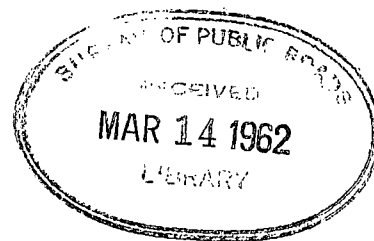


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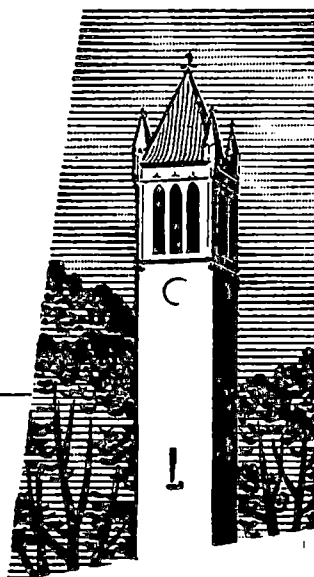


Joint Publication
Bulletin No. 194
Iowa Engineering Experiment Station
Bulletin No. 23
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SOIL STABILIZATION WITH CEMENT

by
D. T. Davidson
and
Associates

IOWA ENGINEERING



EXPERIMENT STATION

IOWA STATE UNIVERSITY
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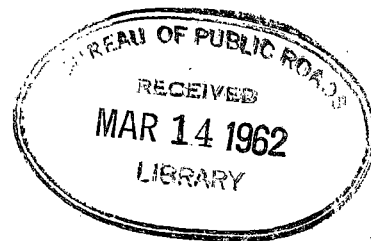
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**The Iowa Engineering Experiment Station
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Soil Stabilization with Cement.

by

D. T. Davidson, Professor, Civil Engineering
and
Associates

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PREFACE

This is the fourth publication in a series of compilations of the reports on research completed for the Iowa State Highway Commission. This research was done for the Iowa State Highway Research Board Project HR-1. *The Loess and Glacial Till Materials of Iowa; an Investigation of Their Physical and Chemical Properties and Techniques for Processing Them to Increase Their All-Weather Stability for Road Construction.* The research, started in 1950, was done by the Iowa Engineering Experiment Station under its project 283-S. The project was supported by funds from the Iowa State Highway Commission.

The principal objectives of the project may be summed up as follows:

1. To determine by means of both field and laboratory studies the areal and stratigraphic variation in the physical and chemical properties of the loess and glacial till materials of Iowa.
2. To develop new equipment and methods for evaluating physical and chemical properties of soil where needed.
3. To correlate fundamental soil properties with the performance of soils in the highway structure.
4. To develop a scientific approach to the problem of soil stabilization based on the relationships between the properties of the soils and those of the admixtures.
5. To determine the manner in which the loess and glacial till materials of Iowa can be processed for optimum performance as highway embankments, sub-grades, base courses, and surface courses.

Many of the papers in this bulletin were prepared originally as graduate theses required for master or doctoral degrees. Each was then rewritten with the assistance of other project workers and was submitted to the Iowa Highway Research Board as a report on a phase of completed research. This explains the several authors for each paper. The research work was all done under Dr. D. T. Davidson as project leader in charge.

Practically all the papers herein have been published previously. The title page for each manuscript identifies all authors and gives the place and date of first publication. No attempt has been made to revise, update, and change the data; hence some contradictions are evident. The facts and conclusions presented are those of the authors at the time the manuscript was submitted. Much of the repetition of material has been eliminated, and the papers have been arranged by subject matter.

The list of REFERENCES at the end of each manuscript gives only the first or original printing, though the paper referred to may have appeared later in various forms in several publications, and some are included herein. Those shown as theses in the Iowa State University Library are so indicated because only in the theses are all the data shown.

J. H. B.

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**EFFECT OF PETROGRAPHIC VARIATIONS
OF SOUTHWESTERN IOWA LOESS
ON STABILIZATION WITH PORTLAND CEMENT**

by

R. L. Handy, Associate Professor, Civil Engineering

D. T. Davidson, Professor, Civil Engineering

T. Y. Chu, Assistant Professor, Civil Engineering

(Highway Research Board Bulletin 98:1-20, 1954, and Engineering Report
22, Iowa Engineering Experiment Station, 1954.)

INTRODUCTION

Loess, the dominant surface deposit in Iowa and in areas of adjoining states, is the first soil material to be studied for stabilization purposes by

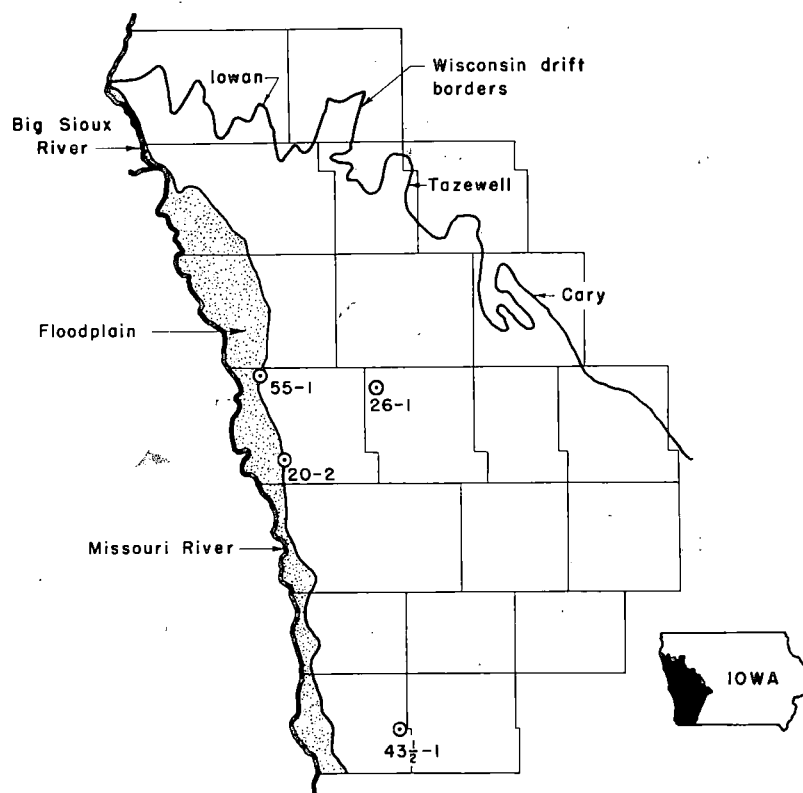


Fig. 1. The Wisconsin loess area in southwestern Iowa, showing locations of the four samples selected for detailed studies.

the Iowa Engineering Experiment Station. In general, loess areas are areas where shortages of aggregate exist or are expected, and a method of loess stabilization is highly desirable. From a scientific point of view loess is an excellent material for study because preliminary studies show that its properties vary gradually over wide areas, and the effects of these variations on stabilization problems may be evaluated.

The largest deposits of loess in North America are Wisconsin in age and are located in southwestern Iowa (figure 1). The detailed property and stabilization studies are being made on loess from this area. By means of similar, somewhat less detailed studies, the loesses in other areas of Iowa will be compared with the southwestern Iowa loess so that their behavior may be to some degree predicted.

Properties of the southwestern Iowa loess vary in general from west to east. The loess becomes finer textured and contains more clay, the carbonate content decreases, and the thickness of the deposit diminishes (figure

