

# Underclay Development Beneath Asphalt Roads in Kansas

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Loessial subgrade materials in contact with asphalt road surfaces in Kansas are undergoing changes in structure, color, and amount of  $<2\text{-}\mu$  clay. Structure is changing from massive or single grain to weak subangular blocky. Color is changing from a pale brown (10YR  $\frac{6}{5}$ ) or light brownish gray (10YR  $\frac{6}{5}$ ) to a green or olive green that is usually a 5y hue in the olive gray range, but the colors appear green to the eye. The amount of  $<2\text{-}\mu$  clay is increasing.

The changes are caused by microorganisms utilizing the asphalt as an energy source. Reducing conditions are set up at the soil-asphalt interface by the actions of the microorganisms where the supply of air and oxygen is limited. This results in a gley or "underclay" development in the upper few inches of subgrade soil. Montmorillonite clay is developing from primary minerals in this zone. Kaolinite is improving in crystallinity in this horizon. Oxidizing microenvironments in a reducing macroenvironment probably accounts for the improvement of kaolinite crystallinity under conditions that favor the formation of montmorillonite. Differences in properties of subgrade materials between failed and adjacent non-failed sections of roadway are not great. Oxygen uptake rates, however, show that failing sections of road have high oxidative action of microorganisms compared to non-failing sections.

•DURING field studies of asphalt road failures associated with loess in north-central Kansas, a thin layer of green or bluish green, plastic, clayey material was observed in the pavement subgrade just below the asphalt mat at failing locations. The green material graded downward through a dark tan zone into Peoria loess and after exposure to air gradually faded to the color of the Peoria loess. Occasionally the green color was faint but the dark tan material was then more prominent. The green material often contained calcium carbonate nodules the same size and shape as the calcium carbonate nodules present in the Peoria loess. These factors could mean that the green horizon was derived from the Peoria loess which mantled the entire area. On the other hand the green material was more plastic than the Peoria loess, which exhibited a massive or single-grain structure, whereas the structure of the green material was weak subangular blocky. These factors indicated that the green material was perhaps not derived from the Peoria loess or had changed in certain properties from the loess. The green plastic material was found only under failed sections of bituminous roads, which might mean that this material was a cause of the failures.

In this study we attempted to determine (a) if the green material was derived from the Peoria loess, and (b) if the green material was causing the failures. To investigate these problems we studied the subgrade material under many failed and adjacent non-

failed sections of asphalt roads. Cut sections of roadway located entirely in Peoria loess provided the study sites. Samples were obtained from the green horizon (usually not more than 0.3 ft thick) at failed sections of roadway. The horizon from 0.3 to 0.6 ft below the base of the mat was sampled at each location and is referred to as tan material in this report. Samples of Peoria loess were obtained from depths of 1.0 to 1.5 ft and from 1 to 3 ft lower. Samples were also obtained from the Peoria loess in the highway backslopes at the same elevation as the green horizon under the mat. A second series of samples was collected from the subgrade of a non-failed section of roadway a few feet from the failed section. These samples were collected from the same depths below the asphalt mat as the samples from below the failed roadway.

Field and laboratory studies consisted of the following:

1. Structure (as defined in Soil Survey Manual (28));
2. Color (Munsell soil color chart);
3. Mat and subgrade temperature (metal sheathed thermometer);
4. Mechanical analysis (hydrometer method of Bouyoucos (3), following the sedimentation times recommended by the Bureau of Reclamation in Earth Manual (9));
5. pH (hydrogen ion meter using a 1:1 loess-water mixture and  $\frac{1}{2}$ -hour tempering time);
6. Microscopic study (oil immersion and Lakeside 70 techniques);
7. Glycerol retention (techniques described by Kinter and Diamond (22)); and
8. Clay mineralogy (X-ray diffraction using standard techniques).

