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PHYSICAL AND PEDOLOGICAL PROPERTIES OF LOESS SOIL AND ITS HIGHWAY USES

by

Ping Kan Fung

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Highway Engineering

Approved:

Signature was redacted for privacy.

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Dean of Graduate College

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I. INTRODUCTION

In the fall of 1945, a thesis "Loess as Highway Material" was submitted by the author as part of the requirement for the degree of Master of Science. Later, it was decided that this study should be extended to cover a wider scope and to investigate some of the questions raised during the previous study. In this paper, although the author cannot say he has exhausted every possible phase of the subject, he hopes a much clearer picture can be obtained through this extended study.

To a layman, loess is no different from any other kind of soil. True, it may be lighter in color, finer and more powdery than some soil, but it is soil material just the same. Aside from what appears to the eyes, he -- a layman -- is quite indifferent to that particular kind of soil one way or another. However, to a highway engineer, an agronomist, a soil physicist, or a geologist, loess presents a vast and interesting field of study. The highway engineer will want to know whether a road can be built over loess successfully or not, whether loess itself can be used as road material, etc. The agronomist will want to know whether plants can be grown in loess, whether the soil is fertile or not, whether the soil is properly aggregated for adequate drainage, etc.

The soil physicist will want to study the physical characteristics of the soil, the clay minerals present, the base exchange properties, the physical and chemical compositions of the soil, etc. Finally, we have the geologist. He will want to study the origin of loess, its parent materials, its pattern of deposition, its age, etc.

However different the interest of each person may be, the study of loess is still a vast and fascinating subject. Although some previous work by different authors has been done on this subject, no one has yet presented it in the light of one system which will furnish informations to students of different fields. In this research, the author has made an attempt to approach the subject in just such a way that the data and informations collected may be of interest to an engineer, an agronomist, a soil physicist and a geologist alike.

The two loess samples studied throughout this project were obtained from western and eastern Iowa respectively. The exact locations and proper designations of the samples will be given in the following section.

Since the study is a continuation of the previous research project, the author feels that some data and materials from the previous project should be included, even at the risk of repetition, in order to make this thesis a complete study of loess.

II. HISTORY AND GEOLOGY OF LOESS

During the past millions of years there had been changes in the physical aspect of the Earth and in the distribution of animals and plants on the surface of the Earth. However, those changes are so remote, and little or nothing can be learned about them. The more recent change recognized by the geologists was the age of glaciation. Although this took place sometime during the last million years, it is still considered as quite recent geologically speaking. In 1839, Lyell named this epoch Pleistocene -- most recent -- because of the modern aspect of the invertebrate fossils in its deposits (17).

When Pleistocene is mentioned, most people think of glaciation, and properly so, because glaciation was the outstanding event of this million-year epoch. What caused glaciation is one question which no one can answer satisfactorily yet. There have been theories advanced by various persons, but none of them were conclusive. Humphreys (29) suggested that fine dust from volcanoes, flung high into the upper air by explosions such as that of Katmai in Alaska, may screen off the sun's heat and lower the temperature by several degrees, initiating an ice age. Brooks (9) has suggested that changes in the position of high and low pressure and of the cyclonic storm paths might cause glaciation.

Huntington suggested that an increase in solar radiation, instead of giving us a warmer climate, would lead to an ice age by greatly increasing the storminess and sweeping away the warm air from the earth's surface and lifting it to levels where its heat would radiate into space and be lost. However, all these elaborate theories are out of the scope of this study, and they will not be pursued any further.

At the end of the ice age, or rather during the recession of the glaciers, great deposits of rocks, boulders, and soil material were left behind. One of the most remarkable of the Pleistocene deposits is the loess. This is only stated in the sense that loess owes its origin to the Pleistocene deposits.

According to A. K. Lobeck (41), the term loess was first applied to the loose unconsolidated deposits which occur along the valley of the Rhine and extended eastward to the Black Sea. They lie just outside the glaciated area. In North America similar deposits occur along the Missouri and Mississippi Rivers, and vast deposits cover the plains of northern China.

Not all loess deposits can be classed as of glacial origin. The part that belongs to this category is, however, quite abundant, and in most places, stands in a fairly definate relation, both areally and stratigraphically, to deposits of unequivocal drift.

When closely studied, loess of glaciated regions is finer-textured, and also thinner, with increasing distance from its source in the drift. It has been found also that the mineral content of the loess resembles that of the corresponding size-grade fraction of the till in the same region (33). According to Grahmann (20) loess derived from deserts can be distinguished from loess derived from outwash by means of the range of its grain size. Loess derived from the deserts has a much wider range of sizes, including a conspicuous quantity of very fine grains. This comparatively poor sorting suggests the fact that the sediment has been sorted only once during the process of transporting by wind. Loess derived from outwash, in contrast, has but a narrow range of grain size, the coarser and finer particles having been screened out. This more thorough screening suggests a double sorting, first by the action of streams and then wind.

A. Loess Deposits of the World

Figure 1 shows the loess deposits of the world. Notice even in central Africa and Australia, there are still traces of loess deposits. However, the heaviest deposits are in:

1. Central North America, where the deposits cover several of the mid-western states, Figure 1. According to Flint (17), there are two distinct loess regions. The first

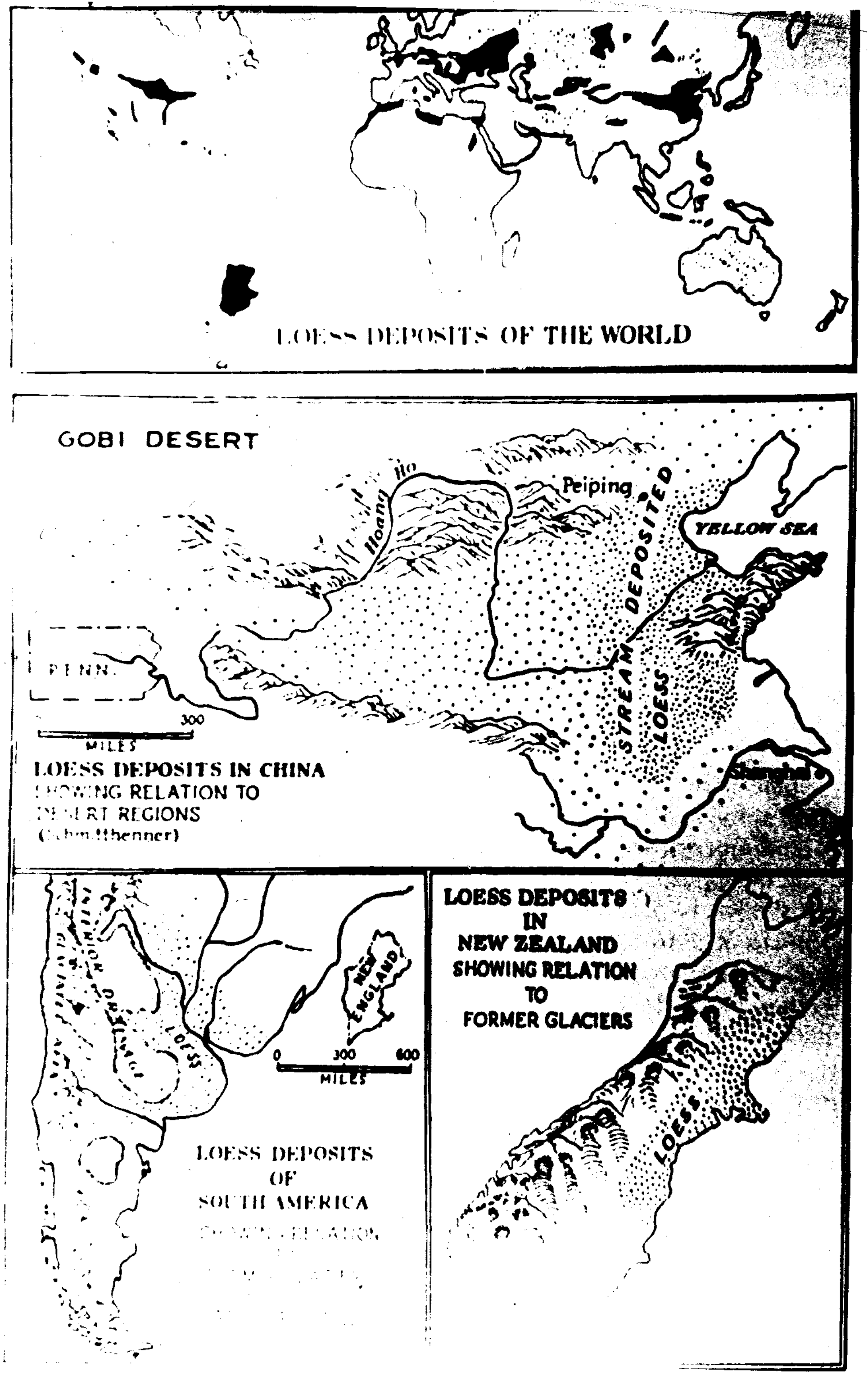
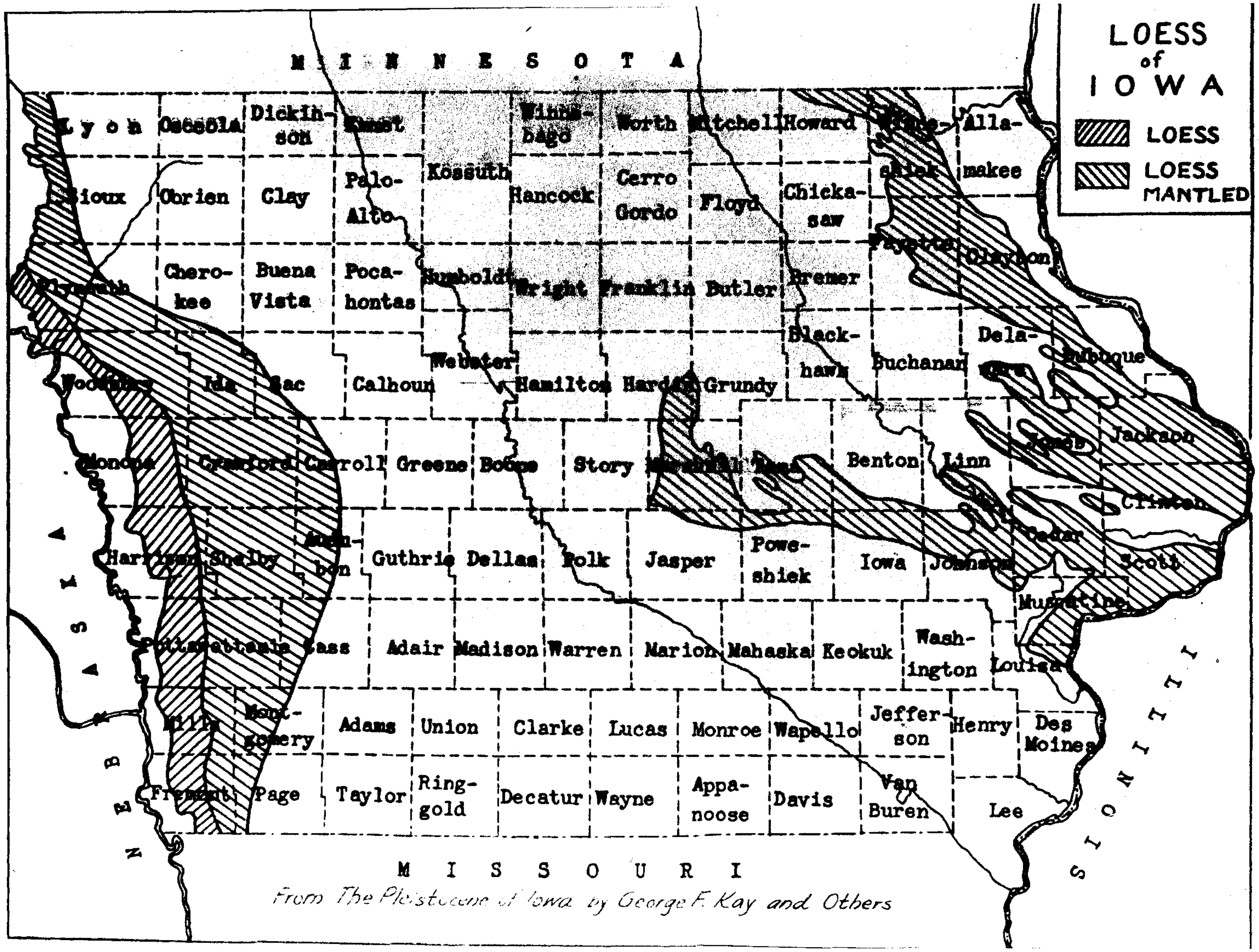


Figure 1. Loess deposits of the world. (From Lobeck's "Geomorphology".) (41, p. 392).



From The Pleistocene of Iowa by George F. Kay and Others

Figure 2. Chief loess deposits of Iowa.

covers western Kansas and Nebraska. (Loess is believed to extend more or less continuously northward into Saskatchewan and Alberta, but little is known and therefore not shown on the map.) This region has a steppe climate and is a source of sediment to windward consisting of extensive exposures of Cenozoic strata.

The second loess region is closely related to the Missouri and Mississippi Rivers and some of their tributaries, notably the Ohio and the Wabash.

Thin loess overlying a Wisconsin drift occurs also in the Palouse area of Washington and Idaho.

2. Asia, where China has the major deposit. Here the loess is specially heavy around the basin of the Yellow River, (The river derived its name from its muddy water caused by the loess deposits.) and adjacent parts of North China, where the deposits form the so-called "loessial region or plateau." This plateau covers the greater part of northern Shensi, southeastern Kansu and western Shansi provinces. For further description, refer to Thorp (64, pp. 14 and 119). However, the term loess is applied to many deposits somewhat similar in appearance to the true loess but differing vastly in age, composition, character, and mode of origin (41).

3. Europe, where the loess is also related to dry climates, to the border of the glaciated region, and to extensive outwash valley trains along principal rivers as

in North America. The deposits there form a rich farm-land belt across northeastern France and Belgium, extending irregularly into Poland, Czechoslovakia, Romania, and southern Russia.

4. South America, where loess forms a broad belt northeast of the extensively glaciated country, covering the plains region of Argentina and Uruguay, especially in the region between latitudes 30° and 40°. The rich black-earth soils of this region are largely of loess origin.

B. Sources and Methods of Occurrence of Loess Deposits

Geologists may vary somewhat in their opinions as regards the origin of loess deposits, but they all seem to agree that the bulk of loess is transported and deposited by the wind. This is brought out by the summaries in Grahmann (20), Obruchev (52), Stuntz and Free (61), and Thwaites (65). Also loess is certainly far more abundant where the climate is dry than where it is moist. Movius (48) has applied this concept of loess as an indication of a somewhat dry climate to China. It has been suggested that the loess in northern and east-central China, areas though today said to be too moist for the accumulation of loess, traces back to glacial-age conditions. Flint (17, p. 467) has this to say,

> A southward shift of the climatic zones through about 4 degrees of latitude would bring the cool dry continental climate now characteristic of Inner Mongolia to northern China. Aided by the glacial

lowering of sealevel with consequent reduction of rainfall from maritime easterly winds, this shift would have brought to northern China distinctly drier conditions favorable to the accumulation of loess. Presumably these conditions were reversed during the interglacial ages.

1. Sources of Loess Deposits in North America. The loess deposits in North America are primarily stream deposits and secondarily wind blown (41). In western Kansas and Nebraska, the loess is believed to be of non-glacial origin. In that fact it resembles the bulk of the loess deposits in central Asia. Loess deposits of the Missouri and Mississippi Valley, however, appear to be derived mainly from outwash. Originally the streams derived the material from the glacial deposits farther north. Some of the dust which has accumulated in the Mississippi Valley, however, is known to come from the wind-blown plains of Colorado, Wyoming, and other western states (41).

In spite of all the research on the sources of loess deposits in North America, there is still some disagreement among different geologists. Leverett (40) believed that the bulk of the loess in central North America was derived from nonglacial sources. Lugn (42, p. 165) though he takes a less extreme position, nevertheless stressed nonglacial sources. On the other hand Kay and Graham (33, p. 73) held the loess in Iowa to be of local origin. So far no general solution has yet been reached.

2. Sources of Loess Deposits in China. Greater part

of the dust which makes up the loess deposits is blown up from the Desert of Gobi in central Mongolia by the prevailing westerly winds and the dry river flood plains of the Hwai and Yangtze. Originally, the loess was thought to have been deposited under water, but its aeolian origin is now universally accepted. However, the great rivers of China, the Yellow River and Yangtze with their tributaries, flowing through the loess territory, have removed large quantities of this fine silt and have redeposited it again over wide expanses of their flood plains (41). This, of course, accounts for the water-borne characteristics.

3. Sources of Loess Deposits in Europe. It was first recognized in 1889 that loess deposits of Europe originated from outwash. This origin is regarded as valid by most geologists for the bulk of the European loess. The outwash is of course related to the glacial deposits which had been carried and spread out by the rivers and also by the spring floods of glacial ages. However, the loess deposits are largely the work of the wind with little stream modification.

4. Sources of Loess Deposits in South America. There is difference of opinion as to the extent to which the loess represents reworked outwash; by some the loess is considered to be in large part the product of deflation of nonglacial alluvium from the semiarid country to the west, in the immediate rain shadow of the Andes.

C. Age and Depth of Loess Deposits

All loess deposits are not of the same age. In 1904, Shimek (57) published several papers on different aspects of loess. In those papers, he pointed out that there is no transition between drift and loess, and that there are loess deposits of different ages.

In determining the ages of loess deposits, one has to go back to the history of the glacial period. It has been more or less agreed by most geologists that the bulk of the loess deposits was the result of the cyclonic winds of the glacial-age. With this brief statement we now turn to the loess deposits of our immediate concern -- the loess of central North America. The stratigraphic position (17, p. 181) of the loess sheets is summarized in Table 1.

The loess sheets of Iowan and Sangamon age are extensive; the extent of the older loess is not known because there is relatively little exposure. However, there is no question of their existence and extensiveness. They must have been largely reworked and removed by erosion, and perhaps also they are widely concealed from view beneath younger deposits.

The Wisconsin loess deposits, classed as glacial, rest on till that is fresh or very little decomposed, showing that they were deposited very soon after (or during) the process of deglaciation.

Table 1

The Stratigraphic Position of the Loess Sheets in Central North America

	"Modern" loess	Very thin loess overlying the latest drift on the Great Plains and other parts of the United States and Canada.
Wisconsin Glacial stage	Tazewell Glacial substage	Thin loess overlying Tazewell drift in western Illinois.
	Iowan Glacial substage	Thick loess overlying Iowa drift and overlain by Tazewell drift. The surface loess of Iowa and of much of western Illinois; present in Nebraska.
Sangamon Interglacial stage		Loess overlying decomposed Illinoian drift and overlain by Iowan drift. Thick in southern Illinois; thinner in Iowa and Nebraska, where it is probably represented by much or all of the Loveland loess.
Yarmouth Interglacial stage		Loess overlying decomposed Kansan drift and overlain by Illinoian till, in Illinois. Loess outside the glaciated region in Nebraska.
Aftonian Interglacial stage		Loess overlying decomposed Nebraskan drift and overlain by Kansan drift in Iowa and Illinois.

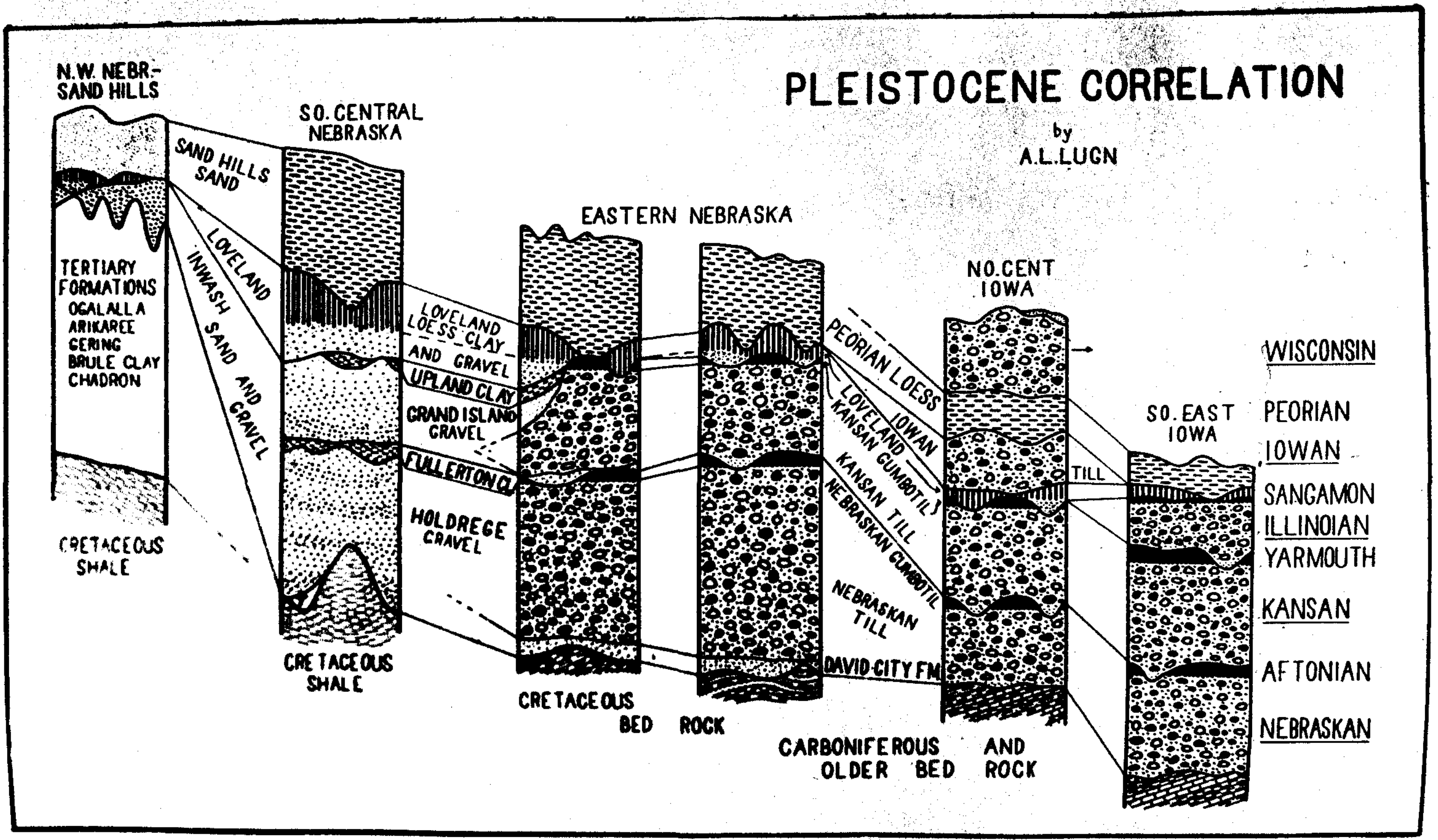


Fig. 3.—Pleistocene relationships in Nebraska and Iowa.

Note—The term Ogallala has had many spellings. It was spelled Ogalalla in the older U. S. Geological Survey reports of Darton. This spelling was used in some of the figure diagrams for this report before it was decided to employ the present day form. The more correct spelling is Oglala.

Figure 3. Diagrammatic sections of glacial and interglacial materials in the Pleistocene relationships of Nebraska and Iowa. (From Lugn's "The Pleistocene Geology of Nebraska") (42, p. 30).

Although there has been a large amount of interesting deductive argument and speculation devoted to the probable optimum time of loess accumulation, the recent tendency in both Europe and America has been to regard the optimum time as the time of maximum glaciation. The character and positions of the Wisconsin loess sheets in North America and in Europe as well, fully support this view.

The Peorian (34, p. 90), which is the youngest loess deposit, covers a large part of western and east-central Iowa. It lies just above the Iowan drift, Figure 3. In fact the loess in eastern Iowa is said to have originated from the Iowan drift sheet. After having made detailed studies of the loess deposits in the Iowan, Kansan, and Illinoian areas, Alden and Leighton (34, p. 108) reached the conclusion that the deposition of the uppermost till of the Iowan drift area occurred but a short time prior to the accumulation of the main sheet of loess which borders and overlaps it, and that the Illinoian till was deposited at a time considerably before this epoch of loess deposition.

The Loveland loess, the older of the loess deposits and which has been subjected to weathering, has been established by stratigraphic method as being much younger than the Illinoian glacial drift and older than the Iowan glacial drift. George F. Kay has this to say (34, p. 98).

> The significance of the determination of the definite age of the Loveland loess must be emphasized. It would seem to settle conclusively the relative ages of the Illinoian glacial stage and the Iowan glacial stage. The Loveland loess was deposited after the development over wide areas on the Illinoian till, chiefly by chemical weathering, of a gumbotil more than three feet thick. Furthermore, there was sufficient time after the Loveland loess was laid down for this loess to be leached to a depth of several feet before the coming of the Iowan ice sheet.

The Loveland loess is generally covered by the other drift deposits, and the accurate depth is hard to determine, although there are some highway and railroad cuts which show the depth of Loveland loess deposits clearly. It is generally understood that the thickness of Loveland loess is variable.

The Peorian loess is, however, near the surface, and the thickness can be determined more accurately and readily. In the Missouri River Valley, the deposits on both sides of the river are one hundred feet or more in thickness, but they thin out rapidly away from the river. The deposits in the Mississippi Valley, however, are not as thick.

In Europe, the vertical range of the loess approaches 2000 feet, so far up the flanks of the highlands has it lodged. In European Russia, the loess is spread over wide areas with thickness of 30 to 50 feet continuous over an area of thousands of square miles. In the region west of the Dneper the loess is thickest and gradually thins out eastwards. Westward too the thickness diminishes, commonly reaching only a very few feet but rising to 20-40 feet along major streams and approaching 100 feet along the east flank of the Rhine valley, its finest development in western Europe.

In China, the loess has been described as 1000 to 2000 feet in thickness, but recent observers doubt if the true loess is much over 200 feet.

In South America, principally Argentina and Uruguay, the thickness of deposits are said to reach 30 to 100 feet over wide areas and in places to exceed 300 feet.

D. Physical and Chemical Composition of Loess Deposits

All loess deposits have similar physical characteristics. They consist of loosely arranged, angular grains of calcareous silt loam intermediate in fineness between sand and clay and of remarkably uniform mechanical composition. Mineralogically it is made up principally of quartz, with smaller amounts of clay minerals, feldspars, micas, hornblende, and pyroxene. Carbonate minerals are variable, ranging as high as 40 per cent. Loess, normally, is without stratification and breaks off in vertical slabs, forming perpendicular cliffs. Sometimes, loess after serious erosions, forms columnar structures. This kind of formations is often seen in China, but is less familiar in this country. The color of loess deposits ranges from light grayish yellow of the unweathered type to reddish yellow of the eroded kind. Fossils, which are abundant in some parts of the loess, consist largely of woodland snails plus a few aquatic snails. Sometimes a few land mammals, mainly rodents but including musk-ox, bison mammoth, may be present.

Another outstanding characteristic of loess is its ability to stand in a vertical cliff. Figures 4 to 5 are some of the pictures taken of the highway cuts west of Magnolia in Harrison County, Iowa, depicting this property. It has been suggested that this is due in part to the angularity of the composing particles, and to the buttressing by rods and tubes which were formed by plant roots and stems. The loess was laid down over and about the plants, and calcium carbonate, which served as a weak cementing agent, was deposited later. This particular characteristic of loess is true only in the case of unweathered deposits.

Lobeck's "Geomophology" (41, p. 389) gives the following description:

> The chemical composition of wind-blown dust varies widely, depending upon the source from which it was derived. The dust falls of the Mississippi Valley contain about 67 per cent silica which represents about 35 per cent quartz, the rest of the silica being aluminum silicates or feldspars. This is much more siliceous than most of the dust storms of Europe which have probably brought their materials from the African deserts. Some of these have less than 10 per cent of quartz but high percentages of silicates, the feldspars running up to over 30 per cent, and an almost equal amount of kaolinite which is the weathered or hydrated form of feldspar. This is all equivalent to saying that Mississippi Valley dust falls resemble far more closely some of the Mississippi loess deposits than they resemble the foreign dust falls.

Figure 4. Harrison County loess, road cut 4 miles west of Magnolia, Harrison County Iowa.

Figure 5. Taking Harrison County loess samples.

The following paragraphs are taken from the Iowa Geological Survey, the Illinoian and Post-Illinoian Pleistocene Geology of Iowa by George F. Kay and Jack B. Graham (33, pp. 172-173).

> Peorian loess is light-yellow and gray in color and shows essentially no stratification. Its particles are angular and are evidently the result of rock abrasion, grinding and impact. Their diameter range from 1/2 millimeter to 1/256 millimeter, but the greatest percentage falls in the size grade 1/8 millimeter to 1/64 millimeter. Quartz is by far the most common mineral. Other constituents are feldspar, muscovite, glauconite, pyrite, magnetite, ilmenite, hornblende, pargasite, glaucophane, actinolite, tremolite, hypersthene, enstatite, augite, aegerite-augite, aegerite, chlorite, andalusite, epidote, zircon, garnet, tourmaline, titanite, biotite, staurolite, topaz, kyanite, rutile, brookite, barite, monazite, riebeckite, basaltic hornblende, and anthophyllite.
>
> Chemically, the Peorian loess of Iowa contains SiO_2, TiO_2, MgO, CaO, Na_2O, K_2O, Al_2O_3, Fe_2O_3, FeO, Mno P_2O_5, H_2O, CO_2, ZrO_2, S, Cr_2O_3, and BaO. Where the loess has been exposed to chemical weathering over a sufficient time, the calcium carbonate has been leached out.
>
> Curiously shaped calcareous concretions known as carbonate about plant roots, are found in many places in the loess. The fossils with few exceptions are of land origin and in large part consist of land gastropods.

The Loveland loess is much finer than the Peorian loess. It has more clay and the organic matter content is higher. The color is more on the reddish side than light-yellow. Because the Loveland loess was deposited earlier than the Peorian loess, it has, therefore, been exposed to weathering longer.

Figure 6. Loess hills along Missouri River in Harrison County, Iowa.

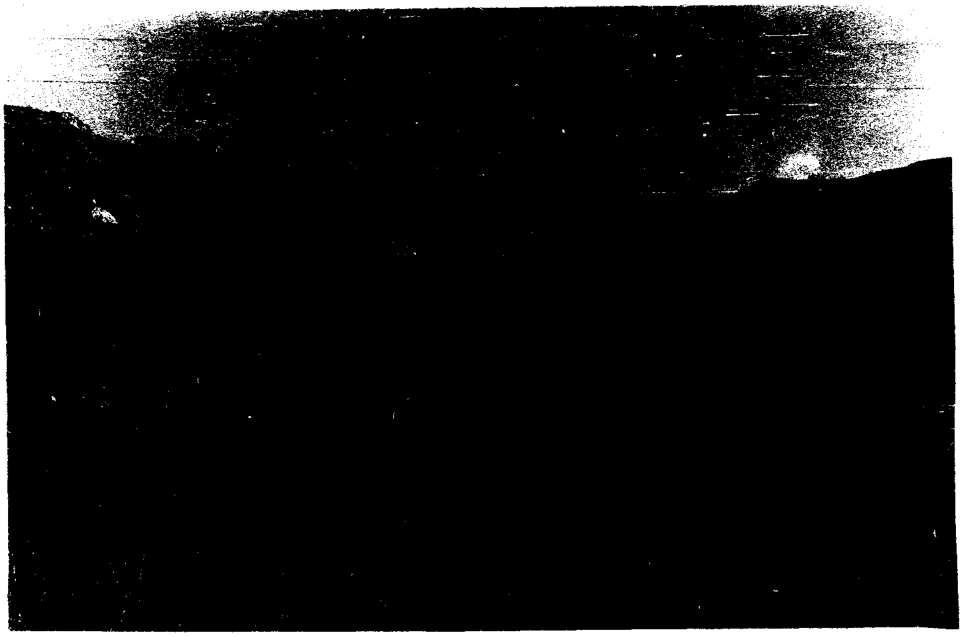


Figure 7. Closer view of the loess hills.

Figure 8. Johnson County loess, road cut north of Iowa City, Johnson County, Iowa.

Figure 9. Taking Johnson County loess samples.

III. LOCATION AND DESIGNATION OF LOESS SAMPLES

Prior to making this study of loess, field trips were made on a tour of inspection of roads and road-cuts in western and eastern Iowa through loess territory. The first field trip to Missouri Valley region was made in the summer of 1944, and later in the fall of that same year, another field trip was made to Iowa City region. A sample of loess from each region was taken as the most typical of the Iowa loess deposits. Tests were performed on those samples, and data and results were presented in the author's first paper. Later on, more samples were obtained from the same locations to conduct further tests and the results are presented in this second paper.

In order to give as complete a picture as possible, it is necessary here to give a brief description of the two loess samples taken from highway cuts in western and eastern Iowa respectively.

The Missouri Valley loess sample was obtained from one of the road cuts on Iowa 127, Harrison County, about four miles west of Magnolia. The sample was taken near the bottom of the cut, which is about sixty feet deep, on the north side of the road, Figure 4. This loess, when dry, has a light grayish-yellow color, and crushes rather easily to a powdery material. It has little supporting strength in its undisturbed condition.

The Mississippi Valley loess sample was taken from one of the road cuts on Iowa 261, Johnson County. The exact location was about seven feet from the top of the road cut at a point about sixty-nine feet from the center of the road on the west side of the cut, Figure 8. The stationing is 46+64, Project FA-765-A (Iowa State Highway Commission Files). This loess when dry has a reddish-yellow color with rusty colored streaks showing the presence of iron.

Previously, for want of better names or designations, the name "Missouri loess" was used on the Missouri Valley loess sample and the name "Mississippi loess" was applied on the Mississippi Valley loess sample. Practically, there is nothing wrong with those designations. In fact, they are the names that appear on most soil survey maps. However, technically, they do not mean very much, and also they cover a wide territory. At this point, the author is faced with the problem of having to furnish the loess samples with suitable terminology.

Turning from the field of soils to the field of geology we have terms like Peorian loess and Loveland loess. Again these terms are too general. If anything, they cover a still wider area. The term Loveland loess is not applicable at all because it represents loess deposits of earlier age and which have been subjected to weathering, and neither the

Missouri Valley sample nor the Mississippi sample is under this category.

Through further research along this line, and through personal correspondence with Mr. R. V. Ruhe of the Department of Geology at Iowa State College, the terms Iowan-Tazewell loess and Iowan loess were obtained, based on the fact that one kind of loess was deposited over the Iowan and Tazewell drift sheets and another over the Iowan drift sheet primarily.

According to Mr. Ruhe, the Missouri Valley loess sample will be under the heading of Iowan-Tazewell loess and the Mississippi Valley loess sample under that of the Iowan loess. Although these two terms will identify the two loess samples from a geological point of view, they still cannot be considered as specific. In other words, they are applicable to loess deposits of vast areas.

In order not to involve too deeply in geological and agronomical terms, the author proposes to designate the two loess samples with simple terms like the names of the counties where the samples were obtained. Hereafter, the Missouri Valley loess sample will be designated as Harrison County loess and the Mississippi Valley loess sample as Johnson County loess.

IV. INVESTIGATIONS

In order to have a complete knowledge of the two loess samples under consideration, certain preliminary tests have to be performed. These are mostly standard tests conforming to the specifications set up by the American Society for Testing Materials (A.S.T.M.), the American Association of State Highway Officials (A.A.S.H.O.), and the Public Roads Administration (P.R.A.). In this case, all the preliminary work had been done previously and therefore will not be repeated here. However, the results are summarized in Table 8.

A. Particle-Size Distribution Study

One phase of this research problem which requires more attention is the particle-size distribution study. The sand and silt fraction of the soil, though important in as much as they are part of the whole system, are not the active factors of the soil. It is the fine materials -- clay and its colloidal components -- that are really responsible for the major chemical and physical activities of the soil, because of the large amount of surface exposed per unit mass (5, p. 63).

There is a recent tendency in the field of highway and soil engineering to pay more attention to the soil colloids.

The Bouyoucos Hydrometer Method of studying particle sizes is becoming unsuitable for this kind of work. In the near future, some standard method suitable for making this kind of study will have to be adapted in the highway engineering field. In this research, three different methods of studying particle-size distribution were employed.

1. Bouyoucos Hydrometer Method.

This method was used in making previous studies and is also standard procedure for determining soil particle-size distribution. No further mention of the procedure will be necessary here. However, more will be said about this method in the later part of this manuscript.

2. Long-arm Centrifuge Method.

This method is primarily used to determine the particle-size distribution of fine clayey material. Norton and Speil (51) developed this method, and with it grain size distribution curves extending to 0.1 micron may be obtained in a few hours.

Apparatus used:

Long-arm centrifuge (as shown in Figure 10).

Hydrometer -- large bulb type suitable to give specific gravity to the nearest 0.0001.

Dispersing agent -- NaOH pellets.

Shaker, 325M screen, balance, thermometer, etc.

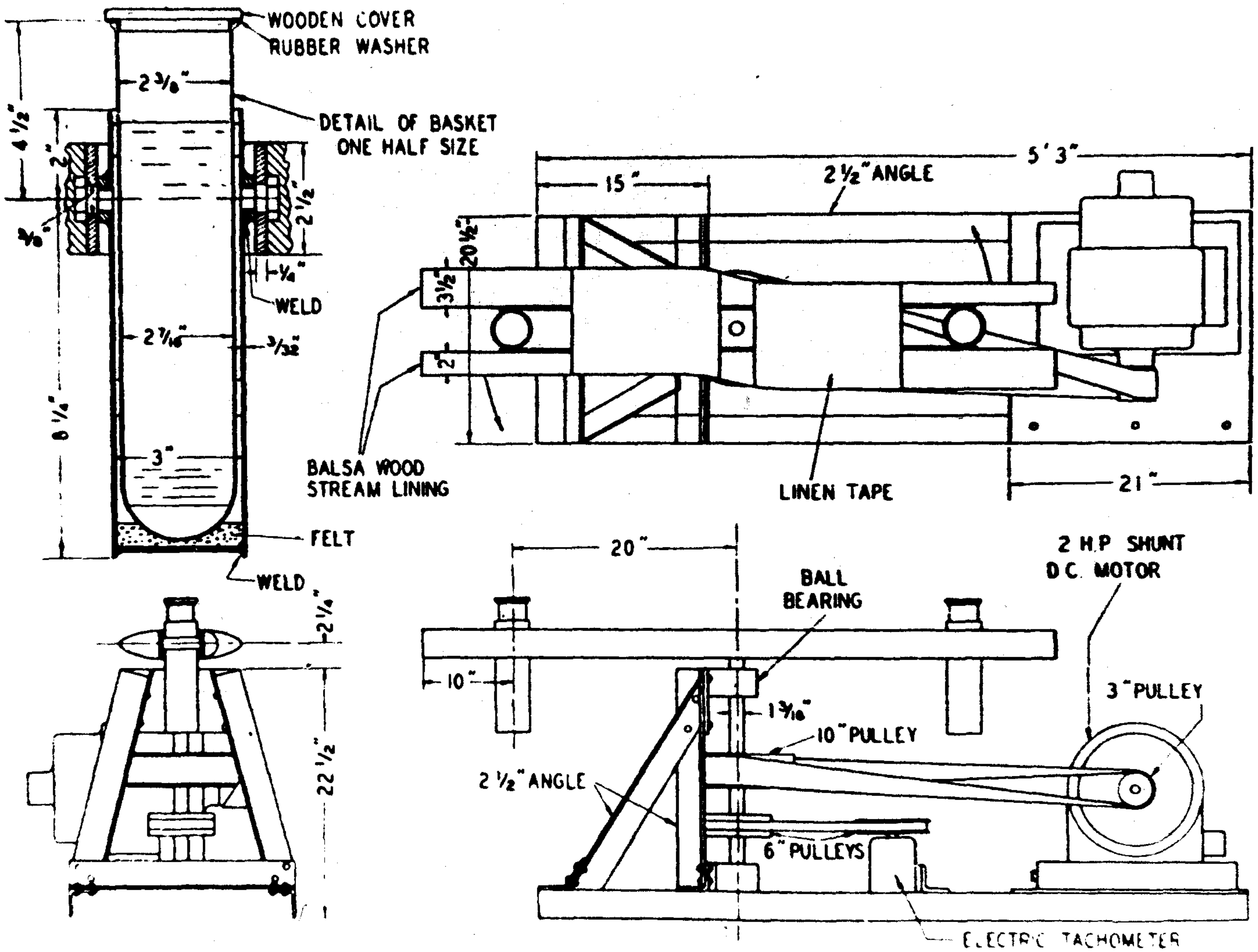


Figure 10. Long-arm centrifuge in diagrammatic form. (From Norton and Speil, Journal of American Ceramic Society.) (51, p. 92).

Procedure:

A representative sample of about 25 to 30 grams of soil passing No. 10 sieve was weighed out to the nearest 0.01 gram. The sample was then soaked in 400 to 500 cc distilled water for overnight. The moisture content of the soil was determined by weighing out a separate sample and drying to constant weight in an oven maintained at 105° C.

After soaking, the sample was transferred to a quart fruit jar. The jar was then placed in the shaker for 4 to 5 days until good dispersion was obtained. After completion of the shaking period, the sample was transferred quantitatively from the jar to the container used in the long-arm centrifuge.

The sample to be analyzed was diluted exactly to 700 cc and NaOH was added as the dispersing agent. Before starting the run the sample was shaken end over end to insure a homogeneous suspension by stoppering the test tube to prevent spillage. The starting time was taken at the instant the test tube was in the vertical, upright position at the end of the shaking period. The test tube was placed carefully but swiftly into the metal basket, and half a minute before a reading the hydrometer was inserted slowly. The specific gravity was read at the top of the meniscus exactly at the scheduled time. Twenty seconds were allowed for inserting and removing the hydrometer and about ten seconds for the equilibrium position to be reached.

Two samples were run concurrently; the second was started 12 minutes after the first sample to prevent any overlapping in the early stages. After the first ten minutes of the test, temperature readings corresponding to the hydrometer readings were taken. Temperatures, precise to 0.2° C. were taken and the temperature of the suspensions was kept as constant as possible during the run. Since differences in specific gravity readings and not actual values of the suspensions were required, the equivalent hydrometer reading on a blank solution containing an equivalent amount of NaOH, was obtained.

Calculation:

Casagrande's nomograph (13) for the Stokes Law was used in calculating the particle diameters. To determine the percentage of material finer than any given size, the following relation was used:

$$W \text{ per cent} = \frac{S}{S-1} \times \frac{100}{c} (R-d) \times 10^3$$

where

S = Specific gravity of suspended material,

c = Concentration of suspended matter, grams per liter,

R-d = Difference in specific gravity between
suspension and blank at the same temperature.

The data were plotted on semi-log paper as shown on Figures 11 and 12. For complete description of this method, refer to the article by Norton and Speil (51).

3. Pipette Method.

This method of mechanical analysis, though not used in the field of highway engineering, is widely used in the agronomy field. Comparatively, this method is more tedious and requires more careful work than the previous two. However, though impractical to obtain a complete particle-size distribution curve with this method, it, nevertheless, is a very useful procedure for checking data obtained by the Bouyoucos Hydrometer and Long-arm Centrifuge Methods. This test is introduced here primarily for the purpose just mentioned.