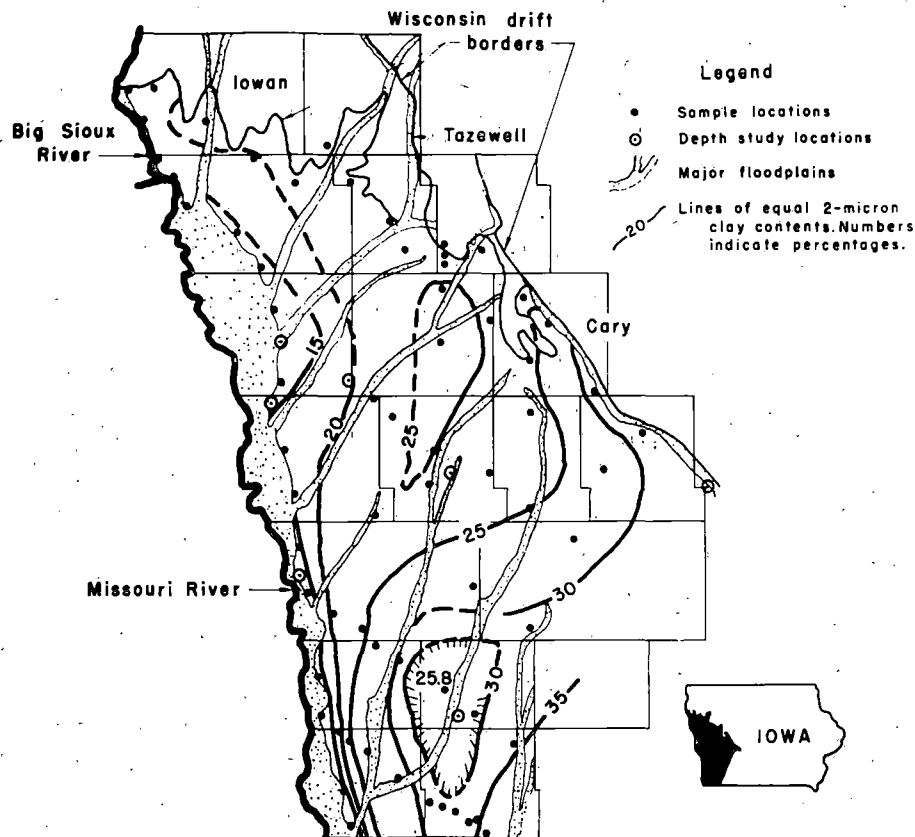


Fig. 2. Tentative map showing areal distribution of clay contents in the Wisconsin loess of southwestern Iowa.

2). On the basis of data from the loess property variation studies^{6, 7, 13}, four loess samples were chosen as representative of variations in the Wisconsin loess of southwestern Iowa (table I).

TABLE I. THE FOUR LOESS SAMPLES SELECTED FOR DETAILED STUDY

SAMPLE NO.	DESCRIPTION	GEOLOGICAL AGE	ENGINEERING CLASSIFICATION
55-1	A very friable loess (low clay and high carbonate contents). Sampling depth: 2½-3½ ft.	Upper Wisconsin (?)	A-4 (8)
20-2	A typical friable loess, higher in clay than the above sample. Total loess thickness: over 100 ft. Sampling depth: 39-40 ft.	Wisconsin (Undifferentiated)	A-4 (8)
26-1	A typical medium-textured loess. It is leached from the surface, but the underlying calcareous loess is not so calcareous as the friable samples listed above. Total loess thickness: 30-40 ft. Sampling depth: 4-5 ft.	Wisconsin (Undifferentiated)	A-6 (9)
43½-1	A typical moderately plastic loess. The entire loess section is leached. Total loess thickness: 15-20 ft. Sampling depth: 5½-6½ ft.	Wisconsin (Undifferentiated)	A-7-6 (18)

PETROGRAPHY

Petrographic Methods

Particle Sizes

Mechanical analyses were performed on the four loess samples by hydrometer and pipette methods which have been described^{5, 14}. Sodium metaphosphate was used as the dispersing agent.

Mineralogical Composition

Silt fraction. Each loess sample was dispersed in water and separated into size fractions with a rising-current elutriator (Appendix A). Samples from each size fraction above 5 microns were then separated into light and heavy minerals by allowing the grains to float or sink on bromoform (sp. gr. 2.87). Because the particle sizes are so small, centrifuging with a special centrifuge tube (Appendix B), was used to speed the separations. Light minerals were mounted in Canada balsam, heavy minerals in piperine, and identifications were made under a petrographic microscope. Mineral percentages were determined by a statistical measurement of grains made with a Leitz integrating stage.

Clay Fraction. Minus 2 micron material was separated from each loess sample by removing a layer from a suspension and drying³. The clays were then subjected to a number of determinative tests, including differential thermal analysis, X-ray diffraction, clay mineral staining tests¹⁹, cation exchange determinations, particle-size measurements, and measurements of optical properties. The test methods and data on the loess samples have been recently summarized⁸.

Grain Shape and Roundness

Sphericity is an expression for grain shape and was estimated for individual grains by visual comparison with charts showing grains of known sphericity²². The charts are based on Krumbein's¹⁷ formula that sphericity is equal to grain width divided by grain length. Averages for a number of grains in each loess fraction were calculated.

Roundness refers only to the relative sharpness of grain corners and was noted qualitatively for a number of grains.

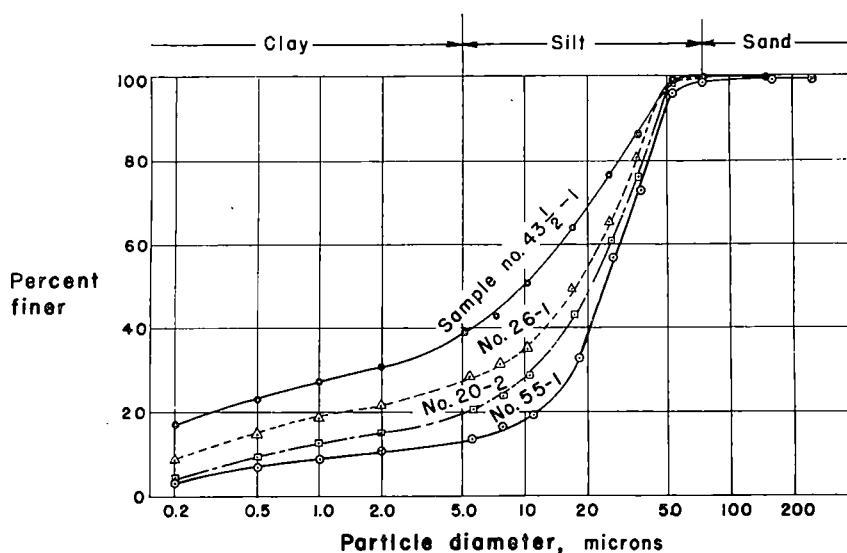


Fig. 3. Particle-size accumulation curves for the four selected loess samples.

Chemical Tests

Chemical tests performed on the four loess samples include the following:

1. Cation exchange capacity, by an ammonium acetate method^{9, 10}.
2. Exchangeable cations, determined with a flame photometer.
3. pH, by an electrometric method (15 g soil in 30 ml water).
4. Carbonate content expressed as percent CaCO_3 , by a versenate method.

5. Sulfate content, by a water-soluble sulfate determination⁴.
6. Chloride content, by Mohr's method.
7. Free iron oxide content, by Jeffries' method¹⁵.
8. Total iron content¹².
9. Organic matter content, by a dichromate oxidation method⁴.

Petrographic Data

Particle Sizes

Particle-size accumulation curves for the four loess samples are presented in figure 3. Curves for other Wisconsin loess samples from southwestern Iowa are similar in shape, and most would fall between the limits shown.

Mineralogical Composition

Non-clay minerals. Mineralogical compositions of the four loess samples are shown graphically by means of histograms (figures 4, 5, 6, and 7). In

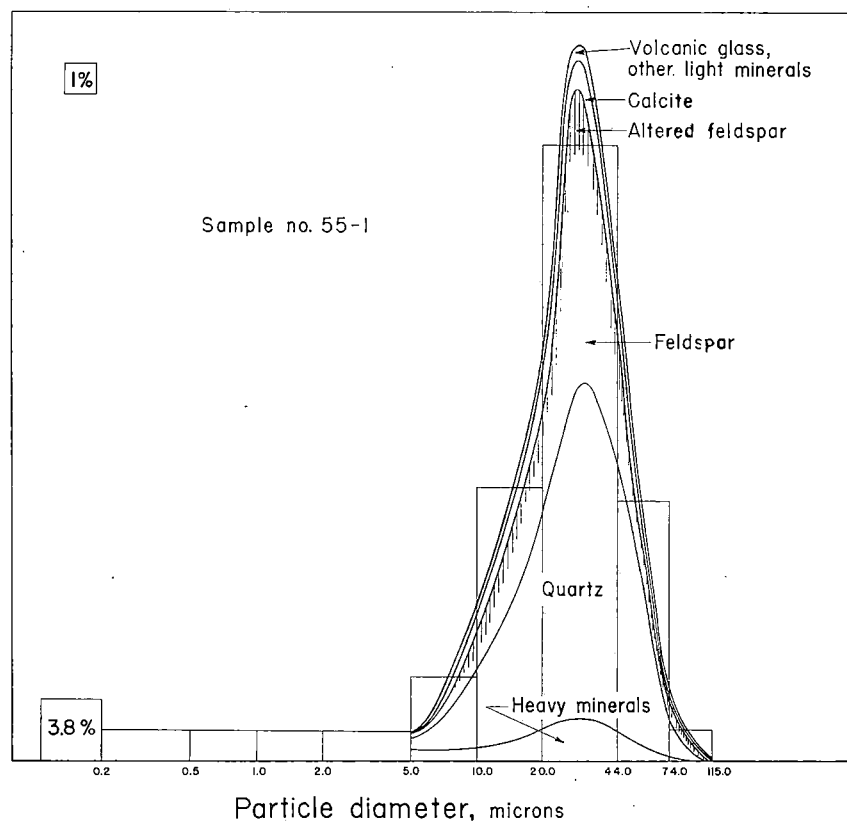


Fig. 4. Mineral composition diagram for Sample 55-1. Areas in the diagram represent mineral percentages by volume.