## RESULTS OF INVESTIGATION

### Structure

The structure studies verified earlier observations. The green material found just under the asphalt mat had a weak subangular blocky structure with the individual peds approximating 5 to 10 mm in size. The Peoria loess exhibited a massive or single-grain structure. Small rounded calcium carbonate nodules were often found in the green material; when found there, nodules of the same size and appearance were also present in the tan zone and in the Peoria loess below.

### Color

In contrast to our early observations, not all failed locations exhibited greenish colors and faint mottling was observed at some locations. Furthermore, some non-failed locations had greenish colors; therefore, the role in producing failures is uncertain. The green material was usually of such a color that it did not match the color chart. The nearest matching colors were usually of a 5y hue in the olive gray range. The color of the Peoria loess was normally a pale brown (10YR  $\frac{5}{3}$ ). The green material faded to this color after exposure to air.

Inasmuch as the green material lost its green color upon exposure to air, it was thought that it might be in a reduced state. The use of the Hoffer test described by Jackson (18) verified that the soluble iron in the green material was reduced. All fresh samples that exhibited a green or blue green color reacted with the acid potassium ferricyanide and produced Turnbull's blue color.

The change in color from green to pale brown upon exposure to air was due to oxidation of the iron to the ferric state. From this we deduced that the green material was formed essentially the same as a G-horizon soil. The Soil Survey Manual (28) describes a G-horizon as follows: "This is a layer of intense reduction, characterized by ferrous iron and neutral gray colors that commonly change to brown upon exposure to the air. It is a characteristic horizon in soils developed wholly or partly by gleying. The process involves saturation of the soil with water for long periods in the presence of organic matter." Referring to the colors of the G-horizon the manual further states: "Some G-horizons have olive colors—a few too nearly green for the standard color chart."

Inasmuch as the color of the green material was due to the reduction of iron, it seemed even more reasonable that the green material was developed from the Peoria loess. In order to study this possibility further, petrographic microscope studies were made of the fine sand fraction of both the Peoria loess and the green material.

### Microscopic Analysis

The minus 250 plus 300 mesh fraction of both the green material and Peoria loess contained an average of 40 percent quartz and 44 percent feldspars. Both horizons contained about 7 percent volcanic ash shards and 3 percent each of hornblende and chalcedony. Both materials contained small amounts of plant opal (2). Each material also contained minor amounts of muscovite, biotite, epidote, chlorite, tourmaline, zircon, tremolite, garnet, and magnetite.

The microscopic studies verified the field observations that the green material was developed from the Peoria loess. The mineral content, the amount and character of plant opal and volcanic ash in the two materials was the same.

### Hydrometer Analysis

Hydrometer analysis revealed that the green material just under the mat contained more clay than the Peoria loess from which it developed. The amount of clay  $<2\text{-}\mu$  in size in the green material averaged 33 percent. The range of the clay fraction in the green material was 27 to 39 percent. The Peoria loess samples from 1 ft or more below the asphalt road, and from the highway backslopes had an average of 23 percent clay with a range of 20 to 27 percent clay. Table 1 gives the clay content of samples.

TABLE 1  
CLAY CONTENT ( $<2\text{-}\mu$ ) TYPICAL OF SAMPLES TAKEN DURING STUDY

Horizon	Sample No.	Percent Clay	Sample No.	Percent Clay	Sample No.	Percent Clay
Green	136	34.6	152	33.4	157	39.4
Tan	137	30.6	153	34.0	158	36.0
Peoria	138	25.6	154	20.4	159	24.0
Peoria	140	26.0	156	22.6	161	24.4
Green	186	32.4	217	27.6	222	32.6
Tan	187	28.4	218	23.6	— <sup>a</sup>	—
Peoria	188	23.2	219	21.0	223	24.6
Peoria	189	21.2	221	21.6	225	25.6
Green	251	34.4	267	27.4	283	29.4
Tan	252	32.0	268	23.0	284	26.6
Peoria	254	22.0	269	23.0	285	22.6
Peoria	255	22.0	271	22.0	287	23.4
Green	315	31.2	331	35.6	419	30.4
Tan	316	29.4	332	28.2	420	24.8
Peoria	317	26.2	334	22.6	421	21.8
Peoria	319	27.4	343	22.6	422	22.8
Green	259	30.4	411	29.6	—	—
Tan	260	27.4	412	25.6	—	—
Peoria	262	22.4	413	22.4	—	—
Peoria	263	23.4	414	21.4	—	—

<sup>a</sup>Green and tan sampled together due to the thinness of each layer.