The fundamental principle of the pipette technique is to determine the density of a suspension at a given depth as a function of time. Variations in density are measured by taking samples of a definite volume at the required depth and determining the dry matter contained therein. For the complete analysis of this method, refer to Baver (5, p. 53).

Apparatus used:

Pipette - 25 cc pipette connected to suction bottles,
Graduate cylinders -- 1000 cc capacity,

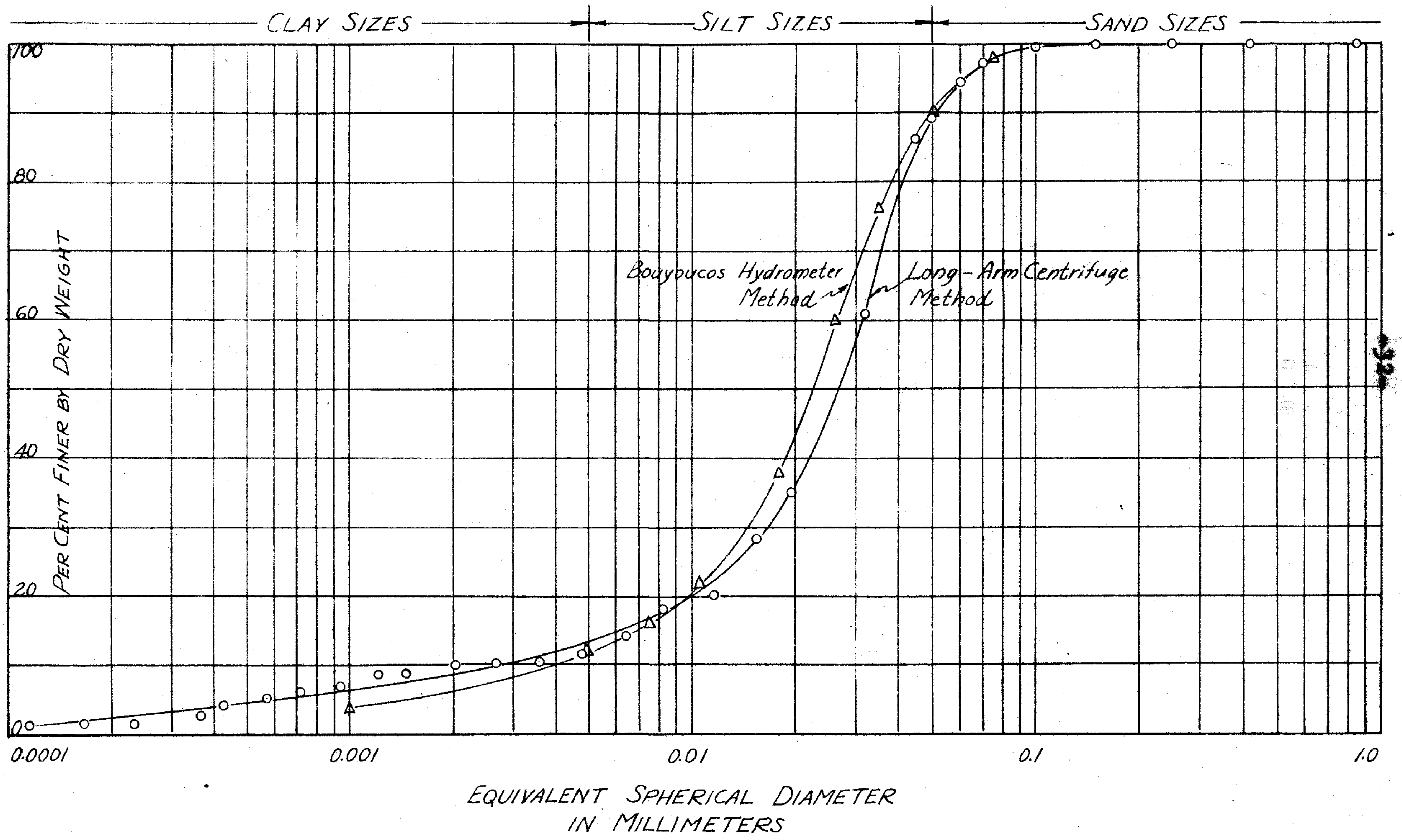


Figure 11. **Particle size distribution curve for Harrison County loess.**

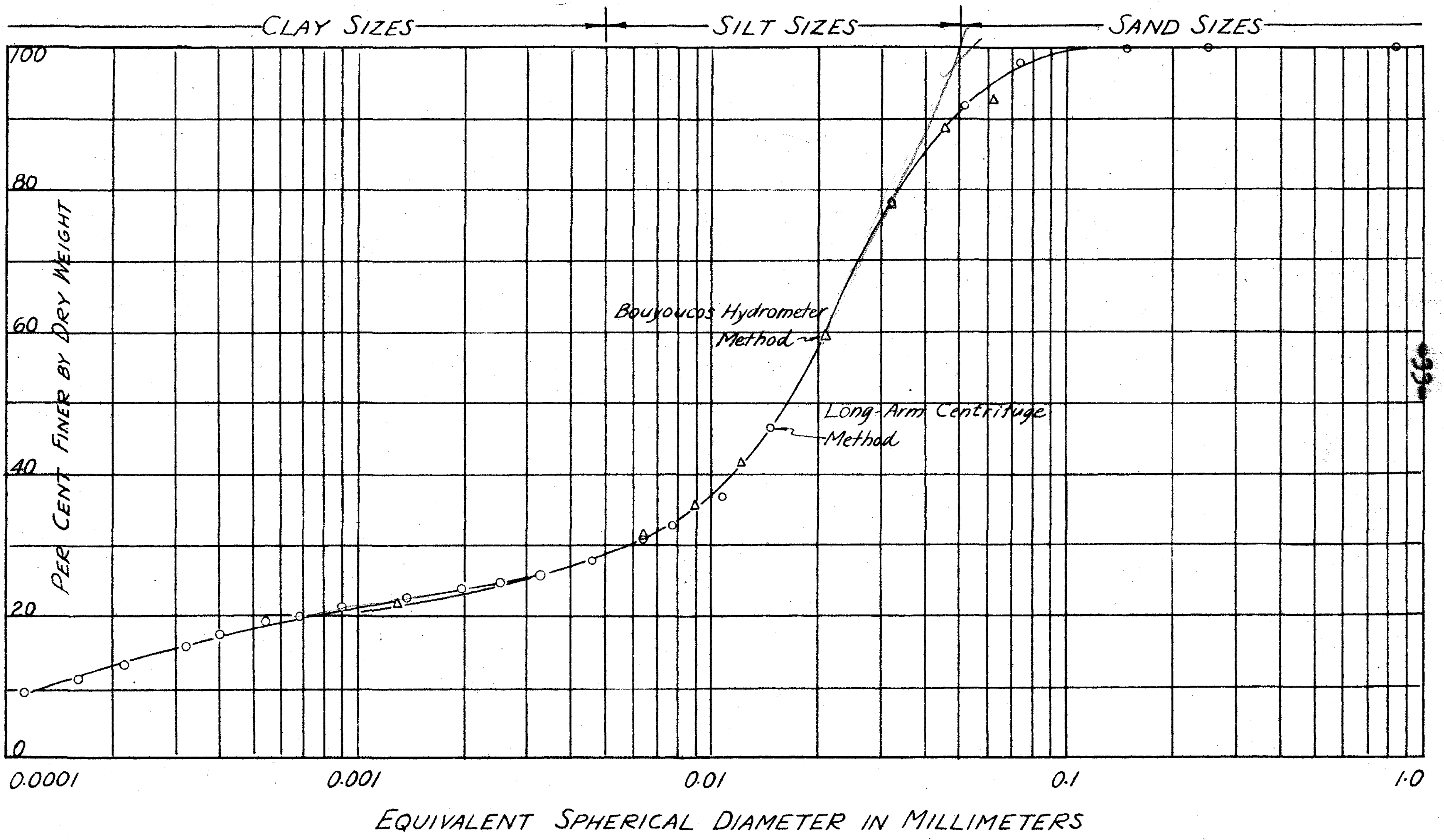


Figure 12. Particle size distribution curve for Johnson County loess.

Balance -- sensitive to 0.001 gram,

Chemicals -- sodium-hexa-meta-phosphate, 0.1N NaOH, 0.1N HCl,

Oven -- capable of maintaining temperature at 105° C.,

Weighing bottles, quart milk bottles, end-over-end shaker, 300 M screen, funnels, etc.

Procedure:

Duplicate 10 gram samples were weighed out for the test. Two different methods of dispersing the soil were used: (a) With sodium-hexa-meta-phosphate -- The 10 gram samples were placed in quart-milk bottles and 300-400 cc of distilled water were added to each bottle together with 10 cc of sodium hexa-meta-phosphate. The bottles were then placed in the end-over-end shaker for over night, about sixteen hours. (b) The 10 gram samples were placed in 200 cc beakers, and about 100 cc 0.1N HCl were added to each beaker. The mixtures were left over a hot plate for at least five hours. The mixtures were then washed through filter paper by suction method removing away as much as possible the HCl, and 0.1 N NaOH was added later until the solutions turned pink to phenolphthalein. The samples were now transferred to quart-milk bottles and 300-400 cc of distilled water were added to each bottle. The bottles were then placed in the end-over-end shaker for at least sixteen hours.

After removing from the shaker, the samples were transferred to 1000 cc graduates and distilled water was added to each graduate to bring the volume up to one liter. Before starting the test each graduate was shaken end-over-end for about one minute. Time of start of the test was taken at the moment the graduate was placed on the table in the vertical position. At each calculated interval and depth, a sample of suspension was removed from the graduate by the pipette, and this in turn was weighed and dried to constant weight in the oven maintained at 105° C.

From the resulting data, the per cent of each size fraction of soil particles for the total sample was determined.

Calculations for rate of settling of soil particles in suspension:

Stokes Law: $V = \frac{d}{t} = \frac{2}{9}(\frac{dp - D}{n})gr^2$

where V = the velocity of particles toward periphery of the bowl in cm/sec.,

r = radius of particles in cm,

dp = density of particle,

D = density of water,

g = acceleration due to force of gravity in cm/sec.^{2},

d = distance of settling,

n = viscosity of suspension in poises.

Percentage of different size fractions to be determined:

Diameter of particles: 0.002 mm, radius = 0.001 mm
0.005 mm, radius = 0.0025 mm
and 0.02 mm, radius = 0.01 mm

dp of Harrison County loess = 2.675
Johnson County loess = 2.685
Average = 2.68

D = 1.00

d = 8 cc (for 0.02 mm particles, d was taken as 15 cm)

g = 981 cm per second^2

For 0.002 mm and 0.005 mm particles:

$$V = \frac{8}{t} = \frac{2}{9}\left(\frac{2.68-1.00}{n}\right)981r^2 = \frac{366.24r^2}{n}$$

and $t = \dfrac{8n}{366.24r^2}$

Table 2

Results from Pipette Method of Particle Size Analysis of Harrison County Loess and Johnson County Loess

Dispersing Agent	Sodium-hexa-meta-phosphate		(Treated with HCl and leached with H_2O)NaOH	
Loess Type	Harrison County	Johnson County	Harrison County	Johnson County
Retained on 300M	31.17%	18.76%	18.22%	11.03%
0.02-0.05 mm	42.20%	50.22%	---	---
0.002 mm and smaller	17.22%	24.16%	14.47%	22.85%

For 0.02 mm particles:

$$t = \frac{15n}{366.24r^2}$$

Table 3

Settling Time of Different Size Particles in Relation to Temperature

Temp.	n in poises	r = 0.0001 cm t = 2184300n	r = 0.00025 cm t = 349490n	r = 0.001 cm t = 40957n
24°C	0.00929	5.636 hrs.	0.9023 hrs.	0.1057 hrs.
26°C	0.00878	5.327 hrs.	0.8528 hrs.	0.0999 hrs.
28°C	0.00838	5.083 hrs.	0.8139 hrs.	0.0953 hrs.
30°C	0.00804	4.878 hrs.	0.7806 hrs.	0.0915 hrs.
32°C	0.00770	4.672 hrs.	0.7472 hrs.	0.0876 hrs.

B. Physico-Pedological Properties of Loess

1. Classification of Loess Samples.

During recent years soil survey data furnished by the U. S. Department of Agriculture have been used quite extensively in highway work, especially in planning preliminary locations of roads and highways. Although the terms used are slightly different, yet the data, soil survey maps, etc. are very useful when they are interpreted properly.

To a pedologist the formation of soil is a function of climate, vegetation, topography, geological material, and time. The terms profile and soil type are units employed in making a study of soil formation. Profile is defined as the vertical cut of soil, and the formation of a soil profile can be divided into the following three steps:

a. Laying down of geological material.
b. Biological development in material -- accumulation of organic matter.
c. Differentiation into layers,
    (1) Horizon of accumulation of organic matter.
    (2) Horizon of oxidation and formation of clay.
    (3) Unmodified geological material.

A soil series is a group of soils with similar profile features. Each series has a defined range in profile characteristics. Expressing this in the form of an equation, we have:

$$\text{Soil}_{\text{(profile)}} = f(\text{Climate, topography, time, geological material, vegetation})$$

By studying the soil profile and the related features of the soil in the field, any soil can be classified according to Glinka's (19) Great Soil Groups. However, a thorough study of this subject is beyond the scope of this research, and any further study on this subject can be obtained from Glinka (19) or U.S.D.A. (66) Year Book, Soils and Men. A more recent reference on soil classification can be obtained in the 1949 publication of Soil Science (58b).

According to the soil survey report of Harrison County (59), there are two loess-derived soils in the county classified in the Marshall and the Knox[1] series. Together they cover 52.5 per cent of the total area. However, the Harrison County loess sample under investigation was obtained at a point near the bottom and about sixty feet from the top of the highway cut. The road cut is about four miles west of Magnolia on Iowa 127. This sample of loess can be considered as the parent material from which the Knox Silt Loam which covers the bluffs along the Missouri River, was developed.

The Johnson County loess sample was obtained from one of the road cuts about a mile north of Iowa City on Iowa 261. The sample was taken at a point seven feet from the top of the road cut. The loess deposits of this area have all been subjected to weathering and erosion, and from these deposits the Clinton, Tama, and Muscatine loess-derived soils were developed. The Clinton Silt Loam[2] is the largest loess type soil and by far the most extensive individual soil in the County, covering 45.9 per cent of the total area (60). The Johnson County loess was sampled in this district.

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[1] To be reclassified as "Ida" series in the future.

[2] To be reclassified as "Fayette" series in Johnson County in the future.

At this point, the author would like to introduce also the U.S.P.R.A. soil-classification. Since the procedure for this step has been included in the first paper, it will be sufficient to state that the Harrison County loess is a "silt," A-4 soil with a group index of 6 and the Johnson County loess is a "silty-clay loam" type of soil and falls in the A-7 soil classification with a group index of 7.

2. Clay Minerals in Loess.

Prior to the introduction of clay minerals into the field of highway and soil engineering, clay to an engineer was just the fine fraction of soil material, which has high strength when dry but loses its stability when excess water is present, which has plastic properties, which has low permeability, etc. However, he did not know what caused the clay to behave in such a manner. Modern studies demonstrate that clays are made up of recognizable minerals. This goes a long way to explain some of the characteristics of the material called clay.

The following groups of mineral constituents are common in clay (36).

From our point of view, the montmorillonite group of clay minerals is by far the most important, since it is responsible for causing most of the detrimental effects in a soil. Besides, it is one of the most widely occurring clay

Table 4

Mineral Constituents Common in Clay

Group	Mineral	Chemical Constituent	Structural Type (lattice)
Kaolin Group	Nacrite	$Al_2O_3.2SiO_2.2H_2O$	Nacrite
	Dickite	$Al_2O_3.2SiO_2.2H_2O$	Dickite
	Kaolinite	$Al_2O_3.2SiO_2.2H_2O$	Kaolinite
	Anauxite	$Al_2O_3.3SiO_2.2H_2O$	
	Halloysite	$Al_2O_3.2SiO_2.2H_2O$	Halloysite
	Allophane	$Al_2O_3.nSiO_2.nH_2O$	No regular lattice
Montmorillonite Group	Montmorillonite	$(MgCa)O.Al_2O_3.5SiO_2.nH_2O$	Montmorillonite
	Beidellite	$Al_2O_3.3SiO_2.nH_2O$	
	Nontronite	$(Al,Fe)O_3.3SiO_2.nH_2O$	
	Saponite	$2MgO.3SiO_2.nH_2O$	
Hydromica or Illite Group	Sericites or Potash Clays	$(OH)_4K_y(Al_4.Fe_4.Mg_4.Mg_6)(Si_{8-y}.Al_y)O_{20}$	(Composition generally varies)[1]
Mica Group	Muscovite	$K_2.Al_4(Si_6O_{20})(OH)_4$	
	Chlorite	$Mg_5Al_2(Si_3O_{10})(OH)_8$	

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[1] Refer to Grim, Bray and Bradley (23).

mineral groups. The lattice, Figure 13, varies in dimensions, but evidently retains the same arrangement throughout the group. Changes in the distribution and amounts of other ions affect the silica content. Montmorillonite consists of structural units of one gibbsite[1] sheet between two sheets of tetrahedral silica groups stacked one above another in the direction of the C-axis. The structural units are loosely held with water in large part between them. The water is so loosely held, in fact, that samples of montmorillonite may be shown to vary perceptibly in water content with the humidity of the atmosphere. Montmorillonite type clay minerals have pronounced basal cleavage, and fragments have flake-shapes. Thin particles sometimes exist in sizes up to several millimeters in diameter, but they can be broken down usually to less than 0.1u by simple agitation in water. Base exchange capacity of montmorillonite is very high. Further discussion of this property will be given in the following section.

The next group of clay minerals which is of importance is the kaolin group. Since the study of clay minerals is not the main purpose of this research, it will be sufficient to just consider the most common clay minerals in this group -- kaolinite. The kaolinite structure is composed of units of one gibbsite sheet with a single sheet of tetrahedral silica group, Figure 13. The lattice structure does not expand with varying water content and no replacements by Fe or Mg of the

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[1] Refer to Baver (5, p. 18).

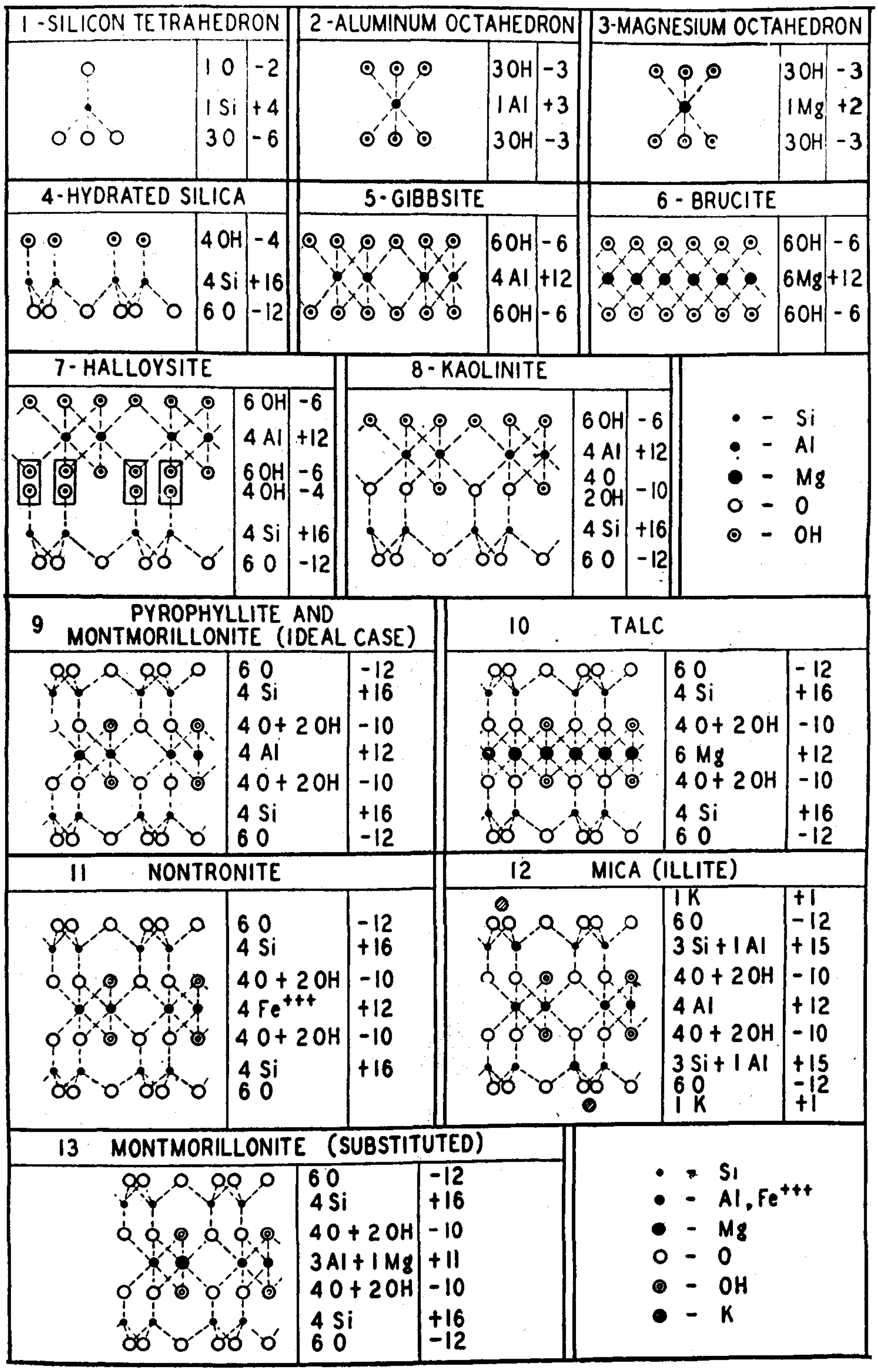


Figure 13. Structural data of the clay minerals.
(From Norton's "Refractories".) (50b, p. 137).

Al in the gibbsite layers have been proved. Kaolinite also has pronounced basal cleavage, and the particles also have flake-like shapes. The particles are generally larger than 0.1u in diameter and they are not readily reduced to sizes below 0.1u.

The illite or hydromica group of clay minerals is of less importance than the two previously mentioned. The compositions of this group of clay minerals vary widely, and it is hard to find any pure representative sample from this group. However, the structure of illite is similar to that of montmorillonite, Figure 13, except that the C-dimension of the illite unit cell does not change with varying water content. Illite also has pronounced basal cleavage, and the fragments have flake-shapes. The particles are usually larger than 0.1u in diameter. Its base exchange capacity lies between those of montmorillonite and kaolinite.

The problem of the modern study of clay minerals is becoming rather complex. There are several different methods for identifying clay minerals and each of them has its own merits. However, they can be divided into four groups:

a. Petrographic methods in which some method of orienting the small crystals must be employed.

b. X-ray methods in which the powder diffraction method is frequently used.

c. Thermal methods which may be divided into dehydration and differential temperature methods.

d. Chemical methods which are of considerable value when used in conjunction with other methods of identification, the interpretation of chemical data being complicated by the many isomorphous substitutions that occur in the clay minerals.

In this research, however, only the differential thermal method is used to identify the clay minerals present in the two loess samples. The differential thermal method is relatively simple compared with the others and it is not as time consuming as the chemical methods. The purpose of this test is to obtain thermal curves for the colloidal clay fractions of the soils, compare them with standard curves obtained from more or less pure clay minerals, and thus furnish a means of identifying the minerals present in the clay.

The thermal curves derived are to be obtained by following the temperature difference between an inert material, calcined alumina, and the soil colloid sample. The specimen and the calcined alumina are placed in adjacent holes in a steel block. The temperature difference is to be measured with a 24-gauge chromel-alumel thermo-couple. The thermocouple is connected to a high sensitivity galvanometer. A continuous record is produced on a strip of bromide paper. The block temperature is also measured by a thermo-couple. The actual temperatures are recorded on the same bromide paper by a signal lamp, which is flashed every time the potentiometer reading comes to an even 50 degree interval.

The temperature of the furnace is raised at a uniform rate of about 12° C. per minute until it reaches 1000° C., and this takes about one and a half hours. The arrangement of furnace and galvanometer is shown in Figure 14.

Apparatus used:

Thermal furnace, program controller, photographic paper, balance, etc.

Preparation of sample:

About 200-300 grams passing No. 10 sieve soil were weighed out in a beaker. Distilled water was added, and the mixture was allowed to soak for at least 24 hours. After soaking the sample was diluted with more distilled water to give a hydrometer reading of no higher than 1.020 or 1.030. The suspension was allowed to set until all the sand and silt had settled to the bottom of the container. The clay-water system was then transferred through a 325M sieve to a five-gallon jar, and the system was put through the super-centrifuge extracting the 0.25u and finer fractions. The clay fraction accumulated inside the centrifuge cylinder was discarded. Later the 0.25u and finer clay-water suspension was again put through the super centrifuge with the speed of the centrifuge and the rate of feeding of the clay-water mixture adjusted in such a way that anything coming out of the centrifuge was finer than 0.05 or 0.06 micron. This time the colloidal material accumulated inside the

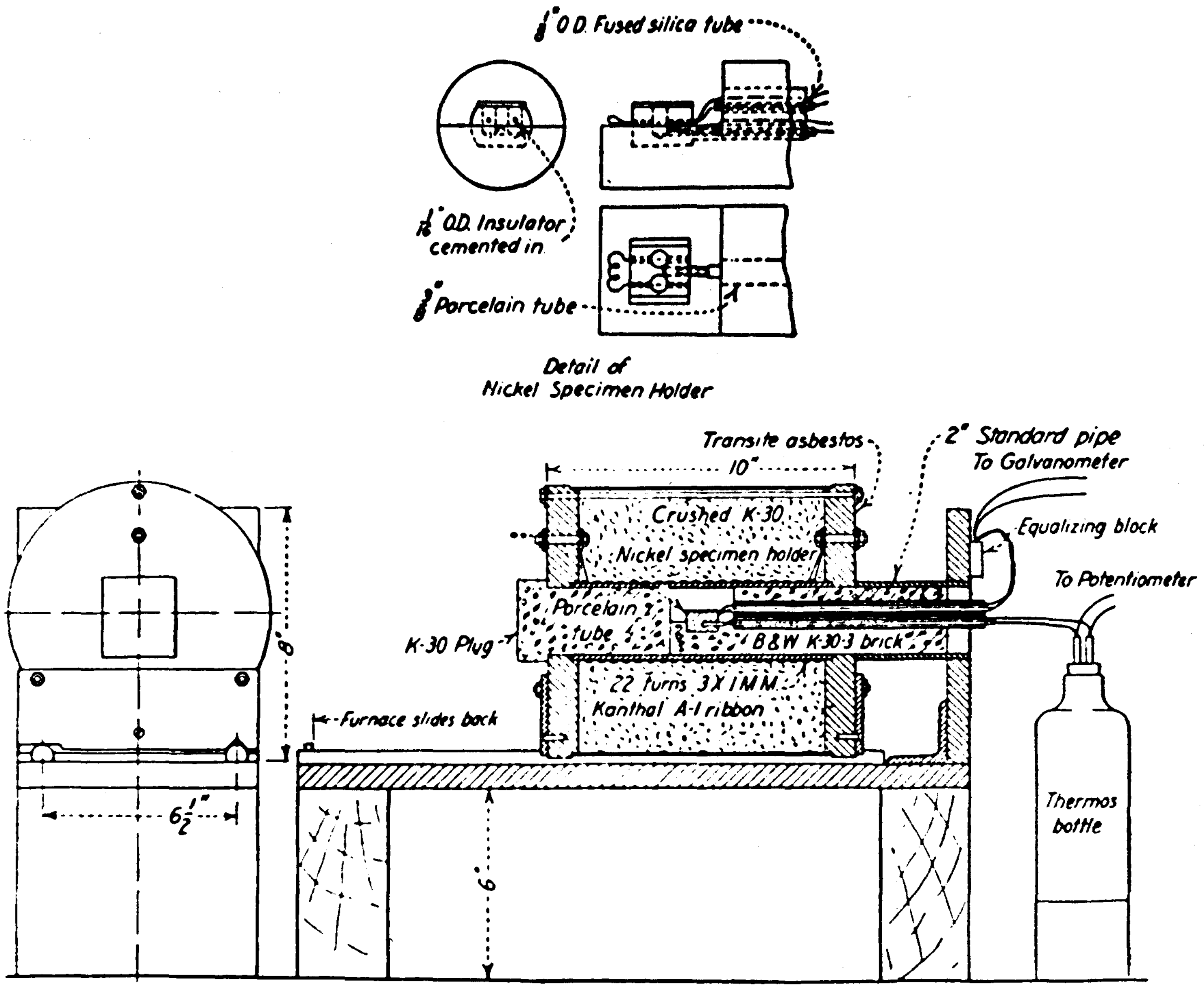


Figure 14. Differential thermal apparatus. (From Norton's "Refractories".) (50b, p. 138).

cylinder was carefully removed and placed in drying dishes to be dried to constant weight in an oven maintained at 105° C. After remaining in the oven for about 24 hours, the 0.25u fraction of the sample was removed and ground to pass a 100 mesh sieve. This sample was then to be analyzed by the differential thermal method for the presence of clay minerals.

Procedure of test:

About 0.4 gram (nearest 0.01 gram) of the sample was weighed out and placed in one cavity of the nickel steel block, while calcined alumina was placed in the other. After filling, the block was inserted in the furnace. Care was taken not to disturb the thermal couples, which should be centered in the holes. Next step was to load the camera box with a sheet of sensitized paper in the dark room. The slit opening of the box was properly covered when carrying from the dark room.

With the furnace and camera box properly loaded and in position, the resistance controlling the deflection of the galvanometer was adjusted to the desired position, and the switch on the galvanometer box which operated the time motor and illuminated the galvanometer mirror was then turned on. Leads to the galvanometer from the furnace were also connected.

The furnace was started with the controller set at 6.2 amperes and with 10 volts. The temperature of

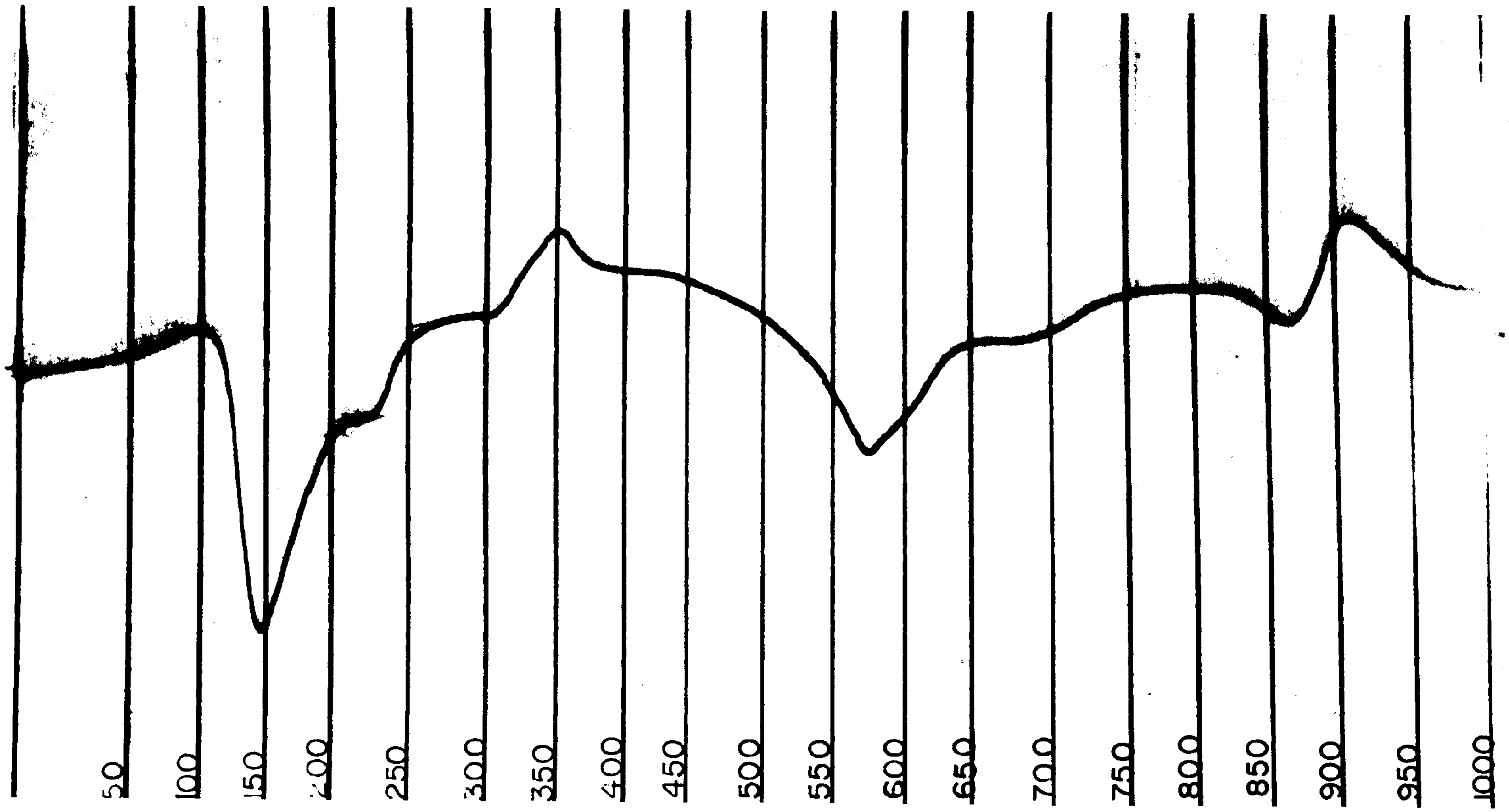


Figure 15. Thermal curve for minus 0.25u portion Harrison County loess.

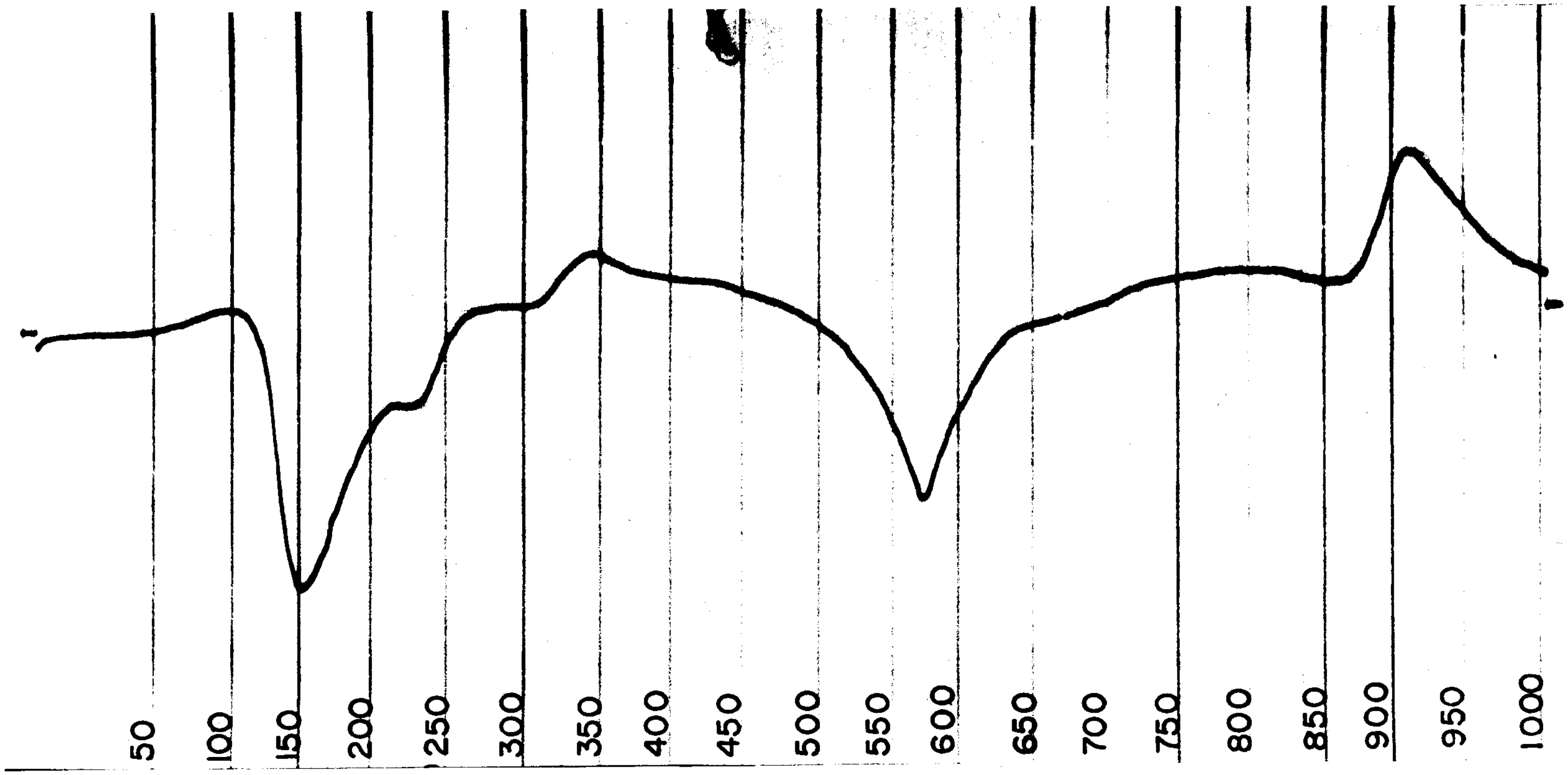


Figure 16. Thermal curve for minus 0.25u portion Johnson County loess.

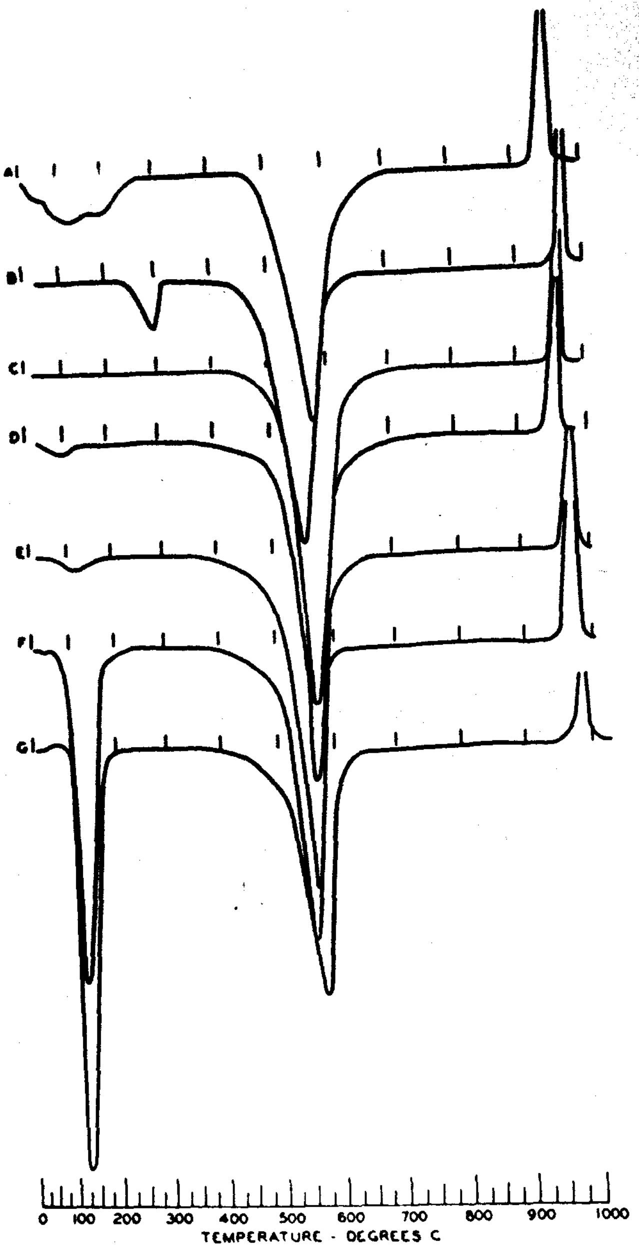


Fig. 3. Kaolinites and halloysites. Scale *B*.

A. Kaolinite, Anna, Illinois.
B. Kaolinite, Spruce Pine, North Carolina.
C. Kaolinite, Dry Branch, Georgia.
D. Kaolinite, wetted and then dried at room temperature, Dry Branch, Georgia.
E. Halloysite, dried at 90°C., wetted, and then redried at room temperature, Djebel Debar, Algeria, from U. Hofmann, University of Rostock, Rostock, Germany.
F. Hydrated halloysite, Eureka, Utah.
G. Hydrated halloysite, Djebel Debar, Algeria.

Figure 17. Thermal curves for kaolinites. (From Grim and Rowland , American Mineralogist.) (24, p. 752).

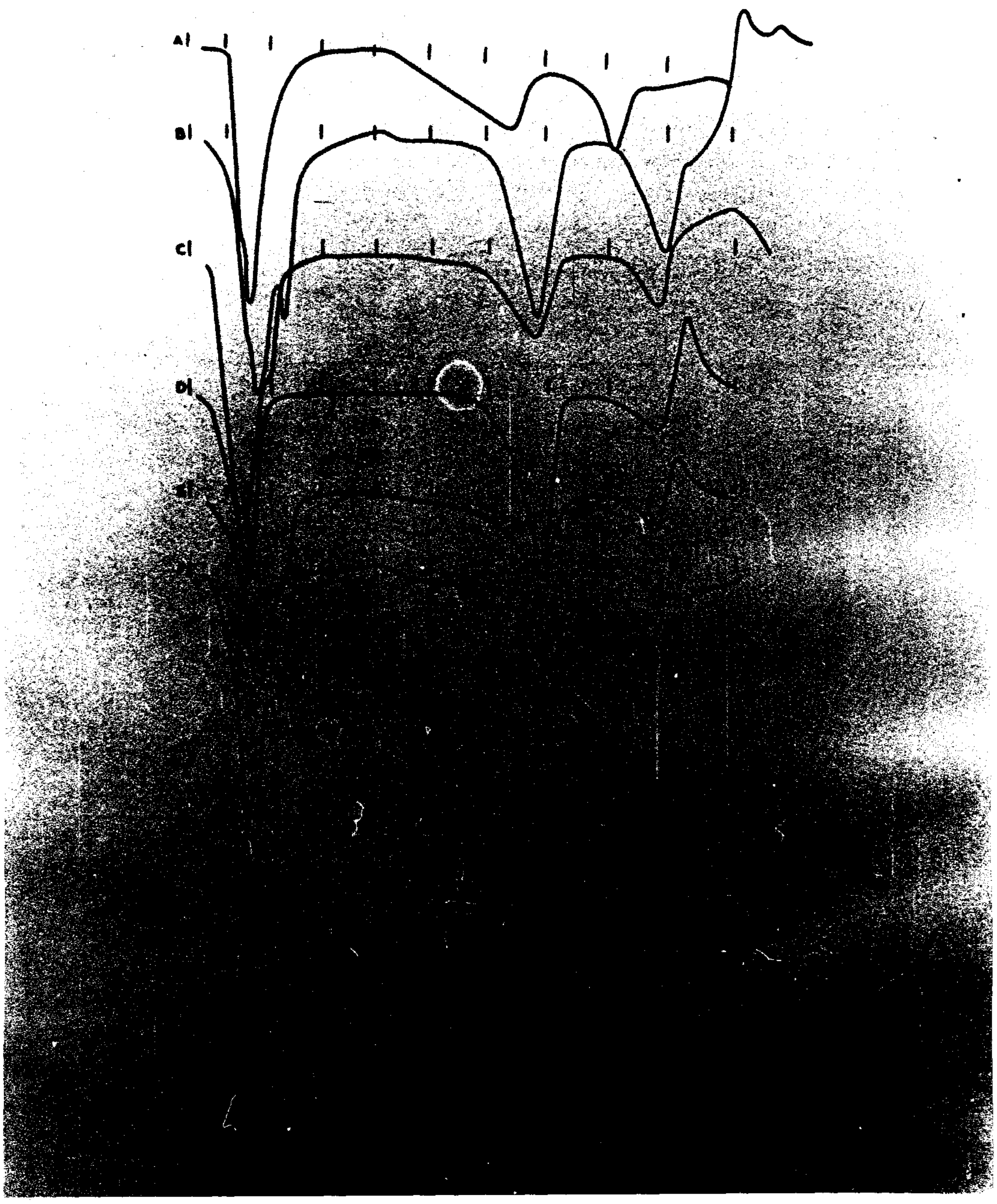


Figure 18. Thermal curves for montmorillonites. (From Grim and Rowland , American Mineralogist.) (24, p. 755).