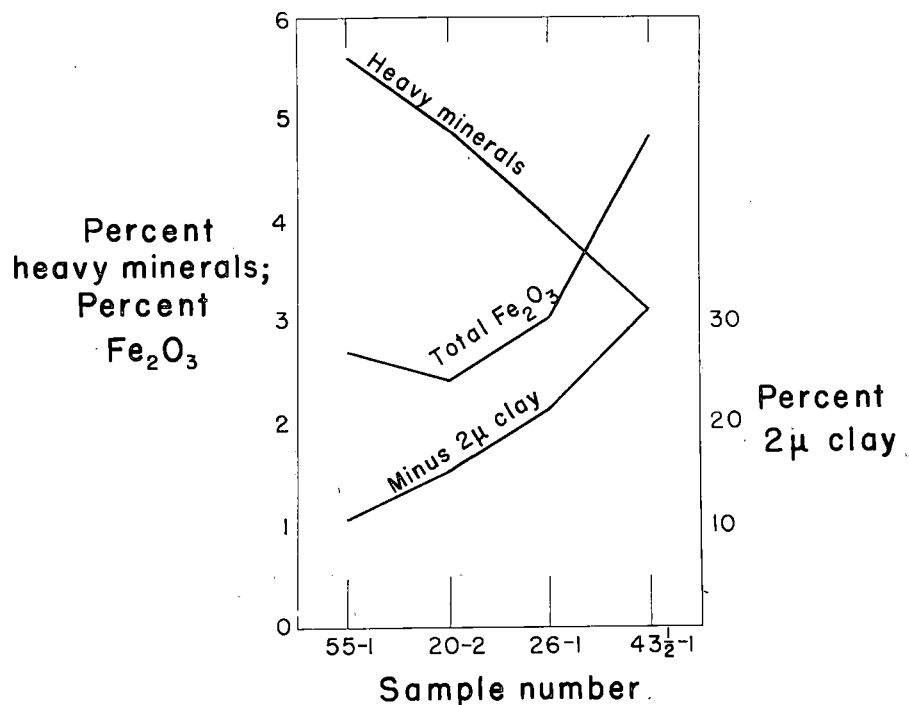


Fig. 5. Mineral composition diagram for Sample 20-2. Areas in the diagram represent mineral percentages by volume.

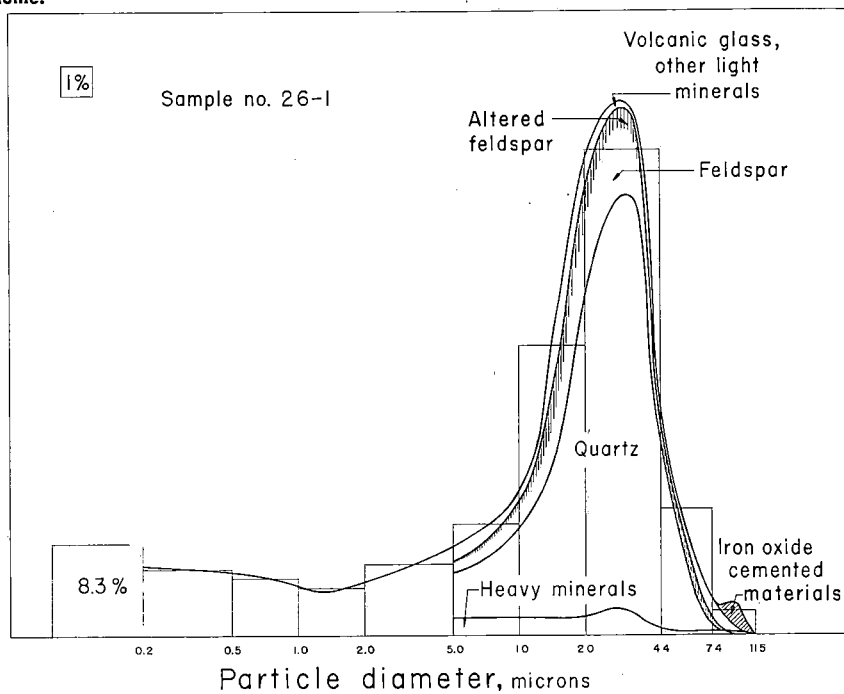


Fig. 6. Mineral composition diagram for Sample 26-1. Areas in the diagram represent mineral percentages by volume.

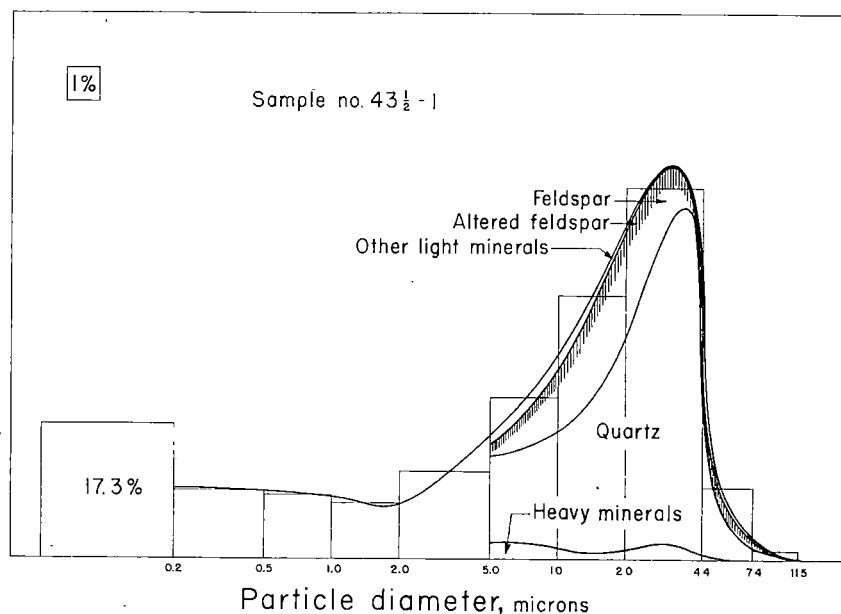


Fig. 7. Mineral composition diagram for Sample 43 $\frac{1}{2}$ -1. Areas in the diagram represent mineral percentages by volume.

TABLE II. MINERALOGICAL COMPOSITION OF MATERIAL LARGER THAN 5 MICRONS
IN THE FOUR LOESS SAMPLES (PERCENT BY VOLUME OF THE
WHOLE SAMPLE)

SAMPLE NO.	55-1	20-2	26-1	43 $\frac{1}{2}$ -1
Total quartz	41	45	48	45
Undifferentiated qtz.	37	38	40	40
Iron-oxide coated*	1	2	4	3
Clay-coated*	1	1	2	1
Chert	2	4	1	2
Total feldspar	25	17	16	15
Undifferentiated feld.	19	9	10	10
Plagioclase	Trace	2	Trace	Trace
Microcline	1	Trace	Trace	0
Altered feldspar	6	5	6	5
Calcite	8	11	1	Trace
Volcanic glass	2	1	1	Trace
Muscovite	1	Trace	1	1
Biotite	Trace	Trace	Trace	Trace
Clay minerals (aggregates)	1	Trace	Trace	1
Total heavy minerals	5.6	4.9	4.0	3.1
Amphiboles	2.0	1.8	1.4	1.2
Pyroxenes	0.8	0.6	0.4	0.5
Dolomite	1.3	1.1	0.0	0.0
Iron oxides	1.1	1.0	1.1	0.9
Others	0.4	0.4	1.1	0.5
Minus 5 micron material	13.0	20.0	27.8	39.0

*After dispersion, elutriation, and bromoform separation.

these histograms the areas are proportional to relative percents by volume of the various minerals in each size fraction (table II).