All samples shown in the table were obtained from failed sections of roadway except samples in the sequence 259 to 263 and 411 to 414, which were taken from below non-failed sections of asphalt road.

In comparing the clay contents of the horizons one should read downward in each group of four samples. Backslope samples from the Peoria loess at the same elevation as the green horizon had clay contents nearly the same as the Peoria loess samples taken a foot or more below the mat.

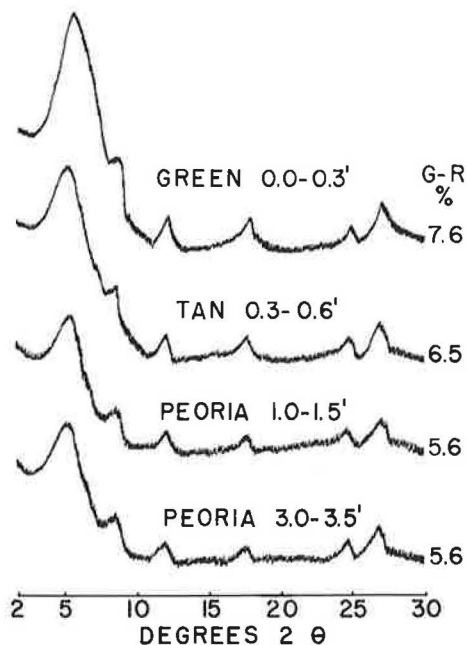


Figure 1. X-ray diffractograms representative of the clays from the horizons studied. The average glycerol retention values representative of the same horizons are shown at the right.

No other clays were found that had not already been identified in the unfractionated clay.

Iron chlorite was differentiated from kaolinite by X-ray diffraction methods after a combination of heating (10) and treatment with warm hydrochloric acid (5), and by infrared spectrophotometer and electron microscope techniques. The chlorite X-ray peaks were destroyed by heating to 450 C, and by acid treatment as well. Kaolinite X-ray peaks were not affected by the acid treatment. The kaolinite X-ray reflections in samples of the Peoria loess disappeared or degraded considerably after being heated to 450 C for one-half hour. This was interpreted to mean that the kaolinite in the loess was rather poorly crystalline. Samples of the green material collected from just under the mat did not show a loss of kaolinite X-ray reflections even when heated to above 500 C. We interpreted this to mean that the kaolinite in the green zone just under the asphalt mat exhibited a higher degree of crystal perfection than the kaolinite in the Peoria loess from which it was derived.

### Glycerol Retention

The glycerol retained per gram of dry soil averaged 7.6 percent for the green material and only 5.6 percent for the Peoria loess. In fact, the glycerol retention values varied in much the same way as did the montmorillonite 001 X-ray reflection; as the area of the main montmorillonite X-ray peak increased, the glycerol retention values also increased (Fig. 1).

### pH

The green horizon and the Peoria loess were both basic; pH was between 7.1 and 8.2 and averaged 7.5 for all samples. The dark tan horizon (0.3 to 0.6 ft) just below the green material sometimes had a lower pH than either the green material or the

### Clay Mineral Composition

X-ray diffractograms of oriented slides of the clay fraction revealed that all of the samples contained primarily montmorillonite and lesser amounts of illite and kaolinite. Figure 1 shows typical X-ray patterns of clays from the green horizon, the tan material immediately below, and the Peoria loess. The relative percentages of the clay minerals present were calculated by measuring the areas bounded by the X-ray curve and the background base line. The areas enclosed under the 001 peaks of montmorillonite, illite, and kaolinite were compared on a 4:1:1 basis. The values obtained were then multiplied by the amount of  $<2\text{-}\mu$  clay. The results showed 27 percent montmorillonite in the green horizon but an average of only 17 percent montmorillonite in the Peoria loess. The illite type of clay found in both the green material and the Peoria loess was 4 percent. Both the green material and the Peoria loess contained an average of 2 percent kaolinite.