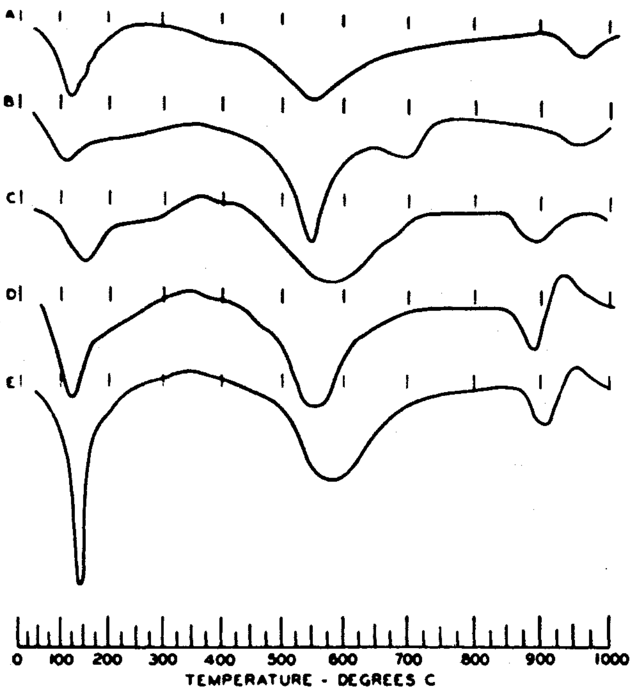


FIG. 4. Illites. Scale *A*.

A. Glauconite, University of Illinois collections.
B. "Glimmerton," Sarospatak, Hungary, from U. Hofmann, University of Rostock, Rostock, Germany.
C. Illite, purified from shale, Alexander County, Illinois.
D. Illite, purified from underclay, Vermilion County, Illinois.
E. Illite, purified from underclay, Grundy County, Illinois.

Figure 19. Thermal curves for illites. (From Grim and Rowland , American Mineralogist.) (24, p. 753).

the furnace was increased by increments of 50 degrees, by carefully adjusting the current and voltage, until it reached 1000° C. About one and one half hours were required to complete the test.

The thermal curves for the two loess samples are shown on Figures 15 and 16. For further details of this method refer to Norton (50) and Grim and Rowland (24).

3. Base Exchange in Loess.

The term "base exchange" has been introduced in the previous section. It is now necessary to go into this study more thoroughly. Many of the physical properties of soils are affected by the nature of the adsorbed ions. It is the amount of ions adsorbed per unit mass -- exchange capacity -- and the energy with which the different ions are held on the surface that largely determine the behavior of the soil (5). It follows that the exchange capacity of colloidal clays depends on the chemical and mineralogical composition of the colloid, and that the montmorillonite type of mineral has the highest exchange capacity and the kaolinitic group the lowest. All these have been mentioned in the previous section.

At this point, it is necessary to describe the mechanism of ionic exchange briefly. This theory can be visualized as follows (32, p. 597):

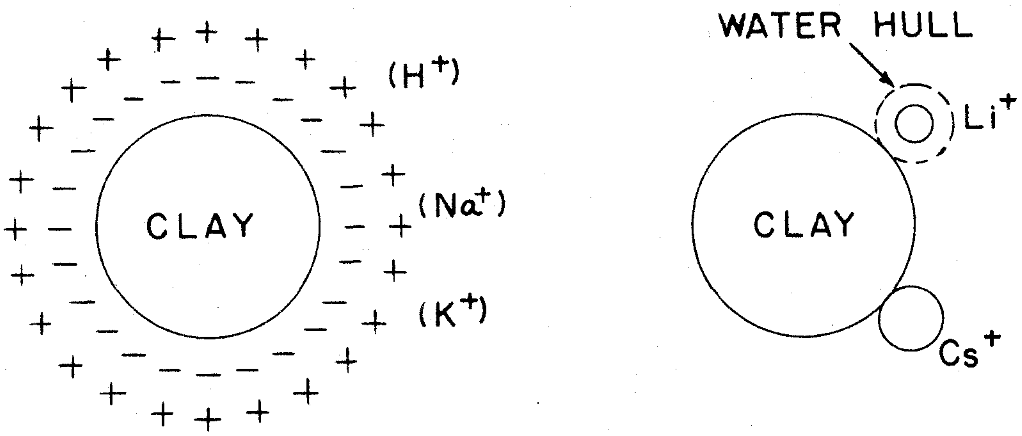
> Colloidal clay particles are plate-shaped crystals which hold on their surface adsorbed cations. Owing to heat motion and Brownian movement the adsorbed ions

> are not at rest but oscillate and at times are at a considerable distance from the wall. If it so happens that on account of Brownian movement a cation of an added electrolyte slips between the negative wall and the positive oscillating ion, the electrolyte cation will become "adsorbed" while the surface ion remains in the solution as an exchanged ion.

Clays with high zeta potentials contain easily exchangeable ions. Thus zeta potential bears a close relationship to the stability of a colloidal system.

Diagrammatically, base exchange or cation adsorption can be represented as in Figure 20. Clay particles are essentially aluminosilicate minerals, and the adsorbed cations which are exchangeable are found on the surface of the clay minerals. Thus, we see clay particles are represented by colloidal anions with cations adsorbed on the surface, Figure 20a. It is also readily seen that there is an electrical double layer at the surface of the colloidal particle. This double layer of charges is known to the colloidal chemists as the Helmholtz double layer. The inner layer forms part of the wall of the particle and determines the sign of the charge on the particle. The ions forming the outer layer are of opposite charges and at a distance of molecular dimension from the inner wall can easily be replaced by other ions in the process of ionic exchange. The following order of exchangeability has been given for common ions, $Na > K > NH_4 > Mg > Ca$. (22).

Cation adsorption is important in the study of a soil, or rather the colloidal clay fraction of the soil, in the



Negatively charged particle

(a)

Ionic adsorption

(b)

Figure 20. Schematic representation of colloidal clay particles in relation to charge (a) and ionic adsorption (b). (From Baver.) (5, p. 23).

sense that the anions present in the particles, the cations adsorbed, and the cations which can be replaced by others are all tied in with the behavior of the soil as a system. They affect its stability, its permeability, its density, its relation with chemical agents in highway and airport soil stabilization work, many of its other physical properties.

Base exchange capacity or degree of cation adsorption is also closely related to the types of clay minerals present in the colloidal clay fraction of a soil and the natural size of individual particles that compose the colloidal fraction. Montmorillonite has high base-exchange capacity, higher than can be accounted for entirely by broken bonds at the edge of fragments. Analysis of montmorillonite usually shows some divergence from the ideal composition, particularly by their content of magnesium, indicating replacements within the lattice, and to such replacements may be assigned the cause of some of the exchange capacity and other properties (21).

In illite the replacement exists to the extent that about 15 per cent of the Si^{+++} positions are occupied by Al^{+++}. The excess charge resulting from this replacement in illite is satisfied by K^{+} and the units are held together without the power of expanding. In the illite structure there are also replacements in the gibbsite sheet, some of which may provide an excess charge available for a replaceable base (21).

It has been mentioned that the kaolinite structure is not of the expanding type, probably due to the attraction between oxygen and hydroxyl layers which are adjacent to one another. Consequently, the mineral does not break up into flakes readily, and therefore the base exchange capacity is very low.

The following table shows the exchange capacities of some of the more important clay minerals:

Table 5

Exchange Capacities of Some Clay Minerals

Clay Mineral	Exchange Capacity in Milliequivalents[1] per 100 gram sample
Kaolinite	3 - 15
Montmorillonite	60 -100
Illite	20 - 40
Muscovite	10.5 (passing 100M screen)
	76.0 (ground for 72 hours)
2 to 5 micron silt	11.5-18

[1] A milliequivalent equals 1/1000 of a gram-equivalent which is defined as the amount of substance equivalent to one gram-atom (1.008g.) of hydrogen.

The base exchange capacity of soil colloids can be increased merely by reducing the natural size of the individual particles that compose the colloidal fraction (35).

There are two conditions important for base exchange: physical accessibility of the ion, and the strength of the attractive force by which the ion is held to the particle, or rather, to the lattice.

Grinding of minerals tend to increase the base-exchange capacities. With mica, grinding tends to separate the sheets of mica down to the thickness of a single lattice layer, all the K^+ ions would be exposed, and hence increases the base exchange capacity.

With kaolinite, upon being ground to extreme fineness, it possesses high cation exchange power. This is believed to be due to the H^+ ions of the crystal lattice of the mineral.

Table 6

Effect of Grinding on the Exchange Capacity of the Clay Mineral Kaolinite

Grinding Period in Hours	Exchange Capacity in Milli-equivalents per 100 gram Sample
Kaolinite (passing 100M screen)	8.0
Ground 48 hours	57.5
Ground 72 hours	70.4
Ground 168 hours (7 days)	100.5

In the study of the two loess samples for their base exchange capacities, two size fractions were chosen -- passing No. 20 mesh sieve and 2u fractions. A determination of the exchange capacities for 2u or smaller in size kaolinite and montmorillonite is also included here for the purpose of comparison.

Equipment and Materials:

Balance, burettes, Buchner funnels, Erlenmeyer flasks, beakers, International centrifuge, graduates, filter paper, HCl, NaOH, NH_4Ac, $CaAc_2$, $KMnO_4$, HNO_3, brom thymol blue, and phenolphthalein.

Procedure:

a. For material passing 20M sieve size fraction:

A 10 gram sample of passing 20 mesh sieve soil was placed in a 250 cc beaker together with 100 cc of distilled water and 5 cc of concentrated HCl. The mixture was allowed to sit overnight, then leached on a Buchner funnel first with 150 cc of 0.1N HCl, next with 100 cc of distilled water, and finally with 400 cc of 1N $CaAc_2$ having a pH value of 7.0-7.2. Brom thymol blue indicator was used to adjust the pH of $CaAc_2$.

The excess $CaAc_2$ was removed from the soil by leaching with 250 cc of boiled and cooled distilled water in five 50 cc portions. Using clean filter flasks the sample was leached with fifteen 20 cc portions of neutral (pH 7.0) NH_4Ac. The leachate was then transferred to a 400 cc beaker, and was allowed to evaporate to dryness on a steam plate. Next step was to wash down the sides of the beaker with about 5 cc distilled water and then add about 2-5 cc of concentrated HNO_3. Again the beaker was placed over the steam plate until the residue became dry. This treatment with HNO_3 was repeated several times until the residue turned dark in color. One hundred cubic centimeters of distilled water were now added together with 2 cc of concentrated HCl. The calcium was precipitated as CaC_2O_4 and the amount of calcium present was determined by $KMnO_4$ using 10 cc of 0.1N oxalic acid as indicator (37).

The result was reported as milliequivalents of calcium per 100 grams of soil, on oven dry (105° C.) basis, or in this case, as the exchange capacity of the whole soil. Actually this last phrase is not quite correct since there may be present in the soil other exchangeable bases. However, for the purpose required here, the error involved is very small and is within the allowable percentage.

b. For 2u size fraction:

To fractionate the 2u size particles a 50 gram sample of soil was used. The soil was placed in a 600 cc beaker with 400 cc of distilled water and 20-25 cc of concentrated HCl. After stirring, the sample was allowed to sit overnight. Next morning, the soil-water mixture was leached on a Buckner funnel with 500 cc of 1N HCl. The excess HCl was removed with 500 cc of distilled water in 50 cc portions. The sample was then transferred to a quart milk bottle and NaOH was added until the pH of the soil-water mixture was about 8 or 9 using phenolphthalein as external indicator. After shaking for 20 hours, the mixture was transferred to a 1000 cc graduate and distilled water was added to bring the volume up to one liter. The 2u clay was siphoned off at a depth of 33 cc at 23.5 hours. This process was repeated four times, and the 2u clay water mixture was evaporated in 2000 cc beakers over a steam plate. The residue was then ground to pass a 60M screen and dried to constant moisture content at 105° C.

After drying, the base exchange capacity of the 2u clay was determined using the following procedure: Duplicate 2-3 gram samples were weighed out in bottles used in the International centrifuge. About 60 to 70 cc of 0.1N HCl were added to the samples to bring the Na^+ saturated clay to neutral plus excess acid. After stirring the samples were placed in the centrifuge with the speed set at 1500-2000 R.P.M. It took about five to ten minutes for all the soil particles to be thrown to the bottom of the bottle. The free HCl was then siphoned off and another 60 to 70 cc of 0.1N HCl were added. The bottles were replaced in the centrifuge. This process was repeated for four more times.

$$\text{Clay } (Na^+ \text{ saturated}) + HCl(0.1N) \longrightarrow \text{Clay}(H^+ \text{ saturated}) + NaCl(\text{siphoned off})$$

The excess HCl was removed with 60% alcohol using the centrifuge as before. This process was again repeated for three or four times until no chlorides were formed when the solution was tested with silver chloride.

Clay(H^+ saturated) + Methyl alcohol (60%) $\longrightarrow$ H_2O + H_x^+ Clay

One normal NaOH was used to titrate the H_x^+ clay until the solution became neutral. Phenolphthalein (pH 8.5) was used as indicator, and the exchange capacity was expressed in milliequivalents per 100 grams of soil.

Calculations:

The actual calculations for the exchange capacities of passing No. 20 sieve fraction and 2u fraction of the Harrison County loess will be given here.

<u>Passing No. 20 sieve fraction</u>:

To determine the normality of the $KMnO_4$, the procedure outlined in Kolthoff and Sandell (37) was used.

25 cc 0.1N $Na_2C_2O_4$ = 50.5 cc $KmnO_4$

Expressing them in terms of normal solutions, we have

25 cc x 0.1N = 50.5 cc x (X)N

$$\text{Normality of } KMnO_4 = \frac{25 \times 0.1}{50.5} = 0.0495$$

To express the amount of calcium present in milliequivalent weights we have the equation

NV = milliequivalent,

where N = normality of solution, and

V = volume of solution in cc.

One normal solution is defined as one equivalent weight of a chemical agent dissolved in one thousand cubic centimeters of distilled water.

$$\text{Therefore KV} = \frac{\text{equivalent weight}}{1000\text{ cc}} \times \text{cc}$$

$$= \frac{1}{1000}\text{ equivalent weight}$$

$$= 1\text{ milliequivalent weight}$$

Sample No. 1 of passing No. 20 sieve Harrison County loess required 22.4 cc of $KMnO_4$ to react with the CaC_2O_4, and

$$\text{NV} = 0.0495 \times 22.4 = 1.11\text{ m.e. Ca/ 10 grams of soil}$$

$$= 11.1\text{ m.e. Ca/ 100 grams of soil.}$$

Sample No. 2 of passing No. 20 sieve Harrison County loess required 22.1 cc of $KMnO_4$ to react with the CaC_2O_4, and

$$\text{NV} = 0.0495 \times 22.1 = 1.10\text{ m.e. Ca/ 10 grams of soil}$$

$$= 11.0\text{ m.e. Ca/ 100 grams of soil.}$$

The average exchange capacity of passing No. 20 sieve Harrison County loess = $\underline{\underline{11.05}}$ m.e. per 100 grams of soil.

Table 7

Base Exchange Capacities for the Harrison County Loess and the Johnson County Loess in Milliequivalents per One Hundred Gram Sample

Passing 20M Sieve Fraction		2u Fraction	
Harrison County Loess	Johnson County Loess	Harrison County Loess	Johnson County Loess
11.0 m.e.	14.1 m.e.	45-50 m.e.	50-55 m.e.

Base exchange capacity for a sample of pure kaolinite = 2.0 m.e.

Base exchange capacity for a sample of pure montmorillonite = 79.3 m.e.

Table 8

Physical Properties of Two Loess Samples[1]

	Harrison County Loess	Johnson County Loess
1. Moisture contents:		
Cut moisture (as sampled)	16.23%	20.27%
Hygroscopic moisture	2.32%	1.90%
Centrifuge moisture equivalent	16.55%	20.92%
Field moisture equivalent	23.70%	31.50%
2. Plasticity:		
Plastic limit	26.35%	21.25%
Liquid limit	31.90%	33.82%
Plasticity index	5.55%	12.57%
3. Densities:		
Cut density (as sampled)	85.48 p.c.f.	88.75 p.c.f.
Standard Proctor dry density	108.75 p.c.f.	109.50 p.c.f.
Optimum moisture	16.50%	15.20%
Modified Proctor dry density	115.50 p.c.f.	122.00 p.c.f.
Optimum moisture	14.25%	13.20%
4. Specific gravity:		
Soil particles	2.675	2.685
5. Gradation -- mechanical analysis:		
Gravel	0.0%	0.0%
Coarse sand	0.0%	0.0%
Fine sand[2]	10.0%	8.0%
Silt[3]	77.0%	64.0%
Clay[4] -- 5u	13.0%	28.0%
1u	5.0%	21.5%
0.5u	4.0%	18.0%
0.1u	1.5%	8.0%

---

[1] Fung, P. K. Loess Soil as Highway Material. Unpublished M. S. Thesis. Iowa State College Library, Ames, Iowa. 1945.

[2,3,4] Modified from data given in previous thesis by the author.

Table 8 (Continued)

Physical Properties of Two Loess Samples

	Harrison County Loess	Johnson County Loess
6. Void test:		
Porosity	26.22%	18.28%
Void ratio	95.43%	88.90%
7. Shrinkage tests:		
Shrinkage ratio	1.612	1.826
Shrinkage limit	21.68%	14.75%
Volumetric change	26.66%	52.50%
8. Flocculation limit	95.00%	93.25%
Flocculation factor	72.70%	71.60%
9. Capillary rise	42 inches	42 inches
Permeability coefficient	0.2395ft./day	0.0422ft./day
10. Per cent of organic matter	0.0718%	0.1315%
11. Cementation test	82.0 p.s.i.	158.3 p.s.i.
12. California bearing ratio test:		
C.B.R. before soaking	90.0%	173.3%
C.B.R. after soaking	3.77%	1.67%
13. Unconfined compression test:		
Maximum stress	106.0 p.s.i.	272.6 p.s.i.
Maximum strain	0.01083"/in.	0.0195"/in.
Angle of shear	23° 11'	24° 10'
Angle of internal friction ∅	43° 38'	41° 40'
14. Base exchange capacities[1]:		
Passing 20M sieve fraction	11.0 m.e.	14.1 m.e.
2u fraction	45-50 m.e.	50-55 m.e.

---

[1] From later study by the author.

Two micron fraction:

Sample No. 1 required 8.4 cc of 0.1079N NaOH to neutralize the H^+ saturated clay.

Again $NV = 8.4 \text{ cc} \times 0.1079N = 0.9064$ m.e.

Since only a 2-gram sample was used, the exchange capacity of soil expressed in terms of 100 grams of soil $= 0.9064 \times \frac{1}{2} \times 100 = 45.32$ m.e. per 100 grams of soil.

Sample No. 2 required 9.6 cc of 0.1079 NaOH to neutralize the H^+ saturated clay.

$$\text{Exchange capacity} = \frac{9.6 \times 0.1079}{2} \times 100$$

$$= 51.79 \text{ m.e. per 100 grams of soil.}$$

Here, the cation exchange capacity of the 2u clay can be said as equal to 45-50 m.e. per 100 grams of soil.

The calculations for the exchange capacities of the Johnson County loess and the kaolinite and montmorillonite samples are exactly the same and will not be repeated here. The results obtained for this phase of the study are shown in Tables 7 and 8.

C. Erosion Characteristics of Loess and Methods of Prevention

One of the most troublesome problems confronting a highway engineer is the erosion of highway cuts and fills. In this country, the money spent every year on fighting soil erosion generally ran up to sizeable figures. During the recent years, more attention has been directed at this problem, yet it will undoubtedly take a number of years more to really make people realize how much damage erosion is doing to the highways and how many headaches it is giving the highway engineers and maintenance officials.

For years the farmers have been fighting soil erosion, fighting to keep the valuable top soil from eroding away. Although the losing of valuable top soil is not the immediate concern of a highway engineer, yet the consequence is just as serious. The tremendous cutting power of water was not fully realized twenty years ago; and today, in many sections of the country, raw, unprotected highway cuts and fills show the fingermarks of erosion. Numerous side-ditches have turned into deep and hazardous gullies. Others have been robbed of most of their original drainage value by heavy deposits of silts. Culverts have been undermined by uncontrolled water or clogged with erosion debris. Large sections of highway cuts and fills have failed and sloughed as a result of serious erosions and formation of gullies.

All these are just some of the more important results of soil erosion. No matter what kind of soil one encounters, there will be erosion problems in highway fills and cuts. The seriousness of the problems will of course depend on the type and characteristics of the soil. Here in this research, loess soil is being considered, and it is one of the many soils most easily succumbed to erosion.

One of the most common forms of erosion in loess, especially the Harrison County type loess, is the formation of ridges along the surfaces of cuts and fills and gullies from the roadside ditches. Many of these can be seen in road cuts along the banks of the Missouri River in Iowa and Nebraska as in Figures 21 and 22. They are the results of water running over unprotected surfaces of the soil. To start with, these ridges and gullies are usually very small, but in due time possibly a few years, they may increase to crevices and gullies of tremendous sizes. Many of those crevices and gullies in western Iowa are ten or twenty feet wide and more than ten feet deep.

In eastern Iowa, this form of erosion, however, is not as serious. One of the reasons may be that the loess of that territory is better covered with vegetation. Even then at places where vegetation failed to take hold, erosion has started to gouge the surfaces of cuts and fills, and gully the roadside ditches. Some of the cuts and fills have slid and sloughed exposing the raw soil for further erosion. Figures 23 and 24 are pictures taken in Johnson County, and they tend to show this kind of slippage.

Vegetation is nature's method of controlling erosion, and in order to combat erosion, highway design should be sympathetic to the growth of vegetation. The Harrison County

Figure 21. Erosion causes deep gullies to form in highway cuts. Harrison County, Iowa.

Figure 22. Erosion leaves its finger marks on the surface of a steep highway cut. Pottawattamie County, Iowa.

Figure 23. When vegetation fails to get a foot hold erosion starts to dig in. Johnson County, Iowa.

Figure 24. Erosion causes loess to slide and slough. Johnson County, Iowa.

loess being high in silt content and low in organic matters, is only suitable for vegetation adapted to these circumstances. In spite of this, there are still some types of grass such as bluegrass, bromegrass, wheatgrass, clover, etc., which may be used in this region. If necessary, some top soil and organic materials may be added to help the vegetation in gaining a foothold. All these will undoubtedly tend to increase the construction cost, but the increase in cost will be much less than the annual maintenance cost if no erosion control measure is taken.

In eastern Iowa the use of vegetation to control erosion in highway cuts and fills does not present a very large problem. The Johnson County loess contains a higher clay content and the rainfall over that territory is heavier. Bluegrass, wheatgrass, clover, etc., can be used in this area to control erosion.

In general practice angular cuts and fills are not recommended. They should be well rounded at the top and bottom. When the cuts are not very steep and the fills not very high a 2:1 slope may prove to provide more suitable conditions for the growth of vegetation than the conventional 1½:1 slope. The flatter slope expedites the application of a layer of top soil and the preparation of a firm, moisture-retaining seedbed. On deep cuts and high fills, it may not be practical to provide more than a 1½:1 slope. This is where contour ditches and wattles come in. They are described by Haffenrichter (25) in the following manner:

> Contour ditches are used on cut banks. They are 8 inches deep and 8 inches wide, at 3 feet slope intervals. Sufficient topsoil is spread over the prepared slope to fill the ditches and cover the entire cut to a depth of 2 to 4 inches. Contour ditches are made by hand on slopes already prepared and finished. They can be made largely with machinery during highway construction operations.
>
> Wattles are used on high, steep fills. They are made from willow stakes 3 to 4 feet long, driven into the fill every 18 inches at 3 feet contour intervals. A furrow at least of 8 x 8 inch size, is made above the wattles, lined with willow brush, back fill and tamped. Live brush and stakes are used except for the upper 12 feet below the shoulder. Here inert material is used. The wattled fill may then be covered with topsoil, but this step is sometimes omitted. Roadside ditches have a minimum width of 2 to 3 feet, with side-slopes of at least 2:1. Topsoil is applied to these sections and to the road shoulders.

For the road cuts and fills in the Johnson County type loess area, it will be sufficient to give the cuts and fills flatter and relatively well rounded slopes and cover them with suitable vegetation. Although deep cuts are seldom encountered in this territory, they can still be taken care of by contour ditches and similar measures. However, in areas where the loess deposits are thick and the road cuts sometimes run up to depths of fifty or sixty feet as in Harrison County, Iowa, it will not be feasible to have flat slopes, and even contour ditches will not help in this case. This is where the verticle cuts in series of steps or terraces will have to be used, Figure 25. Under these conditions, the erosion problem can still be minimized by covering the surfaces of the

Figure 25. Proper growth of vegetation plus good drainage help prevent serious erosion. Harrison County, Iowa.

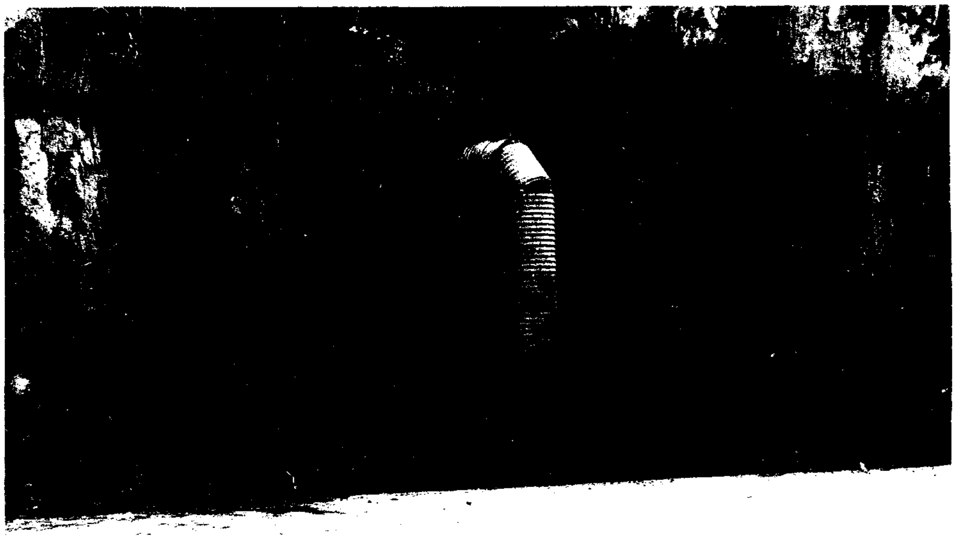


Figure 26. Drainage pipe used in deep highway cut. Harrison County, Iowa.

terraces with proper growth of vegetation and furnishing well protected drainage ditches along the edge of the terraces. These will prevent the rain water from striking the soil directly and give it a chance to soak into the soil instead of running over and gouging the surfaces of the cuts.

D. Frost Action on Loess and Methods of Prevention

Morainic soils are by far the most prolific sources of frost trouble (12). Very fine sands, silt loams, and silty clay loams having little or no apparent soil structure are subjected to some of the worse frost actions on record. However, frost heave is not likely to occur in sandy soils which have centrifuge moisture equivalents less than 12 and which do not have plasticity nor in those clay soils which have liquid limits greater than 50 and whose plasticity indices are appreciably greater than the ratio $\frac{\text{L.L.} - 14}{1.60}$ and whose shrinkage limits do not greatly exceed the ratio

$$21 - 1.1\sqrt{\text{L.L.} - \frac{(\text{L.L.})^2}{800}} \quad (12).$$

Years ago frost heaving and the accompanying pressure effects were assumed to be due to the increase in volume of the water frozen. This assumption was based on the fact that water expands when frozen and also exerts tremendous pressures in closed systems. Recent studies have shown this assumption to be erroneous. Taber (62 and 63), who has done considerable work on frost action in soils, has suggested the following theory (63, p. 303).

> Field observations and recent experiments indicate that soils, when subjected to freezing under normal conditions, usually behave as open systems. When the freezing of saturated soils results in little or no heaving, part of the water is forced through the soil voids below the zone of freezing, compressing or expelling air. Excessive heaving results when water is pulled through the soil to build up layers of segregated ice. These ice layers grow in thickness because water molecules are pulled into the thin film that separates the growing ice crystals from underlying soil particles.

Figures 27 and 28 are photographs taken from Taber's articles (62 and 63). They show the formations of ice lenses or segregated ice layers in cylinders of silt and clay.

There are certain factors which must be present before ice segregation and frost heaving can occur (68). They are:

a. Capillary saturation of the soil at the beginning of or during the freezing process,
b. A free supply of water from within or without the soil,
c. A minimum percentage -- three to ten per cent -- of grains smaller than 0.02 mm, and
d. A gradual decrease in temperature of the air above the soil to below freezing temperature.

If any one or more of the above mentioned factors are not present, frost heaving will not take place.

1. Frost Action in Loess.

Frost heaving is not detrimental and will cause no damage to highway pavement slabs if the heaving is uniform. It is only the differential frost heaving that is giving the most trouble. In western Iowa where the loess deposits are similar face. Melting of this ice usually takes place from the surface downward, so that removal by downward percolation is largely

FIG. 18

FIG. 19

FIG. 18.—Frozen cylinder, half sand and half clay. Much segregated ice in clay but not in sand.

FIG. 19.—Differential displacement of cylinder, due to segregation of ice in clay but not in sand. Cavity caused by [illegible] of dry sand.

Figure 27. Frozen sand and clay cylinders showing ice segregation. (From S. Taber, Journal of Geology.) (62, p. 456).

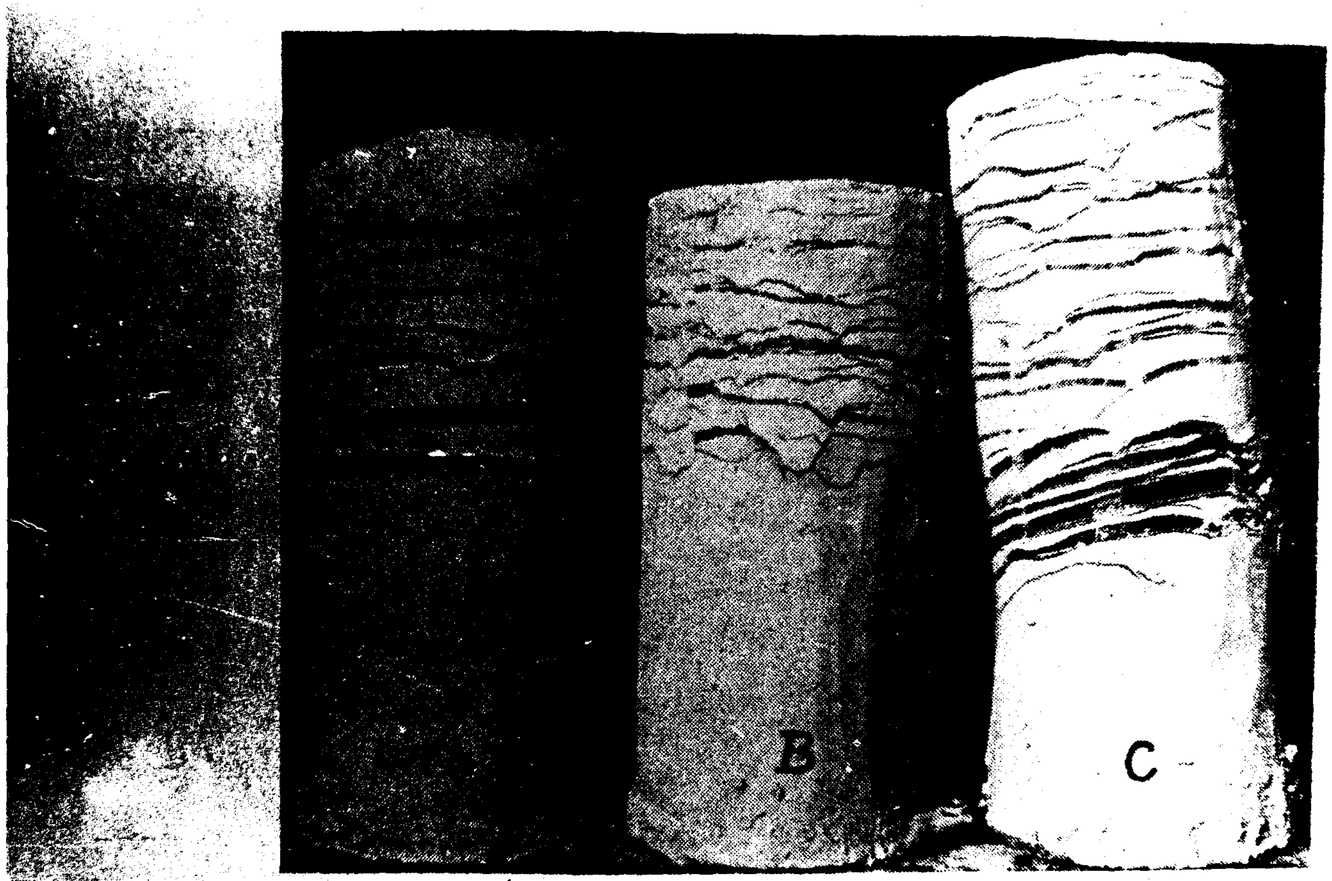


Fig. 11.—**Clay cylinders frozen (*A*) under no surface load**; (*B*) under iron weight **insulated from clay by wooden disc**; and (*C*) under iron weight in contact with clay.

Figure 28. Frozen clay cylinders showing the formation of ice lenses. (From S. Taber, Journal of Geology.) (62, p. 447).

to the Harrison County loess under investigation, frost heavings on some road pavements are reported every year. In some sections, the heaving of the pavements at the joints may amount to several inches. In eastern Iowa, frost heaving does not seem to cause much trouble. Any heaving of pavements laid over the Johnson County loess is usually very slight or uniform and hardly noticeable.

The first study of frost heaving in connection with this research project was started in the winter of 1945 as reported in the previous thesis by the author. A series of road surface roughness tests was performed on sections of concrete roads built on loess soils. Those sections of roads in western Iowa were reported to have considerable frost heaving at the joints. The section of road chosen in eastern Iowa did not have any frost heaving, and was included in the study for the purpose of comparison. Readings on the road surface roughness were obtained with the road surface roughness indicator, Figure 29, devised by the Public Roads Administration. In the summer of that same year another series of tests was completed on the same road sections. Both in winter and summer, sections of pavements, with the roughest road surface as indicated by the roughness device, varied from seven to nine hundred feet long, were chosen from different test courses, and level readings were obtained from them, both for the center and gutter line of the road.

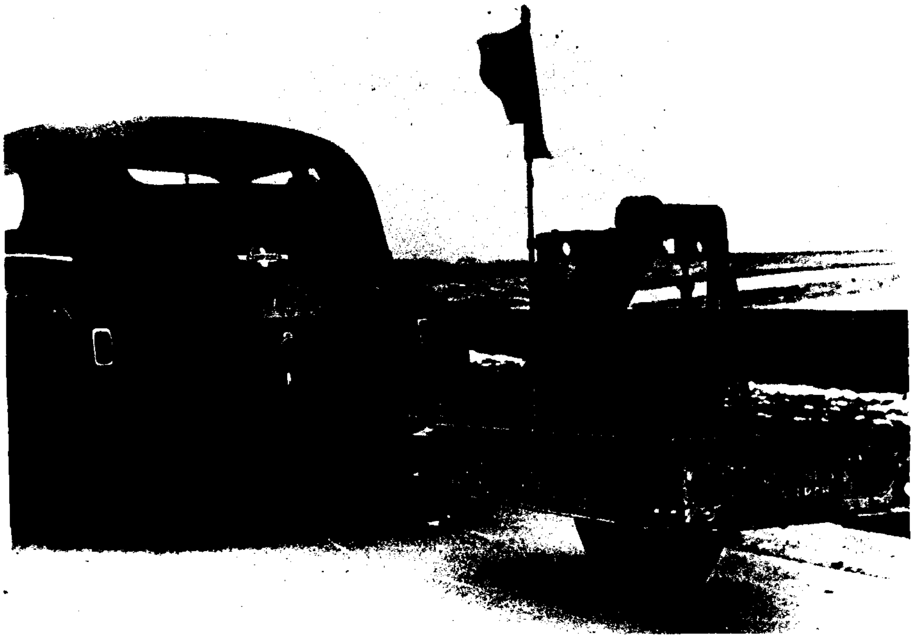


Figure 29. Road surface roughness indicator, showing connection to towing vehicle.

There were nine test courses specially chosen for this study. Although full description of these test courses had been given in the first paper, they will be repeated here for the sake of convenience. Their location and frost heaving conditions were as follows:

1. On U. S. 75, south of Rock Rapids, beginning from city limits, Lyon County, Iowa. Frost heaving was reported to be serious in this section.
2. On Iowa 339, south from Iowa 9, Lyon County. There was no frost action in this section, but it was chosen for comparison with the other sections because of its smoothness.
3. On U. S. 18, west of Inwood, Lyon County. Frost heaving was reported in this section.
4. On U. S. 18, south of Inwood, Lyon County. The subgrade material had special compaction during construction. There was slight frost heaving in this section of the road.
5. On U. S. 75, Plymouth-Sioux county line. Frost heaving in this section was reported to be quite serious.
6. On U. S. 20, from junction of U. S. 71 and 20 to a point 2 miles east, Sac County. Frost heaving was particularly serious in this section. During the worst period, the heaving of the pavement was up to several inches.

7. On Iowa 141, starting from a point three miles east of Manning, Carroll and Crawford Counties. The subgrade material was given special treatment for frost heaving during construction. Little or no frost heaving was reported in this section.
8. On Iowa 141, starting from a point three miles east of Manning, Carroll County. Pavement was quite rough, and no treatment was given to the subgrade material for frost heaving.
9. On Iowa 261, starting from city limits north of Iowa City, Johnson County. No frost heaving was reported here. It was chosen only for comparison with the other test sections.

The subgrades of some sections as mentioned in the above paragraphs had been given special treatments during construction. Frost heaving reported was not as serious as that of the sections of roads where the subgrades had not been treated.

The heaving of pavements is especially serious and noticeable at the joints. One reason for this is that water from melting snow and ice can get into the subgrade immediately under the joint more readily than at any other parts of the subgrade under the pavement slab. Another reason is that the concrete slab is always weaker at the corners and edges which makes them more sensitive to frost action. While frost heaving of pavement joints is serious in winter, it has a tendency to smooth out in summer, as shown by the pavement profiles, Figures 30 and 31, taken from the previous paper by the author. At the same time, the roughness readings are higher in summer than in winter. This fact was borne out in the report by Buchanan and Catudal (11). Several factors may contribute to this fact. One is that the higher readings may be due to the extrusion of the asphaltic material from the expansion joints. Another one may be that the curling action of pavements is more severe in summer than in winter due to the direct rays of the sun and the variable moisture effects in the slab.

2. Frost Action Preventive Measures.

It has already been mentioned that frost heaving can be reduced or minimized with some form of subgrade treatment. This treatment of frost action will be effective if it results in offsetting one or more of the factors which promote ice segregation and frost heaving.

The first problem that comes up in dealing with frost heaving in a soil like Harrison County loess which is primarily a silty material and has no apparent structure at all is the capillary action within the soil. This can be counteracted by one of the following measures. One method is to increase the density of the soil by using heavier compacting equipment. This results in reducing the percentage of voids in the subgrade soil and thus lowering the amount of moisture contained in the subgrade and also retarding the rate of

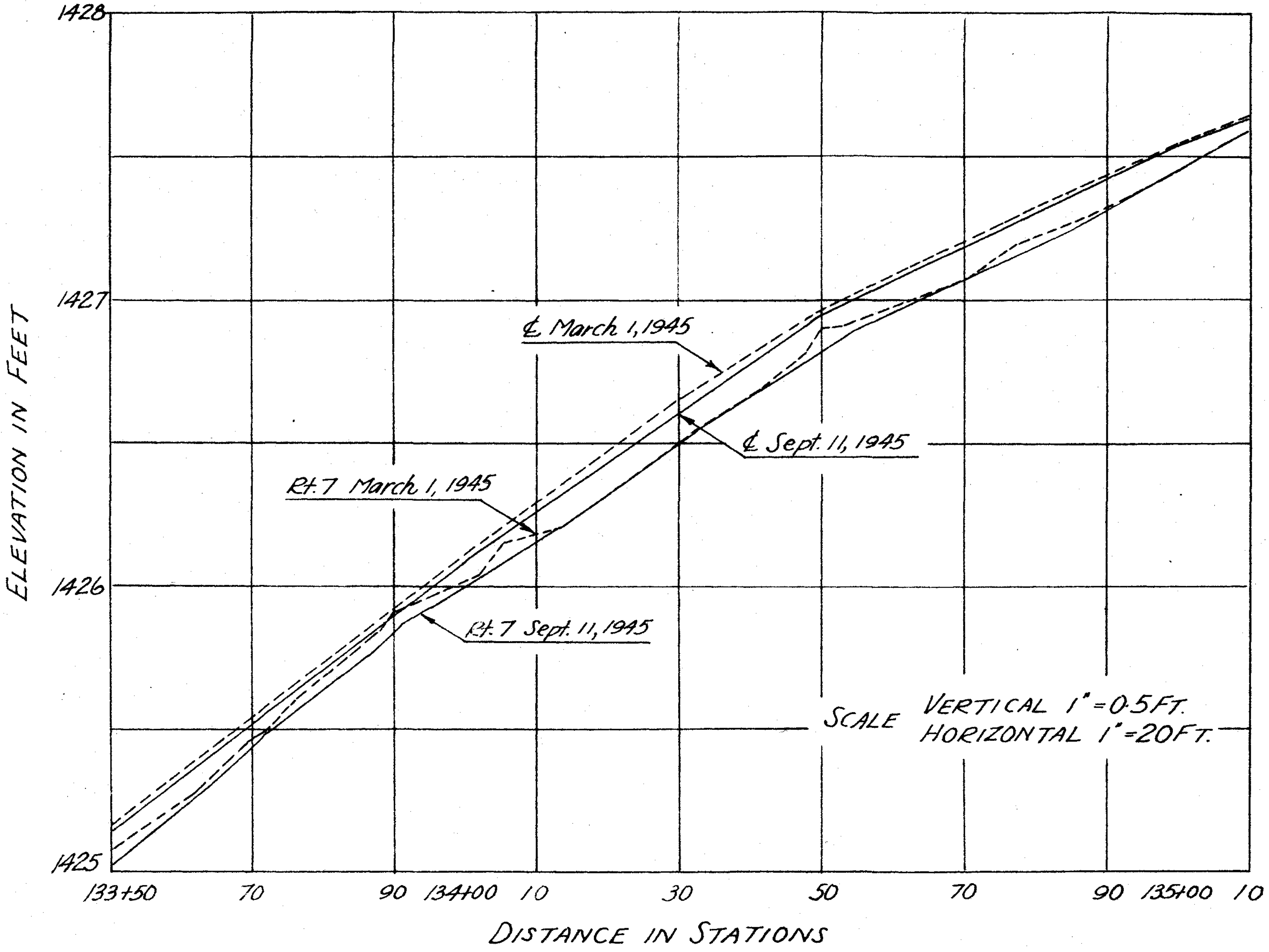


Figure 30. Frost heaving on U. S. 75, Lyon County, Iowa — profiles showing pavement conditions in summer and winter.