In general the percentages of heavy minerals increase with decreasing grain size, probably due to sorting action during deposition of the loess (figure 8). (Heavy mineral grains are more difficult to transport than light

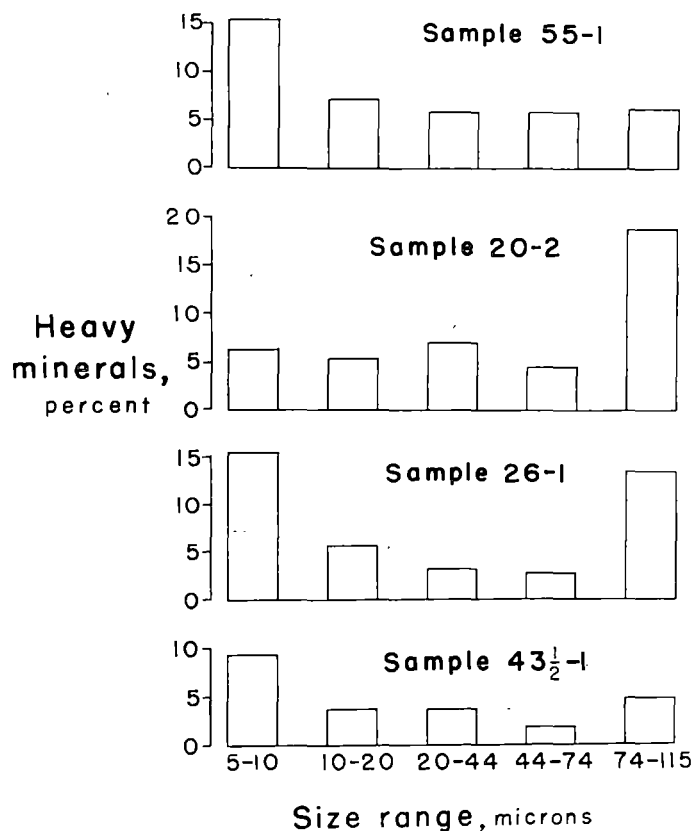


Fig. 8. Percent by volume of heavy minerals in the various size fractions of each sample.

mineral grains of the same size.) The exception is in the sand fraction (74-115 microns), which forms a very minor part of each sample, and contains much secondary iron.

Clay minerals. Clay minerals in the minus 5 micron material are much more difficult to determine quantitatively. The clay minerals are mainly as minus 2 micron material, and determinations were made on this fraction. The results and interpretations of the various tests are summarized in table III⁸. In the differential thermal curves (figure 9) the large initial peaks indicate montmorillonite, but the 700° montmorillonite peak is very much

TABLE III. RESULTS AND INTERPRETATIONS OF CLAY MINERAL TESTS ON MINUS 2 MICRON MATERIAL FROM THE LOESS

Sample No.	Amount of Minus 2 Micron Clay, %	Staining Tests	X-Ray Analyses*				Cat. Exch. Cap., m.e./100g		Differential Thermal Analyses	Optical Tests
			Montmorillonite	Illite	Kaolinite	Quartz				
55-1	10.5	Montmorillonite	Abundant	Almost equal to montmorillonite	Small amount	About 10%	59.3	All indicate that montmorillonite predominates	All indicate montmorillonite and illite. The 700° C. montmorillonite reaction is largely masked, and no variations between samples are shown	All indicate mixtures of minerals
20-2	15.4	"	Abundant	About 1/4 the abundance of montmorillonite	Trace?	About 10%	58.6			
26-1	21.5	"	Abundant	Slightly less than in sample 20-2	Small amount	About 10%	62.8			
43½-1	31.4	"	Dominant	Contains very little	Absent	About 10%	59.9			

*Analyses and interpretations by R. E. Grim.

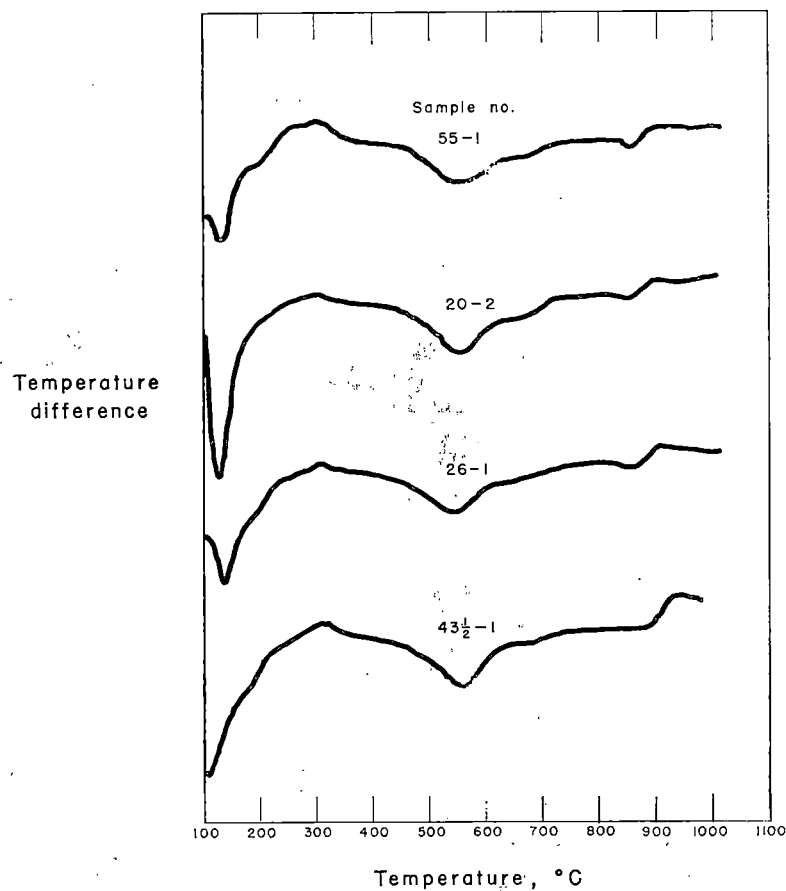


Fig. 9. Differential thermal curves for minus 2 micron clay from the four loess samples.

subdued compared with that of the 550° illite. This may indicate a randomly interstratified mixture of the two types of minerals.

Nontronite, a montmorillonite mineral high in iron, gives a 550° endothermic reaction similar to that of illite. Although the iron content determined chemically in the clay is high, as discussed later, it is probably not high enough to suggest other than an iron-rich beidellite as the montmorillonite mineral.

Only the X-ray diffraction data show any systematic variations in clay mineral composition. Nor could any correlation be found between these variations and the particle-size data: a further indication of an interstratified relationship. The X-ray data indicate an increase in the montmorillonite:illite ratio with increasing clay content.

Clay-Silt Relationships, Grain Coatings

Microscopic examinations of the loess revealed that clay occurs mainly as coatings on larger grains, which tend to increase the effectiveness of the clay. The coatings are of two types: minute greenish specks adhering either singly or in clusters to the host grain (figure 10), and as continuous,

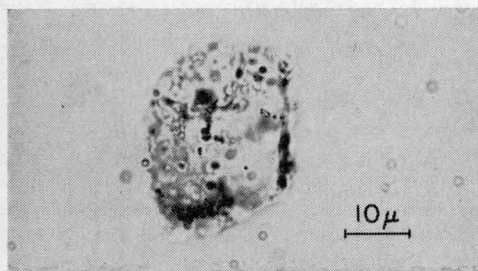


Fig. 10, above.—Photomicrograph of loess grains with particles of clay adhering.

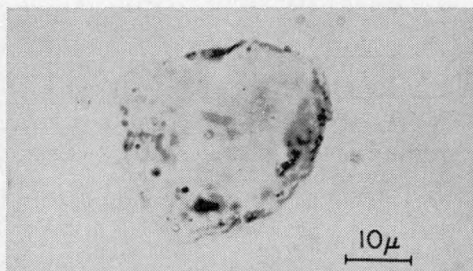
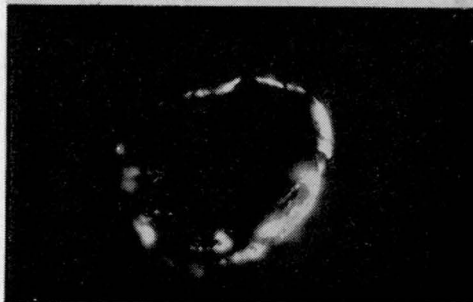


Fig. 11, at right. Continuous clay coatings on a loess grain. Above, under plane polarized light; below, under crossed Nicols.



greenish, birefringent coatings partially covering the surfaces of larger grains (figure 11). The lower photomicrograph shows the birefringence of the clay coating. Since clay mineral grains are highly birefringent only when viewed on edge, they are apparently oriented flat against the host grain.

