

# Reaction of Hydrated Lime With Pure Clay Minerals in Soil Stabilization

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The use of hydrated lime has been growing in the field of soil stabilization. Although it has been used from coast to coast in the United States and by some nations abroad, the reaction of hydrated lime with the soil is still a mystery, particularly with respect to its relative effectiveness and rates of reaction with various soils.

A research project to determine the reaction of hydrated lime and soil is under way at the University of Illinois. Because of the complexity of soils and because lime is of greater benefit to a heavy clay soil, the first part of the investigation has been devoted to a study of the effects of hydrated lime on pure clay minerals.

By the aid of X-ray diffraction and D. T. A. analysis, it has been possible to watch and identify the reactions which take place. The first reaction, which is brought about immediately when lime is added, is replacement of absorbed ions by calcium ions; the second, formation of a series of new minerals; the third, carbonation of the hydrated lime. These reactions, illustrated by typical X-ray examples, offer definite proof as to why different rates of reaction occur with different soils.

● THE DISCOVERY that the workability of a clay soil would be greatly improved by the addition of lime,  $\text{Ca}(\text{OH})_2$ , dates back into the remote past. Highway and airport engineers found that lime as a stabilizing agent greatly improved subgrade soils containing high percentages of expansive clays, by reducing the plasticity indices and increasing the bearing value. Although lime has been used throughout this country and by several nations abroad for stabilization, the reactions of hydrated lime with soil are still for the most part a mystery. The literature contains many reports describing the benefits of lime additions and gives various explanations for the results obtained. Some of the reactions mentioned most often are (1, 2): (a) aggradation caused by flocculation of dispersed clays, (b) exchange of calcium ions for other adsorbed ions such as hydrogen, sodium or potassium, (c) pozzolanic reactions, which were thought to be the formation of calcium silicates by the reaction of the lime with free silica in the soil, (d) the gradual reaction of the lime and  $\text{CO}_2$  from the atmosphere and the soil to form calcium carbonate and thereby cementing the soil particles together. Any or all of these phenomena may occur under the right conditions and with the right soil.

Many engineers have questioned the permanency of lime stabilization. Thus, if it were only a matter of flocculation or ion exchange, fluctuations of ground water levels or percolating ground waters might replace the calcium ion and reduce the beneficial effect of the added lime. 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 stabilization conditions.

At the University of Illinois a research project has been set up by National Lime Association to study the reactions of hydrated lime with soils. The purpose of this study is to investigate the nature of reactions which take place when soil, lime and water are combined and to determine whether or not lime will react significantly with all types of

soils It is planned particularly to study the reactions to see exactly how they influence properties.

The results of previous work, not reported here, (work done by Eades at the University of Virginia) showed that it would be almost impossible to study reactions of small percentages of lime and soils, because of the complexity of soils from the standpoint of mineral composition, particle size gradation, degree of crystallinity of the clay fraction and differences in adsorbed ions. In many cases it is extremely difficult to identify all of the mineral components of an unfractionated soil sample by X-ray diffraction or other means of analysis. It is even more difficult to identify the reaction of lime and soil components.

Grim (3) in 1940 showed that the clay minerals are the components of soil which largely control their physical properties. Therefore, in order to study the reaction of lime with soils more closely, it was believed the reactions with pure clay minerals, of the types which occur in soils, should be studied first. Then if all clay minerals did not react with lime, a clay mineral analysis could serve as a quick test to determine if lime would react with a soil. Further, the analytical data for clay mineral-lime reactions are more easily interpreted so that a start could be made for the interpretation of the more complex data for soil-lime reactions. The investigation reported herein was confined to the effects of treating eight pure clay minerals with lime. The clay minerals included the major types found in soils.

The approach used for this investigation consisted of making X-ray and differential thermal analysis of the untreated clays so that all of their individual peculiarities could be noted before they were treated. The second step was to treat the clays with varying amounts of lime which was followed by curing periods ranging from 72 hr to 60 days at 140 F. The effects of the given treatment were evaluated by X-ray, differential thermal, and compressive strength analyses.

#### DESCRIPTION OF THE MATERIALS USED

Eight samples of four different groups of clay minerals were selected because they represent the various clay mineral groups and variations within the groups that are found commonly in soils. The groups are kaolinite, montmorillonite, illite, and a mixed layered mineral of chlorite and montmorillonite. The eight samples are as follows:

1. Kaolin (a) from Dry Branch, Georgia, a coarse-grained well-crystallized kaolinite with low cation exchange capacity. Five milliequivalents per 100 grams (5 me/100 gr).
2. Kaolin (b) from near Anna, Illinois, a fine-grained poorly-crystalline kaolinite containing a small percentage of quartz. The cation exchange capacity is about 18 me/100 gm (4). The clay is plastic.
3. Halloysite ( $2H_2O$ ) from Eureka, Utah, a mineral having the basic kaolinite-type lattice but being highly disordered and containing layered water in the structure. The cation exchange capacity is 12 me/100 gm (4).
4. Bentonite (a) from Upton, Wyoming, a plastic high swelling  $Na^+$  montmorillonite having a cation exchange capacity of 89 me/100 gm (5). The material is about 92 to 95 percent montmorillonite with the remaining 5 to 8 percent made up of minute fragments of other minerals, the most abundant being feldspar.
5. Bentonite (b) from Aberdeen, Mississippi, a  $Ca^{++}$  montmorillonite with a cation exchange capacity of 64.7 me/100 gm (6). It is much coarser than the Wyoming montmorillonite and has relatively low swelling properties.
6. Bentonite (c) from White Springs, Mississippi, also a  $Ca^{++}$  montmorillonite, having a higher iron content than the Aberdeen montmorillonite and a lower pH than either the Aberdeen or the Wyoming montmorillonites. It is also a low swelling variety of montmorillonite.
7. Illite, from Fithian, Illinois, having a cation exchange capacity of 28 me/100 gm with calcium and magnesium being the chief exchangeable cation (3).
8. "Grundite," from Morris (Goose Lake), Illinois, a poorly crystallized mixed-layered chlorite, illite and montmorillonite, having a lower potassium content than does

the illite from Fithian and a higher plasticity. The cation exchange capacity is 35 me/100 gr.