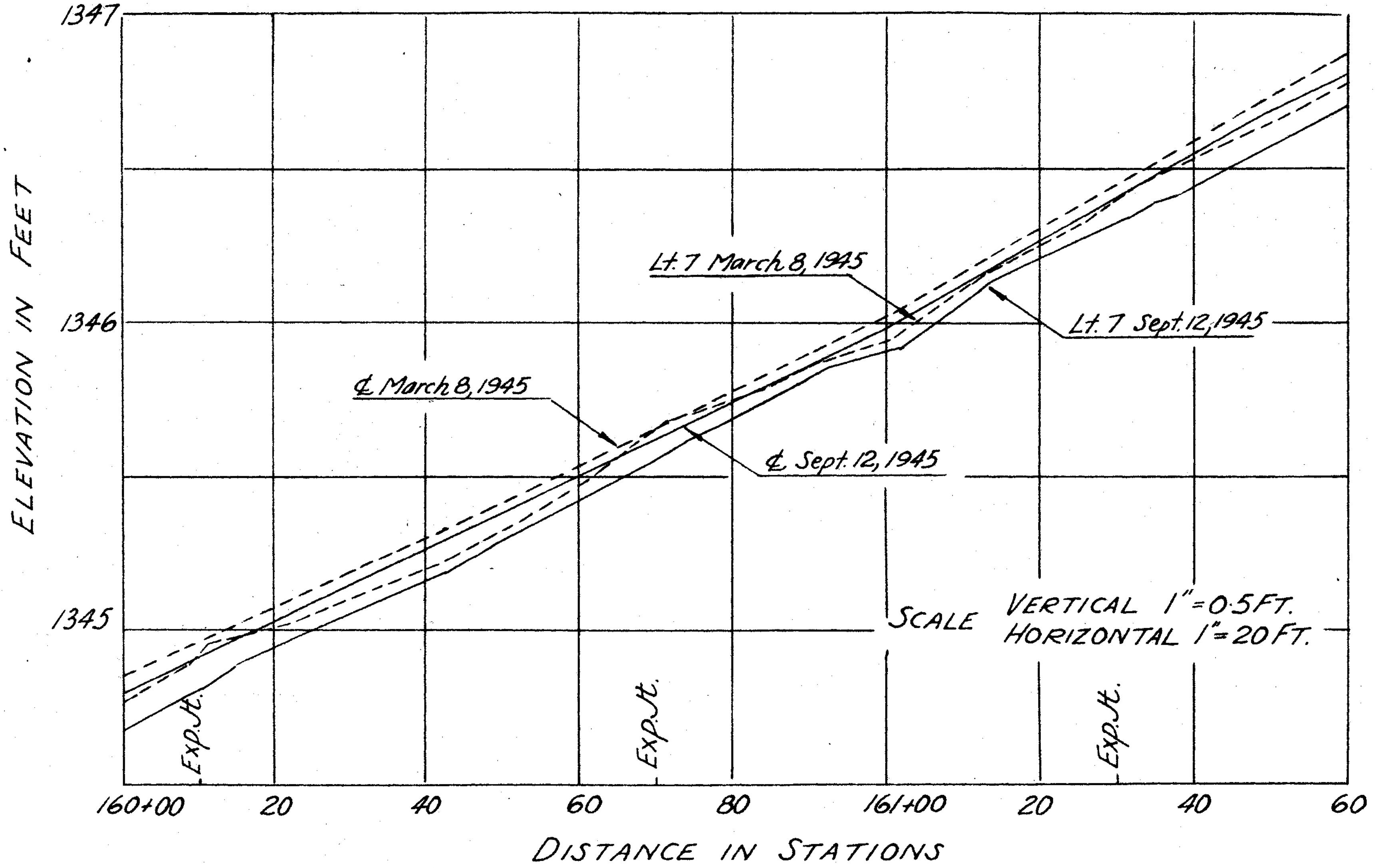


Figure 31. Frost heaving on U. S. 20, Sac County, Iowa -- profiles showing pavement conditions in summer and winter.

capillary rise. This method, however, is only effective in reducing frost heaving, but does not eliminate it entirely. Another method is to introduce a layer of porous material as a subbase. In Michigan, a 12-inch sand subbase has been used and proved quite effective (47). Still a third method can be used here. A watertight bituminous blanket at freezing depth can be introduced to prevent capillary conduction. A fourth method is suggested here, but no experimental proof can be furnished since not enough work has been done along this line. This method involves the treatment of the subgrade loess soil with water repelling agent such as Armac T (more will be said about this chemical in the later part of this manuscript). It is the belief of the author that this chemical can waterproof the soil to such a degree that water or moisture cannot enter into it to cause any detrimental effects.

A second problem that faces an engineer in combatting frost action is the presence of free water around the soil particles. However, this can be solved easily by introducing a system of adequate drainage ditches and sub-drains and thus lowering the existing water table to a depth outside the frost zone. In deep cuts this problem may present some serious trouble, but with properly placed drainage pipes and ditches, free water can always be prevented from accumulating at the bottom of the cut and soaking into the soil.

A third factor that causes ice segregation and frost heaving in the soil is the structure or rather the lack of structure in the soil. This is one of the main reasons why all silty soils including the two loess samples under investigation are subject to frost action. To improve the structure of the subgrade soil, one of the two following methods can be used. The first method is to utilize the soil material in place. However, gravel or crushed stone is incorporated with the subgrade soil and thus forming a stabilized subgrade mixture. The second method involves the complete replacement of the heaving soil to the frost line by non-heaving soil such as sand, gravel, or crushed rock. This is probably the best procedure for eliminating the action of frost. It is also the simplest and less expensive method provided sand and gravel can be obtained from nearby locations. This method was used in constructing a section of Iowa 141, test course Number 7 mentioned previously. Although the material used was reclaimed from an old gravel road and the treatment was extended only to a depth of one foot below the pavement, yet the procedure has been proved to be quite effective in reducing or eliminating entirely frost heaving in that section of the road. In New Hampshire, where frost penetration amounts to about four feet, although the soil is not loess, the following methods of using non-heaving soils have been effective (68):

a. Gravel bases four feet deep through silt and clay deposits or 18 inches deep through these areas when uniform frost heave is to be permitted,

b. Gravel bases 12 to 24 inches deep through graded soil,

c. Gravel bases 6 to 12 inches deep through cohesionless soils,

d. Gravel bases 6 to 12 inches deep on fill sections over 4 feet above ground level. Fill sections less than 4 feet high are treated as cut sections.

The fourth condition which is a prerequisite for the occurrence of frost action is the gradual decrease of air temperature to below freezing. There is no direct method for combatting this factor. However, it can be offset by the application of a layer of material with low heat conductivity such as peat moss beneath the pavement and thus impeding the entrance of frost to underlying layers of soil material.

By using any one or a combination of two or more of the above mentioned methods of subgrade treatment ice segregation and differential frost heaving can be eliminated entirely or at least reduced to a minimum. With this statement let us now leave "frost action on loess" and proceed to another phase of the investigation.

E. Stabilization of Loess

In the first thesis submitted by the author a section of it was devoted to loess soil-stabilization. Before going on, perhaps it is well to give a brief review of the extent of work the author had done on that subject. In the previous study three different materials were used to stabilize loess -- bituminous material such as asphalt, aggregates such as coarse and fine sand, and Portland cement. Loess, however, was only of secondary importance in the first two cases, since in the bituminous stabilization it was used as filler material, and in the aggregate stabilization as binder material.

Two methods were used in designing suitable bituminous mixtures with the two loess soils as filler material. The first was the trial method. After the proper proportion of coarse sand, fine sand and filler was obtained from the triangular chart (10), three different percentages, 4, 6, and 8 per cent, of asphalt were tried with the mixture. For each of the mixtures with one of the chosen percentages of asphalt, several 2 x 1 inch specimens were molded and a series of tests was run on them. The second was the surface area method. This method was used primarily as a check on the first one. Full description of it is given in the 1935 Proceedings of the Highway Research Board (31) and nothing more is needed to be said about it. The results of this study are included in the later section of this paper.

In the aggregate-loess stabilization study, the aggregates used were pit-run gravel and crushed rock. Graded mixtures for a base course and a surface course were designed by the triangular chart method (10) using the two loess soils as binder materials.

Table 9

Proportions of Crushed Rocks, Gravel, and Binder in Designed Graded Mixtures

	Designed Mixtures	Per Cent Crushed Rocks	Per Cent Gravel	Per Cent Binder	Plasticity Index
Harrison County Loess	Surface Course	42.4%	34.2%	23.4%	4.43%
	Base Course	48.25%	38.8%	12.95%	3.73%
Johnson County Loess	Surface Course	18.67%	63.3%	17.93%	7.63%
	Base Course	25.15%	65.6%	9.25%	5.60%

The suitability of the designed mixtures were determined by subjecting them to the Modified Proctor Density Test, the Unconfined Compression Test, and the California Bearing Ratio and Expansion Tests. Further discussion of this study will be given later.

In the soil-cement study three different percentages 6, 10 and 14 per cent of cement by volume were tried on the two loess samples. The only deviation here from the standard procedure was the use of the modified Proctor densities of the soil-cement mixtures instead of the standard Proctor densities.

The soil-cement mixtures were subjected to the Unconfined Compression Test, Freeze-Thaw Test, and Wet-Dry Test to determine their suitability.

The procedures of the tests and durability requirements of the samples conformed to those recommended by the P.C.A. (53) and A.S.T.M. (2). Since this section of soil-stabilization is to be compared with a later study, it is not necessary at this time to go into the problem thoroughly.

With the preliminaries disposed of let us now turn to the problem concerned in the present study which is to stabilize loess soil using some stabilizing agents but keeping in mind that loess is the primary material. The present study of the stabilization of loess soils may be divided into two parts. The first covers the choosing of different mixtures and the second covers the testing of these mixtures for their strength, durability, etc.

1. Stabilizing Loess with Oil-Products -- Asphalt and Tar.

Bituminous soil stabilization is relatively new in highway engineering practice and is still in the process of development. For base and light traffic surface courses, soil-bitumen may prove to be a very inexpensive system of stabilizing and waterproofing a soil. The bitumen is incorporated in a soil, which has satisfactory bearing capacity at low moisture content such as the loess, as a waterproofing agent to maintain a low moisture content and an adequate

Figure 32. Asphalt treated loess soil road. Harrison County, Iowa.

Figure 33. Another view of same asphalt treated loess soil road.

bearing capacity. Obviously for such a purpose a very light liquid bituminous material should be used. In general practice, medium-curing cut-back asphalt and RT-3 to RT-6 grades tar are recommended. When emulsified asphalt is used, the product should be one that will mix readily with the soil (26).

In this study, MC-0 asphalt and grade P-1 tar were used to stabilize the two loess soils. Four different percentages, 2, 4, 6 and 8 per cent by weight of bitumen were used with each of the loess soils. Each soil-bitumen mixture was submitted to the following test:

a. Hubbard-Field stability load test (2, pp. 141-142).

Preparation of Specimens:

Five hundred grams of soil and bitumen were used in each batch so as to obtain five 2 x 1 inch specimens. The weight of soil was calculated on oven-dry basis. Before mixing the bitumen with the soil, water was added to bring the total percentage of water-bitumen in the soil to a value equal to the optimum moisture content. In no case, however, was the percentage of moisture (excluding the bitumen) allowed to go below 10 per cent. After the water was thoroughly mixed in the soil, the proper amount of bituminous material was added and the whole system was again mixed by hand for fifteen or twenty minutes. Then the soil-bitumen mixture was placed in a loose layer one half inch thick, and allowed to cure at a temperature not exceeding 100° F. for a period of 16 to 20 hours.

After the curing period, 2 x 1 inch specimens were molded from the mixtures. To obtain about one inch compacted thickness, about 100 grams of soil-bitumen mixture were used for each specimen. The soil-bitumen was placed into the mold and tamped 50 times with the No. 1 tamper and then 15 times with the No. 2 tamper. Descriptions of the mold, tampers, etc. are given in the A.S.T.M. Procedures for Testing Soils (2). With the plunger in place the specimen in the mold was then subjected to 10,000 pounds total pressure, holding the compacting load constant for a period of 2 minutes after equilibrium was reached.

Procedure of Test:

Two specimens from each batch of soil-bitumen mixtures were tested at room temperature and the average result of the two was considered as the stability strength of the mixture.

The specimen to be tested was placed originally top end down, in the testing mold. The plunger was then inserted. Load was applied at a rate which lowered the testing lead about 1 inch in 25 seconds. As the specimen was loaded gradually, it began to distort at the orifice in the testing ring and the dial pointer rose quite rapidly to a maximum just before the bond was broken. The maximum load registered by the push pointer was recorded as the stability value of the specimen.

Table 10

Hubbard-Field Stability Load in Pounds for the Two Asphalt and Tar Treated Loess Samples[1]

Per Cent Bitumen	Harrison County Loess		Johnson County Loess	
	Asphalt	Tar	Asphalt	Tar
2	2330	2162	8614	8774
4	1702	1366	7710	8653
6	1189	1431	4910	9654
8	1489	1511	3954	5695

[1] Hubbard-Field stability test could not be run on the specimens after the water absorption test since all the specimens swelled appreciably after the first 12 hours, Figure 34.

b. 72-hour water absorption test (2, p. 142).

Specimens used for the test were molded in the same manner as those for the previous test. One specimen from each batch of bituminous mixture was placed in a flat-bottom pan, in which the height of the distilled water was adjusted to a depth of one half inch. The pan was tightly covered and placed in a room maintained at a temperature of approximately 70° F. The specimens were subjected to the Hubbard-Field test after the 72-hour soaking period.

c. Unconfined compression test.

This test is designed to furnish (a) the ultimate strength of the material as a measure of the ultimate bearing capacity of the soil-bitumen, and (b) the stress-strain curve as an indication of the movement due to lateral deformation which can be expected when the soil-bitumen is under load. However, the results derived from this test are only relative and cannot be considered as finite.

Preparation of Specimens:

Specimens two inches by four inches were used for this test. The exact amount of soil (assuming the soil-bitumen density to be the same as standard Proctor density of raw soil) required to mold a specimen (adjustments for different percentages of bitumen were made accordingly) was calculated and weighed out, the hygroscopic moisture being predetermined. The soil-bitumen mixture was prepared in the same manner as in the previous test. However, the curing period was not necessary here since one specimen was to be tested with the presence of moisture.

After mixing, the soil-bitumen was transferred into the mold, and with the plunger in place, the mold was placed in the testing machine. Load was applied to bring the soil cylinder to the required size. The load was kept on the specimen for about a minute before being released slowly.

Four specimens were prepared from each mix. The first specimen was tested immediately after removing from the mold. The second specimen was tested at oven-dry (140° F.) condition. A third one tested after oven-dry (140° F.) and soaked in water for one hour, and the fourth one tested after an air-dry period of seven days. The testing of the specimens was performed in the same way as in the case of concrete cylinders using paraffin to cap the cylinders instead of plaster of Paris. Figures 41-48 show the stress-strain curves for the tests.

2. Stabilizing Loess with Water-repelling Agent.

This phase of the study was first inspired by Mr. D. T. Davidson (15) of Iowa State College who has been studying the effects of large organic cations on soil stability. In his study, Davidson used six organic compounds containing large organic cations -- Armac T, Armac 18D, Armac 12D, Rosin Amine-D Acetate, Amine 220, and Ammonyx T -- with special emphasis on the Armac T. However, in the study worked out by the writer, only Armac T was used and the extent of the research was limited mainly to the waterproofing quality of the compound.

"Armac" is the trade name of Armour and Company,[1] given

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[1] Armour Chemical Division, Armour and Company, 1355 W. 31st Street, Chicago 9, Illinois.

Figure 34. Loess soil-bitumen specimens before and after 72-hour water absorption test.

Figure 35. Loess soil-bitumen specimens after Hubbard-Field stability load test. Top view.

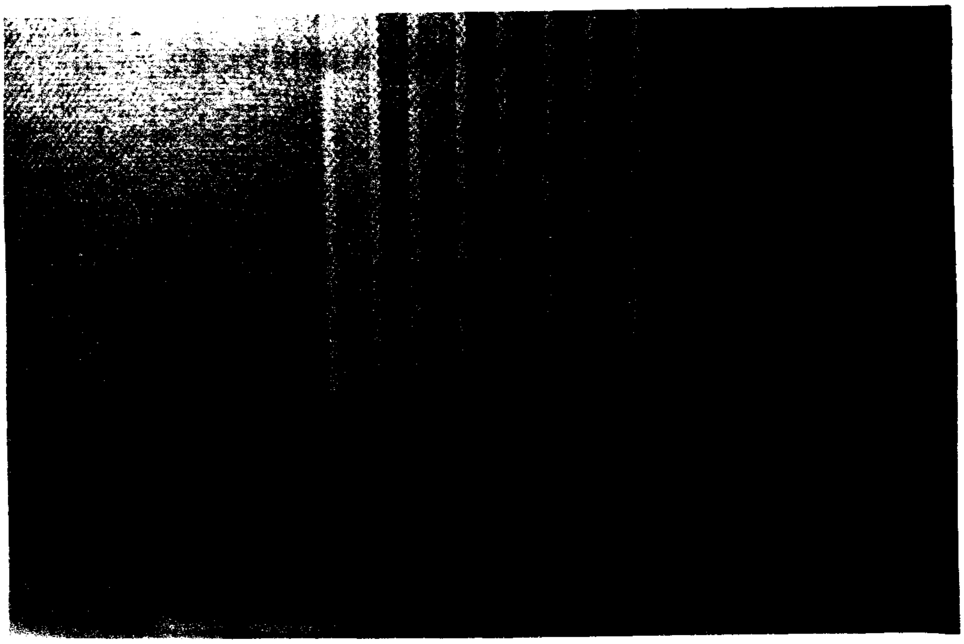

Figure 36. Loess soil-bitumen specimens after Hubbard-Field stability load test. Side view.

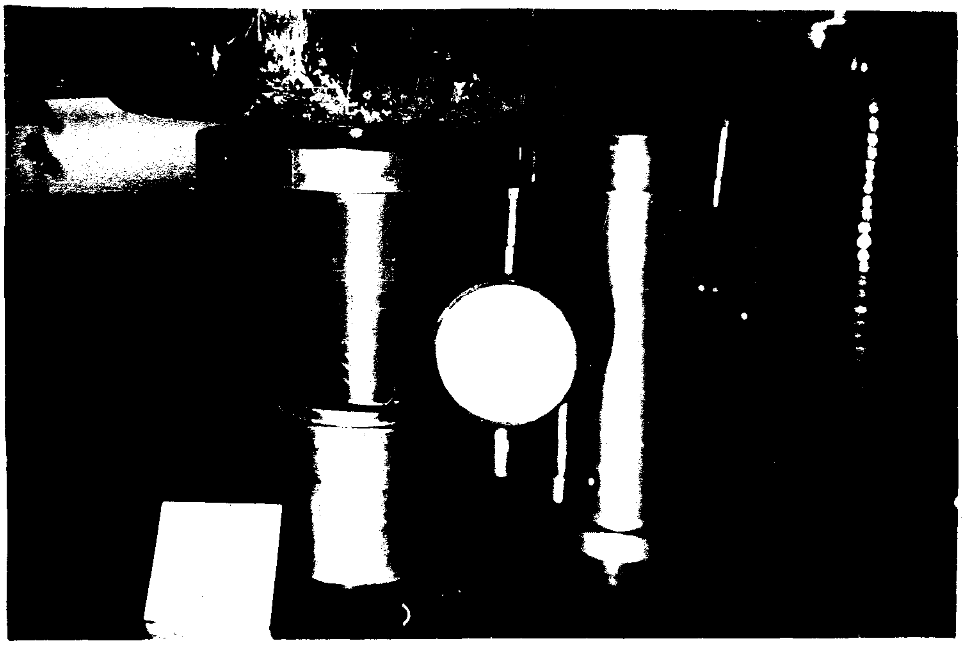

Figure 37. Unconfined compression test.

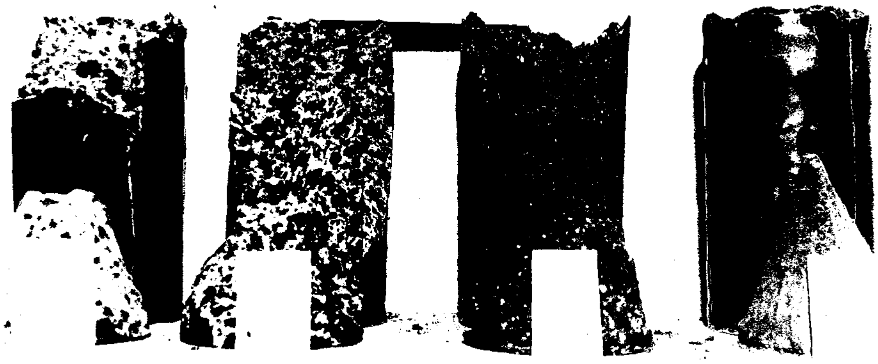

Figure 38. Appearance of loess soil-bitumen specimens with varying percentages of bituminous material after unconfined compression test.

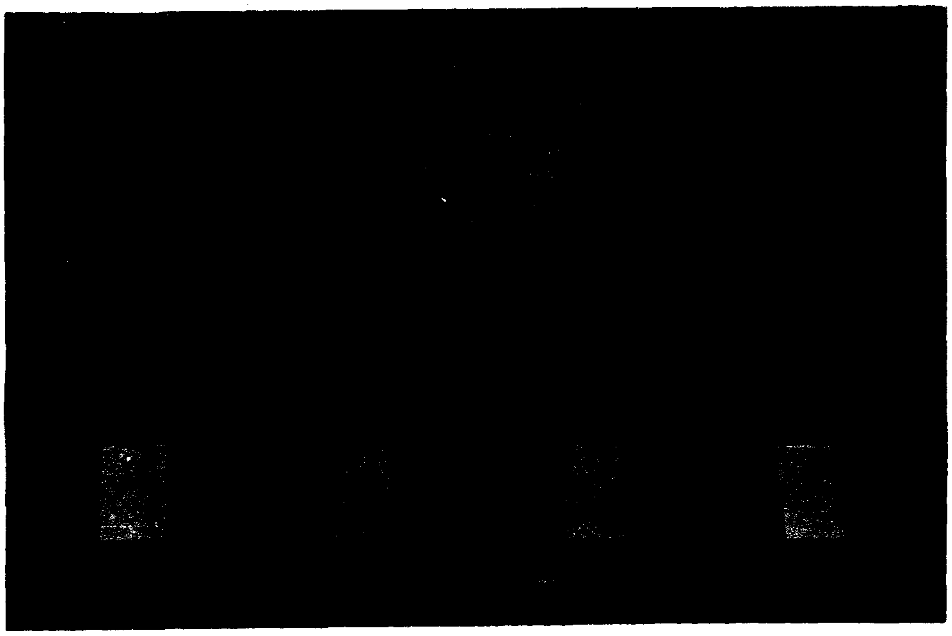

Figure 39. Loess soil-bitumen 2" x 4" specimens before unconfined compression test.

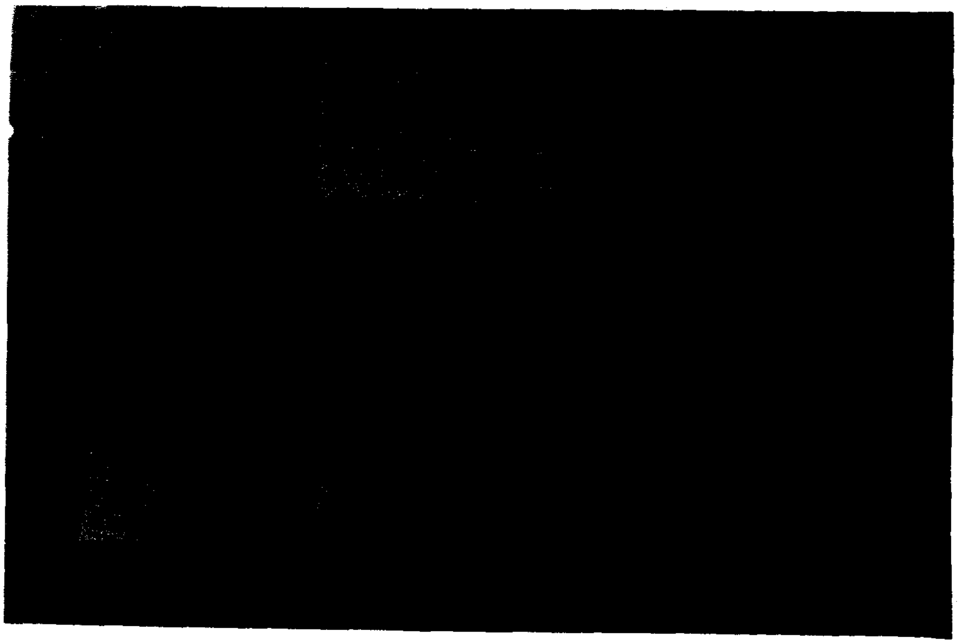

Figure 40. Loess soil-bitumen 2" x 4" specimens after oven dried and soaked in water for 1 hour.

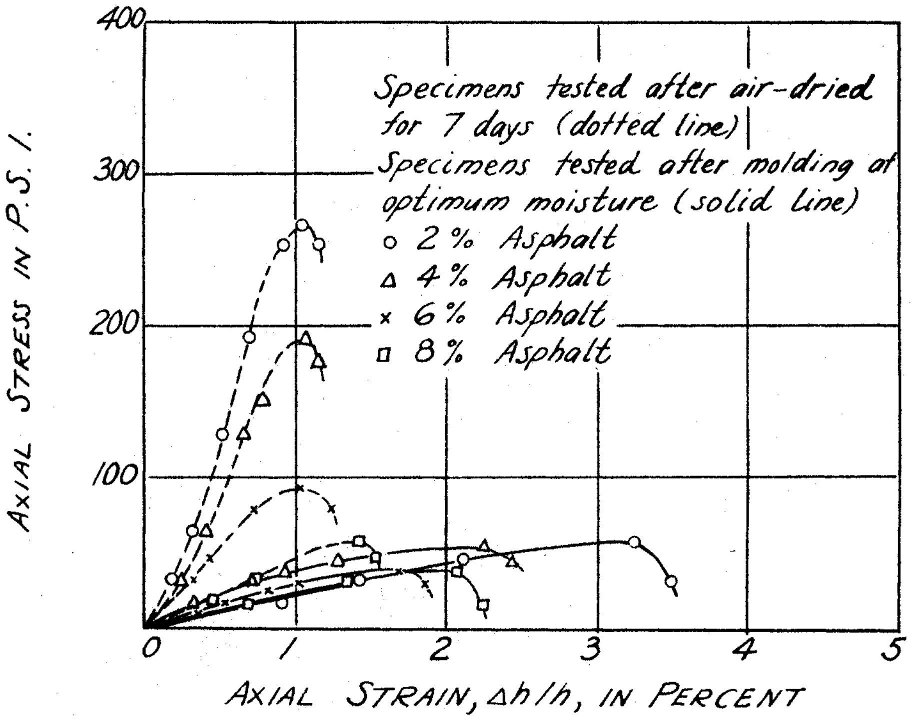

Figure 41. Stress-strain curves for Harrison County loess treated with varying percentages of asphalt. One series of specimens tested after air-dried for 7 days and another at optimum moisture condition. Unconfined compression test with specimens compacted to standard Proctor densities.

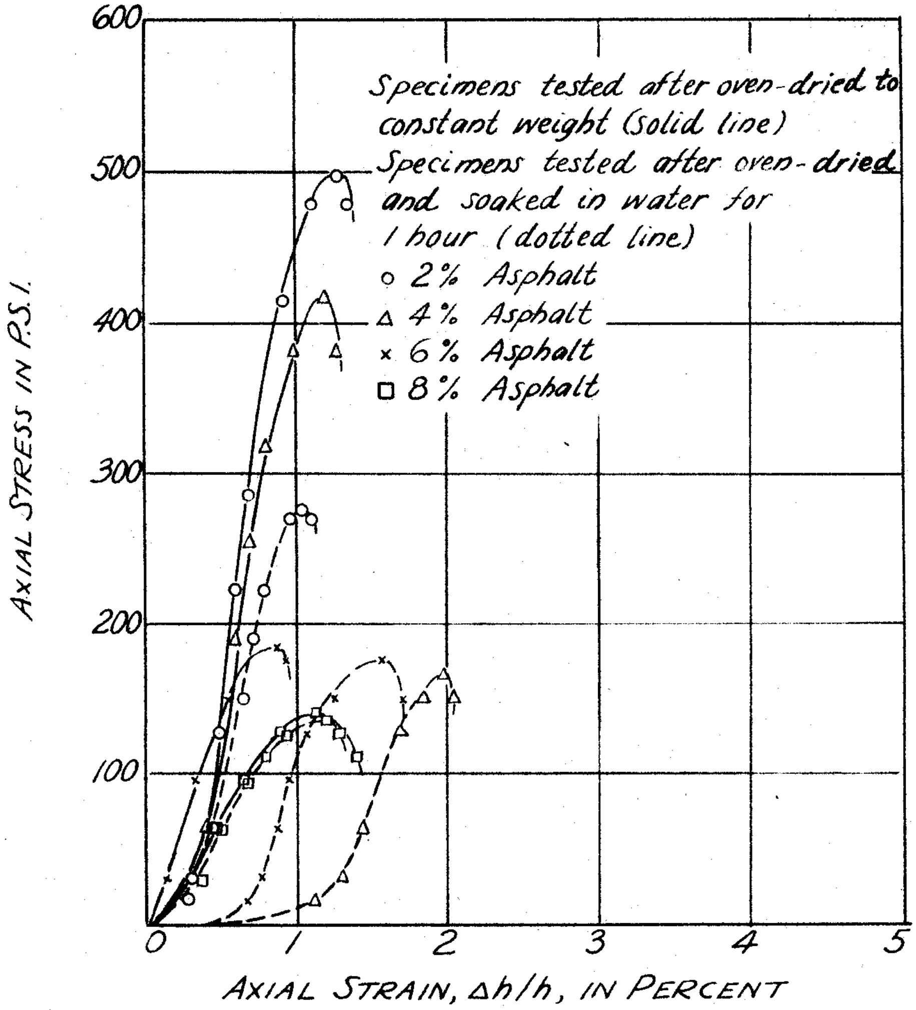

Figure 42. Stress-strain curves for Harrison County loess treated with varying percentages of asphalt. One series of specimens tested after oven-dried to constant weight and another after oven-dried and soaked in water for 1 hour. Unconfined compression test with specimens compacted to standard Proctor densities.

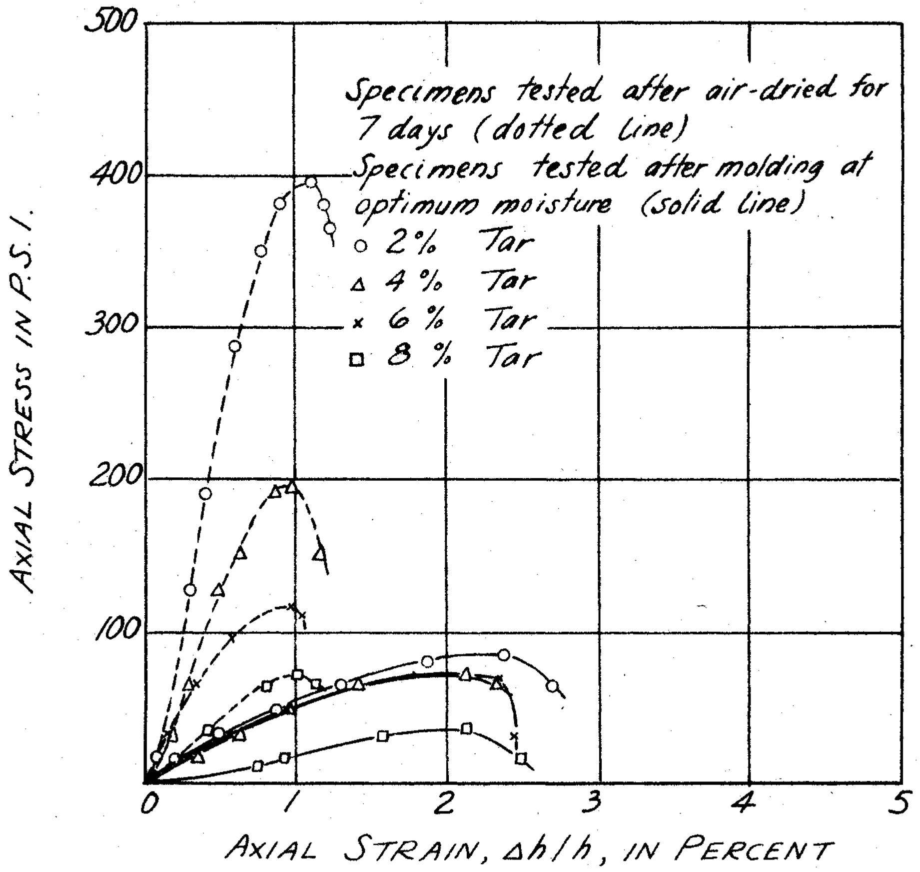

Figure 43. Stress-strain curves for Harrison County loess treated with varying percentages of tar. One series of specimens tested after air-dried for 7 days and another at optimum moisture condition. Unconfined compression test with specimens compacted to standard Proctor densities.

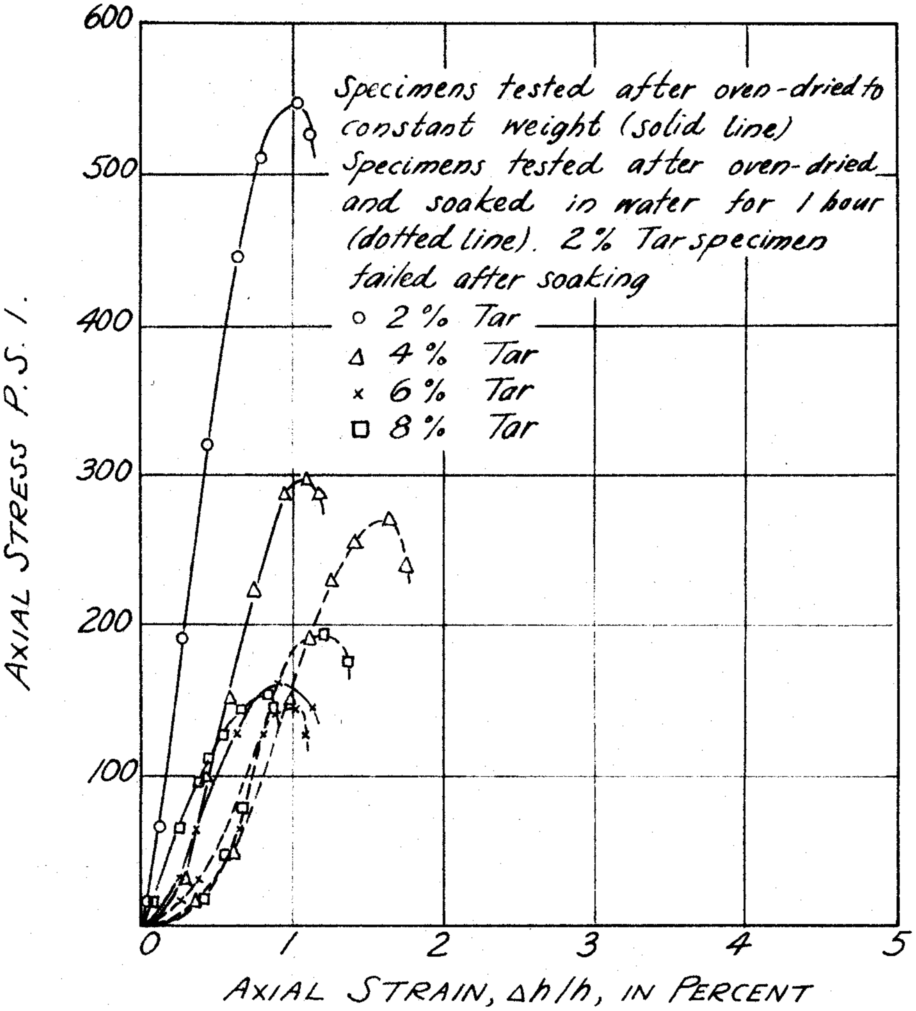

Figure 44. Stress-strain curves for Harrison County loess treated with varying percentages of tar. One series of specimens tested after oven-dried to constant weight and another after oven-dried and soaked in water for 1 hour. Unconfined compression test with specimens compacted to standard Proctor densities.

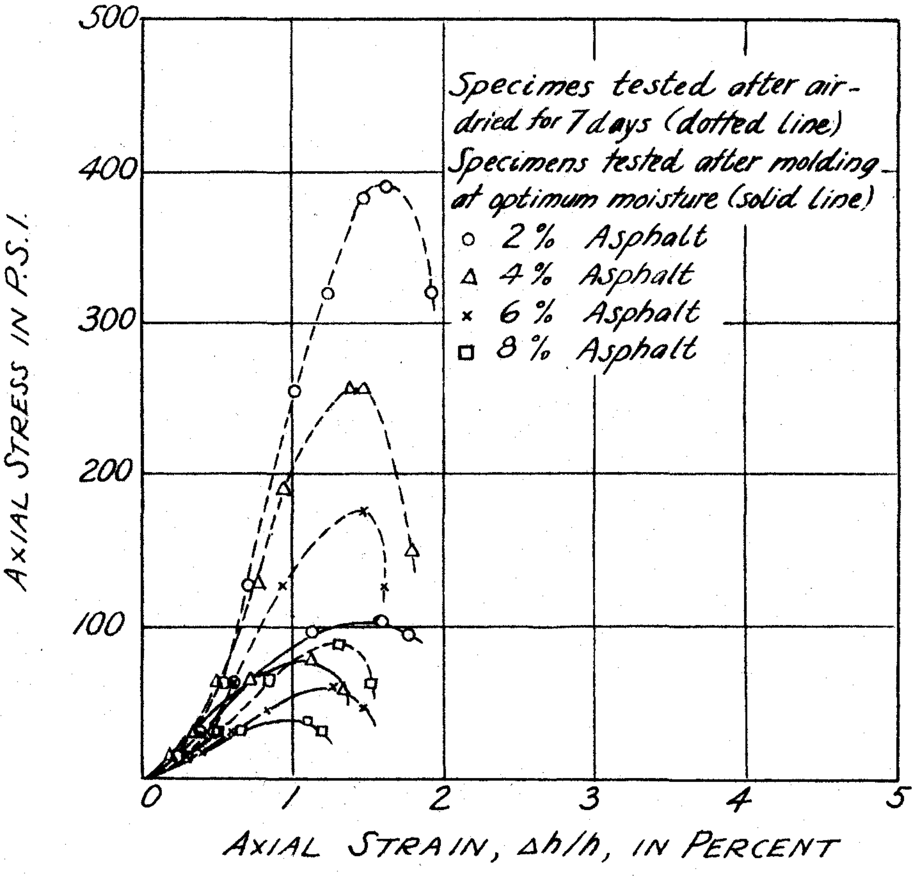

Figure 45. Stress-strain curves for Johnson County loess treated with varying percentages of asphalt. One series of specimens tested after air-dried for 7 days and another at optimum moisture condition. Unconfined compression test with specimens compacted to standard Proctor densities.

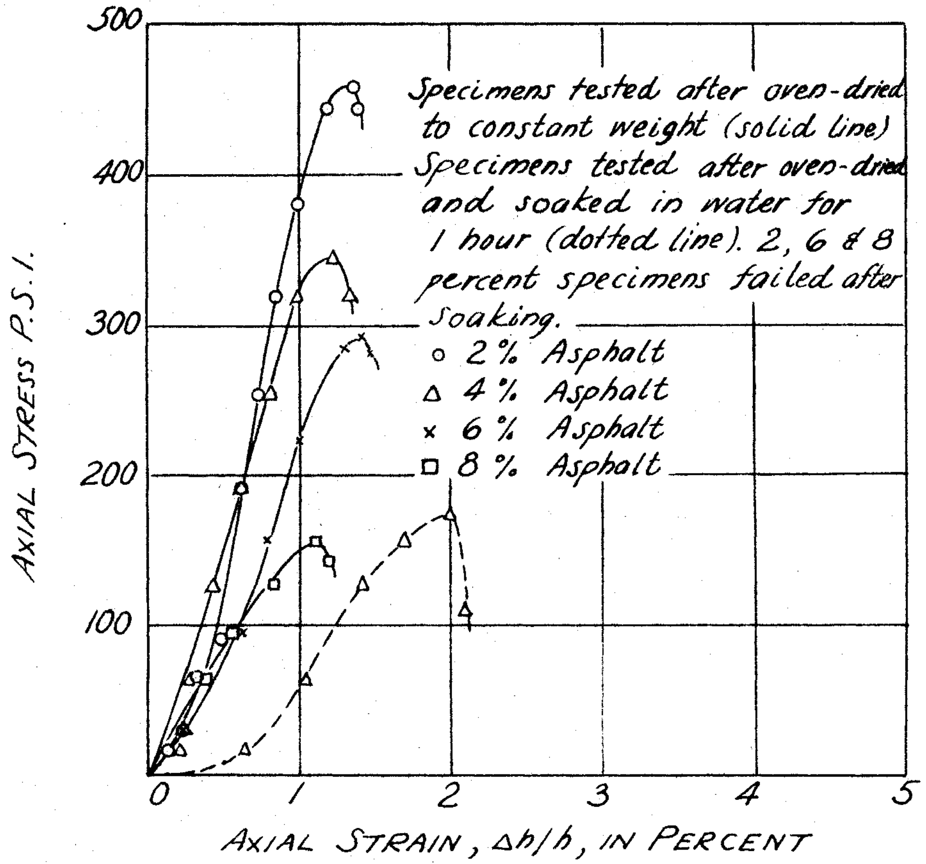

Figure 46. Stress-strain curves for Johnson County loess treated with varying percentages of asphalt. One series of specimens tested after oven-dried to constant weight and another after oven-dried and soaked in water for 1 hour. Unconfined compression test with specimens compacted to standard Proctor densities.