TABLE IV. GRAIN COATINGS IN THE FOUR LOESS SAMPLES

Sample No.	Occurrence of clay particles	Est. % host grains are coated	Kinds of host grains	Other coatings
55-1	As individual particles and clusters of particles adhering to large grains. There are also a few continuous clay coatings	0 to 80, averaging 17.2.	Quartz, feldspars (altered and fresh), volcanic glass. Clay coatings are not common on calcite or heavy mineral grains.	.....
20-2	Same as in sample 55-1	0 to 80, averaging 18.5.	Same as in sample 55-1. Some slightly coated calcite grains were noted.	.....
26-1	Same as in sample 55-1, but with a greater number of continuous clay coatings completely surrounding the host grains.	0 to 100, averaging 23.2.	Same as in sample 55-1.	Red-brown Fe oxide coatings. Host grains 0 to 100% coated, av. about 5%.
43½-1	Same as above, also dispersed as individual particles and in large aggregates which are dominantly clay.	0 to 100, averaging 38.0.	Same as in sample 55-1.	Red-brown Fe oxide coatings. Host grains av. about 5% coated.

Grain coatings on the four samples are summarized in table IV. The estimated extent of coatings on the host grains is given but is of course only an indication of the differences between samples, since the estimates apply only to coatings visible under the microscope.

Sphericity and Roundness of Silt Grains

Sphericity is an index of grain shape; roundness is a measurement of the rounding of corners. The sphericity is probably most important for engineering applications, and as measured here it indicates the intermediate particle diameter divided by the maximum particle diameter¹⁰. There is a range in sphericities in any sample, and these may be averaged (figure 12). Average sphericities for the four loess samples are the following:

SAMPLE NO.	SPHERICITY
55-1	0.76
20-2	0.76
26-1	0.76
43½-1	0.77

The sphericity was also found to be constant in the various particle size ranges above 5 microns. From this it may be concluded that grain sphericity of the loess is not a variable, and its effect on engineering properties cannot be evaluated in this study.

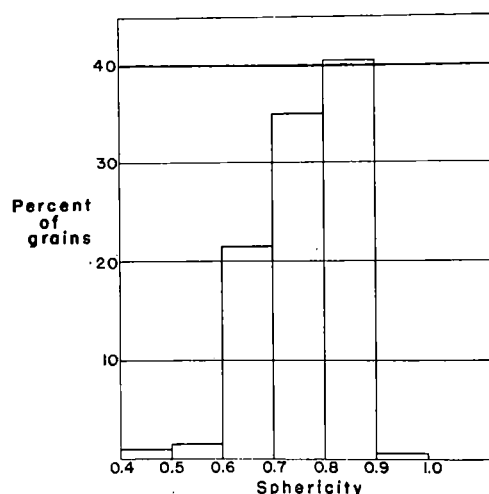


Fig. 12. Histogram showing the range in sphericities of grains in a loess sample.

Roundness of the grain corners was estimated, and no variations among the four samples were found. Angular or subangular grains predominate.

TABLE V. CHEMICAL DATA ON THE FOUR LOESS SAMPLES

Sample No.	Cat. Exch. Cap., m.e./100g	Exch. Cations, m.e./100g			pH	CaCO ₃ , %	SO ₃ , %	Cl ₂ , %	Free Fe ₂ O ₃ , %	Total Fe ₂ O ₃ , %	Organic Matter %
		Na	K	Ca							
55-1	11.2	1.4	2.0	7.8	8.4	10.3	Trace	0.01	0.356	2.70	0.24
20-2	13.4	1.5	1.6	10.3	8.7	9.4	0	0	0.403	2.42	0.17
26-1	18.2	0.9	1.2	16.1	7.0	1.9	Trace	0	0.495	3.02	0.18
43½-1	24.4	1.3	1.3	21.8	6.7	1.6	0	0	0.429	4.82	0.37

Chemical Data

Chemical data may affect the performance of loess as a construction material (table V). The cation exchange capacity is directly related to the clay content, and carbonates contribute slightly to the exchange capacity. Calcium is the principal adsorbed cation. Calcium and magnesium were not separated in the analysis, but a spot test failed to reveal any magnesium.

The pH of the loess samples is related to the carbonate content, the calcareous samples being slightly alkaline and the leached samples nearly neutral. The carbonate contents from chemical tests show close agreement with microscopic data and serve as a check. It should be noted that the samples identified in the field as leached (26-1 and 43½-1) contain slight amounts of carbonates. Although calcium and magnesium carbonate were not separated chemically, the microscopic data indicate that dolomite (calcium-magnesium carbonate) constitutes some 10 percent of the car-

bonates present.

Soluble sulfates and chlorides are important because of their possible deleterious effects on some stabilizing agents. They are absent or are only as traces in the four loess samples.

Free iron oxide contents determined chemically correlate well with the microscopic data for iron-oxide coated quartz (figure 13). The correlation

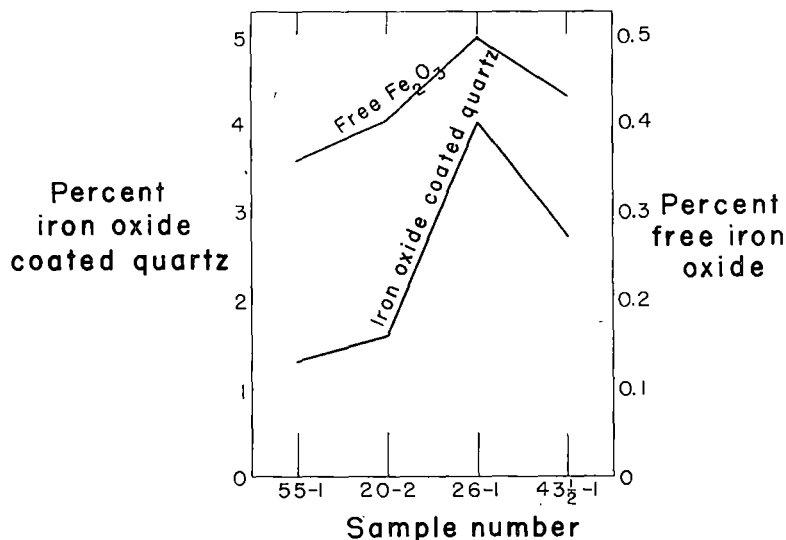


Fig. 13. Comparison of data for free iron oxide determined chemically and iron oxide coated quartz grains measured microscopically.

between free iron and total iron is not close, and they are apparently unrelated. The free iron content is greatest in the loess where there is a source of iron from weathering in overlying soil horizons. Furthermore, secondary iron tends to become concentrated near the water table, accounting for the high free iron content in samples 26-1.

Between total iron content and heavy mineral percentages from petrographic analysis, correlation is almost negative, and it appears much better when the total iron is compared with the clay contents (figure 14). Iron is common in the montmorillonite minerals and in the hydrous micas (illite and mixed-layer minerals).

Organic matter is present in small amounts in all samples. The content is somewhat higher in sample 55-1 due to the presence of plant roots.

BEHAVIOR CHARACTERISTICS

A number of soil mechanics tests were performed which give information on some of the behavior characteristics of the loess. These char-

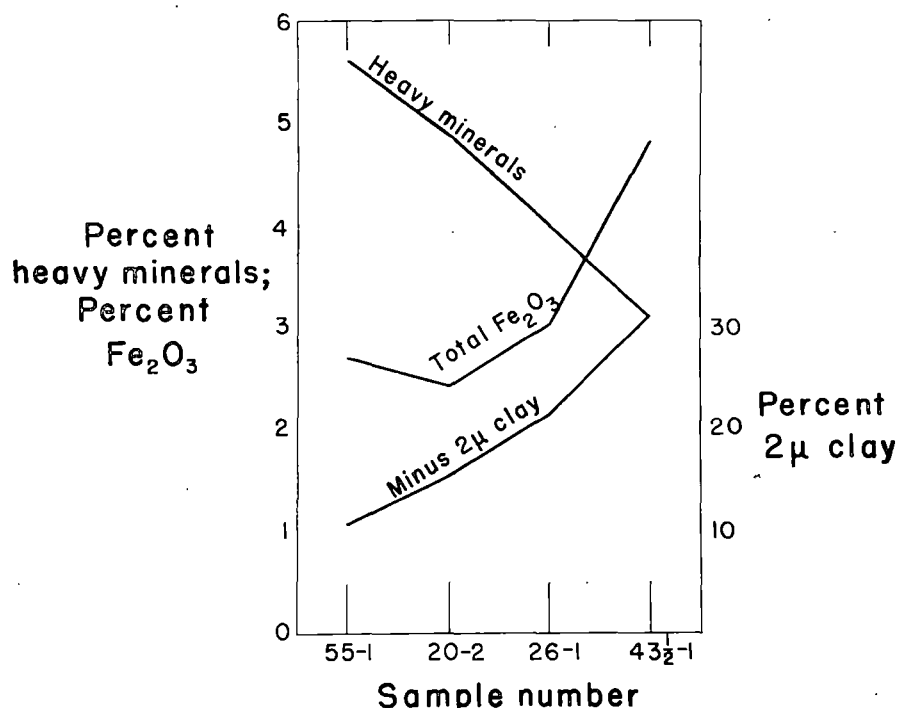


Fig. 14. Relationship of total iron content to clay content in the four loess samples. The contribution of the heavy minerals to the total iron content is noticeable only in samples low in clay (55-1 and 20-2).