Hydrated lime, calcium hydroxide, is a soft burned quick lime with 98.4 to 99.0 percent passing the 325 mesh screen. It is 95.4 to 96.6 percent  $\text{Ca}(\text{OH})_2$ .

## ANALYTICAL PROCEDURE

### Preparation of Materials

The montmorillonite samples were received in a powder form with 100 percent passing a 100 mesh sieve. The kaolinites, illite, and Grundite were received in lump form and were crushed to pass the 100 sieve. Moisture contents were determined and the material was stored in containers with tight fitting lids as a means of trying to control the moisture content. Fresh lime samples were received every 60 days. Chemical analyses were furnished with each shipment by the lime plant's laboratory to insure that the same quality lime was used throughout the project. The lime was stored in airtight containers. (Periodic checks were made on the lime to make sure it was not carbonating.)

### Treatment of Clay

Samples of the minus 100 mesh clay and dry hydrated lime were blended together in a dry state to obtain a uniform mix. Distilled water was then added to the dry mixture to bring it to its optimum moisture content as determined by the standard AASHTO method of test. The material was then compacted in Proctor molds to the standard AASHTO density. The specimens extruded from the molds were sealed in containers to prevent the moisture from evaporating and were cured at 140 F for 72 hr. The 4- by 4.5-in. cylinders were tested by unconfined compression. The deformed test pieces were crushed and representative samples removed for X-ray, and D. T. A. analyses. The samples were dried in a vacuum so that the calcium would not carbonate with the carbon dioxide of the atmosphere.

For each of the clays studied, hydrated lime contents of 2, 4, 6, and 8 percent were employed. For the montmorillonite the tests were extended to include 10 and 12 percent hydrated lime. The additions of hydrated lime were made on the basis of the oven dried clay.

At the beginning of the project it was decided to investigate the effects of lime on the structure of the clay minerals by mixing the clays with a large percentage of lime and curing them for a prolonged period to emphasize the reaction products for identification purposes. This was accomplished by mixing small samples of the minerals with 20 percent lime and enough water to make the mixture fluid. Duplicate samples were sealed in containers and cured for 3, 6, 15, 30 and 60 days. These samples were studied with the aid of X-ray and D. T. A.

## EXPERIMENTAL METHODS

### Unconfined Compression Test

This test was used to measure the effects of the hydrated lime on the bearing strength of the clay. The vertical load was applied at a rate of 0.05 in. per minute.

### X-ray Diffraction Analysis

The vacuum dried clays were ground in an agate mortar to pass a 200 mesh sieve and packed into an aluminum holder. Care was taken to minimize preferred orientation. Oriented aggregates prepared according to Bradley, Grim, and Clark (7) were also investigated. The X-ray diffraction patterns were obtained with a North American Philips Scintillation-Counter (type 52245) with a Pulse Height Analyzer.

### Differential Thermal Analysis

Two nichrome-wire furnaces with a maximum range of 1000 C were used for the differential thermal analysis. The rate of temperature increase of the samples averaged about 6.5 up to 60 C per minute, then the temperature increased at a constant rate of 10 C per minute. A reflecting galvanometer with a Brown Penograph Recorder was used to record the thermal reactions.

## DISCUSSION OF TEST RESULTS

Compressive Strength of Treated Clays

In Figure 1, plots of Georgia kaolin, Fithian illite, Grundite, White Springs montmorillonite, Aberdeen montmorillonite and Wyoming montmorillonite are shown. The average compressive strength in pounds per square inch is plotted versus the percent of lime added. Anna kaolin and Eureka halloysite were added to the original study and were not available in quantities large enough for making a compressive strength study.

As shown in Figure 1, Georgia kaolin, which has a low cation exchange capacity and low plasticity, has the highest increase in strength with increments of lime up to 8 percent. Only one other clay equaled its strength with this amount, and that was the Aberdeen montmorillonite. The increase in strength of the kaolin at 8 percent was only slightly above the 6 percent level. This seems to indicate that an optimum amount of lime which will react with the kaolin for the 72-hr curing period is around 6 percent.

The Aberdeen montmorillonite and White Springs montmorillonite which have similar properties such as plasticity and cation exchange capacity gave about the same strength in the untreated state. But the two materials acted quite differently with the addition of lime. The Aberdeen clay increased in strength with each increment of lime and as it was still rising at 8 percent, additional specimens were tested with 10 and 12 percent. These specimens likewise gave an increase in compressive strength. Therefore, it is assumed the optimum lime content was not reached for the curing conditions used in this experiment. The White Springs montmorillonite on the other hand gave a lower compressive strength with the addition of 2 percent lime, and 6 percent lime was required to raise the strength above that of the untreated cylinders. The material showed an improvement up to 8 percent but it did not equal the Aberdeen clay for the same amount of lime and had a reduction in strength with greater concentrations.

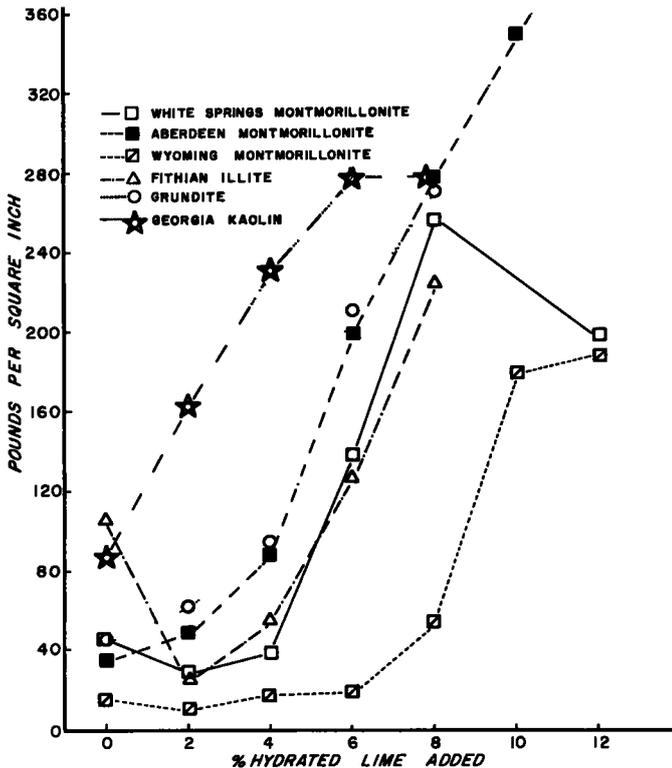


Figure 1. Compressive strengths of hydrated lime treated samples.