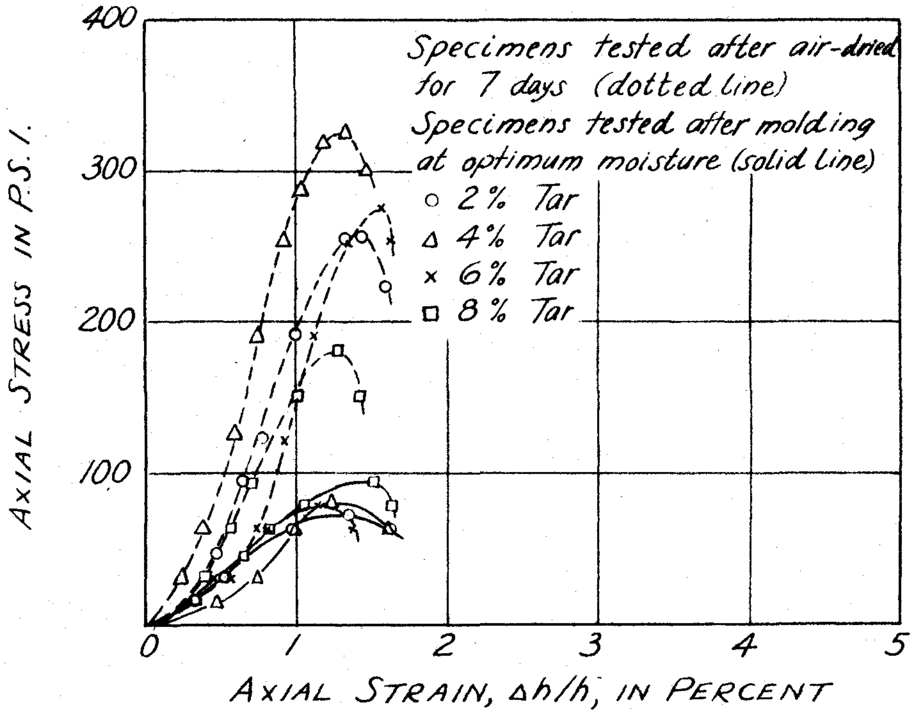

Figure 47. Stress-strain curves for Johnson County loess treated with varying percentages of tar. One series of specimens tested after air-dried for 7 days and another at optimum moisture condition. Unconfined compression test with specimens compacted to standard Proctor densities.

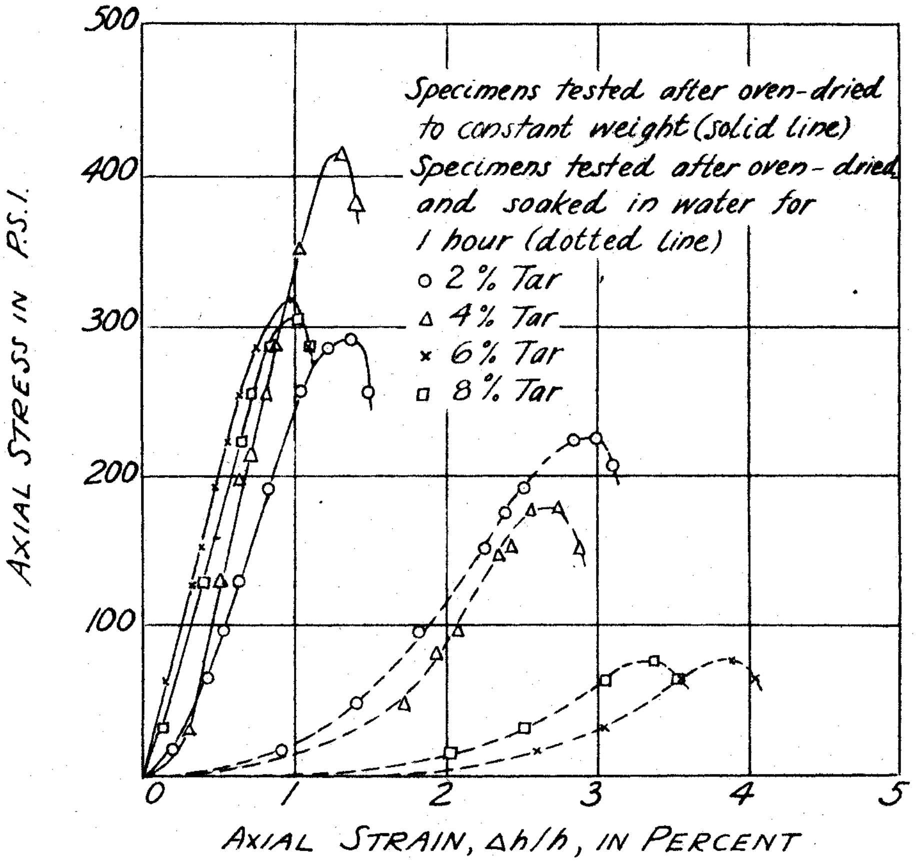

Figure 48. Stress-strain curves for Johnson County loess treated with varying percentages of tar. One series of specimens tested after oven-dried to constant weight and another after oven-dried and soaked in water for 1 hour. Unconfined compression test with specimens compacted to standard Proctor densities.

to the acetate salts made from the Armeens. "Armeen" is the trade name given to amines produced from fatty acids by the same company. The general formula for Armeens is RHN_2 where the R group represents the long hydrocarbon chain found in fatty acids. The Armeens are soluble in oils and oil-like materials but are insoluble in water. However, the Armacs are soluble in both water and oil. For every Armeen there is a corresponding Armac. Thus, Armac T is derived from Armeen T neutralized with glacial acetic acid. Table 11 gives the composition of a few Armeens from which the composition of the corresponding Armacs can be concluded.

In industry Armacs are used to cause surface change phenomena. Small quantities of these chemicals are sufficient to cause certain types of water-loving surfaces to become water-repelling and oil-loving.

The Armac T used in this study has a light yellowish-brown color and a pungent smell. At room temperature, it is a semi-solid just like heavy grease. However, it dissolves quite easily in warm water, forming a soapy solution.

As before, this part of the research consists of two steps. The first is the introducing of the chemical into the soil, and the second is the testing of the admixture for the effect of the chemical on the soil.

a. Cationic[1] treatment of soil.

The two loess samples were treated with 1, 2 and 3

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[1] The name "cationic," when used in connection with a chemical radical, means that the radical is positively charged and travels to the cathode if electricity is passed through its solution (4).

Table 11

Composition and Constants of Armeen T, Armeen 8D, Armeen 12D, and Armeen 18D (4)

n-Primary Amine	Carbon Chain Length	Armeen T	Armeen 18D	Armeen 12D	Armeen 8D
Hexyl	6	--	--	--	3%
Octyl	8	--	--	--	90%
Decyl	10	--	--	--	7%
Dodecyl	12	--	--	90%	--
Tetradecyl	14	--	--	9%	--
Hexadecyl	16	30%	6%	--	--
Octadecyl	18	25%	93%	--	--
Mean molecular weight of primary amine content		263	267	185	129
Molecular combining weight		310	276	191	133
% Primary amine by titration		85	97	97	97
Approximate melting point, °C.		46	55	24	13

per cent by weight of the chemical based on the oven-dry weight of the soil.

Two thousand grams of material which passed No. 10 sieve were used for each of the three chosen mixes. Before adding to the soil the chemical was dissolved in 500-600 cc of distilled water, heating the solution to a temperature not over 70° C. The solution was then diluted to 2000 cc, and immediately added to the soil. The mixture was mixed thoroughly for at least 15 minutes in a large flat pan. Drying was carried out over a warm plate. When the mixture was dried thoroughly, it was then ground to pass a No. 10 sieve and stored for testing. A definite decrease in air-dry strength of the treated soil was noticeable at this time, especially with the Johnson County sample.

b. Tests to evaluate the effect of cationic admixtures.

The following tests were used to study the effect of Armac T on the loess samples:

(1) Unconfined compression test.

Two by four inch specimens were molded for this test at raw soil standard Proctur density and optimum moisture content. The procedure for molding was the same as before. One specimen was tested right after being molded. A second specimen was tested after air-drying for 7 days at room temper-

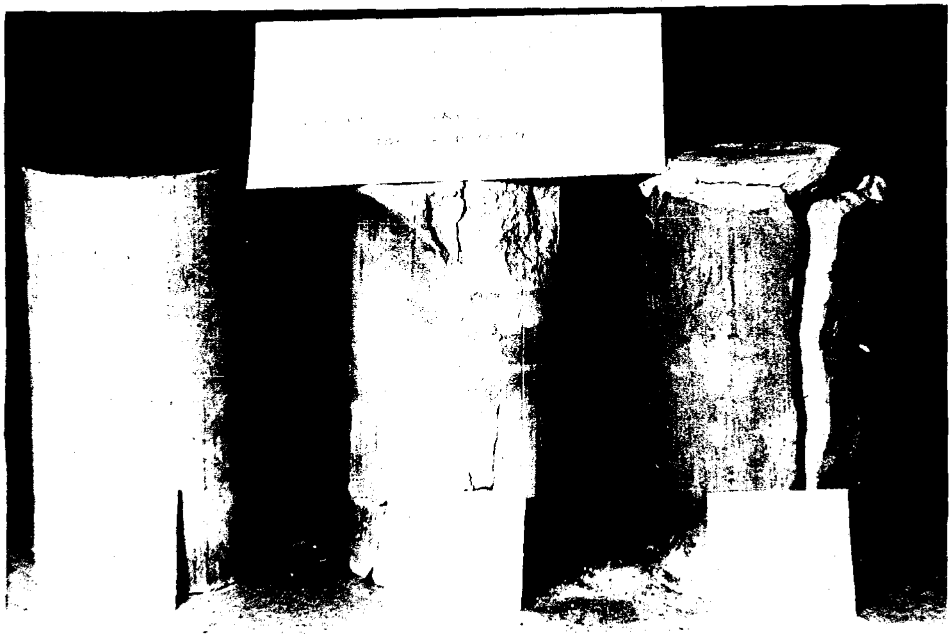

Figure 49. Armac T treated Harrison County loess 2" x 4" specimens after soaked in water for 24 hours.

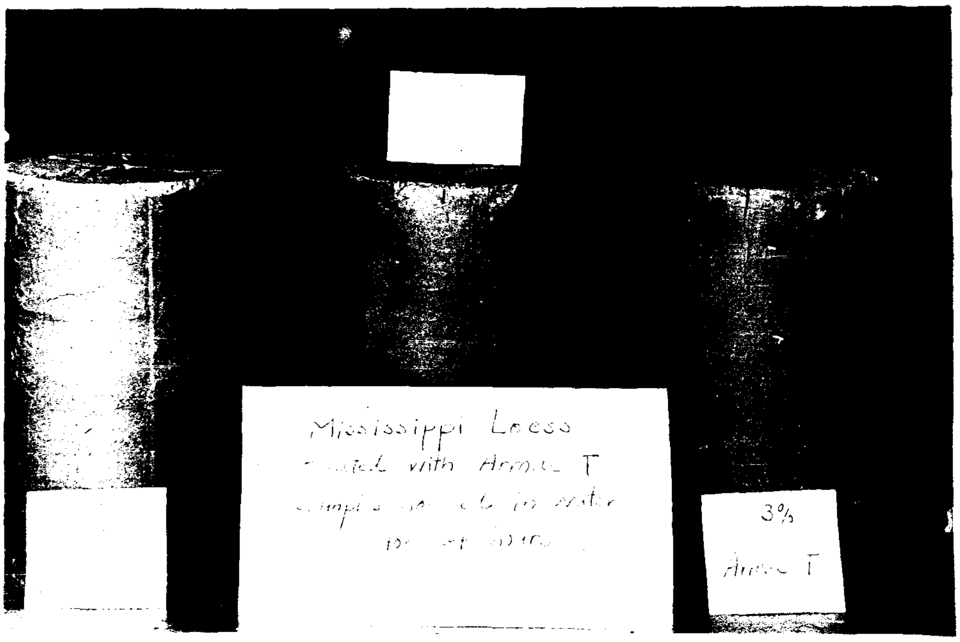

Figure 50. Armac T treated Johnson County loess 2" x 4" specimens after soaked in water for 24 hours.

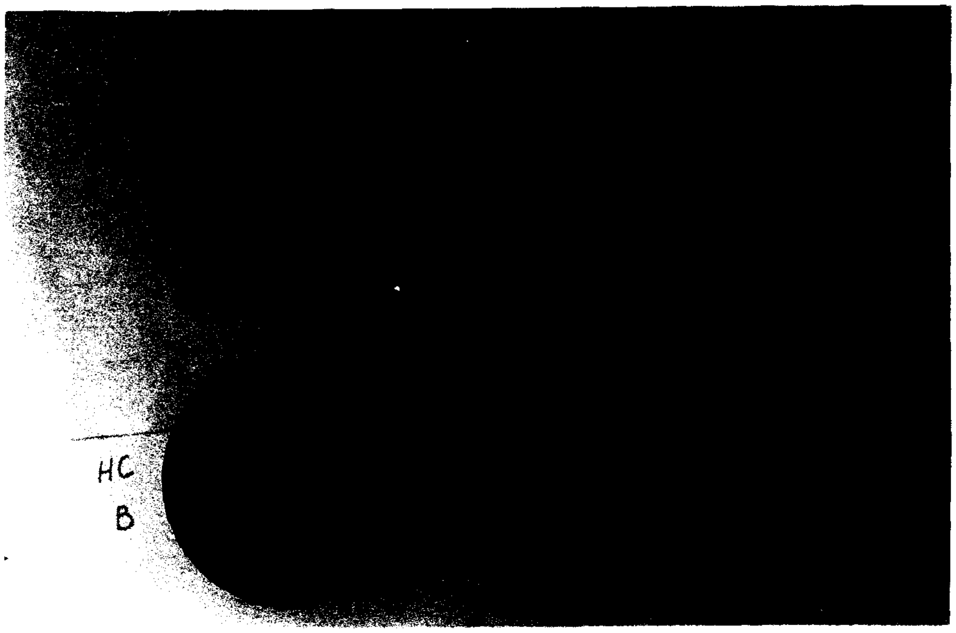

Figure 51. Harrison County loess soil-bitumen specimens after soaking in water for 24 hours. Top right: 6% bitumen. Bottom right: 8% bitumen. Top left: 1% Armac T and 6% bitumen. Bottom left: 1% Armac T and 8% bitumen.

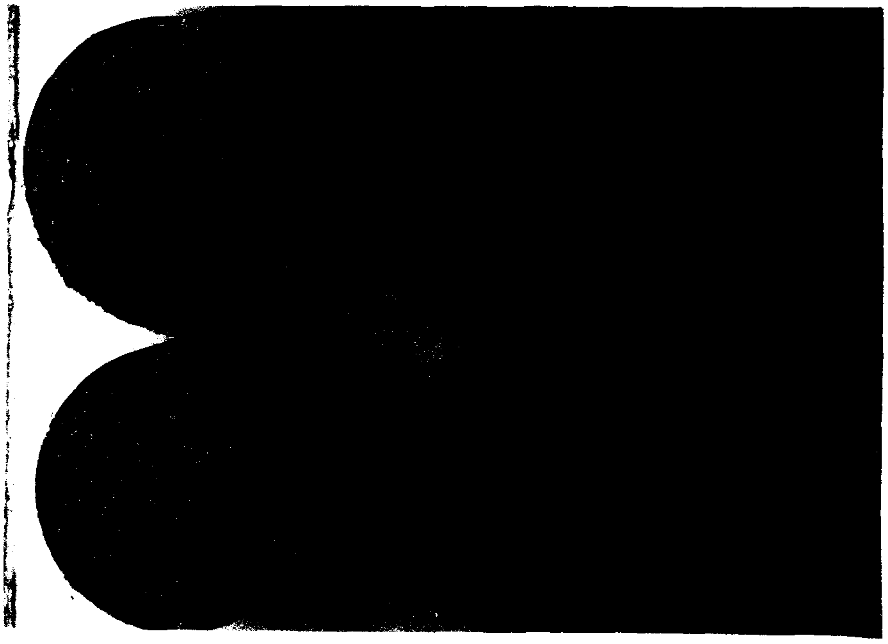

Figure 52. Johnson County loess soil-bitumen specimens after soaking in water for 24 hours. Top right: 6% bitumen. Bottom right: 2% Armac T and 6% bitumen. Top left: 8% bitumen. Bottom left: 2% A$_r$mac T and 8% bitumen.

ature. A third specimen was tested after air-drying for 7 days and soaking in water for 24 hours. The results of this series of tests are presented on the following pages.

(2) Hubbard-Field test.

Previously it has been shown that using up to 8 per cent bitumen alone is not enough to waterproof and stabilize the loess completely. The purpose of this test is to show what the effect would be if the soil is treated with Armac T first before bitumen is added.

Six and 8 per cent asphalt were tried on 1 per cent Armac T treated Harrison County loess and 2 per cent Armac T treated Johnson County loess. These two percentage cationic admixtures were found to give the best results from the first series of tests. Since the procedures for mixing the bitumen with the soil and molding the specimens have already been covered previously, it is not necessary to repeat them here.

After the curing period two specimens were molded from each batch of mixtures. One specimen was tested after molding at room temperature. The other one was tested after soaking in water for 24 hours.

Table 12

Hubbard-Field Stability Load in Pounds for the Two Armac T -- Asphalt Treated Loess Samples

% Armac T	% Asphalt	Tested after molding at room temperature		Tested after soaking in water for 24 hours	
		Harrison County Loess	Johnson County Loess	Harrison County Loess	Johnson County Loess
1	6	1290	---	1155	---
	8	1800	---	1477	---
2	6	---	4933	---	Failed completely
	8	---	4340	---	Failed completely

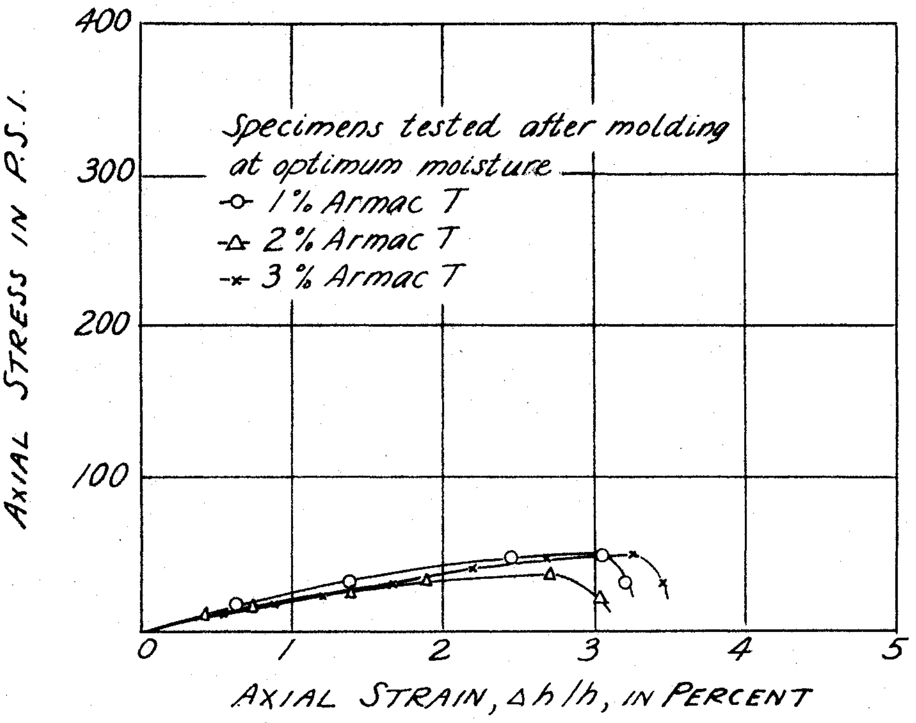

Figure 53. Unconfined compression stress-strain curves for Harrison County loess treated with varying percentages of Armac T. Specimens compacted to standard Proctor densities.

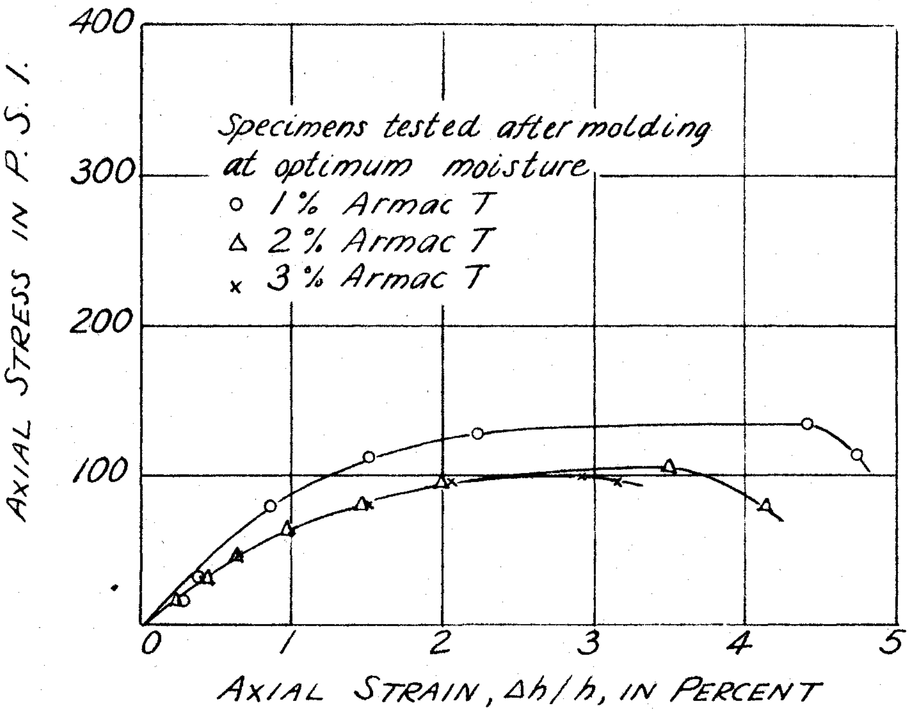

Figure 54. Unconfined compression stress-strain curves for Johnson County loess treated with varying percentages of Armac T. Specimens compacted to standard Proctor densities.

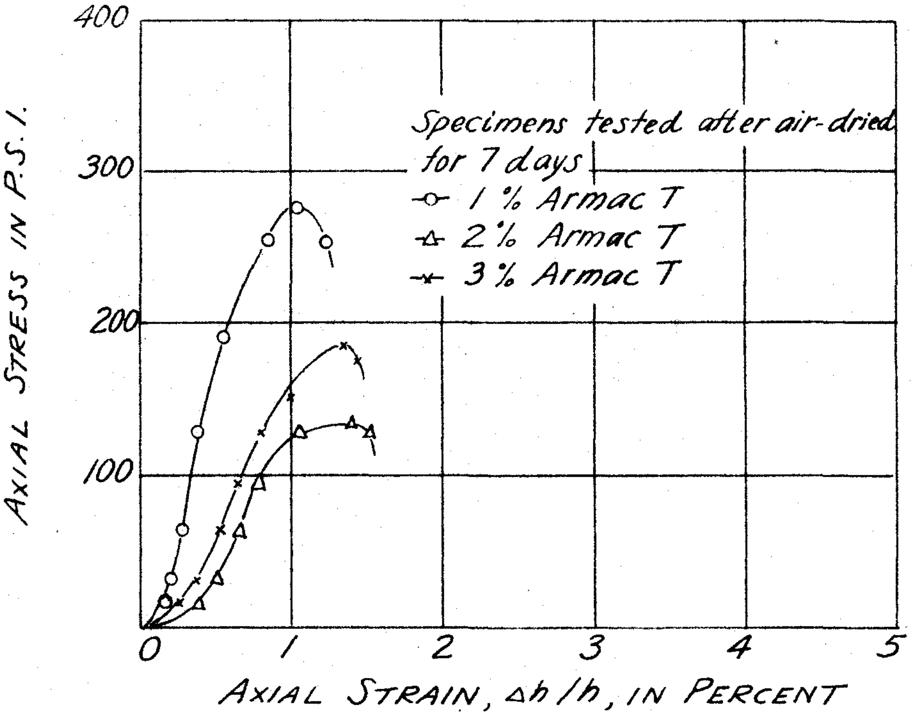

Figure 55. Unconfined compression stress-strain curves for Harrison County loess treated with varying percentages of Armac T. Specimens compacted to standard Proctor densities and tested after air-dried for 7 days.

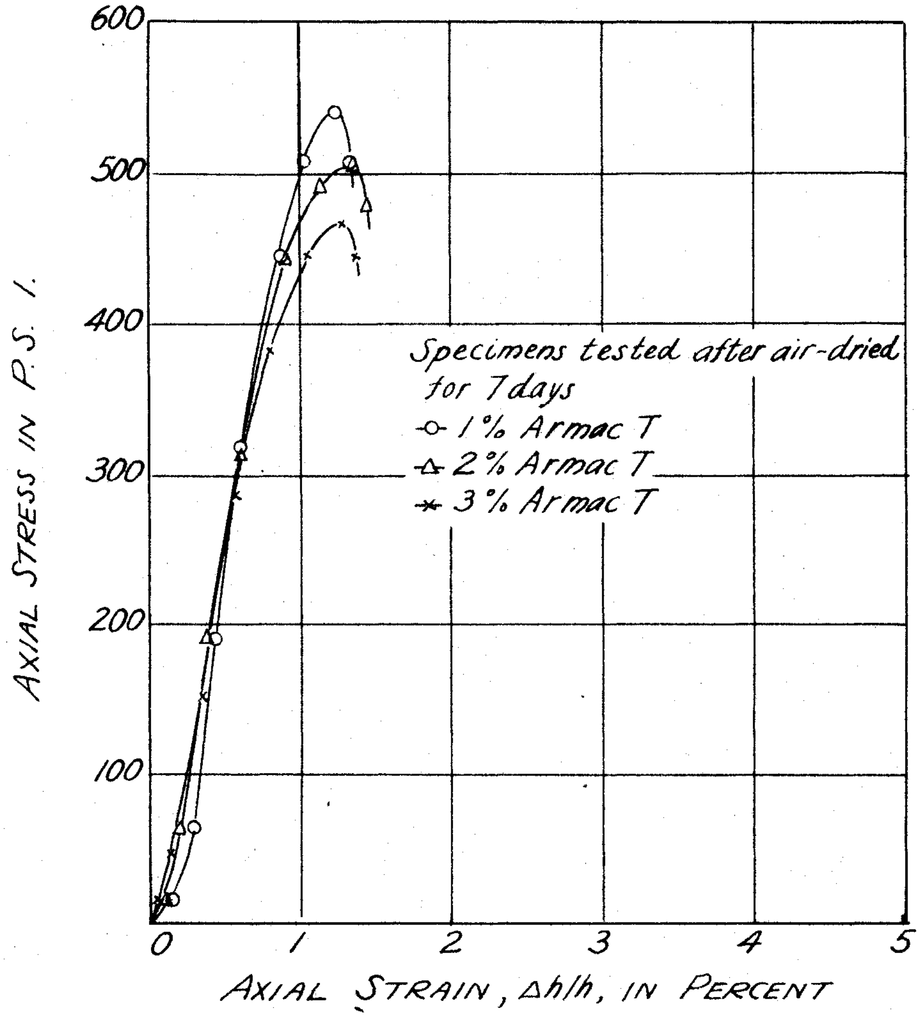

Figure 56. Unconfined compression stress-strain curves for Johnson County loess treated with varying percentages of Armac T. Specimens compacted to standard Proctor densities and tested after air-dried for 7 days.

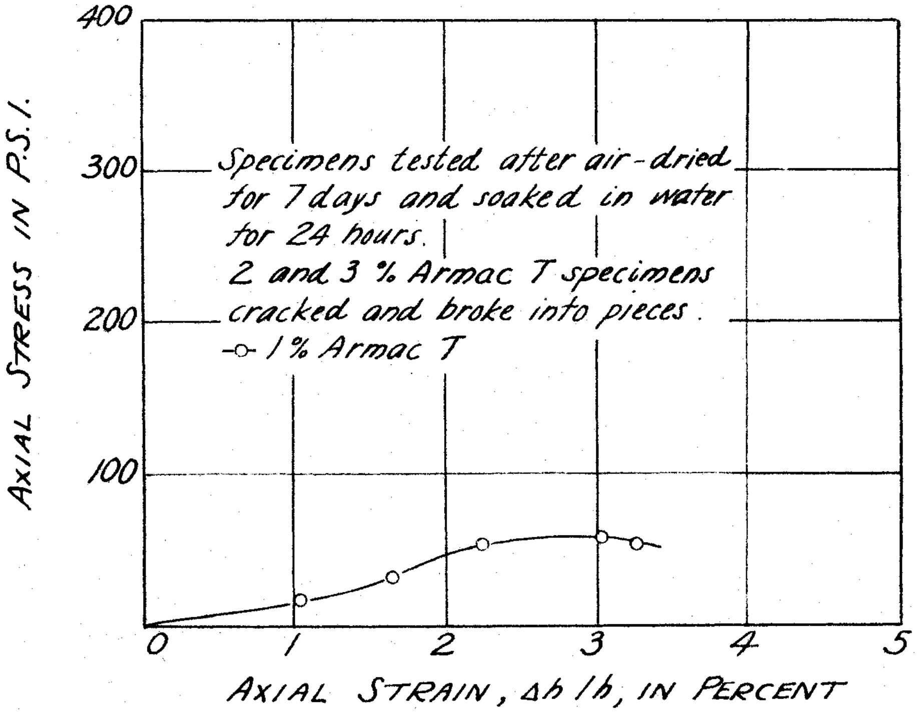

Figure 57. Unconfined compression stress-strain curves for Harrison County loess treated with varying percentages of Armac T. Specimens compacted to standard Proctor densities and tested after air-dried for 7 days and soaked in water for 24 hours.

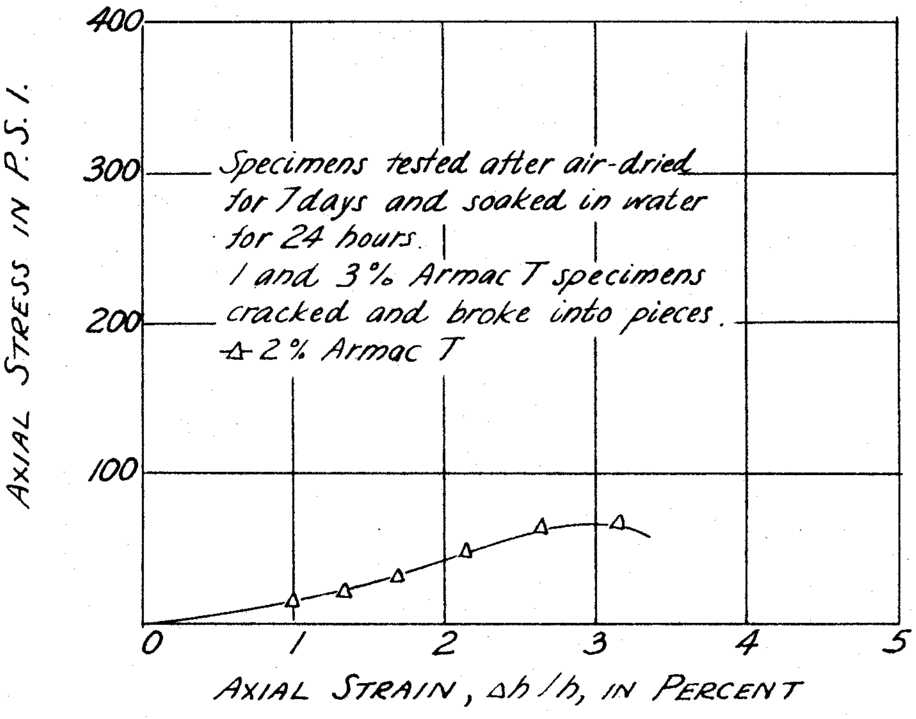

Figure 58. Unconfined compression stress-strain curves for Johnson County loess treated with varying percentages of Armac T. Specimens compacted to standard Proctor densities and tested after air-dried for 7 days and soaked in water for 24 hours.

3. Stabilizing Loess with Portland Cement.

Soil cement in itself opens a broad field of highway construction, and it is also a relatively recent development. Experiments with soil-cement roads were started by the South Carolina State Highway Department in 1932 at the suggestion of Dr. Charles H. Moorefield. Since then, the experiments have been carried on extensively in all parts of the country. In 1935, the Portland Cement Association conducted an extensive research program to get at the fundamental scientific principle required to produce suitable soil-cement mixtures for light traffic road use. After years of laboratory research, the Portland Cement Association has published specifications and basic principles regarding soil-cement work. The control factors required for field success and determined by laboratory tests are (1) proper cement content, (2) proper moisture content, and (3) proper density.

In this series of soil-cement tests, 6, 10, and 14 per cent of cement were used respectively, with the two loess samples. Standard Proctor density and optimum moisture tests were run on the soil-cement mixtures. The maximum densities and their corresponding moisture contents, Figures 64 and 65, were used in the final molding of the soil-cement specimens. Previously, another series of soil-cement tests was performed on specimens compacted to the modified Proctor densities. The results are also included here for comparison.

To determine the strength and durability of the soil-cement mixtures, the following tests were conducted on the different mixtures:

a. Unconfined compression test.

In this test, 2 x 4 inch molds mentioned in the previous part of this paper were used. Four specimens were molded for each soil-cement mixture using the corresponding standard Proctor density and moisture content to calculate the exact amount of soil-cement mixture required for each specimen. The procedure for molding the specimen has been described before, and therefore will not be repeated here.

After being molded, one specimen was tested immediately. The other three were stored in a moist room with high humidity (90% or higher) for curing. At 7 days, two specimens from the same batch were removed from the moist room for testing. One of these two was immersed in water for 1 hour and the other for 24 hours before testing. After 28 days the fourth specimen was removed from storage, soaked for 1 hour, and then tested. Figures 70-77 give the stress-strain curves for different soil-cement mixtures.

b. Freeze-thaw test (53).

This method of testing is intended for determining the soil-cement losses, moisture changes, and volume changes (both swell and shrinkage) produced by repeated freezing and thawing of the compacted soil-cement specimens of different mixtures with different percentages of cement.

Apparatus:

Proctor density mold, standard Proctor density rammer, balances (one of 20 Kg capacity and sensitive to 1 gram and one of 120 grams capacity and sensitive to 0.01 gram), drying oven, freezing cabinet capable of maintaining temperature of -23° C. (-10° F.) or lower, moist closet capable of maintaining a temperature of 70° F.± and a relative humidity of not less than 90%, a wire scratch brush (description given in P.C.A. laboratory handbook), and measuring device sensitive to 0.001 inch for measuring the specimens.

Procedure for molding specimens:

The procedure for molding the specimens was slightly modified from the standard method recommended by the Portland Cement Association. The exact amount of soil-cement mixture required to mold a specimen was calculated, using the maximum density and the corresponding moisture content previously determined, and weighed out in a large dish pan. Enough water was added to bring the moisture content up to the required percentage. The mixture was then thoroughly mixed and put aside for at least one half hour covered with moist rags to prevent evaporation. In the meantime, another batch was being mixed in the same manner. While the second batch was being set aside for the water to soak in, the first batch of soil-cement mixture was tamped into the mold in three layers in the same manner specified by the A.S.T.M. Standard Proctor Density Test. After the third layer was put in and tamped lightly, the mold was placed in the testing machine and the specimen was compressed down to the proper size. In this way, a smooth specimen was obtained.

After the specimen was pushed out from the mold, it was measured, weighed, placed in a moist closet for a curing period of seven days.

Procedure for testing the specimens:

The complete procedure for testing the specimens is given in the Portland Cement Association laboratory handbook (53).

c. Wet-dry test (53).

This method of testing is intended for determining the soil-cement losses, moisture changes, and volume changes (both swell and shrinkage) produced by repeated wetting and drying of the compacted soil-cement specimens of different mixtures with different percentage of cement.

Apparatus:

Proctor density mold, rammer, balances, drying ovens -- one capable of maintaining temperatures of about 110° C. for drying moisture samples, and one capable of maintaining temperatures of 71° C.± for drying compacted soil-cement specimens, water bath suitable for submerging the soil-cement specimens, wire scratch brush, and measuring device for measuring the soil-cement specimens.

Procedure for molding specimens:

The procedure used was exactly the same as in the freeze-thaw test.

Procedure for testing the specimens:

The complete procedure for testing the specimens is given in the P.C.A. laboratory handbook (53).

Table 13

Standard and Modified Proctor Densities for Harrison County Loess and Johnson County Loess Soil-Cement Mixtures

Loess Type	Harrison County Loess				Johnson County Loess			
Density	Standard Proctor		Modified Proctor		Standard Proctor		Modified Proctor	
Per Cent Cement	Dens. p.c.f.	O. M. %	Dens. p.c.f.	O. M. %	Dens. p.c.f.	O. M. %	Dens. p.c.f.	O. M. %
6	105.6	18.8	115.8	14.8	106.65	19.0	116.8	13.8
10	104.0	19.2	114.9	15.4	105.8	19.14	117.4	14.2
14	103.7	20.0	114.7	16.6	105.3	19.4	118.0	14.4

Table 14

Maximum Stresses for Harrison County and Johnson County Loess Soil-Cement Specimens Compacted to Standard and Modified Proctor Densities Respectively in the Unconfined Compression Test

	Maximum Stresses in p.s.i.											
Loess Type	Harrison County Loess						Johnson County Loess					
Proctor Density	Standard			Modified			Standard			Modified		
Per Cent Cement	6	10	14	6	10	14	6	10	14	6	10	14
At O. M.	316	414	425	---	---	---	261	306	379	---	---	---
At 7 days	228	463	532	403	615	905	207	368	413	---	156	456
At 7 days Soaked 24 hrs.	289	439	557	---	---	---	176	401	286	---	---	---
At 28 days	480	687	829	435	670	1065	335	596	828	110	365	560

Table 15

Results for Harrison County Loess and Johnson County Loess Soil-Cement Specimens from Twelve Cycles of Freeze-Thaw Test

Loess Type	Harrison County Loess						Johnson County Loess					
Proctor Density	Standard			Modified			Standard			Modified		
Per Cent Cement	6	10	14	6	10	14	6	10	14	6	10	14
Maximum soil-cement loss in %	14.3	6.8	2.6	11.4	4.2	2.2	35.9	5.7	3.5	11.0	5.1	2.8
Maximum volume change in %	---	1.67	0.73	0.5	---	---	---	1.06	1.14	5.2	0.7	---
Maximum moisture content in %	25.8	23.6	24.3	19.4	18.9	19.7	26.0	22.5	22.9	21.0	18.4	18.7

Table 16

Results for Harrison County Loess and Johnson County Loess Soil-Cement Specimens from Twelve Cycles of Wet-Dry Test

Loess Type	Harrison County Loess						Johnson County Loess					
Proctor Density	Standard			Modified			Standard			Modified		
Per Cent Cement	6	10	14	6	10	14	6	10	14	6	10	14
Maximum soil-cement loss in %	15.5	2.8	3.3	---	4.5	3.0	18.3	5.77	2.45	30	20	10
Maximum volume change in %	0.6	1.1	0.97	---	3.6	1.9	---	2.2	1.6	---	---	---
Maximum moisture content in %	21.7	21.9	23.5	---	17.4	17.6	---	21.7	21.3	---	---	---

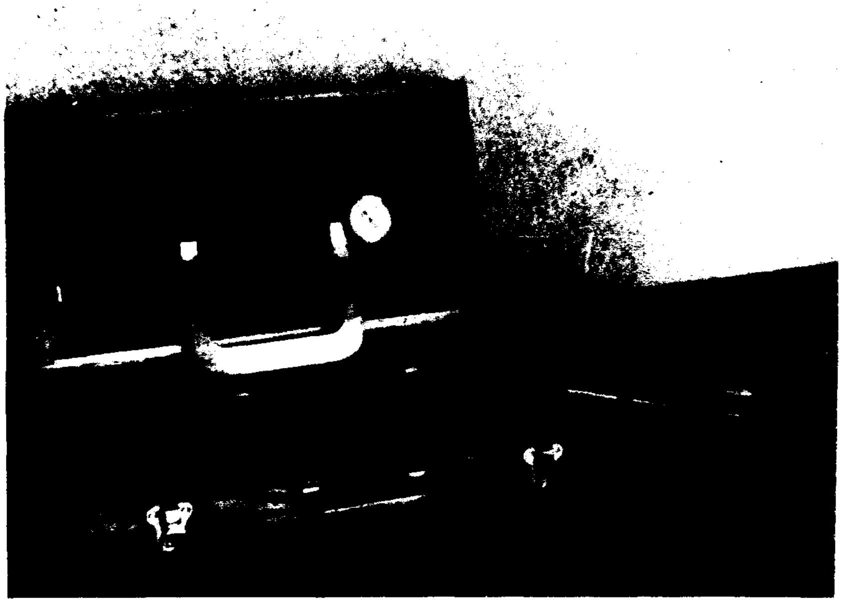

Figure 59. Stiff wire scratch brush for brushing soil-cement specimens and gauges for measuring soil-cement specimens in freeze-thaw and wet-dry tests.

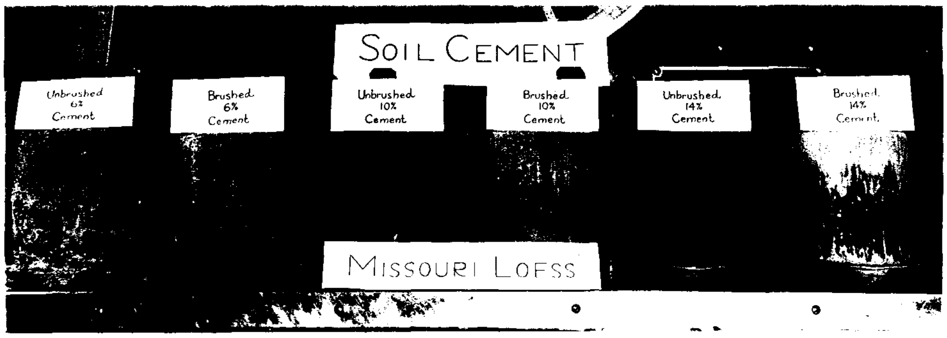

Figure 60. Harrison County loess soil-cement specimens after 12 cycles of freeze-thaw test. Specimens compacted to standard Proctor densities.

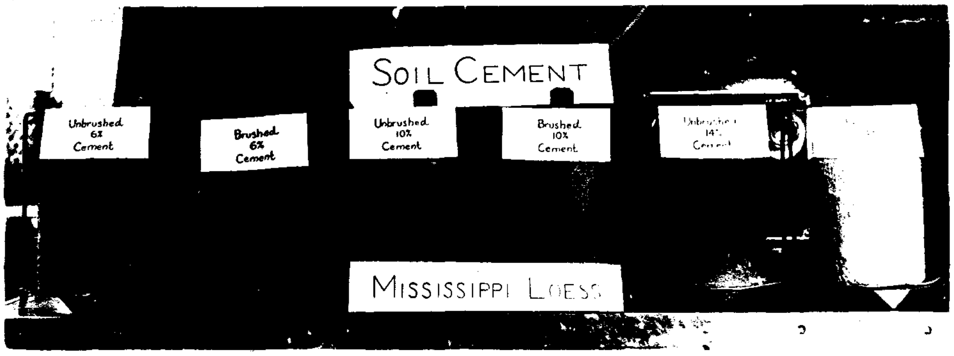

Figure 61. Johnson County loess soil-cement specimens after 12 cycles of freeze-thaw test. Specimens compacted to standard Proctor densities.