acteristics theoretically depend on the more basic petrographic factors such as composition and particle sizes and shapes mentioned above. The tests now completed are listed in table VI, together with the test methods and the data obtained. The sample numbers are arranged in the table from left to right to show the effects of increasing clay contents. All of the data show trends related to clay contents which are readily explained by the resulting increased cohesion and ability to hold water. Also, according to the X-ray data discussed under *Petrography*, as the total clay content in the loess increases, the percentage of montmorillonite in the clay also increases, amplifying the effect of the increase in clay content. For example, according to X-ray analyses sample 55-1, with 10.5 percent minus 2-micron clay, is about 5 percent montmorillonite; while sample 43½-1, with 31.4 percent clay, contains about 30 percent montmorillonite.

The test for capillary rise gave some results which do not correlate directly with clay content. There is an increase in indicated capillary rise from sample 55-1 to sample 20-2, as expected with an increase in clay content and decrease in pore size. However, with successively higher clay contents the indicated rise is lower.

TABLE VI. BEHAVIOR CHARACTERISTICS OF THE FOUR LOESS SAMPLES

Behavior Characteristics		Sample Number				Test Method
		55-1	20-2	26-1	43½-1	
Liquid limit, percent		29.6	30.8	39.4	51.9	AASHO Method T89-49
Plastic limit, percent		27.3	24.6	26.9	18.5	AASHO Method T90-49
Plasticity index		2.3	6.2	12.5	33.4	AASHO Method T91-49
Shrinkage limit, percent		27.2	22.3	23.3	19.1	AASHO Method T92-42
Standard Proctor density test	Max. dry density lb./cu. ft.	110.0	108.4	107.0	104.3	AASHO Method T99-49
	Optimum moisture content, percent	17.8	18.0	17.7	19.1	
Modified Proctor density test	Max. dry density lb./cu. ft.		120.2	116.2	113.2	Same as above except specimens are compacted in five layers by a 10-lb. hammer dropping from a height of 18 in.
	Optimum moisture content, percent		13.9	15.7	17.6	
California Bearing Ratio of soil at standard Proctor density, percent	At optimum moisture	20.4	17.9	15.0	8.8	Essentially the same as the "Suggested Method of Test for California Bearing Ratio of Soils" submitted by Corps of Engineers, U. S. Army, to ASTM ¹⁶ except that specimens prepared are at maximum density and optimum moisture content determined by standard Proctor density tests.
	After 4-day soaking	15.1	8.6	4.5	1.5	
Capillary rise, in.		54	67	66	40	Essentially the same as the "Suggested Method of Test for Capillary Rise of Soil" submitted by Herman to ASTM ¹⁶ .
Engineering classification		A-4 (8)	A-4 (8)	A-6 (9)	A-7-6 (18)	AASHO Method M145-49

The capillary rise test is essentially a measurement of the maximum head of water a column of initially loose, wet soil will support before air breaks through. Loess samples low in clay (55-1 and 20-2) apparently became puddled, or structureless, when put into the tube and soaked. Therefore the finer the loess the smaller the pores, and the higher the head which could be supported. Samples higher in clay (26-1 and 43½-1) upon preliminary breaking up and sieving contained numerous granules or clusters of grains. These probably remained as granules throughout the test. The pores and air spaces between granules would be large, and less water head could be supported by such a sample. Higher clay contents would result in greater stability of the granules, due in part to lower permeability, and there would be a lower indicated capillary rise. The method of test used

therefore succeeds at least qualitatively, probably as a result of some non-scientific good luck. It might be more reliable to measure the more basic responses, capillary potential and capillary conductivity, but these are much more difficult to evaluate.

STABILIZATION

Soil Cement

Cement Requirements

Cement requirements for the four loess samples to meet Portland Cement Association criteria for soil cement were determined by standard methods (A.S.T.M. D558-44, D559-44, and D560-44)¹, (table VII), and the

TABLE VII. CEMENT REQUIREMENTS FOR THE FOUR LOESS SAMPLES TO MEET P.C.A. CRITERIA FOR SOIL CEMENT

Sample No.	BPR Soil group	P.C.A. criteria			Cement requirements to meet criteria, % by volume					
		Maximum soil cement loss, %	Maximum volume change, %	Maximum moisture absorption, %	Soil-cement loss		Volume change		Moisture absorption	
					Wet-dry	Freeze-thaw	Wet-dry	Freeze-thaw	Wet-dry	Freeze-thaw
55-1	A-4	10	2	Not more than that necessary to fill voids at molding	8.0	<u>9.8*</u>	8.5	8.4	8.0	8.0
20-2	A-4	10	2	"	8.0	<u>13.5</u>	10.5	12.1	10.0	11.0
26-1	A-6	7	2	"	14.0	<u>14.6</u>	14.2	<u>15.6</u>	14.0	14.0
43½-1	A-7-6	7	2	"	14.3	16.0	16.1	<u>17.0</u>	15.0	15.2

*Minimum cement contents which satisfy all criteria are underlined.

relationship between cement requirements and clay contents was found (figure 15).

Weathering of Soil Cement

Method. Compressive strengths of 2 in. by 2 in. diameter soil cement cylinders were measured after severe weathering by a procedure developed by the Civil Aeronautics Administration^{1, 23}. The specimens were first moist-cured for 7 days, then subjected to the following treatments:

1. Three days of capillary absorption in a moist cabinet.
2. Four days of total immersion in water.
3. Twelve cycles of alternate freezing at -10°F . for 8 hours and thawing by total immersion in water at room temperature for 16 hours.

4. Twelve cycles of alternate wetting by total immersion in water at room temperature for 8 hours and oven-drying at 160°F. for 16 hours.

5. Seven days total immersion.

The specimens were tested while wet.

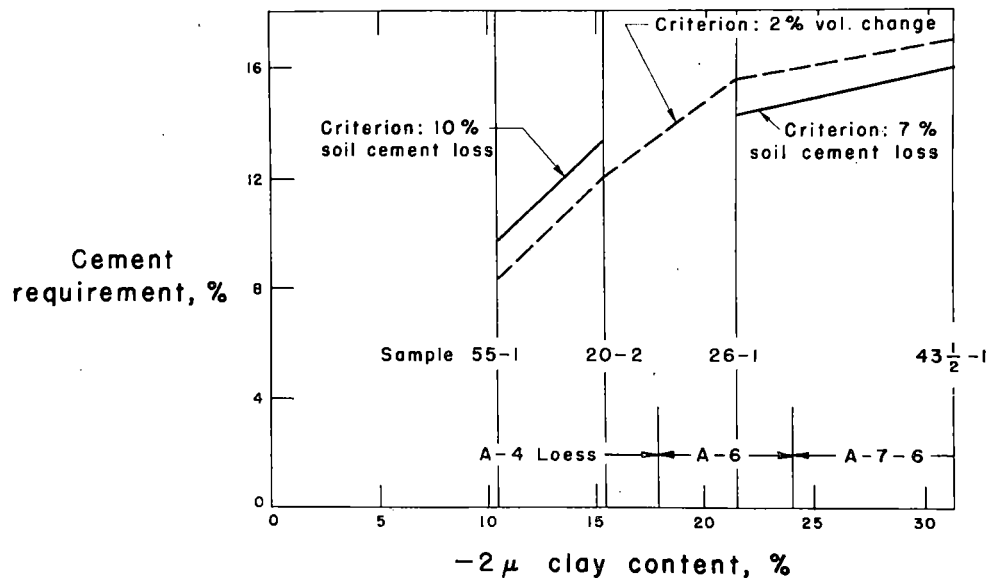


Fig. 15. Relationship between cement requirement and clay content of southwestern Iowa loess. Cement requirements meet P.C.A. criteria for soil cement.