The  $<2\text{-}\mu$  clay was subfractionated into coarse, medium, and fine sizes by the supercentrifuge method (17). Iron chlorite was present in minor quantities in the fine clay fraction along with montmorillonite.

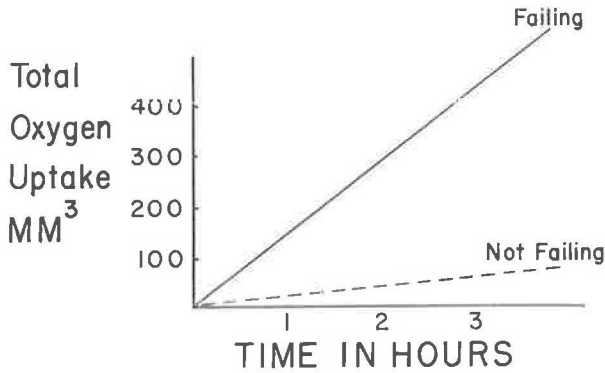


Figure 2. Oxygen uptake rate (per gram of soil) showing high oxidative action in soils under failing asphalt roads (14).

0.3 ft lower were each 90 deg. The Peoria loess 0.5 ft below the base of the mat and 1.0 ft below the mat was 85 deg.

At 12:30 p. m. the air temperature had reached 110 deg. The asphalt in the upper part of the road surface had increased to 112 deg. The soil temperature in contact with the base of the mat had increased to 95 deg. The lower zones had not changed temperature but remained at 90 and 85 deg respectively.

At 4:30 p. m. the air temperature was 98 deg. The temperature of the upper surface of the asphalt mat was 100 deg. The temperature at the soil-asphalt interface was 115 deg. The temperatures 0.3 ft and 0.5 ft below the base of the mat were 100 and 95 deg respectively. At 1 ft the temperature was still 85 deg.

### Bacteria Studies

High populations of bacteria such as *Pseudomonas*, *Micrococcus*, *Flavobacterium*, and *Mycobacterium*, which are capable of utilizing asphalt as a source of energy, were found at the soil-asphalt interface (15). An attempt was made to evaluate the role of the bacteria in asphalt road deterioration, but comparisons between failing and non-failing road sections were inconclusive. Harris (14) made a limited number of oxygen uptake tests. Figure 2 shows high oxidative action associated with soils under failing and low rates under stable asphalt road sections. It is possible that these results are merely fortuitous and that too few samples were studied to give a true result. It may also be possible that even though equally high bacterial populations were found at both failed and non-failed locations, the failed locations produced more active microorganisms. Thus, high bacterial activity may somehow be related to some failures in asphalt mats.

## SUMMARY AND DISCUSSION

Microscopic studies and field relationships have shown that the plastic green material found occasionally at the base of the asphalt roads in the loess areas of north-central Kansas was a reduced horizon or gley derived from the Peoria loess. The clay content of the green horizon increased to 33 percent from an average of 23 percent in the Peoria loess. The increase in clay represented an increase in montmorillonite. Structure changed from single grain or massive to weak subangular blocky. High populations of bacteria capable of utilizing asphalt as an energy source were found at the soil asphalt interface.

Gleying usually involves saturation of the soil with water for long periods of time in the presence of organic matter. The asphalt mat would provide the necessary organic matter, but the green horizon lacked from 0.5 to 4 percent of the necessary moisture

Peoria loess from greater depths. The dark tan horizon occasionally had a pH as low as 6.6, but it was usually above 7.0.

