing B some of the same lines are found that correspond to the calcium silicate-hydrates in Tracing B, which did not exist in Tracing A. A careful check of Tracing C also reveals new lines that are not found on either Tracing A or Tracing B. These lines correspond to the "d" spacing for calcium carbonate.

The X-ray tracings on Figure 3 represent the soil from Route 58, Patrick County, Va., which was derived from a mica gneiss. The feldspars have altered to kaolinite and the micas to illite and vermiculite.

The soil represented by Figure 4 came from the experimental project located on Route 460, Dinwiddie County, Va. This soil was derived from a granite, contained a larger percentage of clay from the standpoint of gradation, and the clay fraction contained less kaolinite and more illite than the soil from Patrick County. The X-ray tracings proved that the calcium silicate-hydrates had been formed and chemical analysis showed that better than 2 percent of the soil is now calcium carbonate.

The soil from Princess Anne County is represented by Figure 5. As the tracings show, the predominant clay mineral is vermiculite. The tracings also show that this marine clay reacted with the lime to form the calcium silicate-hydrates along with calcium carbonate.

MICROSCOPIC EXAMINATION OF THE SOILS

After it was learned that both calcium carbonate and calcium silicate-hydrates were present, it was decided that thin sections of these soils should be made for microscopic study. It might be wise to explain that a thin section is a term used for rock chips or thin slices of soil which are ground or cut to 0.03-mm thickness or until the quartz grains are light gray in color under polarized light. The object of making thin sections was to inspect the soils with a petrographic microscope to see if reaction products could be detected, and the cause of increased strength revealed.

Microscopic examination of these soils revealed without a doubt the source of the strength. Around the larger grains of such minerals as quartz, feldspar, mica, etc., there was a cementing material binding the particles together. The micrographs also show fractured mineral grains which were penetrated with a yellow to red cement. The micrographs showing this cementing material were taken at 400 magnification and have been enlarged 2X.

Figure 6, which is a micrograph of the soil taken from the untreated control section on Route 58, Patrick County, shows the condition of the compacted soil. The large mineral grain is quartz surrounded by weathered mica. The quartz grain exhibits sharp boundaries and there are many voids between the quartz and the groundmass.

Figures 7 and 8 are micrographs of the soil from the section treated with 5 percent lime on Route 58, Patrick County. They show that a cement containing iron oxide has interlaced quartz grain to quartz grain, as well as mica grains to quartz grains. The cement also has penetrated fractures in quartz grains. In general, the quartz grains in the treated soil do not have distinct boundaries. In fact, they were serrated with the groundmass.

Figure 9 is a micrograph of the soil from Route 58, Patrick County, treated with 5 percent lime and cured at 140 F for 72 hr in the laboratory. Attention is called to the width of the bands of the penetrating cement. This brings out the fact that in warm weather good stabilization develops more rapidly.

Figure 10 represents the soil from the control section of Route 460, Dinwiddie County. Here again attention is called to the sharp boundaries of the quartz. However, in Figure 11, taken of the soil from the lime-treated section, the grains are frosted to serrated, showing the corrosive effects of the lime.

DISCUSSION

On the basis of the results presented in this paper it is shown that hydrated lime increases the bearing value of in-place soils. The rate of increase, as shown by Figure 1, is influenced by the temperature at the time of construction. The section constructed in June attained the same strength in 90 days that the section built in September did in 6 months.

Figure 1 also shows how strength is dependent on the amount of hydrated lime available. The section constructed with only 3 percent lime had reached its maximum strength by the end of 7 days. This also probably accounts for the lower bearing value of the Dinwiddie soil (Fig. 2). This soil had a range between 32 and 81 percent passing a 200-mesh sieve, whereas the Patrick County soil only had between 5 and 10 percent passing the 200 sieve. The soil with a greater percentage of fines would need more Ca^{++} to satisfy the cation exchange capacity and have free lime left for further reactions.

The X-ray analyses of the lime treated samples (Figs. 3, 4, and 5) show that calcium silicates-hydrates are formed by the reaction of lime and soils. Because samples were not analyzed each time bearing tests were made it is not possible to show the rate of growth of the minerals. It is known, however, from work by researchers in other fields (5) that a pH above 10 is needed to dissolve silica at a very fast rate. It can be assumed that the reaction would continue as long as $\text{Ca}(\text{OH})_2$ was present. Inasmuch as all the samples contain calcium carbonate it is evident that all the lime was not used to form calcium silicates. It would be interesting to know how fast the carbonate was formed.

The photomicrographs clearly show that the added strength is due to a cementing material. The grains in close contact were cemented together, thereby increasing the internal friction. Grains which were not cemented were frosted or serrated, also creating more friction.

CONCLUSIONS

On the basis of the results of the three field projects studied it may be concluded that with hydrated lime the bearing value of a poor subgrade can be improved. (Note: High-calcium lime was used on all three projects because of the proximity of the projects to the source of high-calcium lime. However, laboratory analyses made with magnesium lime show that it would have reacted equally as well.)

It also may be concluded that the increase in strength is partially due to the formation of new minerals, which are calcium silicates-hydrates. These minerals act as a cementing material interlocking the particles. If portland cement concrete is considered permanent and it depends on hydrated calcium silicates for its strength, then with proof that the same type of minerals are formed, it must follow that lime stabilization is permanent.

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