Results. Compressive strengths of severely weathered 2 in. by 2 in. cylinders were compared with strengths of un-weathered air-dried cylinders (figure 16). Compressive strengths of both air-dried and severely

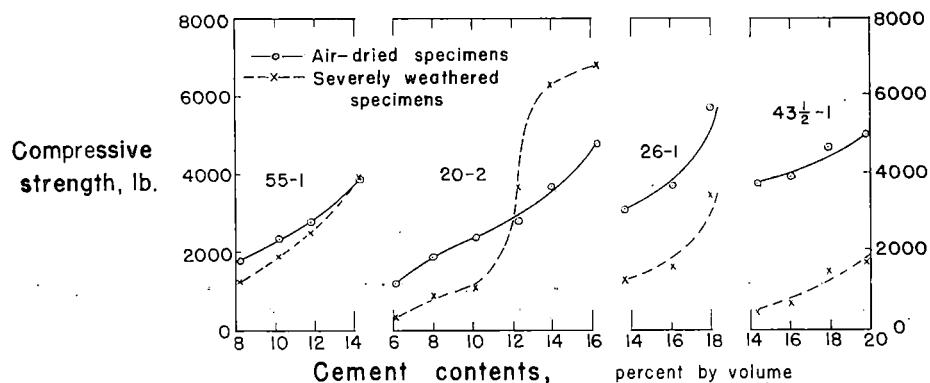


Fig. 16. Compressive strengths of air-dry and severely weathered 2" x 2" soil cement cylinders containing varying amounts of cement. Air-dried specimens were moist-cured 7 days, air-dried 38 days, dried 1 day at 160°F., and tested. Severely weathered specimens were tested immediately after removal from the water bath.

weathered specimens increased with increasing cement content. Not all specimens, however, lost strength as a result of severe weathering, and some showed a large gain. Since curves for the weathered specimens are on the basis of wet strength, and the other curves are on the basis of oven-dry strength, the gain is even greater than is apparent from the graph.

To determine if the weathering strength gain is due to a curing effect in the weathering treatment, specimens were air-dried for periods of up to 45 days. Cement contents used were those which meet P. C. A. minimum requirements. The strength gains with age and is greatest for sample 20-2 (figure 17). This agrees with other data, which indicate that only with

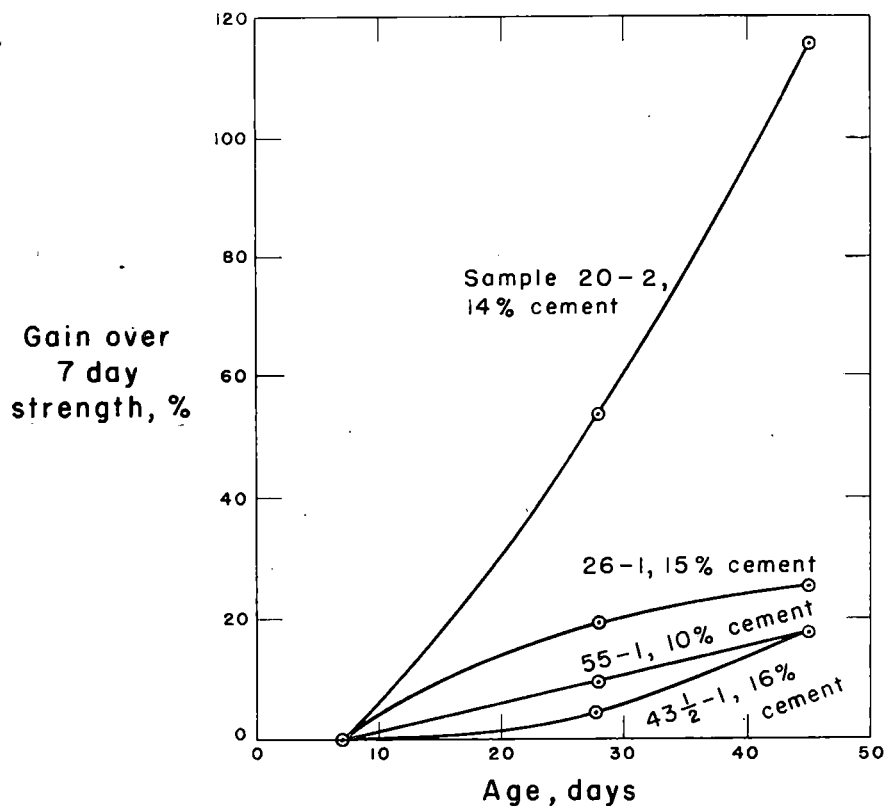


Fig. 17. Gain in compressive strength of 2" x 2" soil cement cylinders by ageing. The indicated age equals 7 days of moist curing plus various days of air-drying. Specimens were tested after drying 1 day at 160° F.

sample 20-2 was the cement content high enough to give considerable strength gain after severe weathering. The conclusion is that the effect of severe weathering may be completely cancelled by a simultaneous cure.

The strength gain is odd in that it is most pronounced in the sample second lowest in clay (20-2). The same behavior was shown by the sample lowest in clay (55-1), but a higher cement content was necessary. Petrographic studies showed nothing out of the ordinary in any of the samples—only the fairly continuous composition change between samples according to clay content. The possible importance of the weathering strength gain justifies further study to find reasons for the gain. Knowing these, it should be possible to determine if and how the gain may be encouraged with lower cement contents or with less susceptible loesses.

At present the reason for the gain can not be stated with certainty because in the loess several variables may be responsible. These variables will be pointed out and discussed, and have been used as a guide in the planning of testing programs now under way. Results of these tests should show if the possibilities pointed out in this paper are correct.

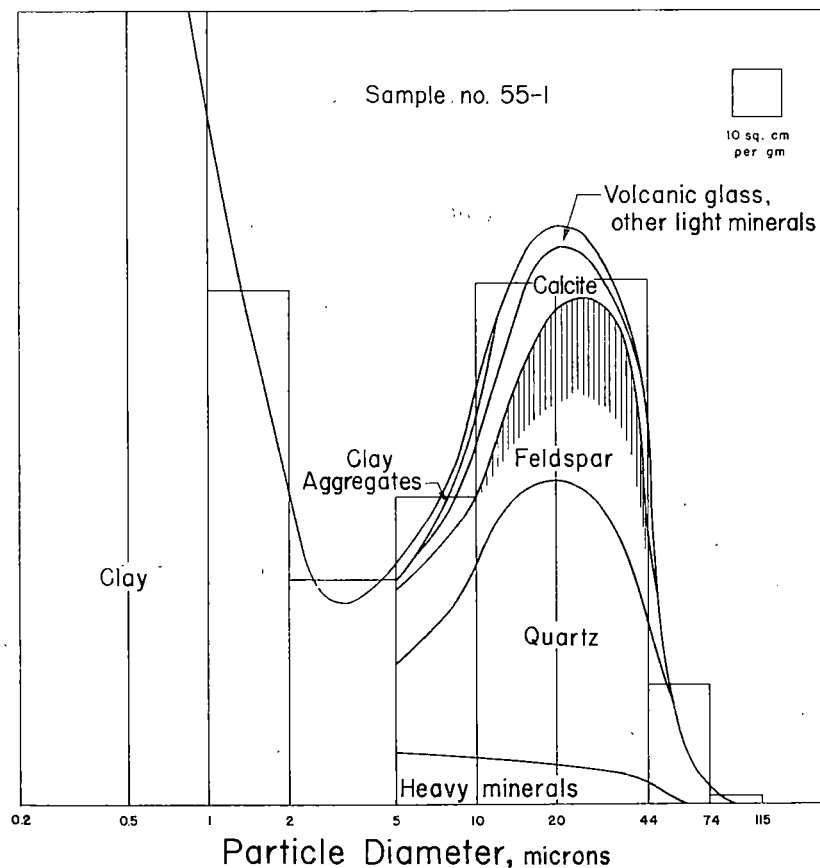


Fig. 18. Mineral surface area diagram for Sample 55-1. Areas in the diagram represent grain surface areas contributed by each mineral.