### Temperature

On a day when the air temperature was predicted to reach 100 F, we measured the mat and subgrade temperature periodically throughout the day. The sky was clear and the sun was bright.

The air temperature at 10 a. m. was 95 F. At this same time the top inch of asphalt pavement had a temperature of 97.5 deg. The top of the green material in contact with the base of the asphalt mat and the bottom of the green horizon

for complete saturation. Adams (1), however, reported that a change in soil color and reduced conditions could be obtained without saturation with water.

Several authors have reported that bacteria readily utilize asphalt as a growth medium and destroy asphalt fractions in the process (6, 11, 15, 20, 31). Little has been published about the possible rapid changes in soil minerals that are in contact with asphalt roads during the degradation of the asphalt by bacteria.

Senstius (26), in discussing climax forms of rock-weathering, states that in a "perhumid" environment, where an adequate supply of air and oxygen is lacking, microorganisms cause many mineral compounds to undergo reduction. A mixture of these reduced substances produces the characteristic greenish and bluish or steel-gray color of subaqueous soils, known by the Russian name of gley. Senstius further states that the "underclay" of coal deposits is nothing else but a fossil of gley.

In the present study the presence of hydrocarbon-utilizing bacteria, a change in color from pale brown to green, the existence of reduced conditions, and an increase in clay content are factors that indicate that an "underclay" is forming in the material just under the asphalt mat. It is postulated that the soil bacteria utilize the asphalt as an energy source and that the conditions established during this process cause an alteration of some non-clay minerals to montmorillonite.

According to Keller (21) the following conditions are considered ideal for the formation of montmorillonite: (a) evaporation exceeding precipitation (semiaridity, soils of western United States), or (b) stagnant water and poor leaching or standing water, (c) alkaline conditions, (d)  $\text{Fe}^{++}$  remaining in system, and (e) silicates susceptible to alteration like ash. The retention of Ca and Mg along with high contents of silica is also considered necessary. Conditions similar to (b), (c), (d), and (e) were present at the soil-asphalt interface where the green colors were observed. In addition to volcanic ash several other minerals such as calcite, hornblende, biotite, chlorite, and feldspars, which are low in Jackson's (19) weathering sequence, were present.

The conditions present at the soil asphalt-interface, while favorable for the formation of montmorillonite, are the opposite of those normally considered optimum for the formation of kaolinite, yet there is evidence that the kaolinite in the same horizon is undergoing an improvement in crystallinity. It is not certain that the same conditions required for the formation of a particular clay are also necessary to improve the organization or crystallinity of that clay. Keller (21) suggested that it is possible that the energy necessary for the reconstitution of a "degraded" mineral may be inherited from the relict lattice of the mineral itself. Keller also states that oxidizing conditions favor the formation of kaolinite but that reducing conditions are not incompatible with kaolinization.

Harris (12) stated that the soils in backfilled pipeline trenches contained both aerobic and anaerobic microenvironments within a small space in the soil. Harris (13) reported the occurrence of mottled clays representing local aerobic areas in an otherwise anaerobic environment. Faint mottling of some of the samples from directly under the asphalt mat in the present study indicates conditions similar to those described by Harris. Microenvironments exist where kaolinization can occur under oxidizing conditions, while montmorillonite can form under reducing conditions. The gross or macro climate observed for the green zone, however, was one of reduction, which would explain the more prevalent formation of montmorillonite.

Weaver (32) indicated that it is possible to differentiate between montmorillonites formed from micaceous minerals and those formed as a by-product of volcanic ash devitrification. Samples of the clay fraction from the green material and from the Peoria loess were treated with KOH, following the method described by Weaver. This test indicated that both micaceous and non-micaceous minerals contributed to the formation of the montmorillonite in the green horizon and the Peoria loess.