The Wyoming montmorillonite which is known for its high percentage of swell, cation exchange capacity and plasticity had a low compressive strength in the untreated condition and dropped off slightly when 2 percent lime was added. The specimens with 4 and 6 percent showed a slight increase but 8 percent was required to raise the compressive strength above the psi of the untreated specimens of White Springs and Aberdeen montmorillonites. There was only a slight increase in strength from 10 to 12 percent, therefore, it would appear the optimum would be near 12 percent.

The Fithian illite had the highest compressive strength in the untreated condition, but when 2 percent lime was added it reacted in the same manner as White Springs montmorillonite, and gave a much lower psi. But with the increased percentages of lime the compressive strength increased and it almost equaled the strength of the White Springs clay at 8 percent.

Grundite, the mixed layered material, reacted to give results which were close to those of the Aberdeen montmorillonite. Untreated Grundite gave a higher strength than the Aberdeen clay and gave a little higher strength for each increment of lime up to the 8 percent, at which point the strength was slightly less than the psi of the Aberdeen clay.

The Fithian and Grundite clays were not tested above 8 percent but it appears the optimum amount of lime for each of the clays would be above 8 percent.

Figure 1 shows that the strength of the kaolin samples increased significantly with the addition of the first increment of lime, whereas for all the other clay minerals there is little increase in strength until 4 percent or more lime is added. It appears that kaolinite and lime react easily, and only small amounts of lime are required to start the reactions. On the other hand for illites and montmorillonites, lime over and above a minimum amount must be added before there is a reaction accompanied by the development of strength.

In the case of montmorillonites which have high cation exchange capacities a certain amount of lime is required to drive the  $\text{Ca}^{++}$  ion into and onto the clay. After the clay has apparently been changed to a  $\text{Ca}^{++}$  variety and only after this does it develop strength. The Wyoming montmorillonite which is a  $\text{Na}^+$  clay requires more lime to become wholly  $\text{Ca}^{++}$  saturated than the Mississippi samples which naturally carry a little  $\text{Ca}^{++}$ . Thus the longer lag in the development of strength from Wyoming as compared to Mississippi montmorillonite is explained.

The Grundite samples carry  $\text{K}^+$  ions and again only after becoming  $\text{Ca}^{++}$  saturated does the strength increase. The initial reduction in strength of the Fithian sample can be explained by the presence of sulfate ions in the clay which are due to the oxidation of pyrite. The sulfate ions react first with the lime and it is not until the  $\text{SO}_4^-$  ions are satisfied that the clays become  $\text{Ca}^{++}$  saturated and the strength increases.

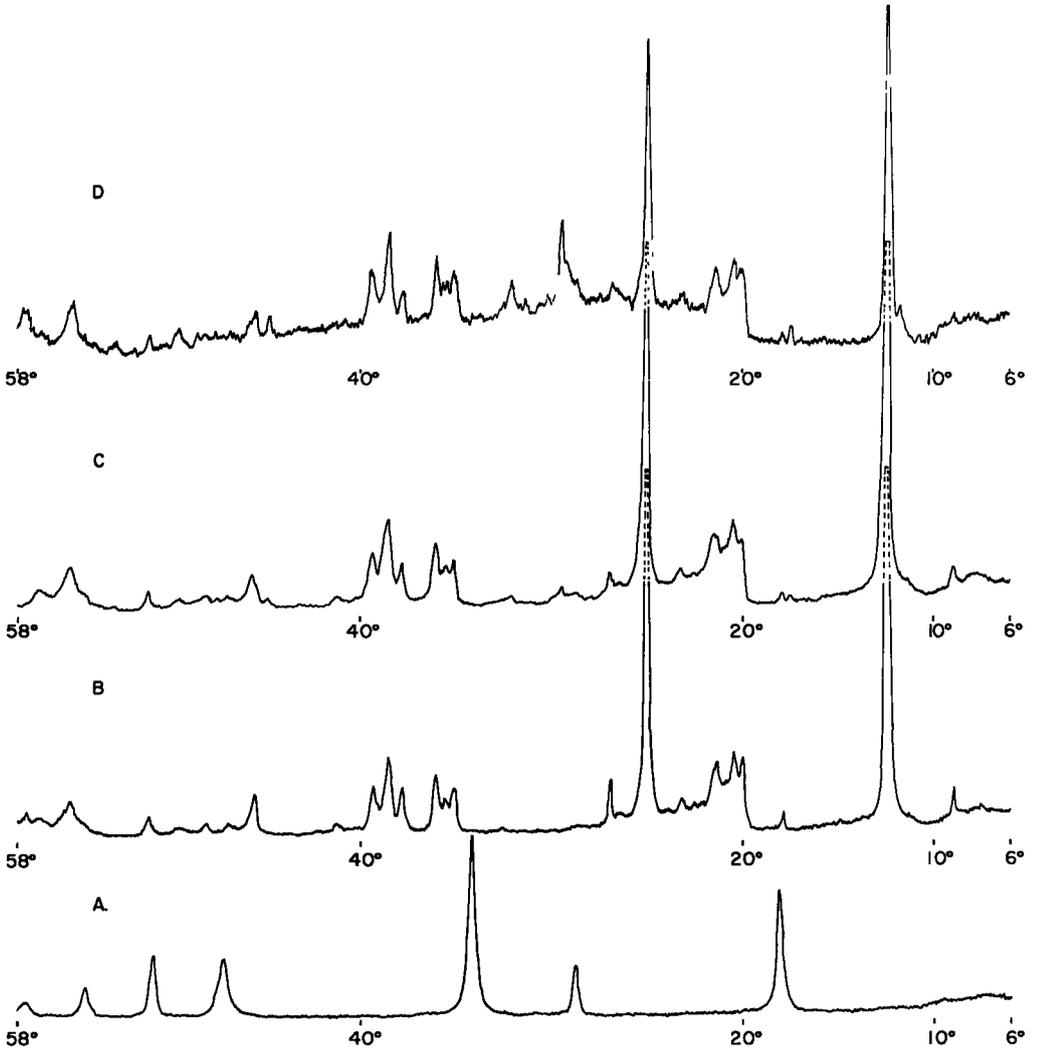
The reasons for the strength increase with  $\text{Ca}^{++}$  saturation will be considered after the X-ray data are presented.