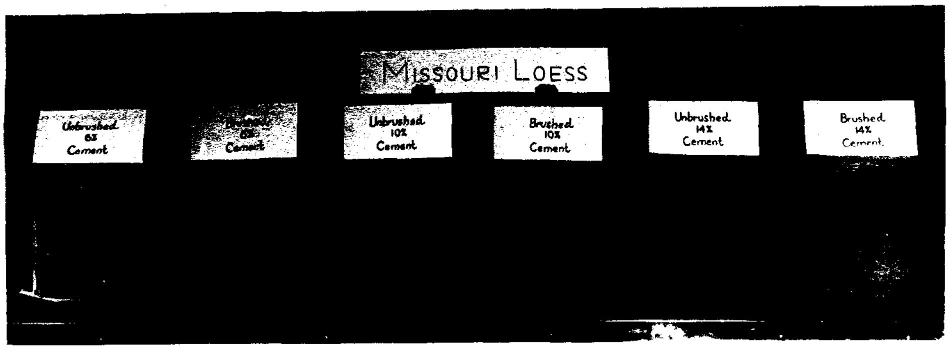

Figure 62. Harrison County loess soil-cement specimens after 12 cycles of wet-dry test. Specimens compacted to standard Proctor densities.

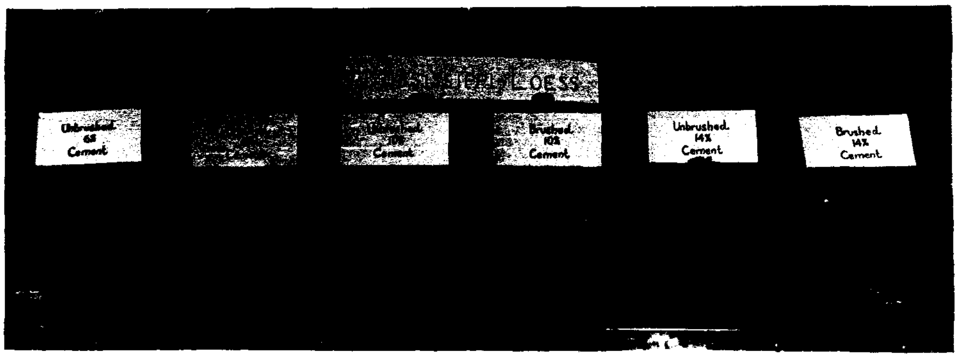

Figure 53. Johnson County loess soil-cement specimens after 12 cycles of wet-dry test. Specimens compacted to standard Proctor densities.

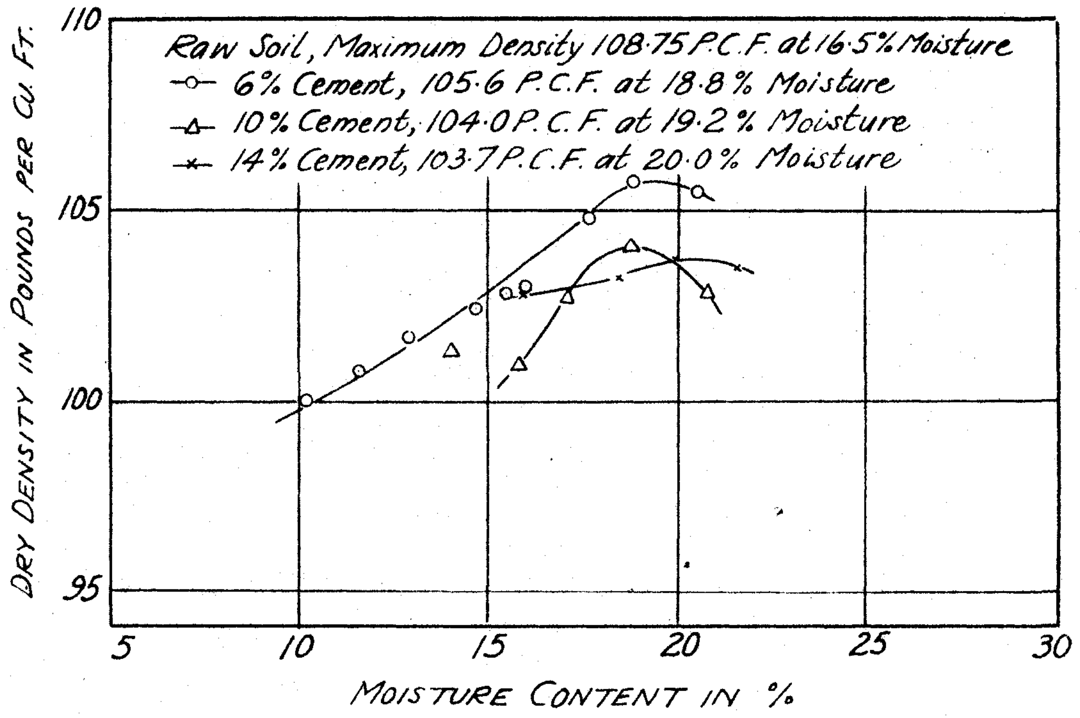

Figure 64. **Standard Proctor density curves for Harrison County loess soil-cement mixtures with varying percentages of cement.**

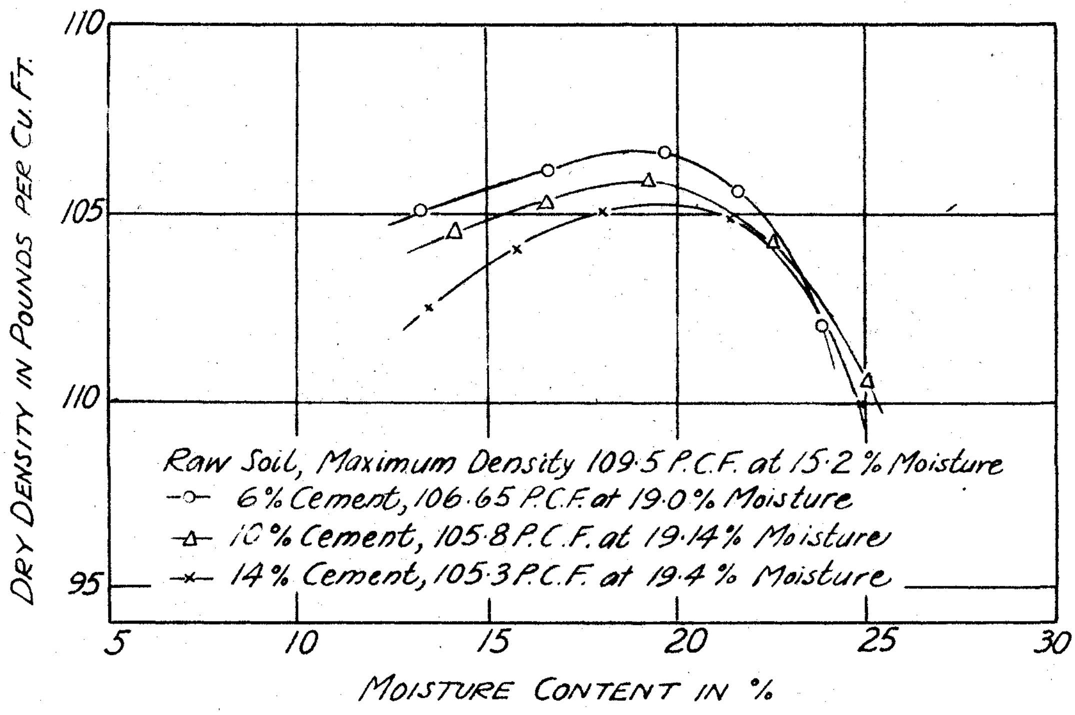

Figure 65. Standard Proctor density curves for Johnson County loess soil-cement mixtures with varying percentages of cement.

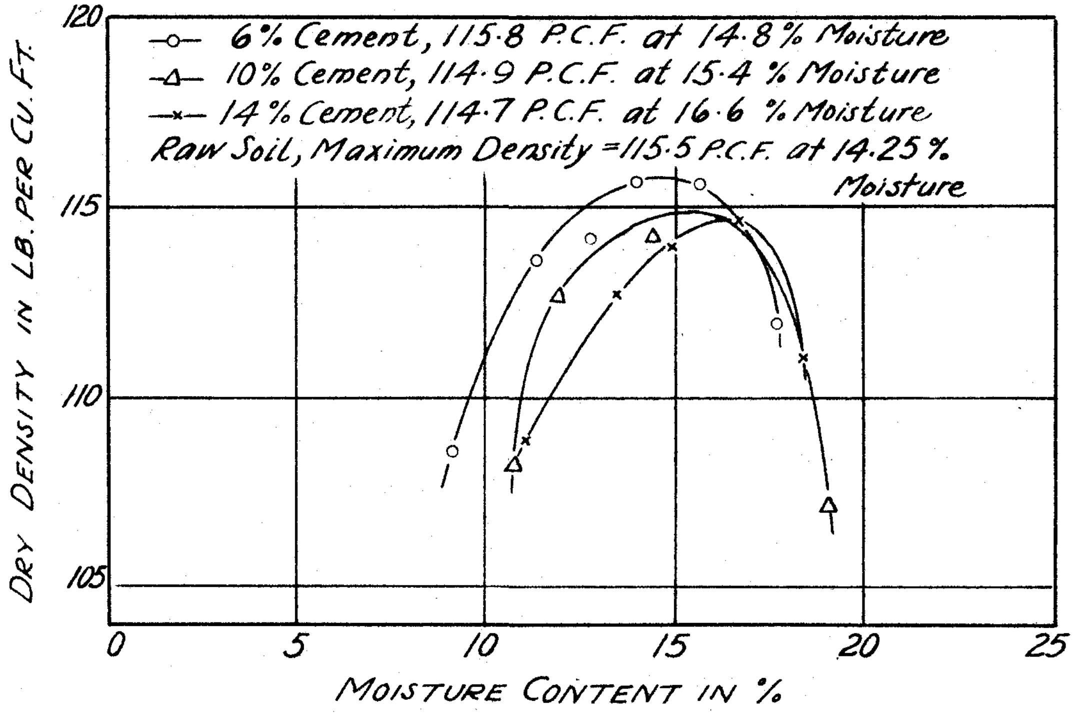

Figure 66. Modified Proctor density curves for Harrison County loess soil-cement mixtures with varying percentages of cement.

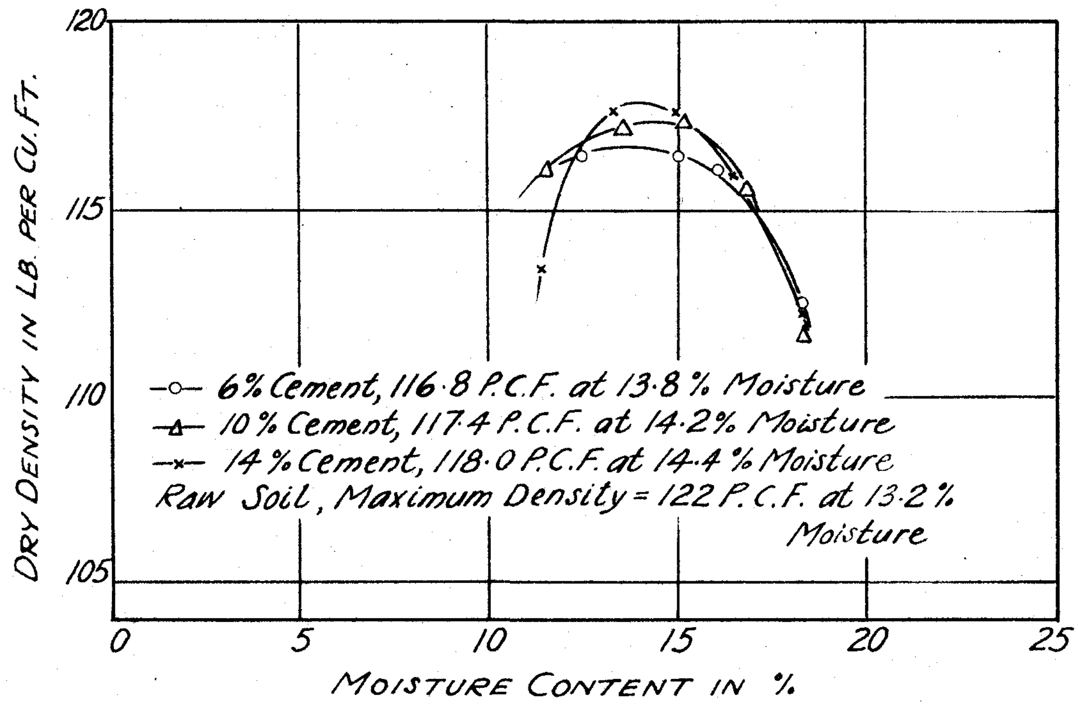

Figure 67. Modified Proctor density curves for Johnson County loess soil-cement mixtures with varying percentages of cement.

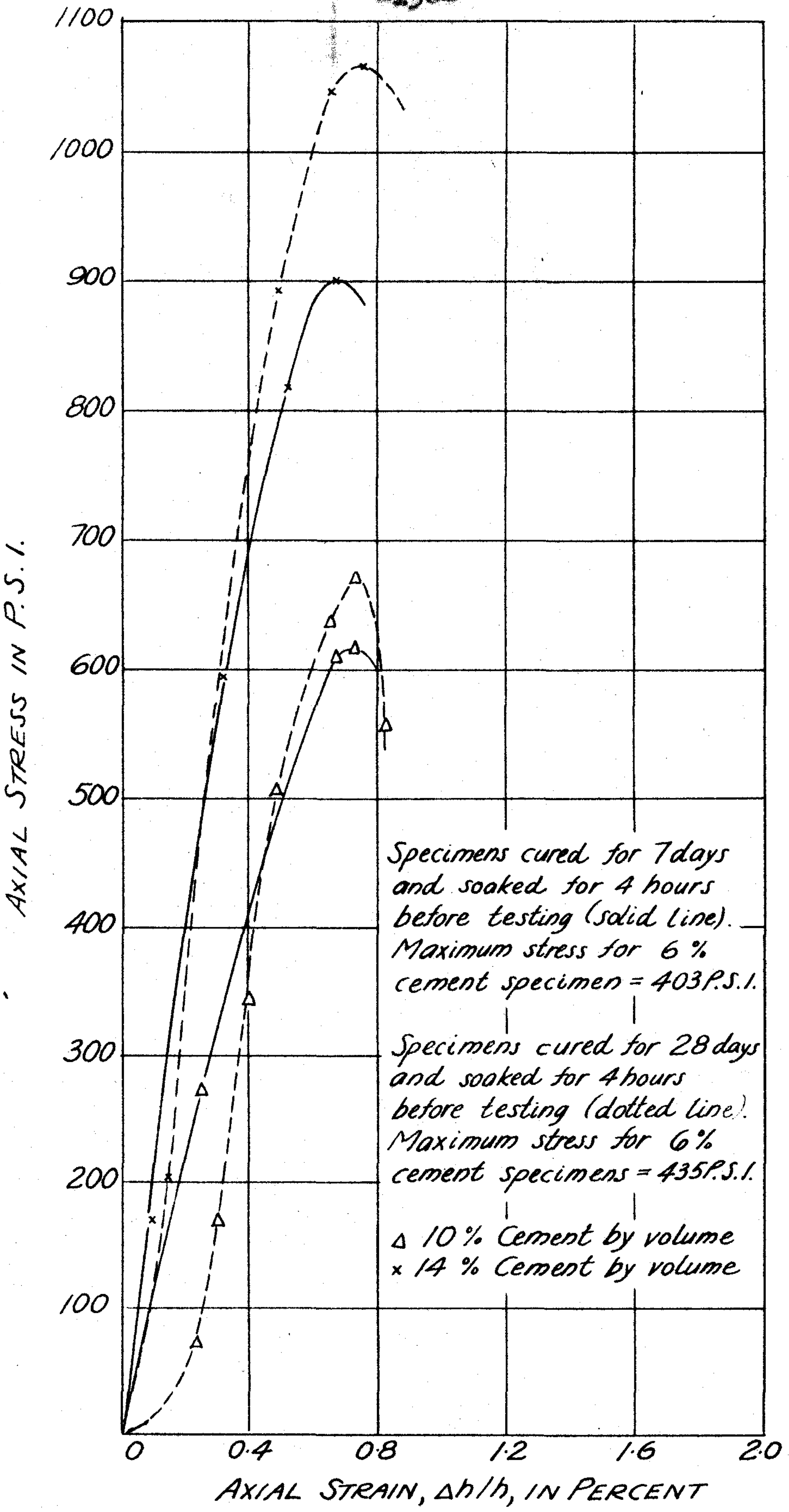

Figure 68. Unconfined compression stress-strain curves for Harrison County loess soil-cement specimens compacted to modified Proctor densities.

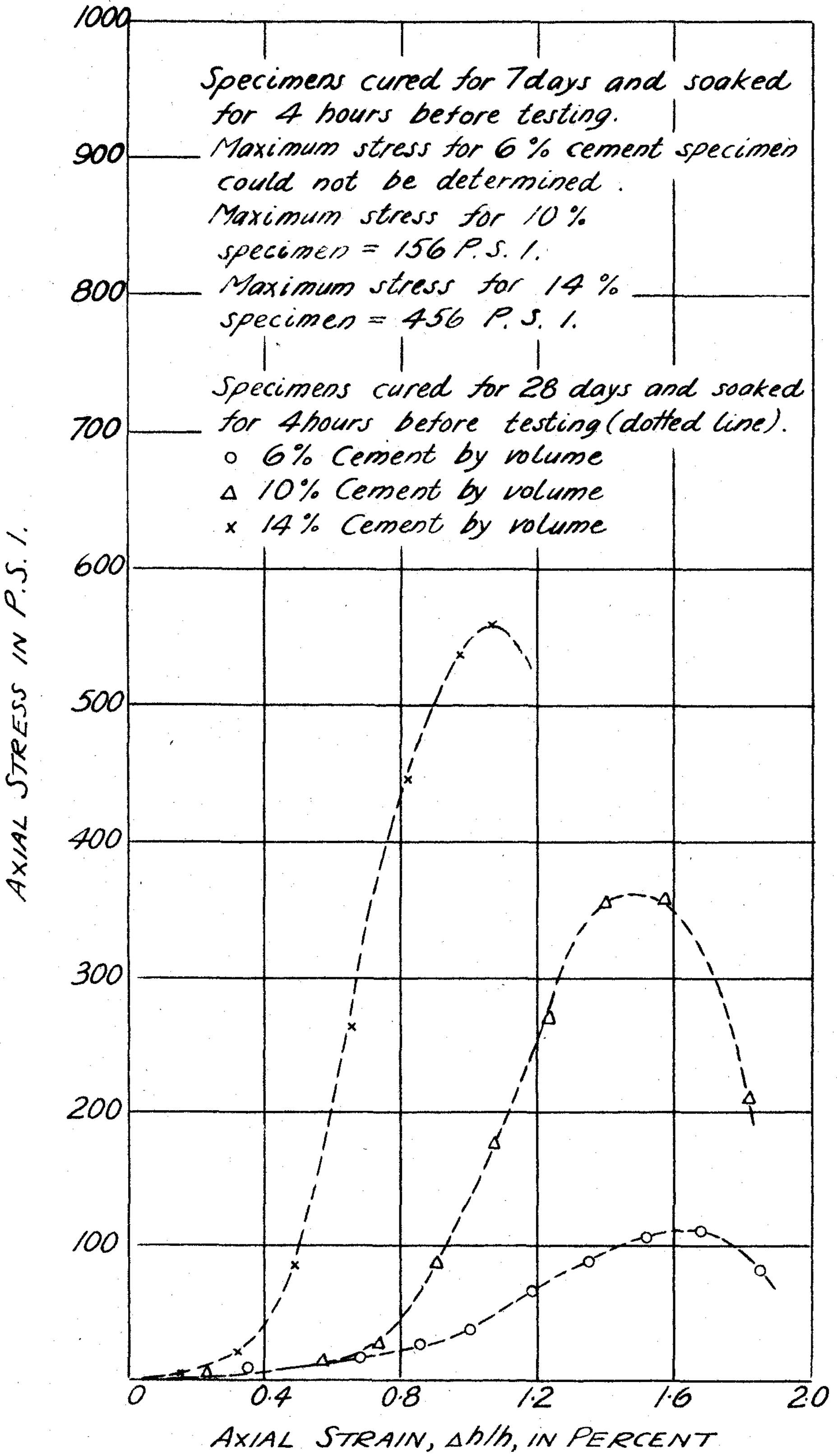

Figure 69. Unconfined compression stress-strain curves for Johnson County loess soil-cement specimens compacted to modified Proctor densities.

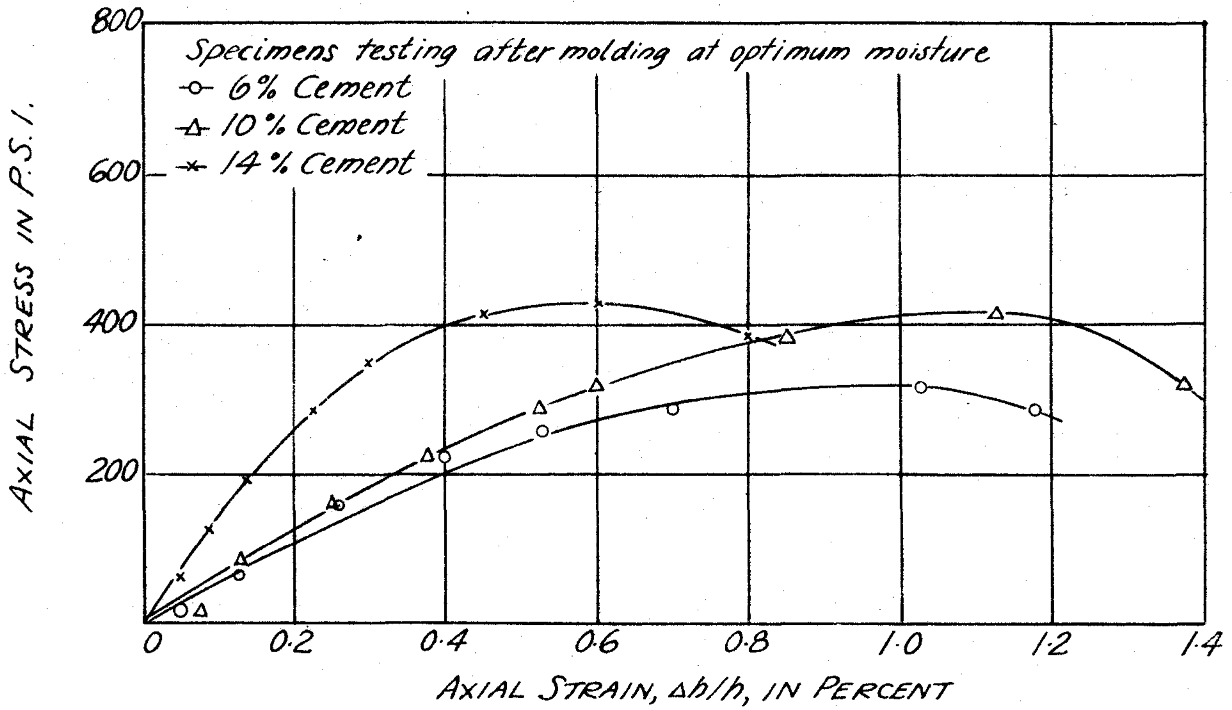

Figure 70. Stress-strain curves for Harrison County loess soil-cement specimens tested at optimum moisture. Unconfined compression test with specimens compacted to standard Proctor densities.

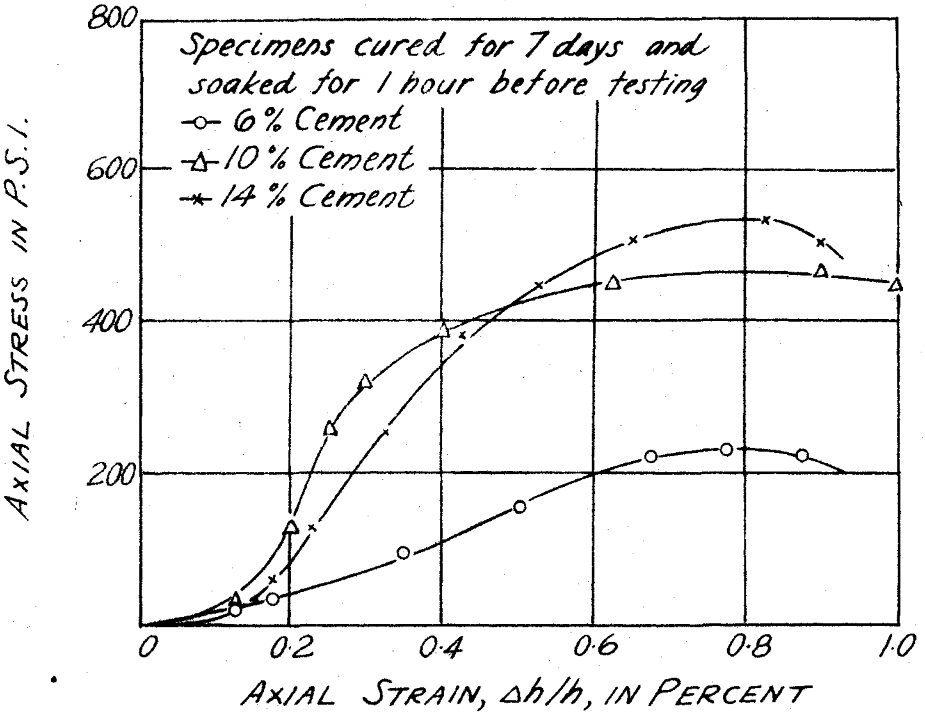

Figure 71. Unconfined compression stress-strain curves for Harrison County loess soil-cement specimens compacted to standard Proctor densities.

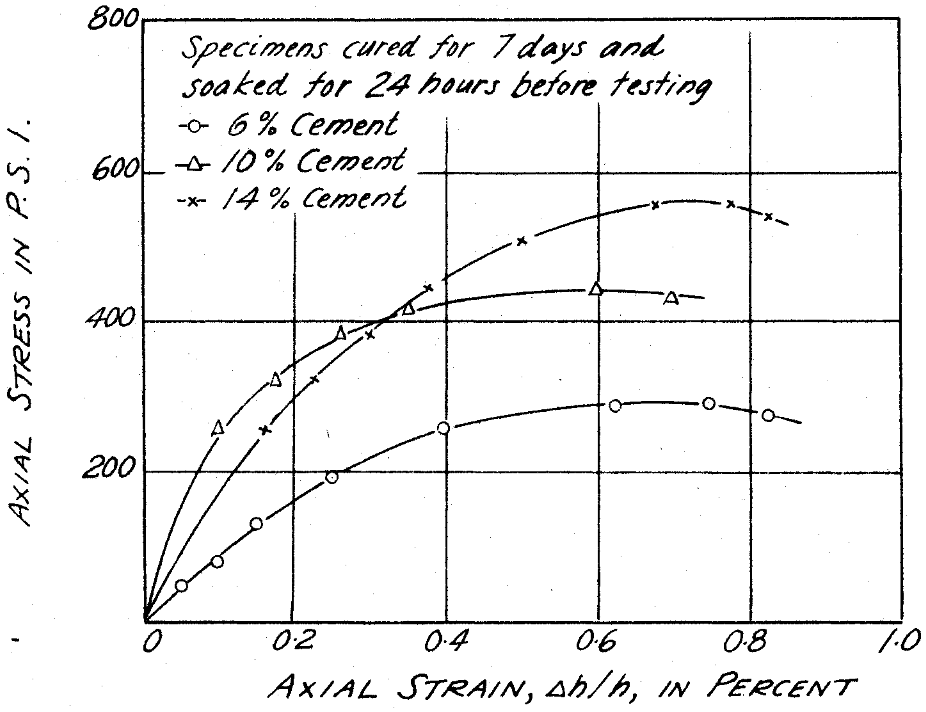

Figure 72. Unconfined compression stress-strain curves for Harrison County loess soil-cement specimens compacted to standard Proctor densities.

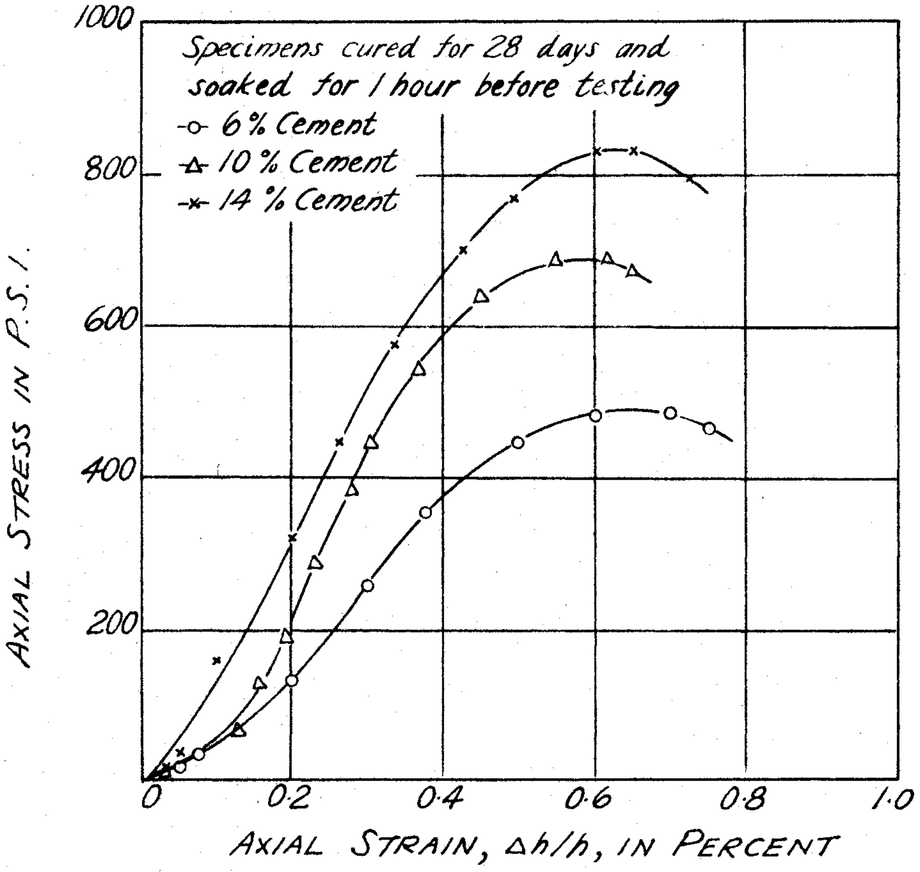

Figure 73. Unconfined compression stress-strain curves for Harrison County loess soil-cement specimens compacted to standard Proctor densities.

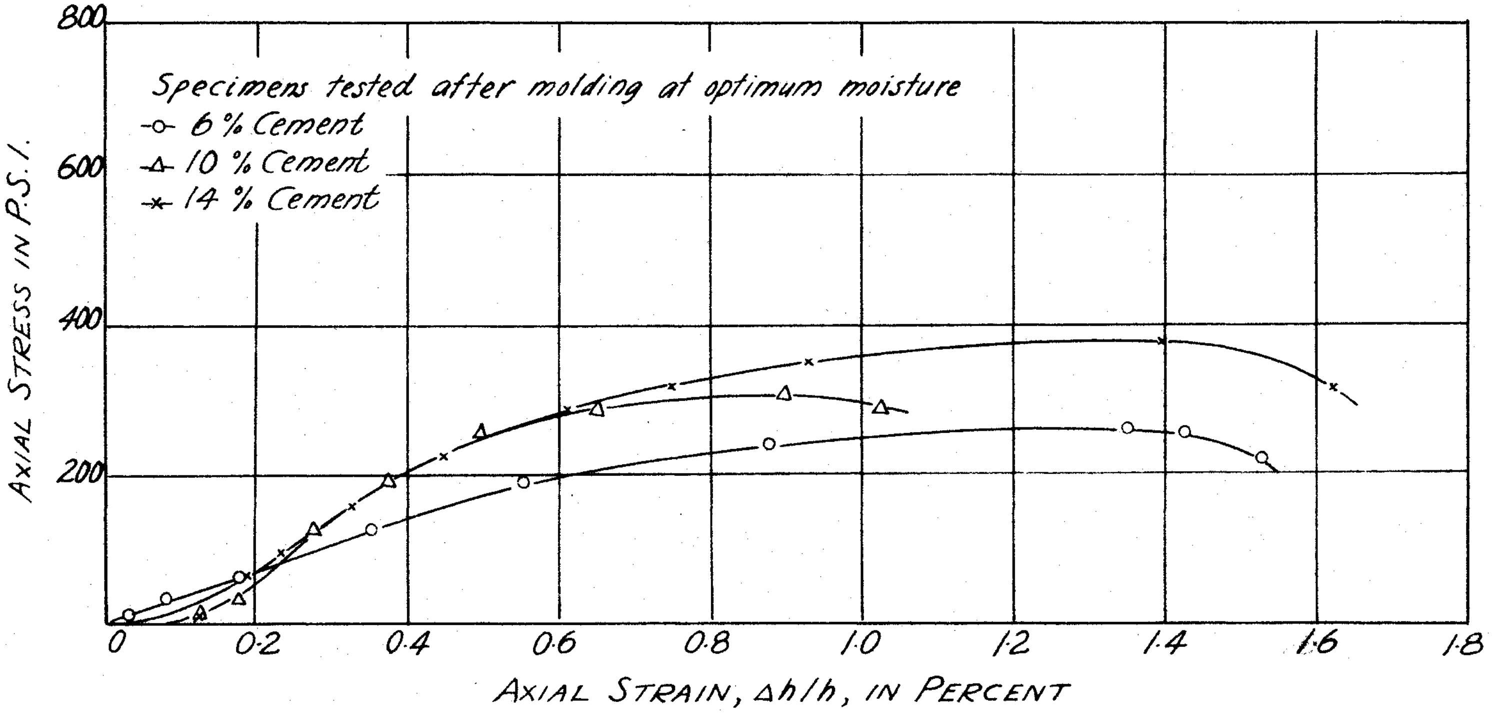

Figure 74. Stress-strain curves for Johnson County loess soil-cement specimens tested at optimum moisture. **Unconfined compression test with specimens compacted to standard Proctor densities.**

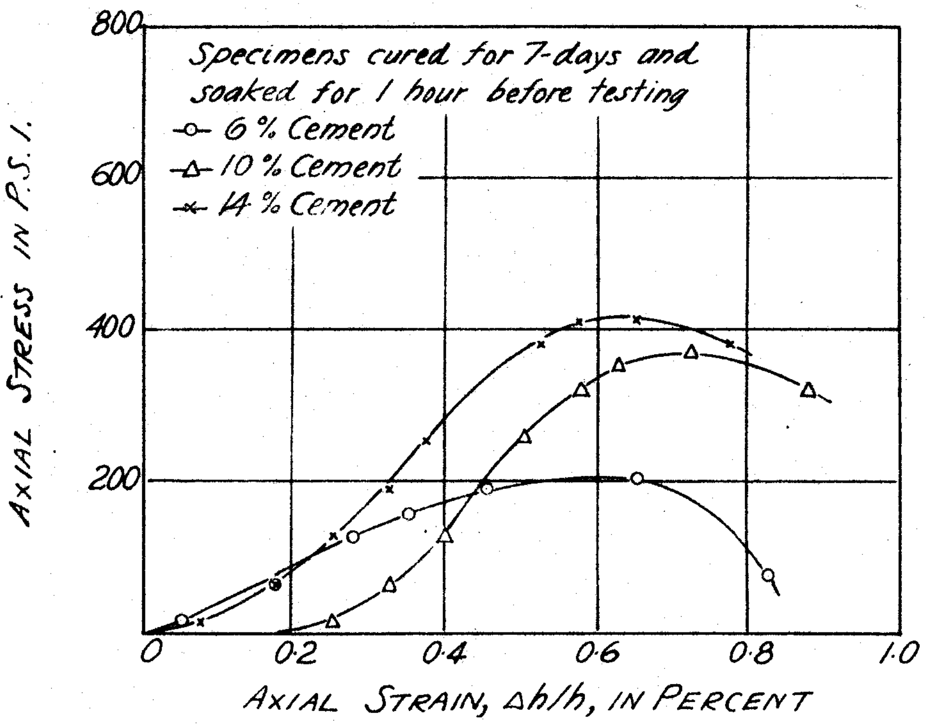

Figure 75. Unconfined compression stress-strain curves for Johnson County loess soil-cement specimens compacted to standard Proctor densities.

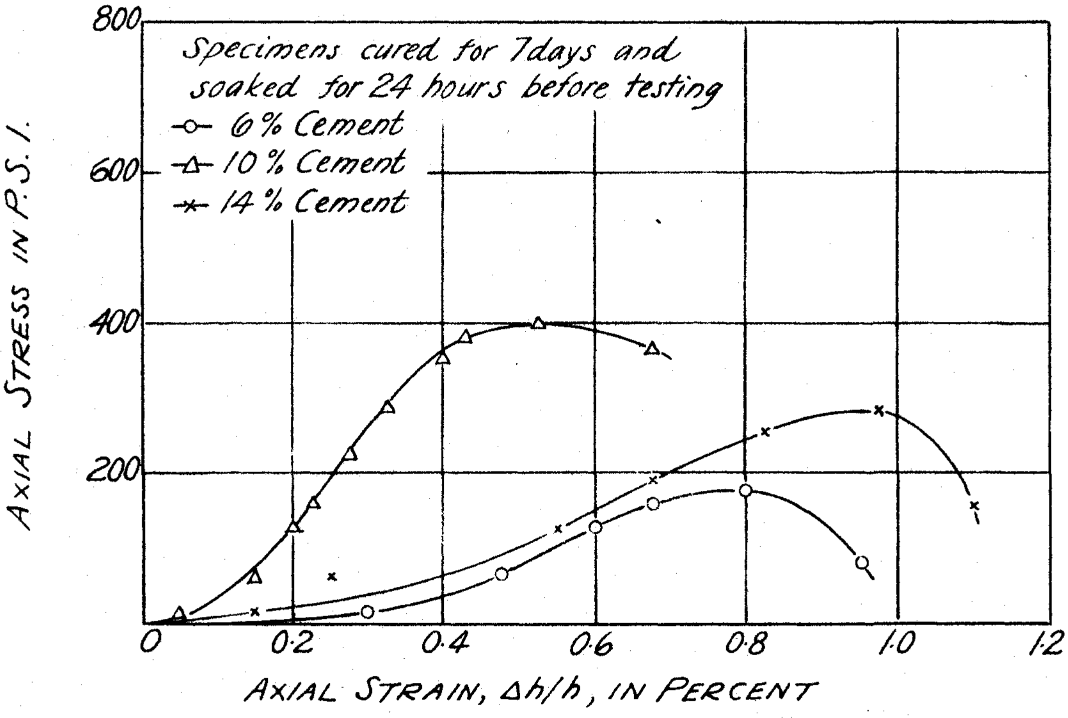

Figure 76. Unconfined compression stress-strain curves for Johnson County loess soil-cement specimens compacted to standard Proctor densities.

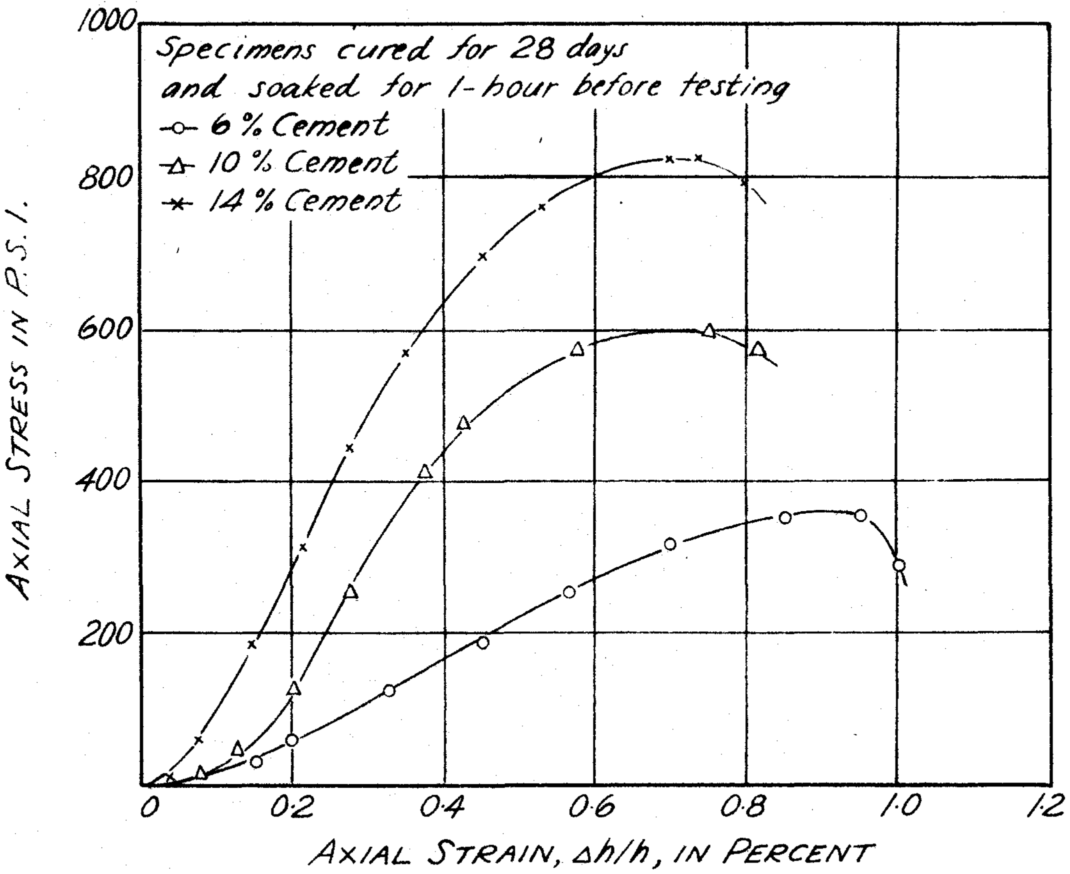

Figure 77. Unconfined compression stress-strain curves for Johnson County loess soil-cement specimens compacted to standard Proctor densities.