The petrographic studies revealed that the green material and the Peoria loess were the same. This would at first seem to indicate that nothing had altered to form montmorillonite. In making the petrographic comparisons the fine sand fraction  $>50\text{-}\mu$  in size was used, whereas the hydrometer analysis indicated that it was the 37- to 5- $\mu$  silt material that was reduced in amount proportional to the increase in the clay fraction.



Statistical petrographic studies of the 37- to 5- $\mu$  fraction have not been made. The mineral content of a few samples of the green material and unaltered Peoria loess have been compared in the 37- to 5- $\mu$  range. In these limited studies it was found that the albite, andesine, muscovite, biotite, and volcanic ash contents of the green samples were notably lower than in the Peoria loess samples. This would tend to verify that the montmorillonite was derived from both micaceous and non-micaceous minerals.

The idea of rapid alteration of primary minerals to clay minerals or the alteration of one clay mineral to another at low temperatures and pressures is rather recent among mineralogists, geologists, and soil scientists. Laboratory experiments and field studies, however, have shown that such an alteration is possible (4, 7, 8, 16, 23, 24, 25, 27, 29).

Winterkorn (33) reported a color change from brown to blue, a reduction of ferric compounds to the ferro state, and an accompanying change in the physical properties in a slurry of a homoionic Ca-modification of Putnam soil. Laboratory experiments indicated that the Ca-ion stimulated the growth and activity of anaerobic bacteria, which reduced the iron compounds while oxidizing the organic matter in the soil. Loss of organic matter and the presence of ferro-ions changed the physical properties of the soil. Winterkorn suggested that a decrease in stability of earth fills containing compacted surface soils, which have given trouble on old roads in Missouri, is probably due to some such bacterial action.

The reduced green horizon in the present study was usually found associated with calcium carbonate nodules in the Cca horizon of the loess. The montmorillonite clay was a calcium modification. Thus it is likely that the calcium present in the loess could stimulate the growth and activity of the bacteria present at the soil-asphalt interface.

At present we do not know how much time is needed for a measurable clay increase to occur at the base of an asphalt mat. It is known that the asphalt roads studied in this investigation were surfaced from 10 to 20 years prior to the time of sampling. We have not definitely established that the development of a gley or "underclay" beneath asphalt roads produces failures. There was little consistent difference in the properties of the subgrade material found under failed and adjacent non-failed areas of roadway. Of the 14 locations mentioned in this report, however, 12 reduced zones were associated with road failures and only two were not. This is about the ratio that we have noted throughout the study, but the relationship is not 100 percent. Furthermore, failures were observed that did not have a reduced horizon at the base of the asphalt mat.

It is probable that the type of asphalt and the type of montmorillonite as well as the type of bacteria are important in the montmorillonite-asphalt-microorganism relationship. It has been observed that certain montmorillonite soils and shales in areas of western Kansas sometimes have an undesirable effect on asphalt and road oils, resulting in what is termed as "killing" of the oils or asphalt. "Asphalt rot" is another term commonly used by maintenance men to describe certain types of deteriorated asphalt roads with a characteristic putrid odor. Asphalt roads exhibiting severe "asphalt rot" usually have all the symptoms of bacterial decay of the asphalt and signs of underclay development beneath the road.

If a serious problem does exist, however, one solution would be to use granular material under the asphalt mat. The thickness of the granular material would not have to be great for the purpose of reducing the bacterial action. We observed that where only an inch or two of crushed stone or sand gravel was present under the asphalt mat, no evidence of underclay formation or reduced condition was found. A second alternative, which involves the use of chlorinated asphalt, has been suggested by Ben Burgess (personal communication) who has incorporated pentachlorophenol in asphalt in Montana to inhibit growth of microorganisms. Coal tar roads should be essentially immune to the problem. The studies of Harris (14) indicated that the soil bacteria of the type present under Kansas asphalt pavements do not readily utilize coal tar.