#### X-RAY DIFFRACTION STUDIES

Goldberg and Klein (2) on treating a Wyoming bentonite with amounts of calcium hydroxide up to 8 percent, reported no changes in the X-ray spectrum except that the calcium hydroxide reflections disappeared. Therefore, it was decided to use a much larger percentage of lime and to heat-cure the samples at 140 F for 60 days. If reactions were recorded for these conditions they would serve as a guide, and specimens cured for shorter periods of time and with smaller percentages of lime could be compared with these reactions.

Goldberg and Klein (2) reported that when clays treated with calcium hydroxide were exposed to the atmosphere, calcium carbonate was formed. In the experiments reported herein, when small samples were allowed to dry in an oven under atmospheric conditions, the lime carbonated. The X-ray diffraction patterns of these samples in addition to the clay reflections gave strong reflections for the carbonate and only a few additional lines. However, when steps were taken to dry the material in the absence of  $\text{CO}_2$ , new interplanar spacings appeared showing that there had been considerable reaction between the clay and the lime. Because many of the new reflections were close to those of the carbonate and the carbonate lines were strong, they tended to overshadow the new minerals.

Figure 2 shows the X-ray spectrometer tracings for the hydrated lime used, Georgia kaolin untreated, Georgia kaolin containing 6 percent lime cured for 3 days at 140 F, and Georgia kaolin containing 20 percent lime cured for 30 days at 140 F. Not shown in Figure 2 but the same reflections which occurred from the 60 day cured specimens with 20 percent lime can be obtained with specimens cured for 3 days with only 6 percent lime.



- A- HYDRATED LIME  
 B- UNTREATED GEORGIA KAOLIN  
 C- GEORGIA KAOLIN + 6% HYDRATED LIME CURED 72 HRS. AT 140°F  
 D- GEORGIA KAOLIN + 20% HYDRATED LIME CURED 30 DAYS AT 140°F

Figure 2. X-ray diagrams of lime-treated Georgia kaolin.

The Georgia kaolin which is well crystallized gives a diffraction pattern of kaolinite with sharp basal and prism reflections in the untreated state. As the kaolin is treated with small percentages of lime the prism reflections lose their sharpness and intensity. The basal reflections are not changed in sharpness. This seems to infer that this mineral, usually considered quite stable, was attacked at the edges and within the two-layer silicate sheets, thereby causing a weakening of the prism reflections. That is, the initial reaction is not merely one of spreading apart the silicate layers, but an attack on the basic structure. As the lime content and curing period were increased there also appeared to be a reduction of the basal reflection, and an increase in the percentage of new minerals as indicated by nonkaolinite diffraction lines. It is significant that new crystalline phases appear about immediately with the treatment of kaolinite with lime.

Figure 3 shows the changes which accompanied the treatment of Anna kaolin with 20 percent lime for 3, 15, and 60 days. The Anna kaolin is not as well crystallized as the Georgia kaolin which is shown by the ragged prism reflections. The low-angle diffraction in the samples treated with moderate amounts of lime suggests that for such kaolinite there is considerable spreading apart of the silicate sheets as well as an attack on the basic silicate structure in the initial reaction. As curing continues, the low-angle diffraction disappears and the material having caused it becomes reorganized into new phases.