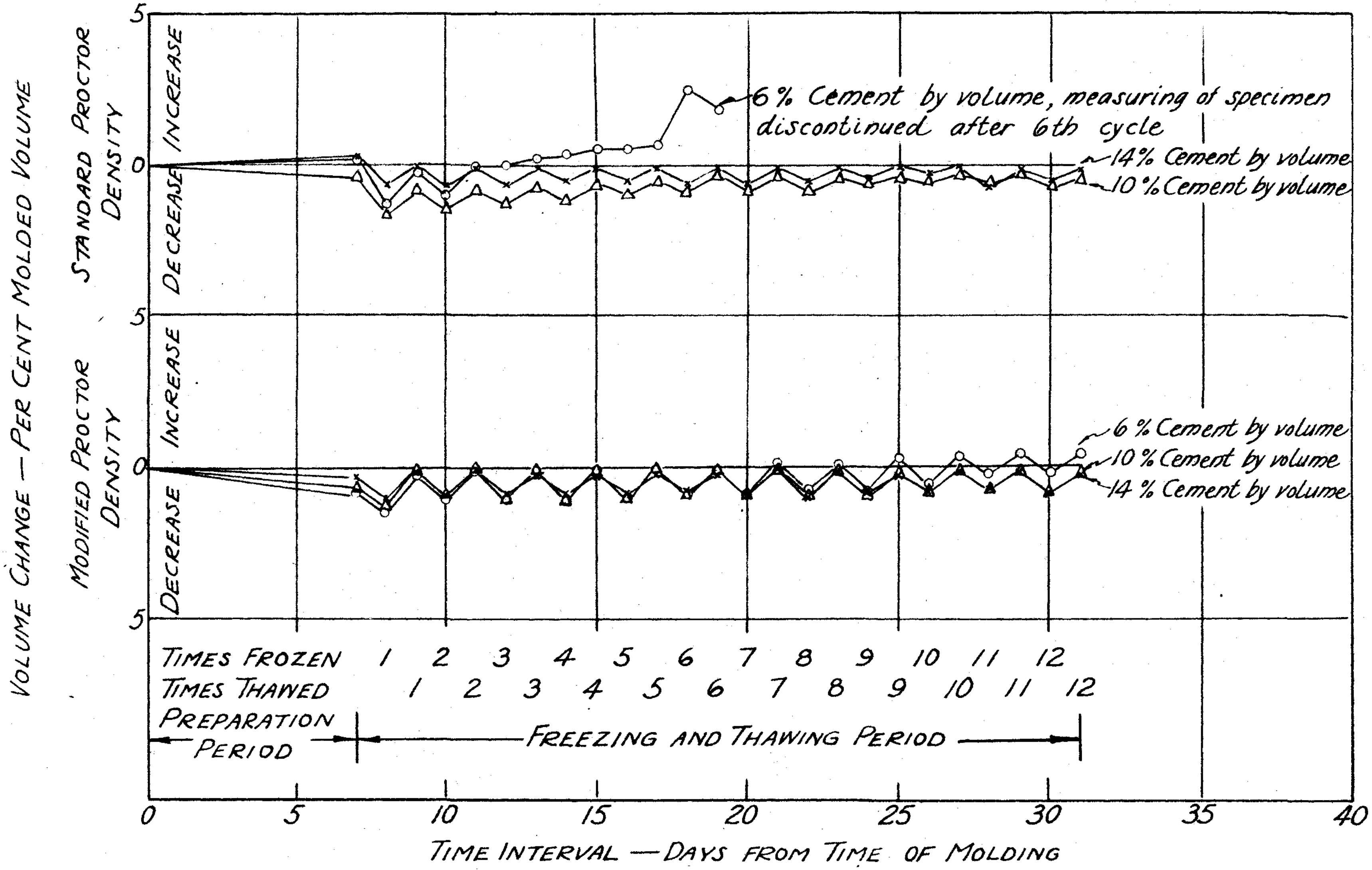

Figure 78. Soil-cement volume changes during 12 cycles of freeze-thaw test. Specimens compacted to standard Proctor and modified Proctor densities respectively. Harrison County loess.

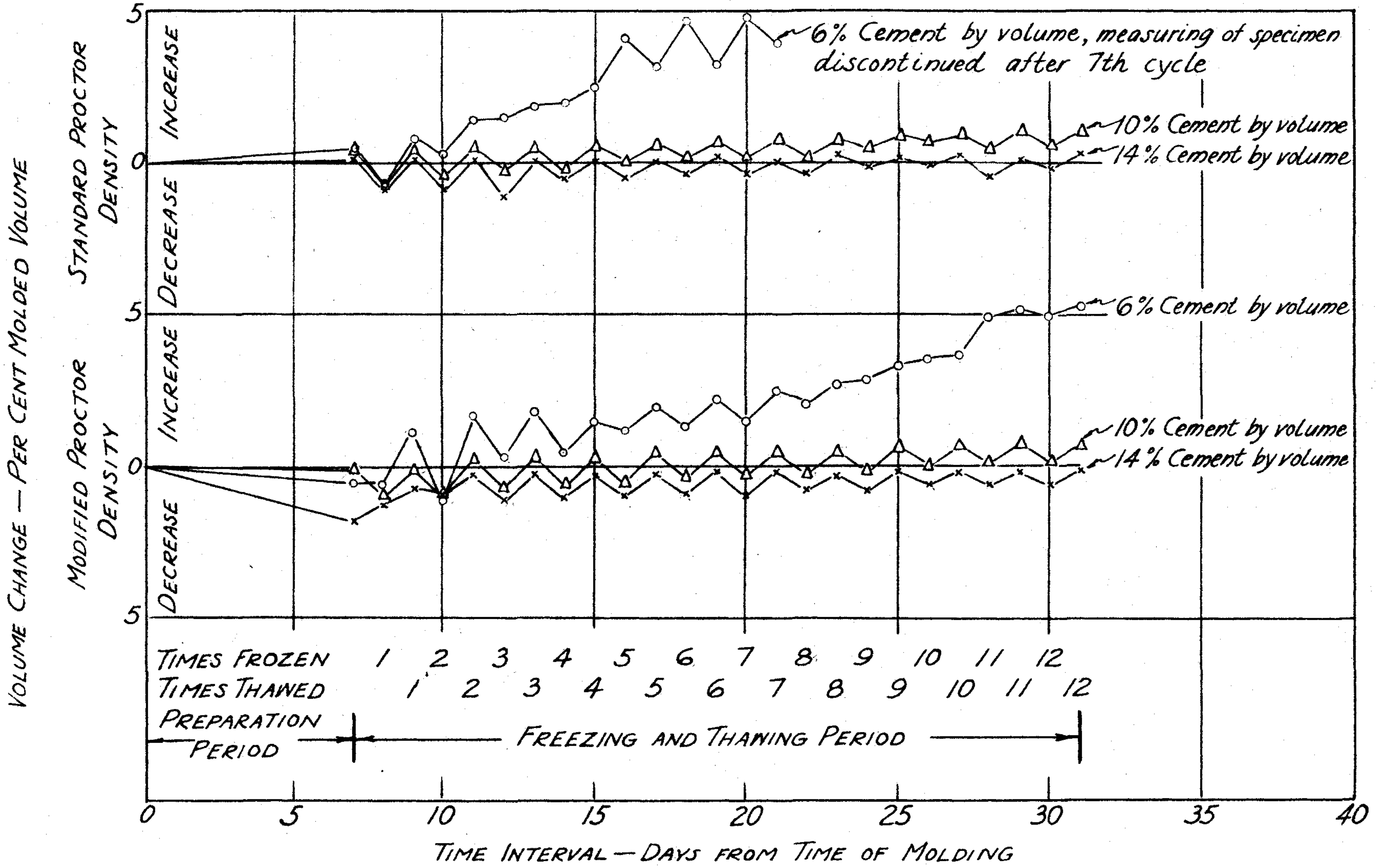

Figure 79. Soil-cement volume changes during 12 cycles of freeze-thaw test. Specimens compacted to standard Proctor and modified Proctor densities respectively. Johnson County loess.

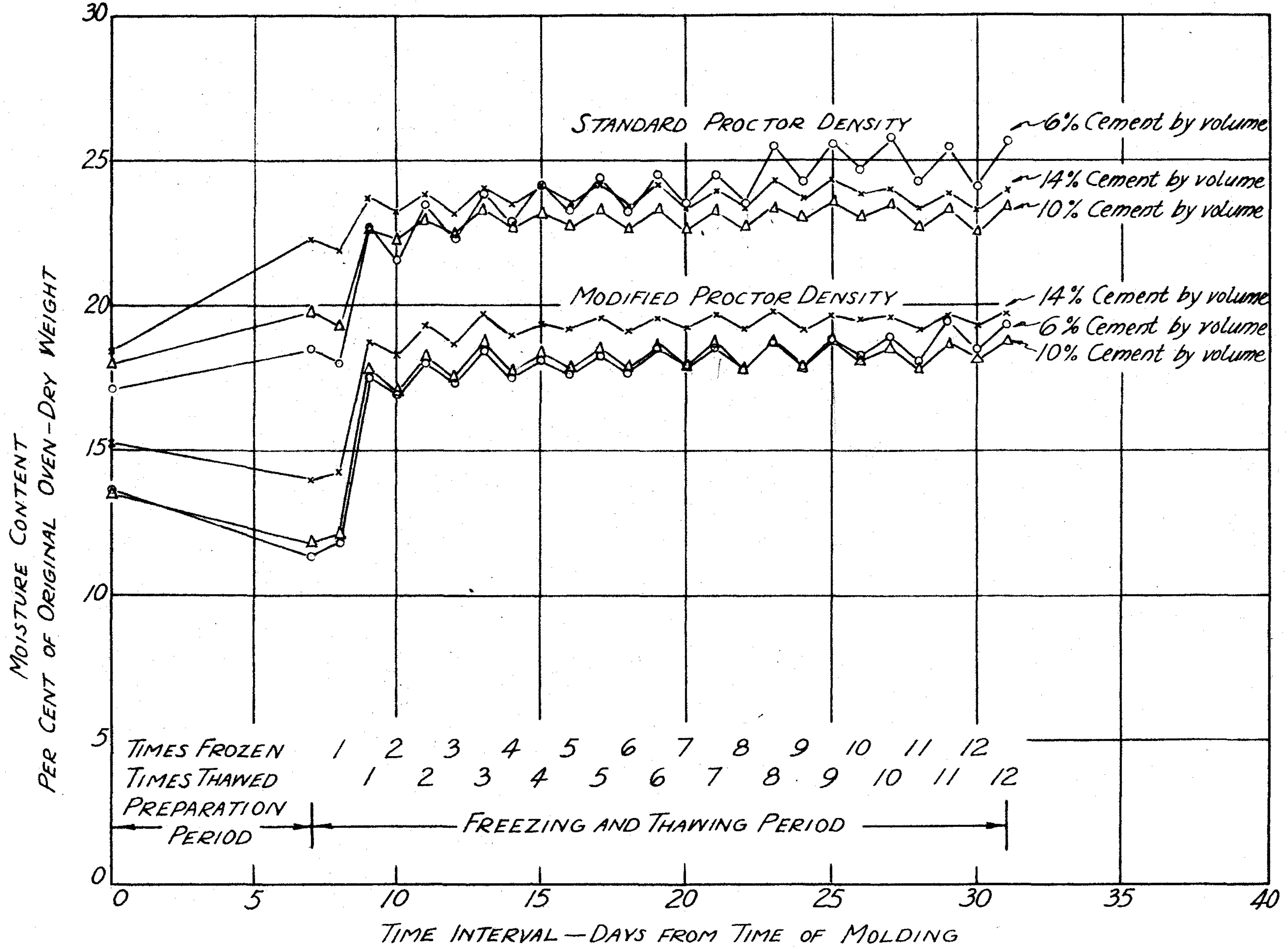

Figure 80. Harrison County loess soil-cement moisture changes during 12 cycle of freeze-thaw test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

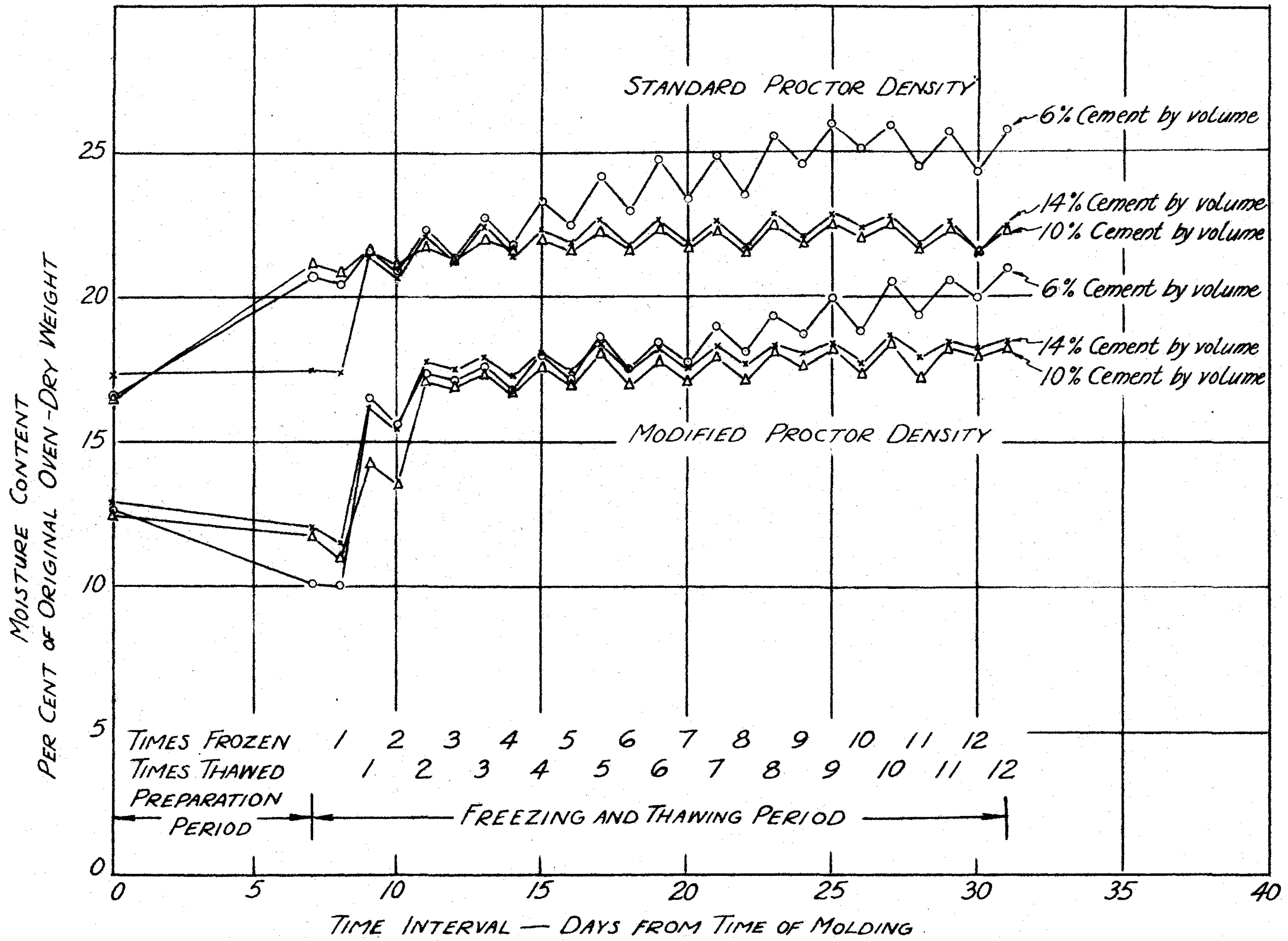

Figure 81. **Johnson County loess-soil-cement** moisture changes during 12 cycles of freeze-thaw test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

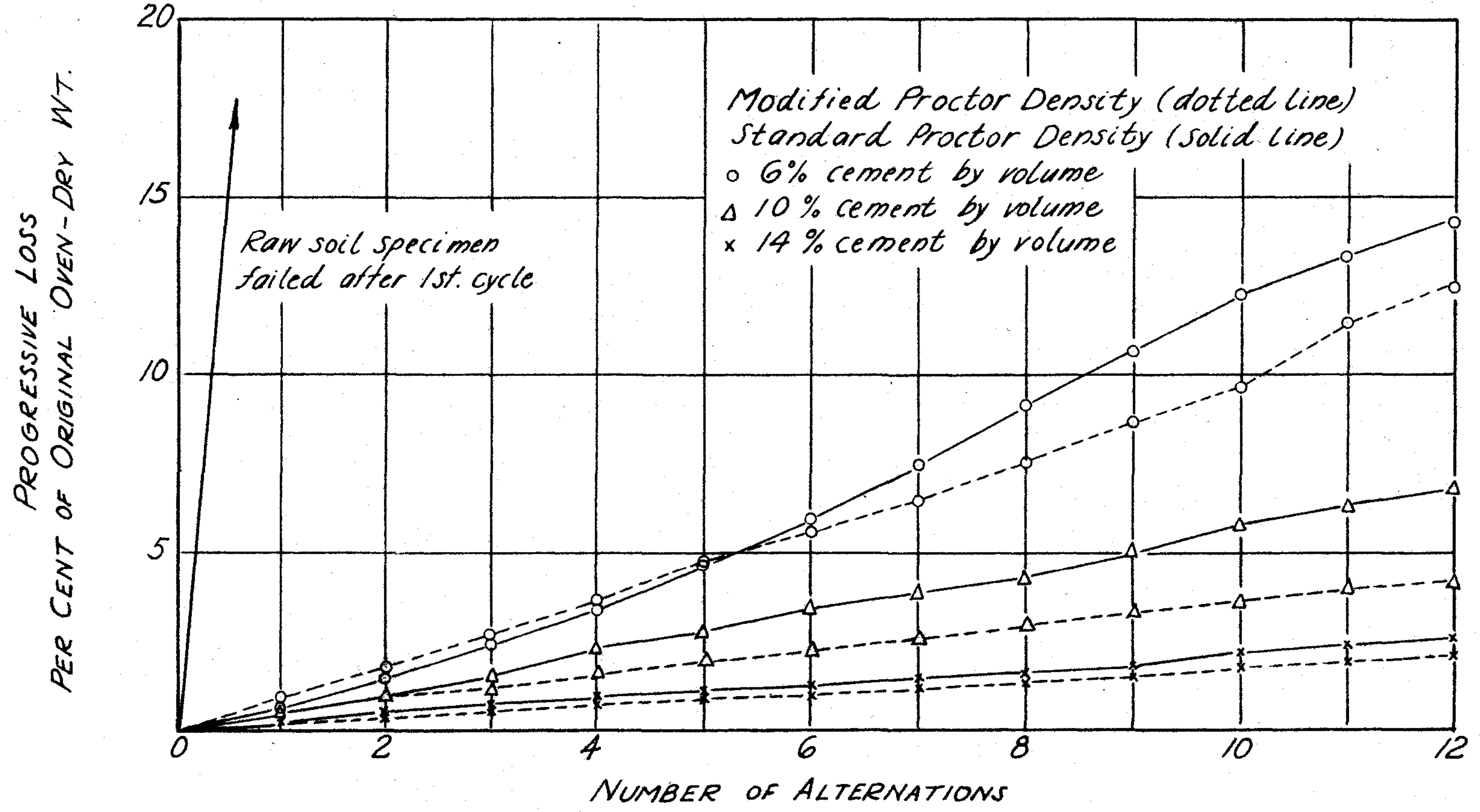

Figure 82. Harrison County loess progressive soil-cement losses resulting from 12 cycles of freeze-thaw test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

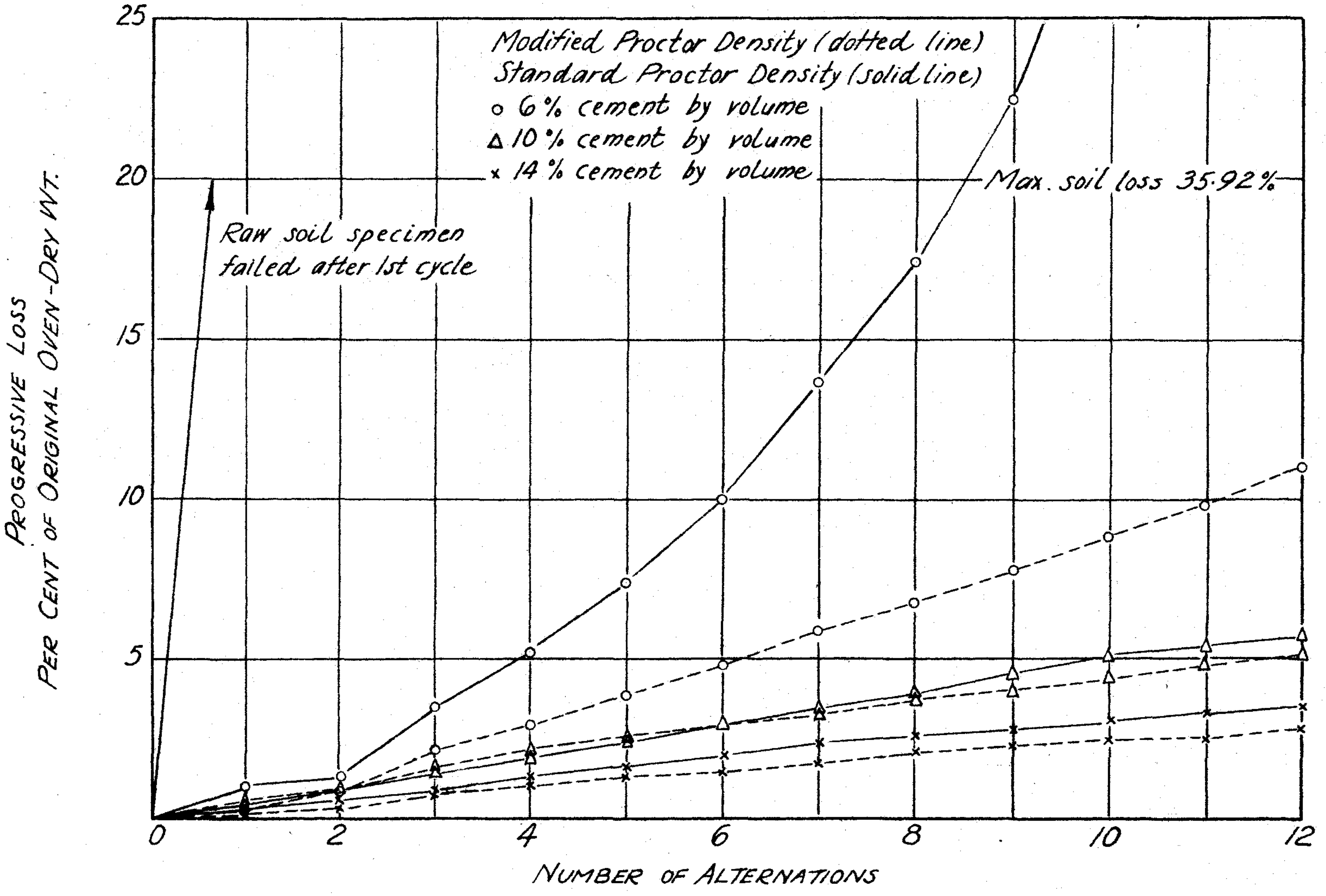

Figure 83. Johnson County loess progressive soil-cement losses resulting from 12 cycles of freeze-thaw test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

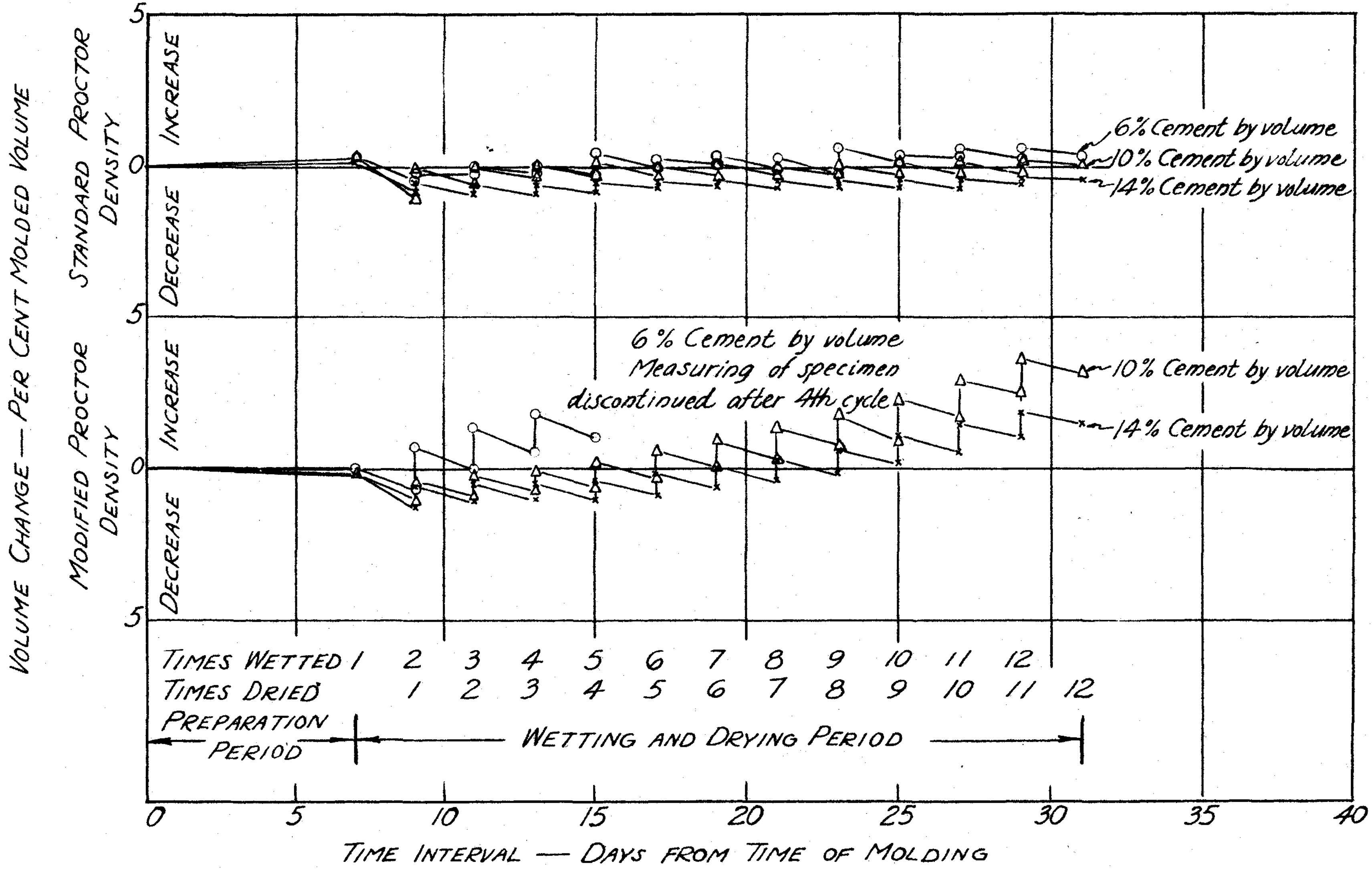

Figure 84. Harrison County loess soil-cement volume changes during 12 cycles of wet-dry test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

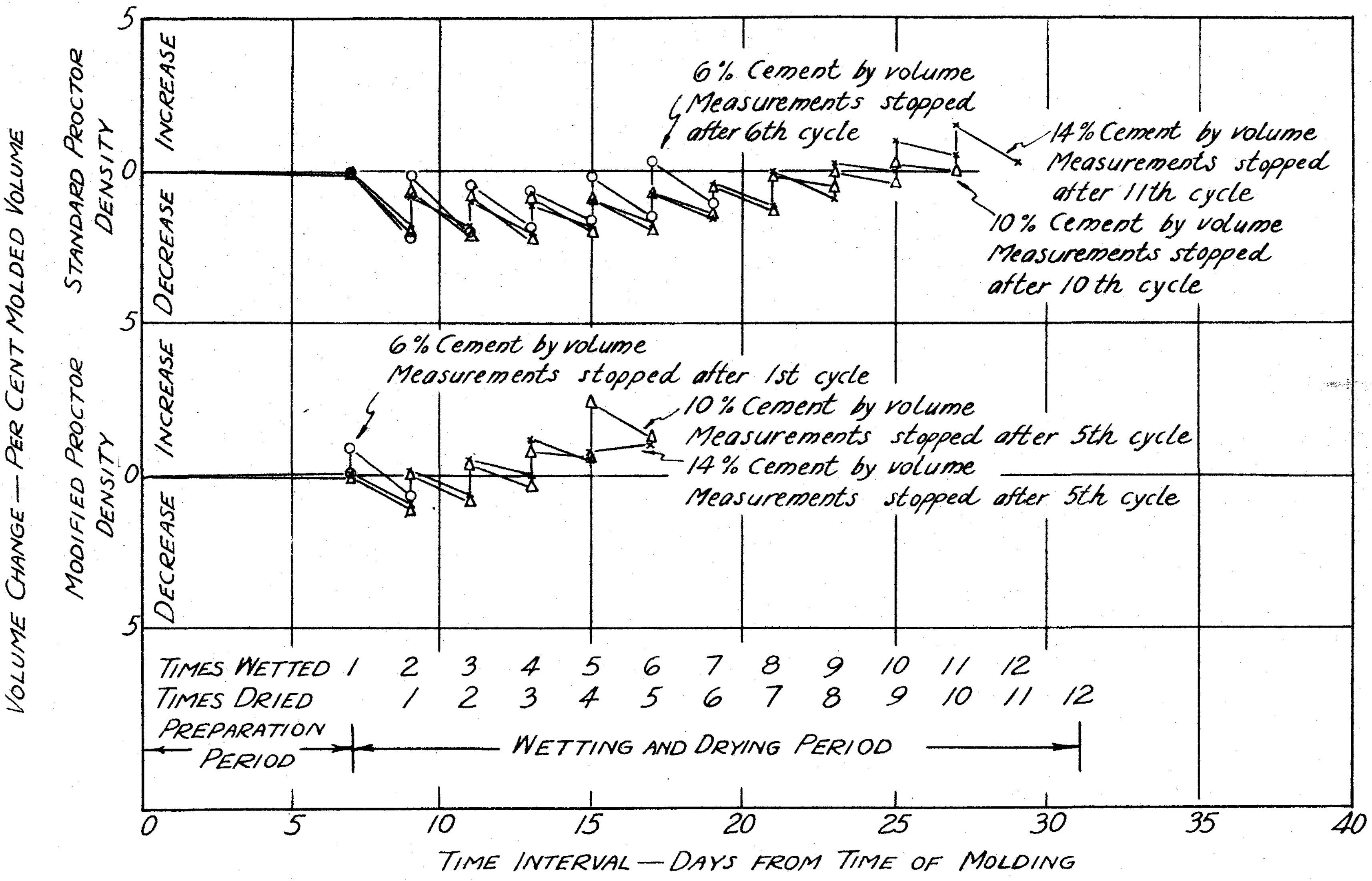

Figure 85. Johnson County loess soil-cement volume changes during 12 cycles of wet-dry test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

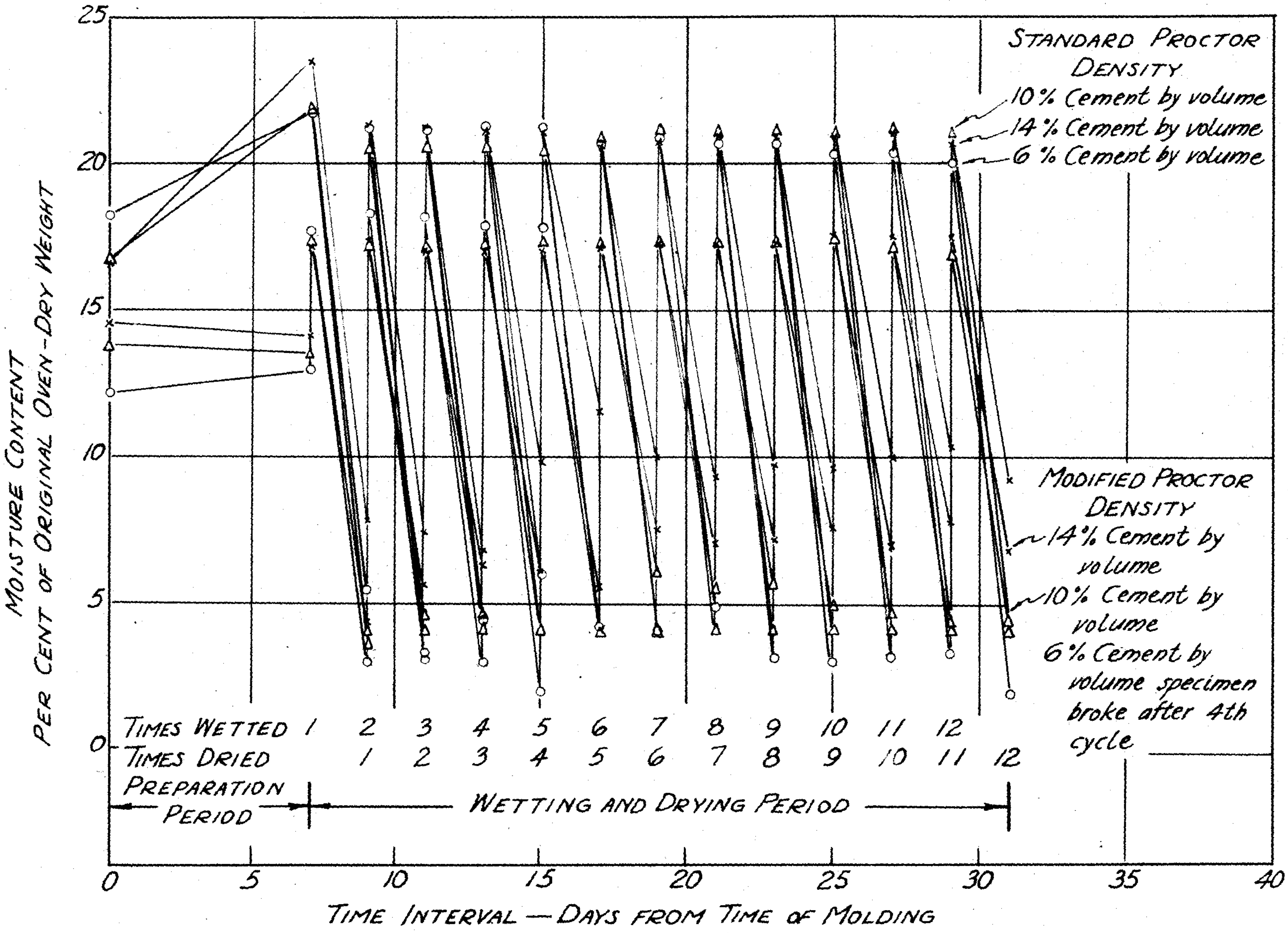

Figure 36. Harrison County loess soil-cement moisture changes during 12 cycles of wet-dry test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

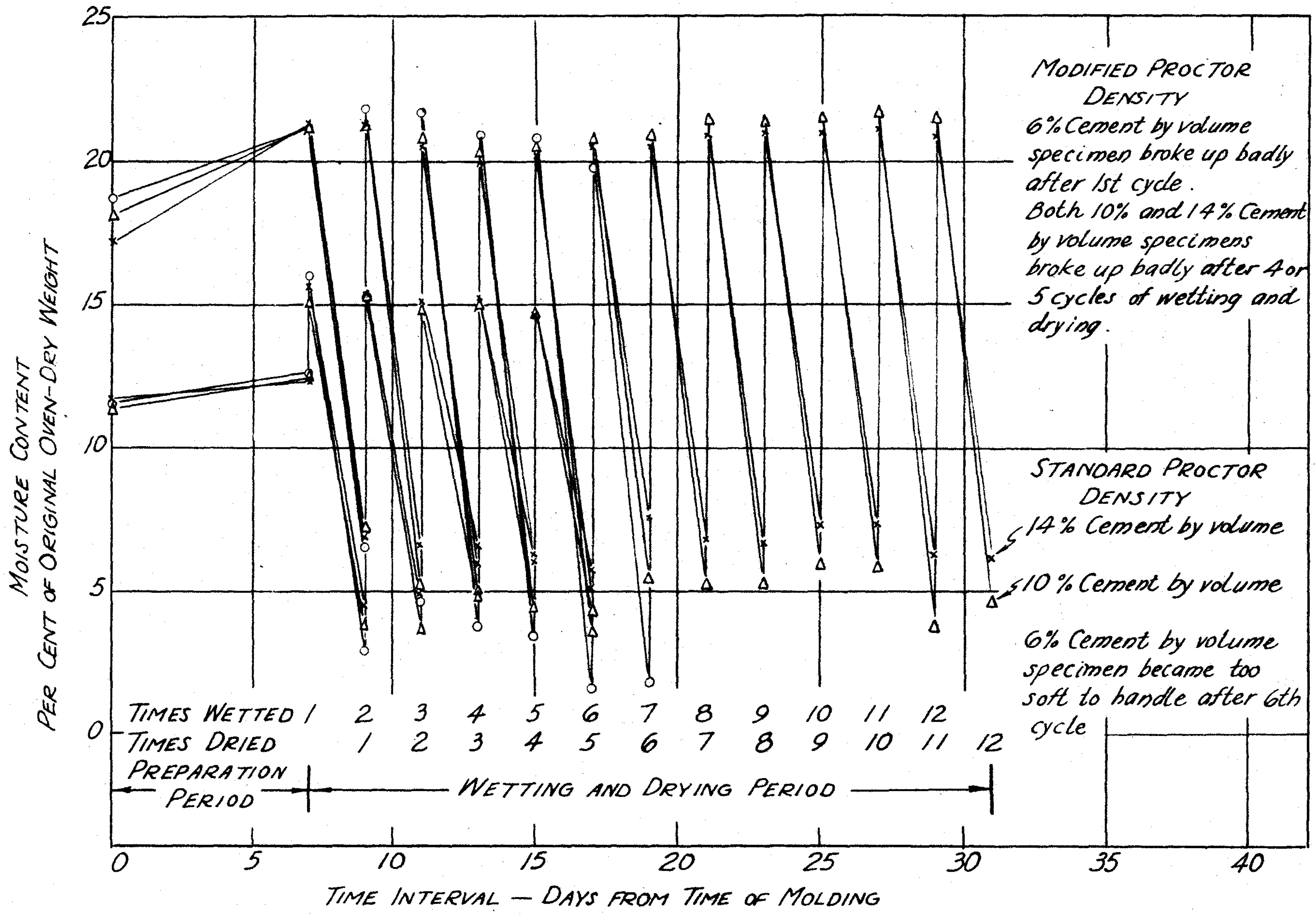

Figure 87. Johnson County loess soil-cement moisture changes during 12 cycles of wet-dry test. Specimen compacted to standard Proctor and modified Proctor densities respectively.

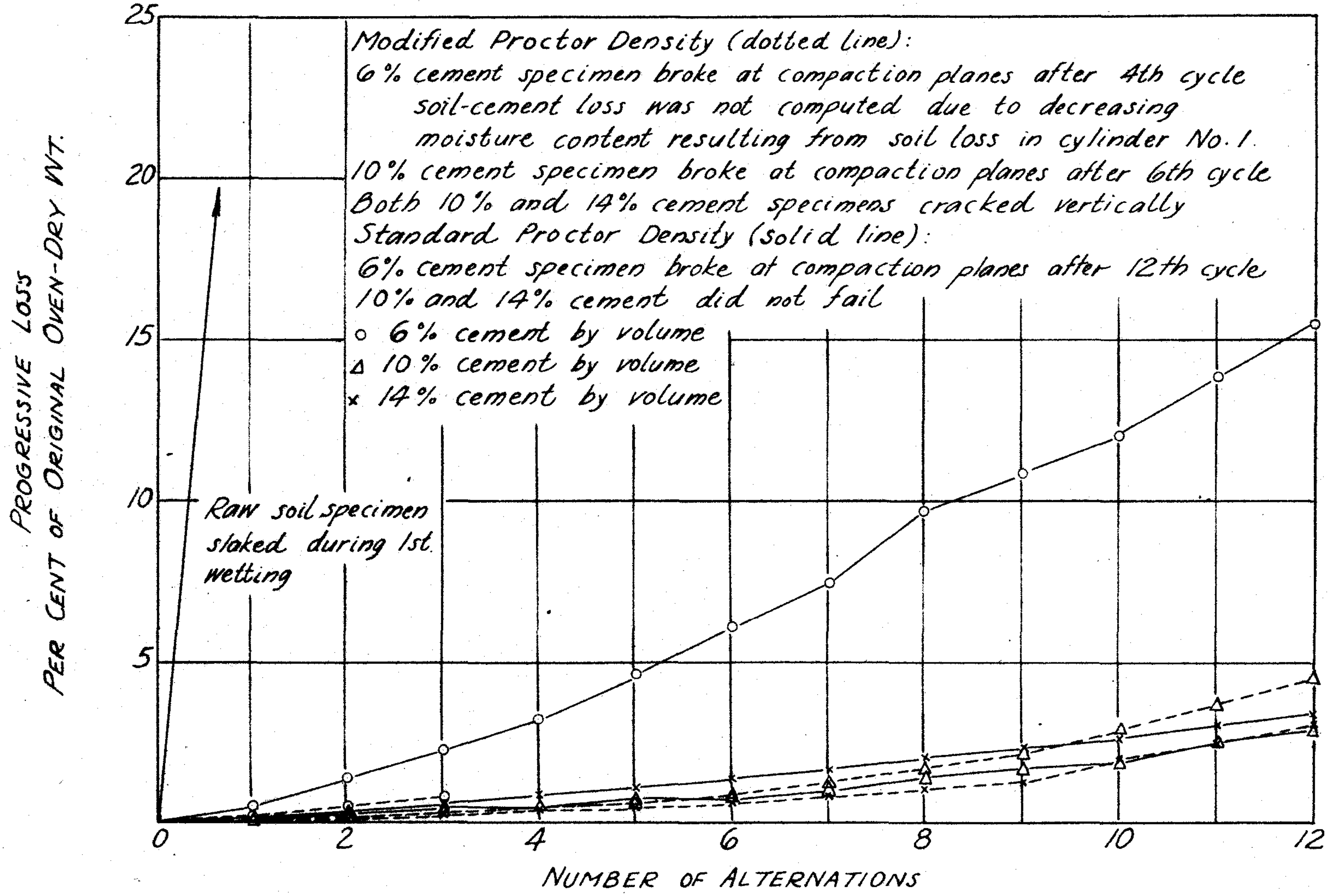

Figure 88. Harrison County loess progressive soil-cement losses resulting from 12 cycles of wet-dry test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

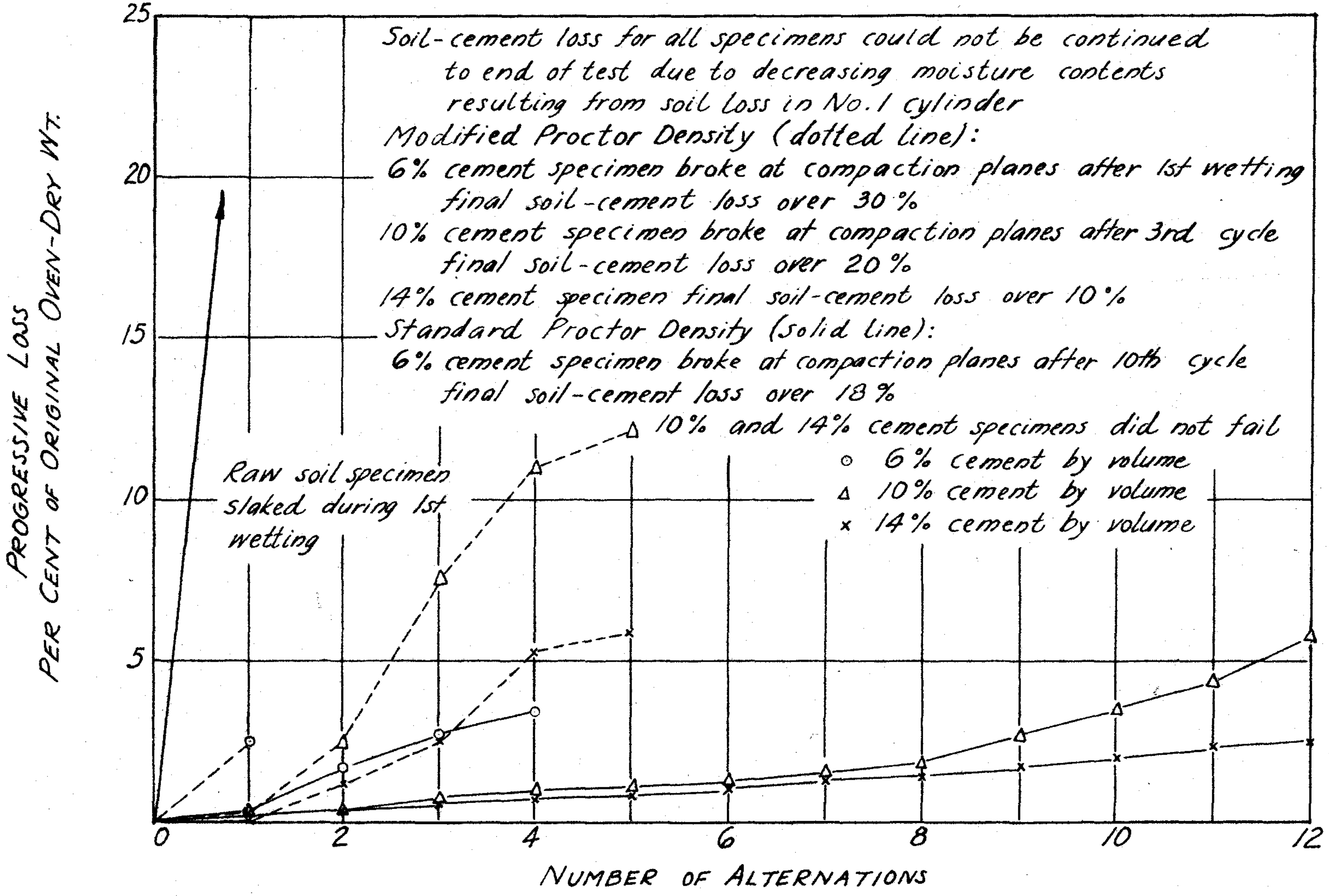

Figure 89. Johnson County loess progressive soil-cement losses resulting from 12 cycles of wet-dry test. Specimens compacted to standard Proctor and modified Proctor densities respectively.