Since the completion of the field studies connected with the work contained in this report, attempts have been made to establish an accelerated alteration of minerals to clay in our laboratory. The laboratory experiments, however, generally produced a reverse of the situation noted in the field where montmorillonite had apparently increased. Studies in the laboratory were made using glucose or gelatine as an energy source for the bacteria. A slurry of loess and water was prepared and one of the energy sources added without mineral salts. The color of the slurry usually changed from tan to gray in a short time. Iron was reduced from ferric to the ferrous state in a few days. Sterile controls did not change color or state of iron. The pH of the glucose-treated samples lowered to the acid sides, whereas the pH of the gelatine-treated samples remained high on the alkaline side.

X-ray diffractograms were made of oriented slides of the clay fraction from the samples after two weeks. The montmorillonite basal peak was weak or nearly absent from the X-ray pattern of the treated samples. The illite and kaolinite peaks were the same as in the untreated samples. At the end of three weeks, the montmorillonite peak was often entirely absent. The intensity of the illite and kaolinite peaks remained unchanged. After standing for 8 to 12 weeks in the treated slurry, the montmorillonite peak began to reappear in the oriented slide X-ray patterns. At the end of 8 months the montmorillonite peak appeared about as intense as in the original untreated material (Fig. 3). It is possible that after several years the montmorillonite peak may become even more intense than originally. The loss of the montmorillonite X-ray reflection was even more pronounced when the finer than  $0.08\text{-}\mu$  fraction of the loess clay was treated with gelatine in the presence of bacteria (Fig. 4).

We are not yet certain what is causing the apparent loss of montmorillonite from the oriented X-ray patterns. At the end of 2 weeks time the montmorillonite peak was very similar to the montmorillonite found in A horizon soils. Sterile controls treated with

either gelatine or glucose produced a similar X-ray pattern after 2 weeks' time. However, the sterile control samples did not show a further loss of montmorillonite at longer time, whereas the samples containing bacteria often revealed a complete loss of montmorillonite from the X-ray pattern. Therefore, the bacteria must alter the organic matter or montmorillonite or both.

The low X-ray intensity of the montmorillonite peaks produced by organic-treated sterile control samples suggests that organic matter may influence the intensity of the montmorillonite peaks in A horizon soils. The montmorillonite reflection in this soil horizon is usually of low intensity and quite broad. Standard peroxide treatment would not necessarily oxidize the organic matter. Taylor (30) found that the  $<2\text{-}\mu$  clay fraction of soil treated for 120 hours in 30 percent hydrogen peroxide still contained 0.42 percent carbon. Our studies also indicate that when the organic matter becomes attached to the montmorillonite clay, it is often quite resistant to oxidation by hydrogen peroxide.

The loss of intensity in the montmorillonite peak may be only a matter of aggregation and loss of orientation in the oriented slide X-ray pattern. However, the orientation of the illite and kaolinite peaks is apparently not affected by the organic matter. Another possible explanation is that the organic matter becomes adsorbed to the external surfaces of the mont-

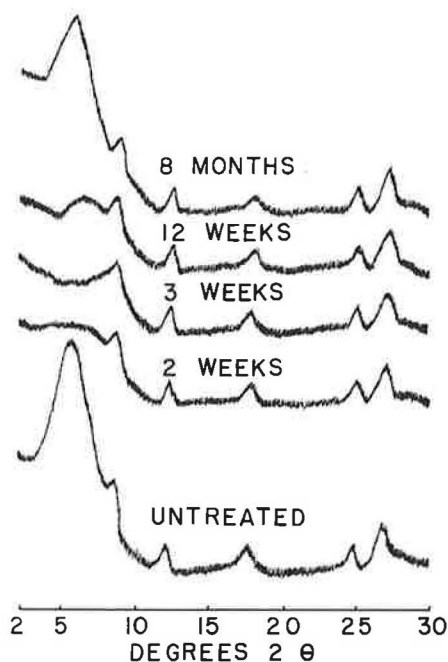


Figure 3. X-ray diffractograms of the  $<2\text{-}\mu$  clay fraction from clayey loess showing effect of treatment with gelatine and bacteria at the end of 2, 3, and 12 weeks, and 8 months.