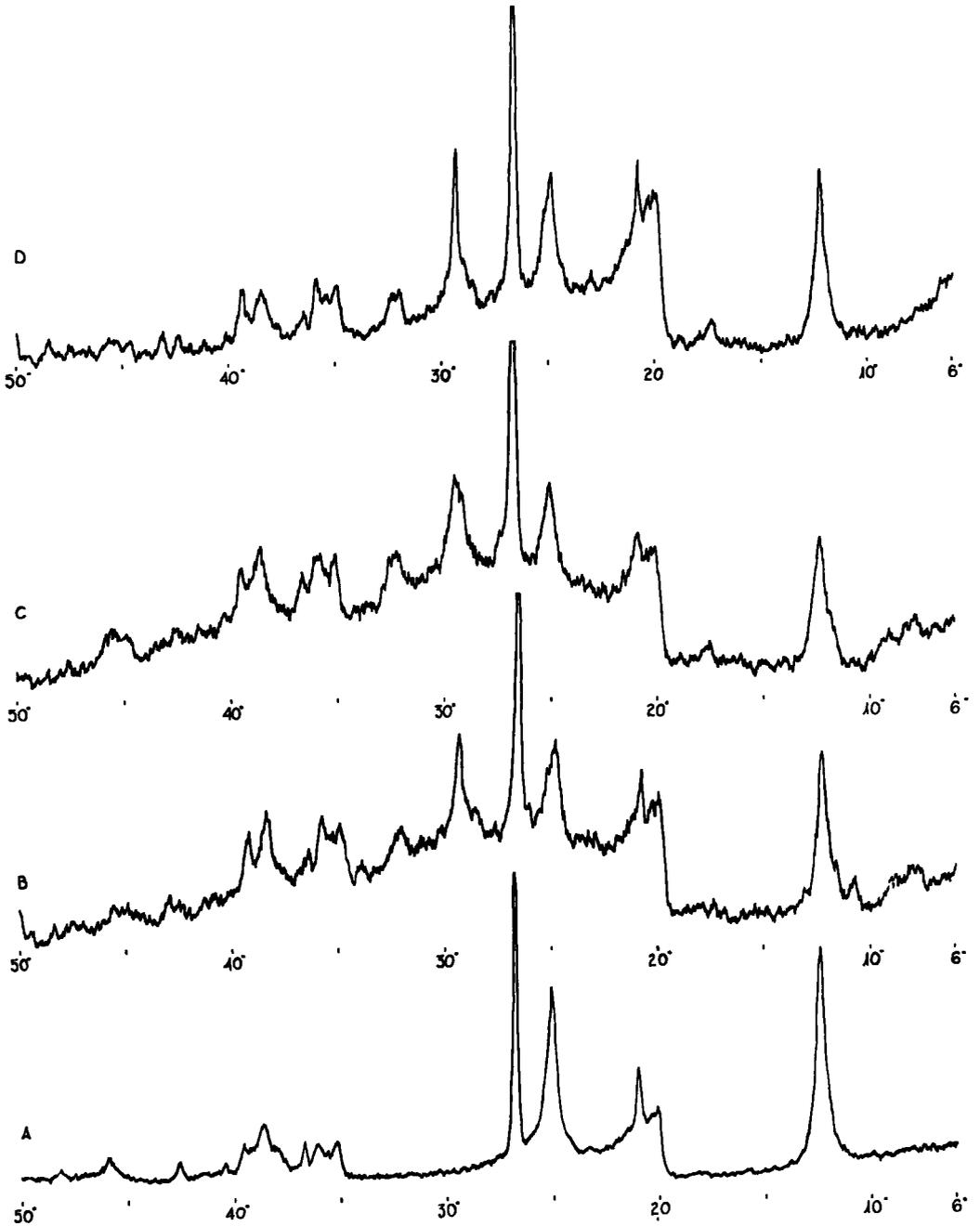
Halloysite (Fig. 4) has the basic kaolinite structure but contains layered water in the structure. This mineral gave the same reflections after it was treated with 20 percent lime as the two kaolinites. The experiments were not continued with the smaller percentages of lime.

The Fithian illite which gave low compressive strength until more than 4 percent lime had been added did not react as quickly as the kaolinite. That is, diffraction patterns for the 20 percent lime series for 3 and 6 day curing periods still contained reflections for hydrated lime. The same new minerals, which occurred with the kaolinites, were present in the diffraction diagram for the 20 percent lime and 3 day curing period but they were in small percentages. The reflections for the illite were reduced in intensity and basal reflections were changed from a peak to a broad band suggesting a general gradual destruction of the illite lattice.

Figure 5, which shows the reactions of lime with Grundite, the mixed layered material, shows that after only 6 days the calcium tends to separate the mixture into more distinct reflections for illite and montmorillonite. However, as curing was continued, as shown by the diffraction pattern for the 30 day curing period, the clay mineral structures were gradually lost. The treated Grundite did not give as many reflections for new minerals as the illite. Reflections for lime were present for the 3 and 6 day curing periods but were not present on the patterns for the 15 day period. It appears that lime reacts much slower with the illites and mixed layered materials than it does with kaolinite.

Figure 6, showing the reaction of Aberdeen montmorillonite and lime, well represents the reaction of lime with all three montmorillonites tested inasmuch as diffraction data were the same for all of them. The diffraction patterns indicated a substantial breakdown of the structure after lime is in contact with the montmorillonite for prolonged periods. Diffraction data not shown in Figure 6 indicate that small percentages of lime do not affect the structure, and as a matter of fact, the basal reflections seemed to be intensified. This probably is to be correlated with adsorption of  $\text{Ca}^{++}$  between the silicate sheets replacing other cations. Only a few reflections were encountered that had not been present in the untreated state showing a scant formation of new crystalline reaction products.

It is impossible to be certain of the identity of the new crystalline reaction products, but the data give every indication that the new minerals are hydrous calcium silicates. The new reaction products for kaolinite give essentially the same X-ray diagram characteristics as those given by Bernal (8) for the low temperature calcium silicate hydrate and dicalcium silicate hydrates which are formed during the hydration of cement. The X-ray diagrams differ somewhat from specimen to specimen for the kaolinites. The strongest values correspond to spacings 5.09, 3.04, 2.8 and 1.8 Å. Additional spacings occurred



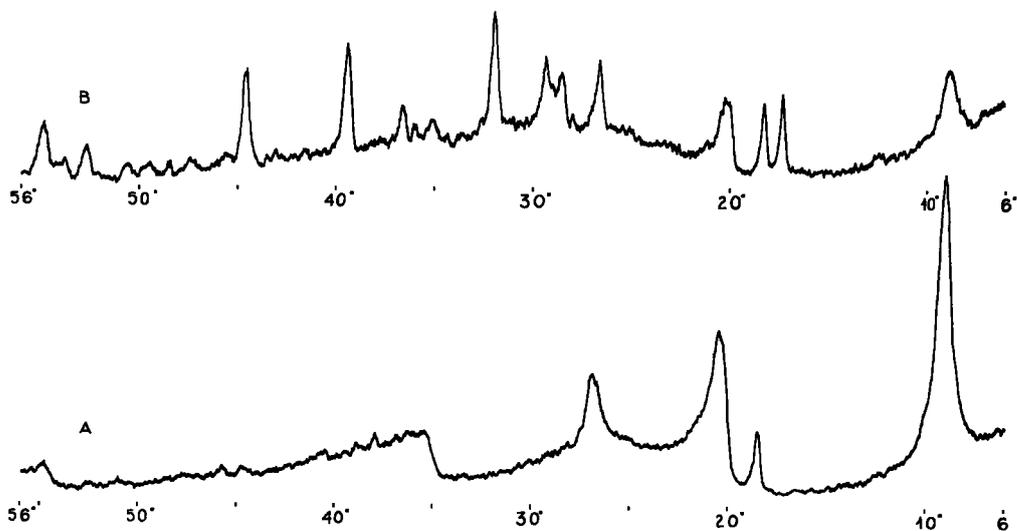
A- UNTREATED ANNA KAOLIN

B- ANNA KAOLIN + 20% HYDRATED LIME ( $\text{Ca}(\text{OH})_2$ ) CURED FOR 3 DAYS AT 140° F.