V. DISCUSSION AND INTERPRETATION OF RESULTS OF INVESTIGATIONS

Since the fall of 1944 the author has been carrying on a study of the soil "loess." Throughout the course of several years a large volume of data has been collected for the soil in regard to its physical properties and its use and adaptability in the field of highway engineering. Part of the data was presented in the form of a thesis by the author in partial fulfillment of a Master of Science degree in the fall of 1945. Here in this second paper, the rest of the data is presented. Although it has been mentioned before, the author likes to stress again the fact that for the sake of clarity, some of the data and results which have already been presented in the first paper are repeated here.

The investigations conducted in this research can be said to divide into two parts. The first was the study of the physico-pedological properties of the loess soil samples, and the second was the study of their uses in the practical field of highway engineering. Here the data and results will be discussed and analyzed in the same order.

A. Properties of Loess -- Physical and Pedological

In the previous paper and in the first part of this one the author has given a complete description of loess in regard to its origin, method of deposition, relation to different stages of glaciation, etc. It is not necessary to discuss this part of the study any further. With these few words we are now ready to take up the discussion of the experimental data.

1. Gradation of Loess Particles

First let us consider the different methods used in making this particle-size distribution study. The Bouyoucos Hydrometer Method is the most common procedure used in the highway and soil engineering field. It is simple and does not require a lot of time and careful work. For all practical purposes it gives fairly accurate results which are quite satisfactory for ordinary engineering work. However, for the determination of the colloidal fraction of the soil, this method alone is not sufficient, because the colloidal clay particles are so fine that they will stay in suspension for days, weeks and even months. For instance, in order to be able to measure and determine the 0.001 mm size fraction, the suspension will have to be left standing still for over 29 hours, for the 0.0005 mm fraction a period of over 83 hours is required, and for the 0.0001 mm fraction, a period of over 83 days is required. So we see this method alone is entirely inadequate for this sort of work. Here is where Norton's (51) Long-arm Centrifuge Method comes into use. In this method centrifugal force many times that of gravity is developed which is used to help speed up the settling of the colloidal clay particles. Instead of having to wait for over 83 days for one reading, only 4 hours and 15 minutes are required. Other than the introduction of the centrifugal force to speed up the settling of the clay particles, the Long-arm Centrifuge Method is similar to the Bouyoucos Hydrometer Method. With a little care and practice, fairly reliable results can be obtained.

The Pipette Method is used quite extensively by the agronomists in determining the different size fractions of a soil. However, the procedure is very time consuming and great care has to be exercised in sampling and weighing the clay-water suspension. Also in this case one will be dealing with very small representative soil samples, and any small error introduced in weighing will be magnified many times in the end. This method was included in the study as a check for the other two methods, and no attempt was made to obtain a complete particle distribution with it. Table 3 gives the results obtained with this method. However, in general, they are slightly higher than those obtained with the first two methods. This can probably be attributed to the fact that the 10 gram samples for the two loess soils were too small to be representative.

In carrying out this particle size distribution study, several dispersion agents were tried with the three methods.

Daxad 23, sodium hydroxide, and sodium silicate were used with the first two methods. Sodium-hexa-meta-phosphate and sodium hydroxide were tried with the Pipette Method. With the exception of the organic compound Daxad 23, all the other dispersion agents seemed to give good dispersion to the two loess soils. The Daxad 23 though worked fairly well with the Johnson County loess, had little or no effect on the Harrison County sample. Since little work has been done along this line, no explanation can be offered at this time.

Another interesting fact observed in this particle size distribution study is the effect of the time and method of shaking and stirring on the degree of dispersion of the soil-water system. With the Bouyoucos Hydrometer Method the standard procedure is to disperse the soil-water system in a malted-milk stirrer for a period of five minutes. However, this five minute period was found to be insufficient to completely disperse the aggregates present in the Johnson County loess. With the Long-arm Centrifuge Method rather consistent results were obtained for the Johnson County loess showing higher clay content for every test than that obtained by the Bouyoucos Hydrometer Method. In the Long-arm Centrifuge Method, the soil-water system was shaken for 4-5 days, and it was assumed that the aggregates of clay particles were completely broken up during the shaking period. In other words, complete dispersion was assumed to take place after shaking. Since these two methods are basically the same, the only reason for the difference in results would be in the method and time of mechanical dispersion. This was found to be true by increasing the time of dispersing in the malted-milk stirrer for the Bouyoucos Hydrometer Method. After increasing the shaking period from 5 minutes to 10-15 minutes, the resulting particle size distribution curve for the Johnson County loess was found to be in perfect accordance with that obtained by the Long-arm Centrifuge Method. This is seen quite clearly in Figure 12. With the Harrison County loess, five minutes in the malted-milk stirrer seemed to give complete dispersion to the soil-water system. The particle size distribution curves for the Harrison County loess obtained by the two methods shown in Figure 11 seem to agree quite well with one another. The reason for this is probably because the Johnson County loess has a much higher clay content than the Harrison County loess. Some modifications have to be made here in the mechanical analysis data included in the first paper presented by the author. The changes are shown in Table 8.

Both the Harrison County and Johnson County loess soils have very high percentages of fine material. The Harrison County loess contains 90 per cent silt and clay with 10 per cent sand and no coarse sand and gravel at all. The Johnson County sample contains a little less silt -- 64 per cent -- but has more than twice as much 5u clay -- 28 per cent -- and 8 per cent fine sand. In both cases there is too much fine material present, and the two samples are not suitable for use as surface materials or as subgrade soils alone.

2. Classification of Loess Samples.

The classification of the two loess samples has been fully discussed in the earlier part of this manuscript, and it is not necessary to go into it any further here.

3. Clay Minerals in Loess.

There are several methods for identifying clay minerals, but the one used in this study is the most widely used because of its simplicity and ease in operation. The Differential Thermal Method of identifying clay minerals does not, however, give the exact amount of different kinds of clay minerals present in the soil. At present there is no one simple method that would furnish this information.

There are usually several clay minerals present in the clay in various amounts and also there may be present some organic material which will cause variations in the curve. It takes an experienced operator to interpret the thermal curves correctly and to identify the clay minerals present in the soil. For instance, in the case of kaolinite, there is a definite endothermic reaction at 550-600° C. as shown in Figure 17. However, with the presence of some organic matters or impurities the endothermic peak may shift somewhat to the left or to the right making it hard to say for sure whether the clay mineral in question is pure kaolinite or has some illite in it. Trained workers can identify different clay minerals from the thermal curves quite accurately, but in many cases, they can have only a rough idea of what to expect in those soils.

Figures 15 and 16 are thermal curves for the 0.25u fractions of the Harrison County and Johnson County loesses respectively. Although the curves are obtained from two different loess samples, they are remarkably similar in all respects. This shows that the clay minerals present in the two loess samples are the same or at least similar.

Let us first consider the thermal curve for the Harrison County loess. The curve shows an initial endothermic peak at 100-250° C. signifying the presence of montmorillonite. This peak apparently represents the loss of water held between the basal planes of the lattice structure (i.e., swelling water). Figure 18 taken from Grim and Rowlands (24) shows clearly this characteristic. Illite (Figure 19) also has an endothermic peak at around this temperature range, but the peak is very much smaller. The exothermic peak that appears around 350° C. together with the endothermic peak appearing between 500-650° C. seem to indicate the presence of illite (Figure 19) in the loess sample. Montmorillonite (Figure 18) also has an endothermic peak between 600-700° C., but the peak appearing in this curve is at a lower temperature range and does not coincide with that of the montmorillonite. This second endothermic peak indicates the loss of most of the water from the lattice. The third endothermic peak that appears in the thermal curve for the Harrison County loess between 850-900° C. is usually interpreted as being associated with the final destruction of the clay mineral structure, and it appears in both the curves for illite and montmorillonite. The exothermic effect which follows right after the endothermic reaction is probably due to the formation of spinel. This final exothermic reaction also appears in the curves for illite and montmorillonite. Kaolinite type clay mineral does not seem to be present in the loess since there is no abrupt intense exothermic reaction at 950-1000° C. (Figure 17) which appears in all thermal curves for kaolinite type clay minerals.

The thermal curve for the Johnson County loess has the same shape as that of the Harrison County loess with the exception that the endothermic peak at 500-650° C. is slightly steeper. Since all the other exothermic and endothermic reactions are the same as in the previous case, it is not necessary to devote any more time here to analyze them.

The presence of montmorillonite in the two loesses accounts for many of the behaviors of the soils. It accounts for the swelling of the Johnson County loess under the effect of water, the high C.B.R. value when dry and the extreme low reading after soaking in water, the ability to absorb a large amount of water and at a very slow rate, etc. The Harrison County loess, though apparently shows the presence of the same kind of clay minerals, is proved to be the better of the two loess samples. Its physical properties in general are similar to those of the Johnson County loess, yet water does not have such comparable detrimental effect on it. One of the important reasons is that the amount of colloidal material in the Harrison County loess is much lower than in the Johnson County loess -- 1.5% to 8.0% -- and consequently the per cent of montmorillonite and illite present in one soil is very much lower than in the other.

4. Base Exchange in Loess.

It has been said before base exchange or cation adsorption is important in the study of the behavior of a soil. It also ties in with the type of clay minerals present in the soil. The differential thermal method of identifying clay minerals used in conjunction with the study of base exchange in a soil serves as a very reliable procedure for determining the type of clay minerals.

In this study the base exchange capacities for two size fractions -- passing 20M sieve fraction and 2u fraction -- of each loess sample were determined. One outstanding fact is that the exchange capacity for the 2u fraction for either one of the two loess samples is four or five times higher than the exchange capacity for the passing 20M sieve fraction. This tends to show that clay minerals exist mostly in the fine fraction of a soil and that the base exchange capacity for a soil increases as the soil particles are reduced to smaller and finer sizes.

Table 7 shows the exchange capacities for the two loess soils and also the clay minerals kaolinite and montmorillonite. The exchange capacity for the 2u Harrison County loess was found to be 45-50 m.e. and that for the 2u fraction Johnson County loess was found to be 50-55 m.e. From Table 7 and the actual exchange capacity obtained for a sample of montmorillonite -- 79.3 m.e. in this case -- we see that only the montmorillonite type clay minerals have really high exchange capacities. Illite also has fairly high exchange capacity but is no where near that for montmorillonite. We can safely say that montmorillonite is present in both loess soils, probably with the presence of some illite too.

5. Erosion in Loess and Methods of Prevention.

In the undisturbed state, the Harrison County loess is very dry and fluffy. It can absorb a lot of water without damaging its ability to stand upright in a road cut as mentioned before. However, once water starts to run down its surface, it will start to erode, and in time, huge gullies and crevices will be formed (Figures 21 and 22). This form of erosion seems to be typical of the Harrison County loess, and gives the most trouble in deep highway cuts where conventional cut slopes cannot be used and thus making it hard for vegetation to take a foothold. The vertical cuts, in a series of terraces or steps, found in western Iowa serve two purposes. By keeping the steps to a height of twelve or fifteen feet, sliding of the cuts due to shear failure can be minimized. Also by having those horizontal faces, proper vegetation can be used to slow down the erosive action of water. Figures 25 and 26 show some of these terraces with grass and weed coverage.

The Johnson County loess in its undisturbed state is not as dry and fluffy as the Harrison County sample. It can also take in water, but at a slower rate. Erosion can also cause rather serious trouble in road cuts if grass or some other form of plant growth is not grown over the surface of the slopes (Figures 23 and 24). Due to topographical reasons, the highway cuts through the Johnson County loess deposits are seldom over ten or fifteen feet. Conventional 1½:1 slopes can always be used for the road cuts, and proper growth of vegetation can be used to stop or minimize the damaging effects of water.

6. Frost Action on Loess and Methods of Prevention.

Frost heaving is one of the major problems encountered on roads having the Harrison County type loess as subgrade material. The Johnson County type loess, however, rarely develops excessive frost heaving. The main reason for the

Harrison County loess to develop excessive frost heaving is because it is high in silt content -- 77% -- and also has no apparent soil structure. In winter, water is drawn into the subgrade by capillary action and freezes in the form of ice lenses which cause the subgrade to expand and in turn cause the pavement to heave. The Johnson County loess has a much higher clay content, which gives the soil a better structure and at the same time makes it more impervious. Water cannot get into the subgrade so readily from the pavement joints or from any other source to cause serious frost action in winter.

There were nine test courses chosen for this phase of the study. They are sections of roads through loess territory where frost action prevails. Some of the sections of roads were chosen because of excess frost heaving and some were chosen because of their lack of frost heaving. Complete discussions on them were presented in the first paper on this subject, and only a very brief analysis will be given here.

Several facts were observed during the course of this investigation. One was that compaction alone does not solve the problem of frost heaving. In silt soils like the Harrison County loess, compaction cannot reduce the voids between soil particles to a value small enough to prevent water from getting in and causing frost action during low temperatures. Another was that frost heaving can be completely eliminated by removing and replacing the subgrade loess soil with gravel or well graded material. This has been shown quite clearly on test section No. 7. Still a third interesting observation was that even though the subgrade soil was actually frozen with the presence of water in the Johnson County loess region, no frost heaving was noticed in winter. The presence of water in the subgrade was borne out by the fact that water was seen coming out from a few pavement joints during the early part of March when the road surface roughness test was conducted.

B. Stabilization of Loess

A brief summary and discussion of the previous study on this subject has been presented in the earlier part of this manuscript. The following discussion will be devoted to the analysis and interpretation of the data and results obtained in this subsequent study on the different methods of stabilizing loess for the use of highway construction.

1. Stabilizing Loess with Oil-Products -- Asphalt and Tar.

Since in this bituminous soil stabilization, the loess soils used were very fine silty material, some very light oil-product had to be used. The asphalt MC-0 and tar P-1 used in the investigation were very light surface oil. Their primary function in this bituminous soil stabilization was to waterproof the loess soil particles and to give them some cohesion. The percentages of bitumen used were 2, 4, 6, and 8 per cent.

In the Hubbard-Field stability load test, the specimens tested immediately after molded all gave stability load over 1200 pounds which is the minimum allowable load (2), with the exception of one specimen as shown in Table 10. However, this load value seems to be slightly out of line with the others and cannot be considered as conclusive. The Johnson County loess soil-bitumen specimens gave much higher load values than the Harrison County specimens. The reason is that it has a higher clay content and can be compacted to a higher density even under the same compacting load.

In the 72-hour water absorption test, the specimens for both loess samples failed completely (Figure 34), and hence the Hubbard-Field stability load test could not be run on them. The reason here for the complete failure of the specimens seems to depend not so much on the waterproofing ability of the bitumen as on the compacted condition of the specimens. However, since no experimental proof can be offered here, this discussion will not be carried any further.

In the unconfined compression test, from the Figures 41 to 48, it is quite evident that the soil-bitumen mixture having the lowest percentage of bitumen had the highest compressive strength, and this applied to both the Harrison County and the Johnson County loess samples. Of course this was true only when the specimens were dry, that is, when the specimens were tested at air-dried and oven-dried conditions respectively.

However, as far as deformation is concerned, the soil-bitumen mixture with the highest percentage of bitumen -- 8% -- gave the largest axial strain. This was true in all cases, and it tends to show that if too large a percentage of bitumen is used, there is a tendency for the bituminous material to lubricate the soil particles and thus lower the supporting strength of the soil. After the specimens were oven-dried and soaked in water for one hour, their compressive strengths were greatly reduced (Figures 42 and 44) and both the Harrison County loess and Johnson County loess with only 2 per cent bitumen failed completely. This shows that 2 per cent bitumen is definitely not sufficient to waterproof the loess soil particles. Figure 38 shows the appearance of loess after being mixed with 2, 4, 6, and 8 per cent of bitumen respectively.

Although both asphalt and tar were used in this study, there was little or no noticeable difference in their waterproofing quality. One fact that comes out in the investigation is the use of some light oil-products such as MC-0 asphalt and P-1 tar to stabilize a soil like loess is effective only to a limited degree, and that the per cent bitumen used should not be less than 6 or 8 per cent.

2. Stabilizing Loess with Water-repelling Agent.

The first question that comes up in a problem like this, whether out in the field or in the laboratory, is the method of mixing the water-repelling agent with the soil so that the best result can be obtained. The Armac T used in this study is cationic in character, and when added to the soil, in this case loess, it reacts with the soil chemically and replaces some of the exchangeable cations found on the surface of the clay particles and thus causing certain types of water-loving surfaces to become water-repelling and oil-loving. Thus we see the best method of mixing the chemical with the soil is to saturate the soil with the chemical which has been dissolved in an excess amount of water. This method really gives the chemical a chance to fully react with the exchangeable bases present in the soil. This method though used in this study may not prove to be suitable for most field uses from the practical and economical point of view. Other methods of mixing cationic chemicals with soil need to be studied, but they are out of the scope of this study and therefore will not be discussed here.

From Figures 53 and 54 we see that the Armac T treated loess soils when compacted to standard Proctor densities at their corresponding optimum moisture contents did not show very high axial stresses at their moist condition especially in the case of the Harrison County loess. However, when the unconfined compression test was run on the specimens after 7 days air-dry period, the stresses were many times higher. As the amount of Armac T added to the soil was increased, the compressive strength of the admixture was decreased. This was true with both loess samples as shown in Figures 53 to 56.

After submitting the 2 x 4 inch specimens to a 24 hour water soaking period, an interesting fact was observed. In the case of the Harrison County loess, the specimen with 1 per cent by weight of Armac T remained in perfect condition. The other two specimens with 2 per cent and 3 per cent by weight of cationic chemical all cracked and failed (Figure 49). In the case of the Johnson County loess, the specimen with 2 per cent by weight of Armac T stood up best. The other two specimens both cracked slightly and showed signs of failure (Figure 50). All these seem to point to the fact that the presence of an excess amount of the cationic chemical in the soil tends to decrease the effectiveness of the chemical in reducing the activity of the clay fraction of the soil. This fact has also been borne out in the findings of Davidson (15). One explanation for this behavior may be that the presence of the excess chemical in the soil will waterproof the individual soil particles and reduce the cohesiveness of the soil to such a degree that water can get in between the particles and force them apart. However, this is only a surmise and until further studies can be made, no definite conclusion can be reached here.

Figures 57 and 58 show the unconfined compression stress-strain curves for the two specimens tested after the 24 hour soaking period. In the case of the Harrison County loess, the maximum stress obtained was almost the same as that obtained for the specimen tested at optimum moisture. However, with the Johnson County loess, the maximum stress was lowered slightly. As far as the experimental data can show, the Armac T was quite effective in waterproofing the two loess soils.

In the Hubbard-Field stability load test only 6 and 8 per cent asphalt were tried on 1 per cent Armac T treated Harrison County loess and 2 per cent Armac T treated Johnson County loess. These two percentage cationic admixtures were chosen since they seemed to give the best results in the first series of tests. From Tables 10 and 12, it is evident that the presence of the cationic chemical in the two loess soils before the addition of the bitumen had little or no effect on the stability load values of the soil-bitumen specimens when tested after molding at room temperature. On the other hand it seemed to cause the two loess soils to become water-repelling and oil-loving. Previously, when the loess soils were not first treated with Armac T, even the 8 per cent bitumen specimens failed to stand up under the effect of water. However, by treating the loess soils first with the chemical, even the 6 per cent bitumen specimens stood up fairly well under the 24 hour water soaking period (Figures 51 and 52). In the case of the Harrison County loess, the Hubbard-Field test was run on the two specimens obtaining stability loads of 1155 pounds and 1477 pounds, respectively. These values were greater than the allowable limit -- 500 pounds -- as given in the A.S.T.M. Procedures for Testing Soils (2).

The apparent effect of the Armac T on the two loess samples was that it decreased their cohesiveness, air-dry strength, but greatly improved their resistance to the effect of water, and caused them to become water-repelling and oil-loving.

3. Stabilizing Loess with Portland Cement.

In regions where oil products or crushed stone or gravel aggregates are not available, cement will be another agent for soil stabilization. Formerly, it had not been too widely used for highway construction in this country, due to economical reasons, but in recent years, soil-cement has come into more use. It has also been used quite successfully in airport runway construction during the war period when speed and ease of construction of this type surface was an important consideration.

In judging the suitability of soil-cement mixtures, the following standards are recommended by the Portland Cement Association (53, p. 54):

a. Soil-cement losses during 12 cycles of either the wet-dry test or freeze-thaw test (A.S.T.M. Designations: D559-40T and D560-40T) shall conform to the following limits:
    U.S.P.R.A. soil classifications A-1, A-2 and A-3, not over 14 per cent.

U.S.P.R.A. soil classifications A-4 and A-5, not over 10 per cent.
U.S.P.R.A. soil classifications A-6 and A-7, not over 7 per cent.

b. Maximum volume during either wet-dry test or freeze-thaw test shall not exceed volume at time of molding by more than 2 per cent.
c. Maximum moisture content during either wet-dry test or freeze-thaw test shall not exceed that quantity, which will completely fill the voids of the specimen at the time of molding.
d. Compressive strengths shall increase with age and with increases in cement content in the ranges of cement content producing results meeting requirements 1, 2, and 3.

In the soil-cement study presented in the first paper by the author (18), modified Proctor densities for all the soil-cement mixtures were used as standards. However, in this study, the standard Proctor densities for the soil-cement mixtures were used as recommended by the Portland Cement Association (53). The results and findings of this study are discussed and compared with those obtained previously in the following pages.

In the first series of soil-cement atudy emphasis was placed on the densities of the soil-cement mixtures. In this second series of soil-cement study, moisture contents in the soil-cement mixtures during compaction was the primary consideration. Figures 64 and 65 show the standard Proctor density curves for the Harrison County loess and the Johnson County loess soil-cement mixtures. In both loess samples, as the percentage of cement used was increased, the density of the mixture decreased. On the other hand, the optimum moisture content increased with the increase in cement content. These were also true in the case of the modified Proctor density tests. There, however, the densities were in general about 8 or 9 per cent higher, and the optimum moistures about 30 per cent lower (Table 13).

Figures 70 to 77 show the unconfined compression stress-strain curves for the Harrison County and Johnson County loess soil-cement mixtures compacted to their corresponding standard Proctor densities at optimum moistures. In both samples, the compressive strengths increased appreciably as the per cent cement used and the curing period were increased. The 10 and 14 per cent cement Harrison County loess specimens gave relatively high compressive strengths even at optimum moisture conditions. After the 7-day curing period, the compressive strengths were increased about 20-25 per cent above those for the optimum moisture conditions. The Johnson County loess soil-cement specimens, however, only showed an increase of 10 per cent or less in compressive strengths. At 28-day period, the compressive strengths for all specimens were very much higher. In the case of the 14 per cent cement Harrison County loess specimen, the increase in compressive strength was almost 100 per cent over that for a similar specimen tested at optimum moisture condition.

After the soil-cement specimens had been curved for 7 days, a soaking period of 24 hours in water seemed to have little effect on the compressive strengths of the specimens.

Figures 72 and 76 seem to bear this fact out quite clearly. The same, however, cannot be said for the specimens compacted to modified Proctor densities and at lower moisture contents. Here, the Johnson County loess soil-cement specimens, after soaking in water for three and one half hours, both the 6 and 10 per cent cement specimens broke off into layers. Even the 14 per cent sample also showed signs of failing before submitting to the compression test. Also the compressive strengths for the specimens for 28 days were actually lower than those of the specimens compacted to standard Proctor densities at higher moisture contents due to the effect of water (Figures 68 and 69, and Table 14).

During the freeze-thaw test, the Harrison County loess soil-cement specimens stood up under the twelve cycles of freezing and thawing quite well. Only the 6 per cent cement specimen showed signs of softening up, and measuring of the specimen was discontinued after the sixth cycle. Figure 60 shows the soil-cement specimens after the twelve cycles of test. The volume changes of the 10 and 14 per cent cement specimens were very low. The maximum volume change for the 10 per cent cement specimen was about 1.6 per cent, and for the 14 per cent cement specimen about 0.7 per cent. When the specimens were compacted to modified Proctor densities, the volume changes were still lower. Even for the 6 per cent cement specimen, the volume change was only slightly over 0.5 per cent of the specimen volume during the time of molding.

Figure 78 shows the change in volumes of the soil-cement specimens during the twelve cycles of freeze-thaw test.

Since the Harrison County loess is an A-4 type of soil, the allowable soil loss on the specimens during either the freeze-thaw test or the wet-dry test should not be more than 10 per cent. Here, only the 6 per cent cement specimen had a total soil-cement loss of over ten per cent -- 14.3 per cent to be exact. The 10 per cent and 14 per cent cement specimens had losses of 6.8 per cent and 2.6 per cent respectively. Although the soil loss in the 6 per cent cement specimen was higher than the allowable limit, the specimen held together throughout the test. At modified Proctor densities, the soil-cement specimens had lower soil-cement losses, but the soil-cement loss for the 6 per cent cement specimen was still above the 10 per cent limit.

During the twelve cycles of freeze-thaw test of the Harrison County loess soil-cement specimens were observed to show moisture variations of about 7-8 per cent from the initial moisture contents (Figure 80). However, the presence of moisture had little effect on the 10 per cent and 14 per cent cement specimens. With the high compaction obtained by using the modified Proctor equipment, the voids in the specimens were further reduced. The moisture variations in the specimens from their initial moisture contents were only about 4 or 5 per cent.

With the Johnson County loess, although the volume change of the 6 per cent cement specimen was higher, the other two -- 10 per cent and 14 per cent cement specimens -- however, showed little volume change, not much over 1 per cent to be exact. When the specimens were compacted to modified Proctor densities, the volume changes in the specimens were in general still smaller, and the 6 per cent cement specimen showed a maximum volume change of slightly over 5 per cent although it became quite soft after 6 or 7 cycles of the test.

Since the Johnson County loess is an A-7 type of soil, the high soil-cement loss of the 6 per cent specimen -- 35.9 per cent as shown in Figure 83 and Table 15 -- shows that a higher per cent of cement would have to be used to stabilize the soil. The total soil-cement losses for the 10 per cent and 14 per cent cement specimens were 5.7 per cent and 3.5 per cent respectively. They were still within the allowable percentage, which is 7 per cent for this kind of soil. With the specimens compacted to modified Proctor densities, the total soil-cement loss for the 6 per cent cement specimen was 11 per cent lower, but was still too high for this type of soil. The soil-cement losses in the 10 per cent and 14 per cent specimens were also lower and within the allowable percentage.

During the twelve cycles of freeze-thaw test, the Johnson County loess soil-cement specimens were observed to show moisture variations of about 5-9 per cent from the initial moisture contents (Figure 81) with the 6 per cent cement specimen showing the highest variation. In the case of the specimens compacted to the modified Proctor densities, the maximum moisture variation shown by the 6 per cent cement specimen was about 8 per cent from the initial moisture content. This shows that even with high compaction, a low cement content still cannot be used satisfactorily with the Johnson County loess. The use of heavy equipment might keep the per cent of voids down during compaction, but it would not be able to destroy the capillary action.

In the wet-dry test, the Harrison County loess soil-cement specimens were able to stand the twelve cycles of wetting and drying without showing signs of breaking up with the exception of one specimen -- the 6 per cent cement soil loss specimen -- which broke up after the twelve cycle. The specimens compacted to modified Proctor densities on the other hand did not hold together too well. Both the No. 1 and No. 2 cylinders with 6 per cent cement broke off into layers at the compaction planes after the first three or four cycles. However, this breaking up into layers cannot be considered as failure of the samples, since in actual construction work, soil-cement roads are not compacted in layers as they are in the laboratory tests, and the layer failures probably would not develop.

Figure 84 and Table 16 show the volume changes of the specimens during the wet-dry test. All the specimens showed maximum volume changes of 1 per cent or less which are all within the allowable limit of 2 per cent. However, when the specimens were compacted to higher densities and at lower moisture contents, the maximum volume changes were higher for all the specimens. Only the specimen having 14 per cent cement can be considered as satisfactory, because the 10 per cent cement specimen had a maximum volume change of close to 4 per cent, and the 6 per cent cement specimen broke up badly during the test.

The maximum moisture variations were found to be around 10 per cent from the initial moisture contents for all the Harrison County loess soil-cement specimens. However, the moisture absorbed in the process of the experiment did not seem to have much effect on the specimens. For the specimens compacted to higher densities and at lower initial moisture contents, the moisture variations were around 8 per cent, but the damaging effect of the moisture on the specimens was more noticeable. Figure 86 shows the moisture contents of the specimens during the twelve cycles of wet-dry test.

With the exception of the 6 per cent cement specimen, which had about 15.5 per cent total soil-cement loss, the other specimens showed relatively low soil losses -- 2.8 per cent for the 10 per cent cement specimen and 3.3 per cent for the 14 per cent cement specimen. In the case of soil-cement cylinders compacted to modified Proctor densities, the soil-cement losses on the whole were actually higher. The 6 per cent cement specimen even broke into pieces before the completion of the test making it impossible to get an accurate value on the total soil loss for that particular specimen. Figure 88 is progressive soil loss diagram for the two series of soil-cement studies.

With the Johnson County loess, the soil-cement specimens on the average did not yield such satisfactory results as the Harrison County loess soil-cement specimens in the wet-dry test. However, they still withstood the twelve cycles of wetting and drying better than the specimens compacted to higher densities at lower initial moisture contents. Figures 85 and 89 bear out this fact quite clearly.

The 6 per cent cement specimen scaled and cracked pretty badly after the first three or four cycles making it impossible to obtain accurate volume change measurements, and the actual measuring was stopped after the sixth cycle. However, the maximum volume change was estimated to be over 2 per cent. With the 10 per cent and 14 per cent cement specimens, measurements were obtained until around the ninth and tenth cycles. The maximum volume changes were found to be around 2 per cent. For the specimens compacted to higher densities, measurements were obtained only up to the fifth cycle, and with the 6 per cent cement specimen, only up to the second cycle. No accurate volume changes were obtained for those specimens, but it is believed that they would be well over the allowable 2 per cent of the original molded volume.

Figure 87 and Table 16 show the moisture variations of the specimens during the twelve cycles of wet-dry test. For the specimens compacted to standard Proctor densities, the maximum moisture variations for the specimens were around 15 per cent. The damaging effect of the moisture on the specimens was noticeable, but was not as great as on the specimens compacted to higher densities when the maximum moisture variation for the specimens was only around 9 to 10 per cent.

The total soil-cement loss for the 6 per cent cement specimen is not shown in Figure 89, but it was estimated to be over 18 per cent. The total soil-cement losses for the 10 per cent cement and 14 per cent cement specimens, however, were within the allowable 7 per cent for this type of soil. For the 10 per cent cement specimen, the total soil-cement loss was 5.8 per cent, and for the 14 per cent cement specimen, the maximum loss was 2.5 per cent. Although no accurate soil-cement losses were obtained for the specimens compacted to modified Proctor densities, the total soil-cement loss was estimated to be over 30 per cent for the 6 per cent cement specimen, over 20 per cent for the 10 per cent cement specimen, and over 10 per cent for the 14 per cent cement specimen.

In this discussion of soil-cement studies, several interesting facts have been brought to light. From the test results, it seems that when the loess soil-cement mixtures were compacted to high densities at low moisture contents -- modified Proctor densities and corresponding optimum moistures -- wetting and drying do more damage to the specimens. However, if the specimens were only compacted to the standard Proctor densities but at relatively higher moisture conditions, freezing and thawing will do more damage. One explanation for these behaviors is that when the soil-cement mixture is compacted to a high density at a relatively low moisture condition, the per cent voids within the soil-cement is greatly reduced, but owing to the low moisture condition during compaction, insufficient moisture is available to fully hydrate the cement. This condition is similar to that of mixing concrete. When insufficient water is added to the concrete mix, the concrete after curing will show high strength, but at the same time will be brittle. Because of the low per cent void space within the soil-cement, little water can get inside through capillary action. There is little chance of the water inside the soil-cement to freeze and expand and thus cause the soil-cement to crack and fail. However, when the soil-cement is subjected to wetting and drying, an entirely different situation takes place. Because the cement has not been fully hydrated, it does not have the chance to fuse the soil particles together. So when the soil-cement is being wetted and dried off alternately, the soil particles held together loosely by the partly hydrated cement will eventually break off from the rather weak bond and thus cause the soil-cement to crack and fail.

On the other hand, when the soil-cement mixture is compacted to a lower density but at a relatively higher moisture condition -- standard Proctor density and corresponding moisture content -- an opposite situation takes place. The per cent voids will be larger making the soil-cement susceptible to more serious capillary action, but at the same time, the cement will be hydrated more completely due to the presence of more moisture and thus binding the soil particles together more firmly. In this case, the soil-cement becomes easily affected by the action of freezing and thawing, but can stand the action of wetting and drying much better.

From the above discussion, it seems that in loess regions where rainfall is not heavy but freezing and thawing in winter are quite serious, if cement is used to stabilize the soil, higher densities and lower moisture contents during compaction may be used. But it is not very good practice to keep the moisture conditions so low that the cement cannot be satisfactorily hydrated. However, in loess areas where water is the perennial source of trouble, if soil-cement is to be used, enough moisture should be used during the process of compaction even at the risk of getting lower densities so that the cement can be fully hydrated.

Further, it seems that with proper amount of moisture in the soil-cement during compaction, the Johnson County loess can be fairly satisfactorily stabilized with 10 per cent of cement, while the Harrison County loess can be stabilized with less. In the previous study, however, it was found that Johnson County loess could not be satisfactorily stabilized with less than 10 per cent cement, and that the Harrison County loess required about 10 to 12 per cent. Thus it can be concluded that while density is important in soil-cement work, proper moisture content is even more important.

VI. SUMMARY

Loess deposits are widely distributed all over the world. One of the largest deposits is found in north-central China where better roads are in demand. The author feels that in order to deal with loess efficiently, he must have a complete knowledge of the properties and behaviors of the soil. This is one of the main reasons for conducting this research study.

Since loess samples could not be obtained from China, two loess samples were chosen from the loess deposits of Iowa. One loess soil was sampled from Harrison County, and the other from Johnson County. The Harrison sample, as far as everyone knows, has been subjected to little or no weathering. The Johnson County samples, however, have been subjected to some weathering.

After the loess samples were obtained, they were subjected to a series of analytical tests in the laboratory to determine their physical characteristics and behaviors. The geological and historical background was also investigated carefully through library research and personal correspondence with other workers along this line. Part of the data and results were presented by the author in his thesis for the Master of Science degree.

In this second paper, the author has tried to look at "loess" from a broader point of view and to answer some of the questions raised in the course of the first research study. As before, the first part of this paper has been devoted to a brief review of literature which has included the historical and geological significance of the soil.

In the investigation, further analysis of the soil was undertaken. The first part of the investigation has included the particle size distribution study -- three methods were used here: (a) Bouyoucos Hydrometer Method, (b) Long-arm Centrifuge Method, and (c) Pipette Method; clay mineral determination using the Differential Thermal Method; base exchange study, etc. Some of the findings of the first study together with frost action and erosion characteristics in loess have also been included here.

In the second part of the investigation, different methods for stabilizing loess were studied. First, some light surface road-oil such as MC-0 asphalt and P-1 tar were tried. They were used here with the purpose of waterproofing the soil particles and at the same time making the loess soil less dusty. A series of tests were performed on the soil-bitumen admixtures to determine the suitability and effectiveness of the bituminous materials as stabilizing agents for loess. Next, a cationic chemical Armac T was used with the loess. This chemical when added to some soil is supposed to cause cationic exchange phenomenon in the soil and thus make the soil water-repelling and oil-loving. Tests were performed on the Armac T treated loess for the effectiveness of the cationic chemical as a stabilizing material. Bituminous material was also tried on the chemically treated soil to prove the effectiveness of the chemical in making loess oil-loving. Lastly, Portland cement was tried with the two loess samples. Three different percentages of cement were tried with each loess sample using the standard Proctor densities and optimum moisture contents as the compaction standards. Previously, modified Proctor densities and their corresponding optimum moisture contents were used. Each group of soil-cement specimens were subjected to the following tests: (a) Unconfined Compression Test, (b) Freeze-thaw Test, and (c) Wet-dry Test, to evaluate the correct percentage of cement to be used with each loess soil, and also the suitability of cement as a stabilizing agent for loess.

The sand-bituminous and aggregate stabilizations of loess which were presented in the first paper, have not been included in this study.

VII. CONCLUSIONS

On the basis of the entire investigation including the findings of the previous study, the following conclusions have been reached:

1. Both the Harrison County loess and Johnson County loess are very fine wind-blown soil and high in silt content. Their apparent lack of structure makes them unsuitable to be used as highway material alone.

2. High densities, as compared with the low cut densities of the undisturbed soil in place for both loess deposits, can be obtained by the use of heavy compacting equipment.

3. In making a particle size distribution study of a soil like the Johnson County loess, stirring the soil-water system in a malted-milk machine for 5 minutes is not sufficient to give the system complete dispersion. A 10-15 minute period should be used.

4. With the loess, especially the Harrison County loess, Daxad 23 does not make a good dispersion agent. Some sodium salt such as sodium hydroxide or sodium silicate should be used.

5. Both loess soils are high in capillary rise and low in permeability even in their loose condition.

6. Both soils show high stability, especially the Johnson County loess, when compacted at optimum moisture,

but lose their strengths completely when saturated. They also show high expansion values during the water saturation period.

7. If at any time either the Harrison County loess or the Johnson County loess is to be used alone as subgrade soil, the drainage design has to be worked out carefully. The water table under the subgrade should be kept as low as possible and surface water removed from the pavement as rapidly as possible.

8. Both loess samples were found to have similar clay mineral constituents. Montmorillonite type clay mineral or clay minerals seemed to predominate with the presence of some illite or illite type clay minerals.

9. The presence of montmorillonite type clay mineral or clay minerals in the two loess soils, especially in the Johnson County loess, is principally responsible for the serious swelling property of the soils.

10. Base exchange capacities for the 2u fractions of the two loess soils are quite high which again shows the presence of montmorillonite in the samples.

11. Erosion is more serious with the Harrison County loess than with the Johnson County loess. Sliding, sloughing, and gullying are the common forms of erosion in loess with the last one the most serious in areas having the Harrison County type loess deposits.

12. The presence of a large amount of silt in the Harrison County loess makes it more vulnerable to frost action. The frost heaving in this type of loess subgrade cannot be avoided entirely by compacting the subgrades to high densities. It may be reduced in some cases. The Johnson County loess covered in this study, however, is free from this trouble.

13. The best procedure to prevent frost heaving in the Harrison County type loess subgrades is to remove the loess to the depth of frost penetration and to substitute the loess with some easily drained materials like sand, gravel, or crushed rocks. In some cases, frost heaving can be prevented or at least minimized by merely excavating and substituting the subgrade loess to a depth of about twelve inches.

14. Both the Harrison County loess and the Johnson County loess can be stabilized with suitable agents such as asphalt or tar, aggregates, and cement.

15. Cationic chemicals like Armac T can be used to waterproof the loess soils and thus stabilize them to a certain degree. Armac T also makes the loess soils water-repelling and oil-loving causing them to mix with bituminous materials like asphalt and tar more readily.

16. The presence of an excess amount of Armac T in the two loess soils has a tendency to reduce its effectiveness in resisting the effect of water.

17. For light traffic, a bituminous mixture with sand

as aggregate and either the Johnson County loess or the Harrison County loess as filler will provide a satisfactory riding surface, provided the correct amount of bitumen is used.

18. Light surface road oils are not suitable to be used as stabilizing agents for the two loess soils.

19. With the proper amount of aggregates, both the Harrison County loess and the Johnson County loess can be stabilized and compacted to give firm road beds. Stabilized loess soils can also be used as road surface material for secondary roads.

20. Under favorable conditions, cement may prove to be the best stabilizing agent for use with loess soils.

21. In stabilizing loess soils with cement, high densities are not the primary factor. Enough moisture in the soil during compaction to allow for the complete hydration of the cement is the controlling factor for successful loess soil-cement stabilization.

22. With Harrison County loess, 8 to 10 per cent of cement by volume will provide a stable soil-cement mixture. However, the moisture in the mixture during compaction should not be less than 18 or 19 per cent.

23. With Johnson County loess, 10 to 12 per cent of cement by volume will probably have to be used in order to have a fairly stable soil-cement mixture. The moisture in the mixture during compaction, however, should not be less than 17 or 18 per cent.

24. In loess regions like northwestern Iowa where the climate is fairly dry but hard freezing takes place frequently in winter, loess soil-cement roads can be compacted to higher densities with lower moisture condition during compaction.

25. In southeastern Iowa for instance, where rainfall is fairly abundant at times, sufficient moisture should always be present during the compaction of loess soil-cement roads even at the risk of getting slightly lower densities.

26. As a final statement, with loess soil-cement roads, it is important that water be kept away from the soil-cement. Although the surface is generally protected by an asphalt seal coat, provisions should be made to allow for easy and quick draining of any water on the surface of the road.

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