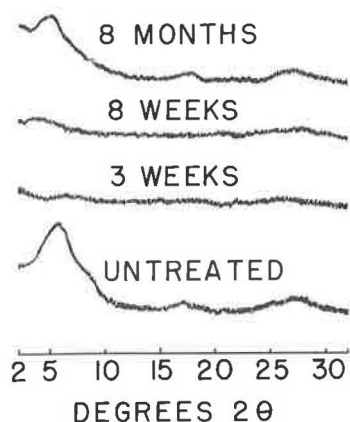


Figure 4. X-ray diffractograms of the  $<0.08\text{-}\mu$  clay fraction from the loess showing the nearly complete loss of clay X-ray peaks 3 weeks after treatment with gelatine and bacteria and the recurrence of the X-ray peaks after 8 weeks and 8 months.

In another study finely ground biotite ( $\sim 200$  mesh) was inoculated with bacteria from the loess soil and a mixture of glucose and gelatine added as an energy source. After standing six months, the sample was vacuum filtered and washed over a Whatman number 42 filter paper. The material caught on the filter paper contained several rounded nodules of silica. Some of the silica nodules were the size of small peas and far larger than any material placed in the plastic jars. No apparent solid material was present in the clear colorless filtrate.

After standing in a plastic bottle for a year, the originally clear and colorless filtrate from the treated biotite sample had turned brownish in color and a brownish sediment was covering the bottom of the container. X-ray and microscope studies of this material revealed that it was biotite. The origin of the biotite is uncertain, but it is believed that it did not pass through the filter paper as solid particles. It is felt that the biotite was reconstituted from a liquid solution containing all of the necessary ions. The biotite flakes observed with a petrographic microscope, however, were noted to be small aggregates of smaller particles. Dekeyser (8) reported a similar recurrence of biotite, possibly forming from solutions containing the necessary ions. Boyle (4) found that acid extracts of biotite were chemically the same as biotite, except for a higher iron and aluminum content.

Studies utilizing asphalt as an energy source for bacterial growth were more difficult to conduct. The clay fraction of asphalt-treated samples was difficult to obtain. MC-0 asphalt was used in the initial studies because of its fluidity at room temperature. This was not the same type of asphalt that had been used in the roads under study. However, a limited amount of data using asphalt as an energy source has been obtained. The asphalt-treated samples in the presence of bacteria were noted to exhibit the greatest apparent change in physical properties. Samples of Peoria loess treated with 2 to 5 percent MC-0 asphalt doubled in plasticity index values compared to the untreated samples. The liquid limit and plastic limit of these samples both increased, but the greatest increase was in the liquid limit. The X-ray diffraction pattern of the clay fraction of the asphalt-treated samples revealed a montmorillonite 001 peak that was sharper and slightly more intense than the untreated samples. The

montmorillonite particles and thereby masks them from the X-ray beam. A thick enough layer of organic material may be adsorbed so that the intensity of the diffracted X-ray beam is lowered. A third possibility may be that the organic matter expands the montmorillonite lattice enough so that the entire 001 reflection is hidden in the area of the main X-ray beam. At the present time, it seems that the masking of the montmorillonite by the organic matter best fits the experimental data. However, two or possibly all three processes may be involved.

The laboratory studies indicate that calcium is released from the exchange position of the bacteria-treated clays. The calcium reacts with  $\text{CO}_2$  produced in the system and forms calcite. An increase in calcite was noted particularly in samples in which the clay fraction only was treated with protein in the presence of soil bacteria. Quartz sometimes increased in these samples as well as calcite, and occasionally very tiny doubly terminated quartz crystals were observed in the treated clay matrix.

kaolinite and illite peaks were apparently unchanged. No data are yet available on what happens to the montmorillonite X-ray peak of the asphalt-treated samples with longer time lapse.

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