C- ANNA KAOLIN + 20% HYDRATED LIME ( $\text{Ca}(\text{OH})_2$ ) CURED FOR 15 DAYS AT 140° F.

D- ANNA KAOLIN + 20% HYDRATED LIME ( $\text{Ca}(\text{OH})_2$ ) CURED FOR 60 DAYS AT 140° F

Figure 3. X-ray diagrams of lime-treated Anna kaolin.



A-UNTREATED HALLOYSITE

B-HALLOYSITE + 20% HYDRATED LIME( $\text{Ca}(\text{OH})_2$ ) CURED 60 DAYS AT 140° F

Figure 4. X-ray diagrams of lime-treated Halloysite.

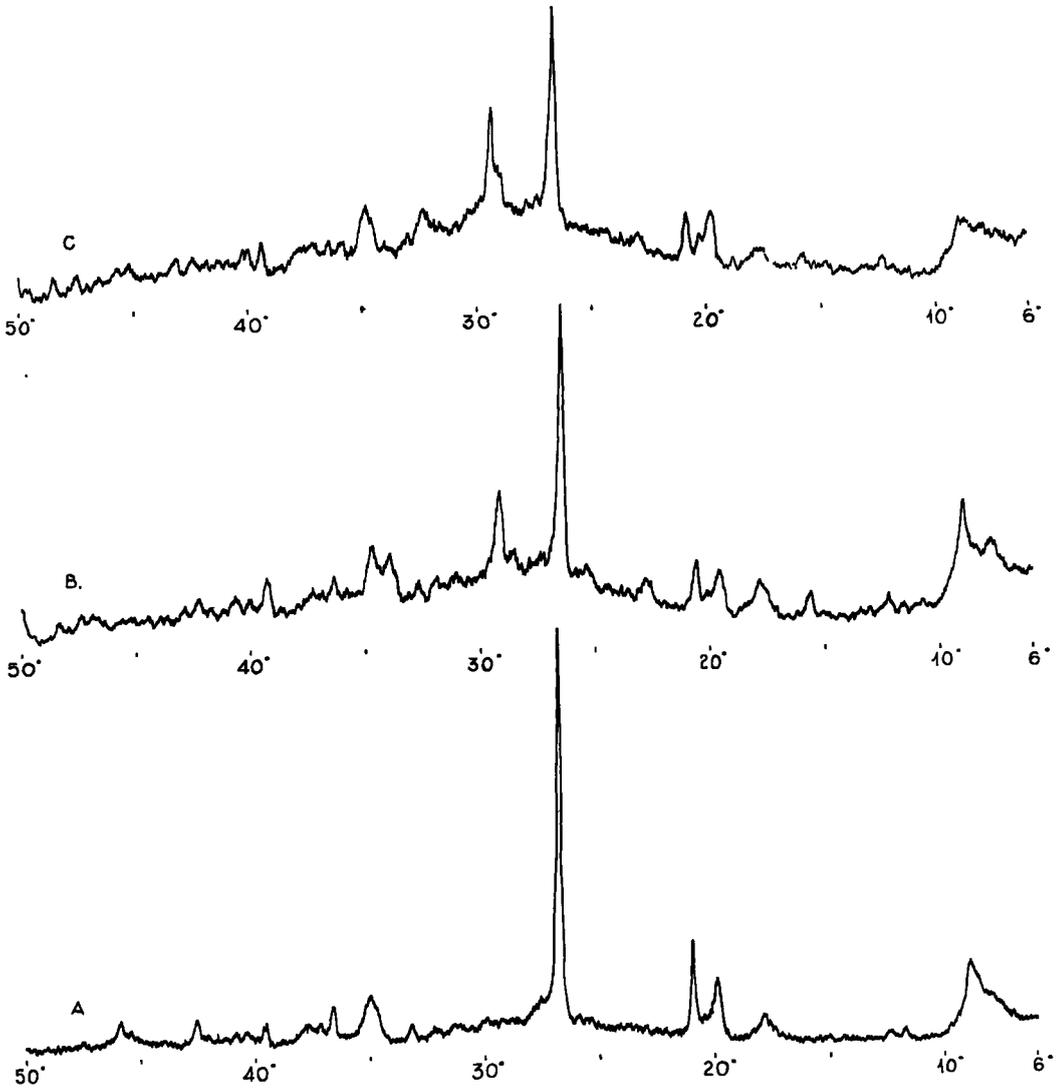
with some samples. Because there are a number of intermediate products in the calcium silicate hydrate system it is believed that several different compounds may exist at one time until equilibrium between the silica which is removed from the structure of the clays and the excess lime is reached. Studies made of the reaction products of cement (9) have shown where there is an excess of  $\text{Ca}(\text{OH})_2$  the silicates are interlayered with the  $\text{Ca}(\text{OH})_2$ . Work done at the Swedish Cement and Concrete Research Institute (9) has shown when the calcium silicate hydrates, in the presence of an excess of  $\text{Ca}(\text{OH})_2$ , are examined by the use of an electron microscope they must be prepared in the absence of carbon dioxide to prevent the formation of calcite, which covers the silicate minerals. This probably explains why the silicate reflections do not appear with treated samples when the sample is allowed to dry in the presence of carbon dioxide.

For the illites, the diffraction data indicate only scant formation of new crystalline phases. They suggest, however, that the phases are the same as for the kaolinite.

The X-ray data for the montmorillonites demonstrate there is a destruction of the mineral structure with little formation of new minerals. However, the compression strength values for the treated clays seem to indicate there is a reaction after enough lime is added and the reaction results in added strength. There is a possibility that although the X-ray diagrams do not contain reflections for new minerals that calcium silicate hydrate gels are formed which are not crystalline. These gels could just as easily interlock the particles together and give the added strength without having a crystalline structure. It is hoped that further research will clear up this aspect of the problem.

#### Differential Thermal Analysis

Treated and untreated samples of the clays were studied by differential thermal analysis up to 1000 C. It was felt that this method would aid in revealing the presence of new calcium compounds and would serve as a guide for their reduction.



A-UNTREATED GRUNDITE

B-GRUNDITE + 20% HYDRATED LIME ( $\text{Ca}(\text{OH})_2$ ) CURED FOR 6 DAYS AT 140°F

C-GRUNDITE + 20% HYDRATED LIME ( $\text{Ca}(\text{OH})_2$ ) CURED FOR 30 DAYS AT 140°F

Figure 5. X-ray diagrams of lime-treated Grundite.

Figure 7 shows D. T. A. curves of the Georgia kaolin untreated (A), kaolin with 20 percent lime uncured (B), and with 20 percent lime cured for 3 days (C). Curve B clearly demonstrates the presence of lime by the endothermic peak at 500 C. A comparison of curve C with curve B shows that the endothermic peak disappears after treatment, and a new endothermic peak occurs between 300 and 400 C. The new peak indicates a new phase which could possibly be correlated with the hydrated calcium silicate suggested by the diffraction data.

Figure 8, a series of D. T. A. curves for Wyoming montmorillonite, shows the effects

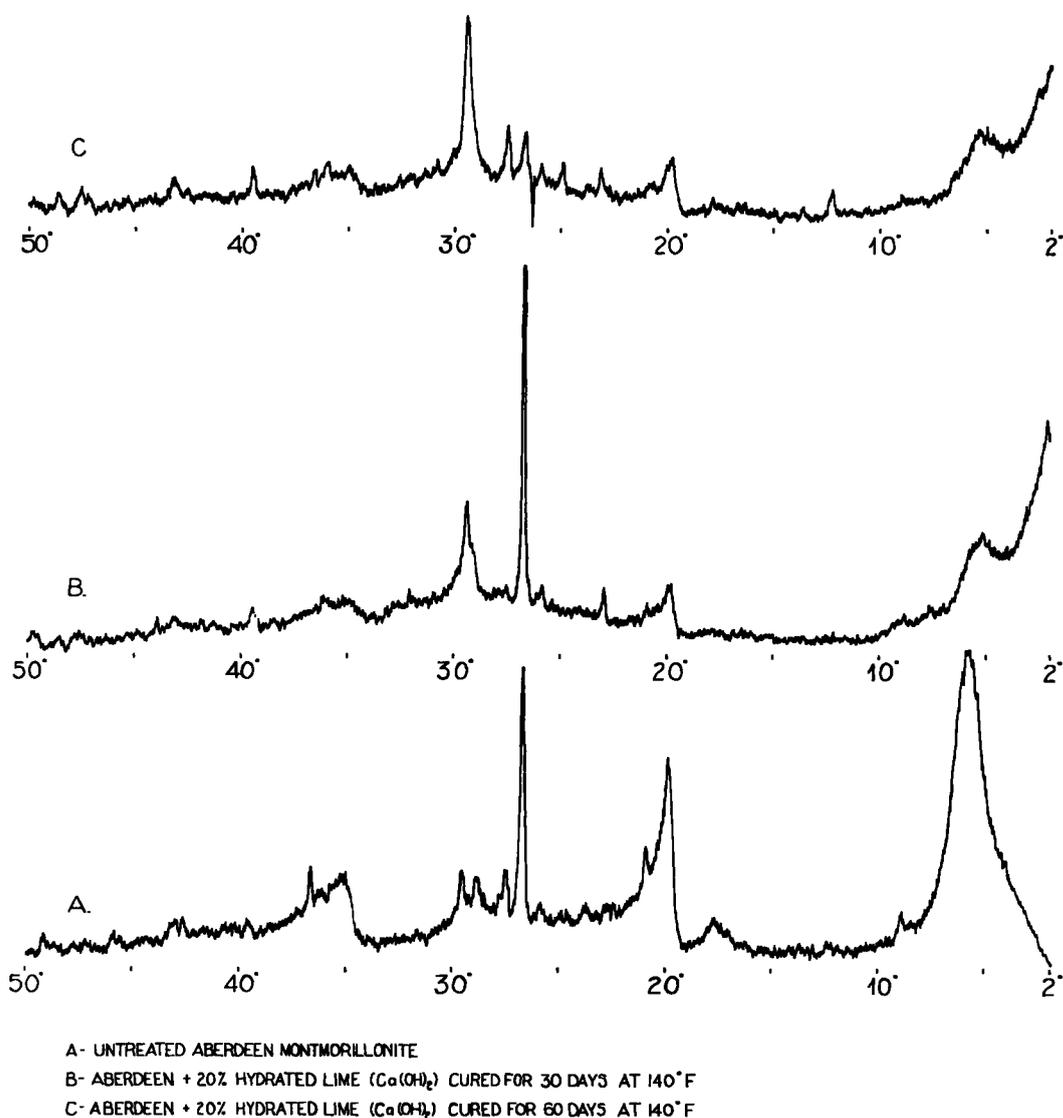


Figure 6. X-ray diagrams of lime-treated Aberdeen.

of lime on the montmorillonite structure. As in the case of the kaolinite, the presence of lime is not exhibited by the thermograph after the samples are allowed to cure. The curves demonstrate the exchange of the  $\text{Ca}^{++}$  ion for the  $\text{Na}^+$  ion. The single endothermic peak between 100 and 200 C in curve A is characteristic of the adsorbed water held by the  $\text{Na}^+$  clay. Curve C of the montmorillonite treated with 5 percent lime and cured for 3 days has a double peak between 100 and 200 C, which is characteristic of a  $\text{Ca}^{++}$  clay. Although curves for the montmorillonite treated with less than 5 percent lime are not shown by Figure 8, the double peak did not appear until the clay had been treated with 5 percent showing that an excess of lime is required before substantial ion exchange will take place in this particular clay. Curve D for the montmorillonite with 20 percent lime shows the structure of the mineral has been almost completely destroyed by the

very small endothermic peaks. Details of the curve cannot be explained at this time; however, it is significant that there are no distinct low temperature thermal reactions suggesting a crystalline calcium silicate hydrate.

### CONCLUSIONS

On the basis of results which have been presented in this paper it is shown that kaolinites, illites, montmorillonites and mixed layered clay minerals react with lime to give greater bearing strengths. The quantity of lime needed to effectively treat a clay mineral is dependent on the type of mineral present.

In the case of kaolinite clays, the increase in strength begins with the addition of the first increment of lime. In the case of illite, montmorillonite and

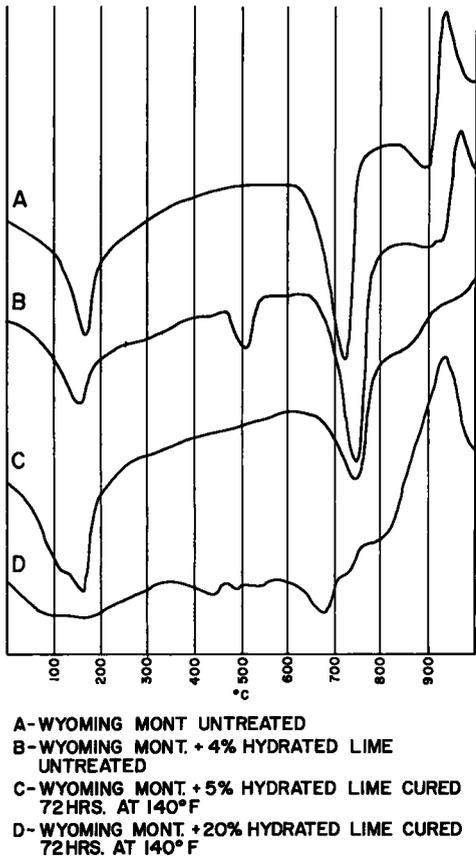
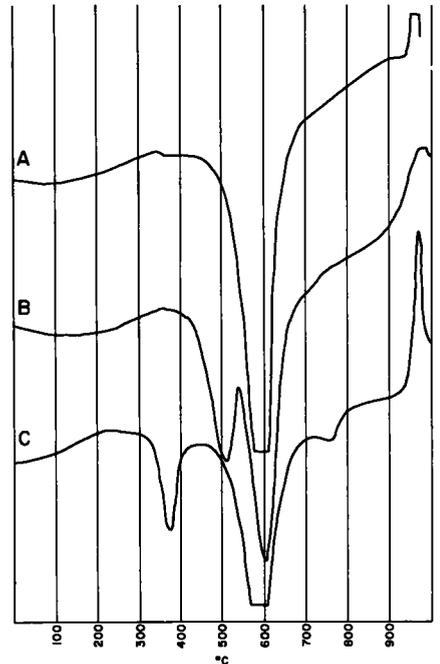


Figure 8. D.T.A. curves of lime-treated Wyoming montmorillonite.



A- GEORGIA KAOLIN UNTREATED  
B- GEORGIA KAOLIN + 20% HYDRATED LIME UNTREATED  
C- GEORGIA KAOLIN + 20% HYDRATED LIME CURED 72 HRS. AT 140°F

Figure 7. D.T.A. curves of lime-treated Georgia kaolin.

some mixed layered structures, lime in excess of 4-6 percent must be added before any strength developed.

The reaction of lime and kaolinite leads to the formation of new crystalline phases which are tentatively identified as calcium silicate hydrates. This reaction seems to take place by the lime eating into the kaolinite particles around the edges with a new phase forming around a core of kaolinite. In contrast the reaction of lime with three layer clay minerals (illite, montmorillonite) begins by a replacement of existing cations between the silicate sheets with  $\text{Ca}^{++}$ . Following the saturation of the interlayer positions with  $\text{Ca}^{++}$  the whole clay mineral structure deteriorates without the formation of substantial new crystalline phases. For illite and montmorillonite there is little strength developed until after the clay is saturated and the clay mineral begins to be destroyed. For the kaolinite the strength begins to increase as some of the calcium attacks the edges of the kaolinite particles.

Although the X-ray and D. T. A. diagrams do not give reflections for calcium hydroxide it is concluded that an excess of calcium is present because of the rate at which calcium carbonate is formed when treated samples are exposed to the atmosphere. That is, during the reaction some free lime is available for the formation of carbonate.

Because the development of strength is accompanied by distinct structural changes in the clay minerals, it seems certain that the changes are relatively permanent. The reaction products causing the increase in strength would be expected to be no more susceptible to leaching than other forms of calcium silicates.

#### REFERENCES

1. "Lime Stabilization of Roads." Bull. 323, National Lime Assoc.
2. Goldberg, Irving, and Klein, Alexander, "Some Effects of Treating Expansive Clays with Calcium Hydroxides." ASTM Special Pub. No. 142, pp. 53-67 (1952).
3. Grim, R. E., "The Clay Minerals in Soils and Their Significance." Proc., Purdue Conf. on Soil Mech. and Its Application, Purdue Univ., Lafayette, Ind., pp. 216-223.
4. White, W. Arthur, "Water Sorption Properties of Homoionic Clay Minerals." Illinois State Geol. Survey, Report of Inv. 208.
5. Ross, Clarence S., and Hendricks, Sterling B., "Minerals of the Montmorillonite Group, Their Origin and Relation to Soils and Clays." U.S. Dept. of Interior, Geol. Survey Professional Paper 205 B (1945).
6. Data furnished by American Colloid Company, Chicago, Ill.
7. Bradley, W. F., Grim, R. E., and Clark, G. F., "X-ray Study of Montmorillonite." Z. Krist., 97, pp. 216-222 (1937).
8. Bernal, J. D., "The Structure of Cement Hydration Compounds." Proc., Third International Symposium on the Chemistry of Cement, pp. 216-260 (1952).
9. Grudemo, A., "An Electronograph Study of the Morphology and Crystallization Properites of Calcium Silicate Hydrates." Swedish Cement and Concrete Res. Inst., Royal Inst. of Tech., Proc. NR 26, Stockholm.