Discussion

Mineral Surface Areas

In applying petrographic data to stabilization problems, it was reasoned that fine material in a soil has a greater effect on chemical stabilization, including soil cement, than a like amount of coarse material with the same composition, since with most methods of stabilization the grain surfaces are to be coated. Therefore in this study mineral content was expressed on the basis of surface areas in addition to the usual weight or volume percentages. Histograms were modified to show surface areas of grains of various minerals in each size fraction (figures 18, 19, 20, 21). By comparison

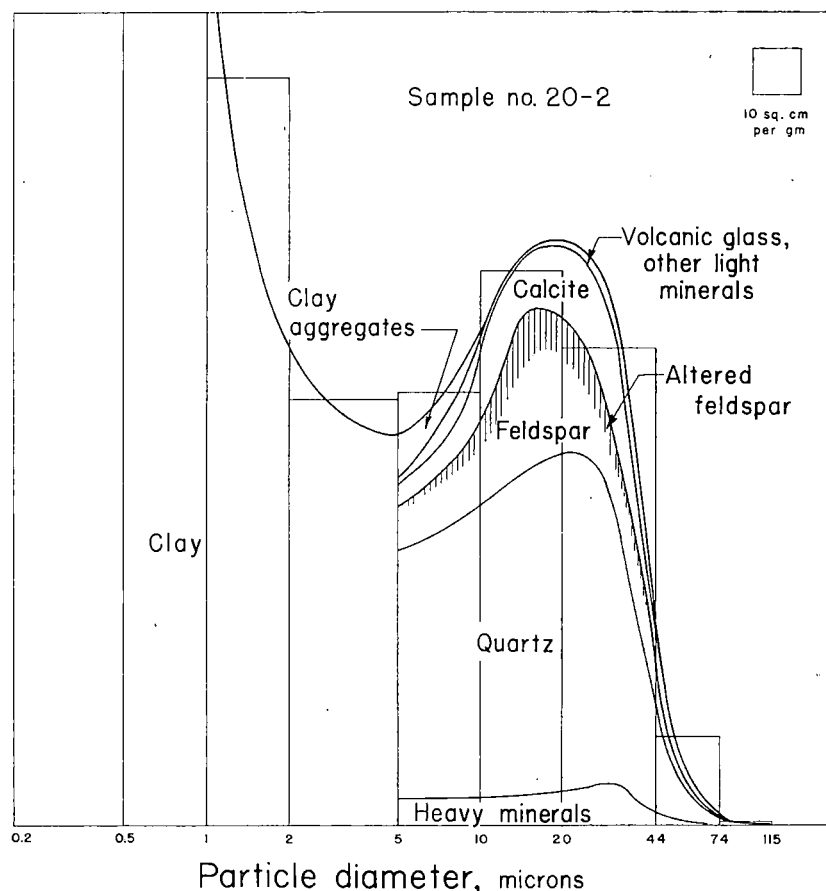


Fig. 19. Mineral surface area diagram for Sample 20-2. Areas in the diagram represent grain surface areas contributed by each mineral.

with the standard histograms showing volume percentages (figures 4, 5, 6, and 7), the new emphasis on the finer fractions may be noted. Since com-

position of each sample varies in various size fractions, it is necessary to calculate and add together surface areas of the various minerals in each size fraction and thus obtain the total area of each mineral in a sample. The areas may then be reduced to percentages (table VIII). A discussion of the surface area calculations and errors involved is given in Appendix C.

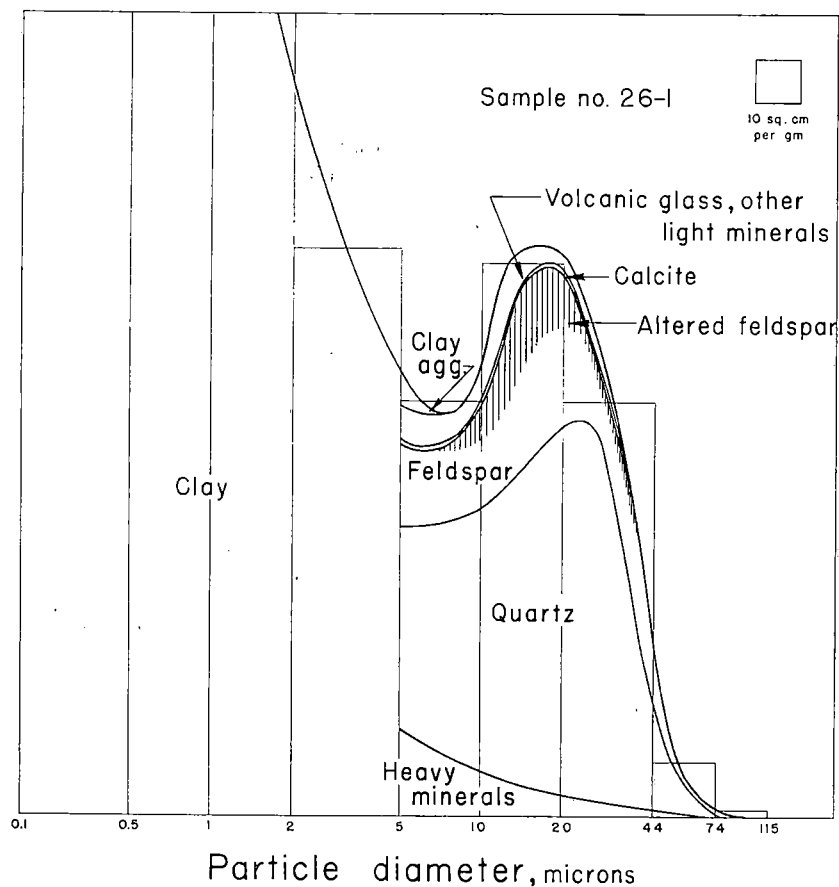


Fig. 20. Mineral surface area diagram for Sample 26-1. Areas in the diagram represent grain surface areas contributed by each mineral.

Application to Southwestern Iowa Loess

It may be noted in table VIII that the contribution of quartz to the surface area increases with increasing clay content. In the silt surface areas in the four loess samples an increase with increasing clay content may be noted (figure 22). This is due to decreasing particle size of the silt.

Sample 20-2, which behaved so uniquely in the C. A. A. weathering

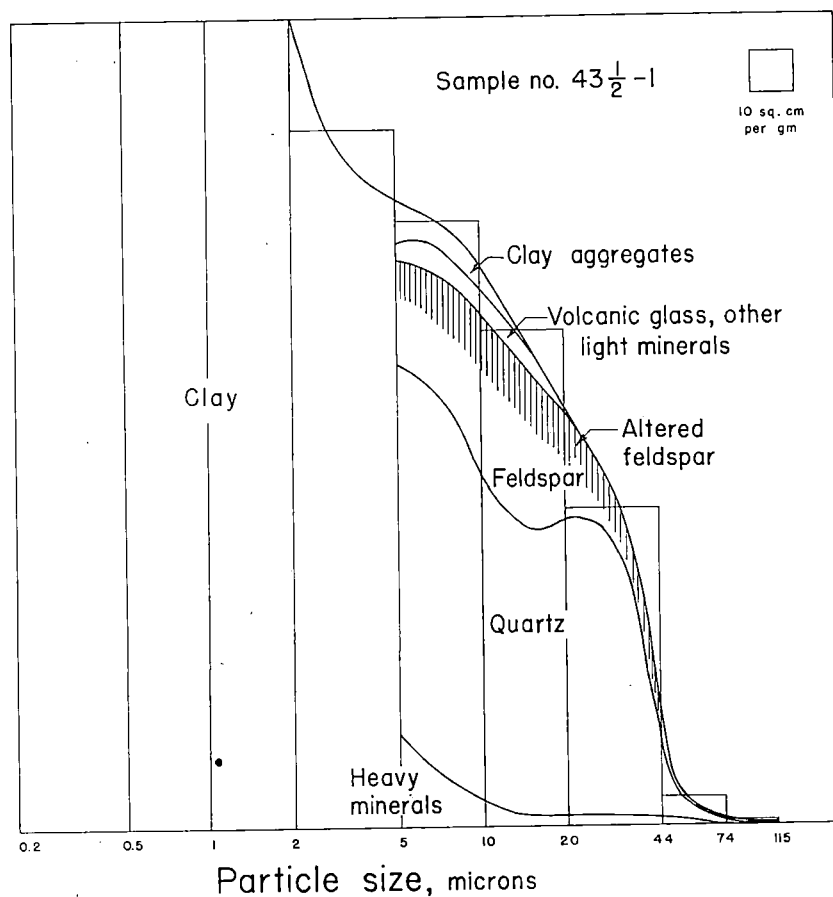


Fig. 21. Mineral surface area diagram for Sample 43½-1. Areas in the diagram represent grain surface contributed by each mineral.

TABLE VIII. MINERAL SURFACE AREAS IN THE PLUS 5 MICRON FRACTION OF EACH LOESS SAMPLE

(Values given are percentages of the total sand-silt surface area)

Sample No.	55-1	20-2	26-1	43½-1
Quartz	49.3	58.3	64.0	66.0
Feldspar	29.0	20.5	23.0	24.0
Calcite	9.7	12.8	1.2	0.8
Volcanic glass	2.5	1.4	1.1	0.4
Heavy minerals	8.3	6.3	7.6	6.3
Other minerals	1.2	0.8	2.8	2.5

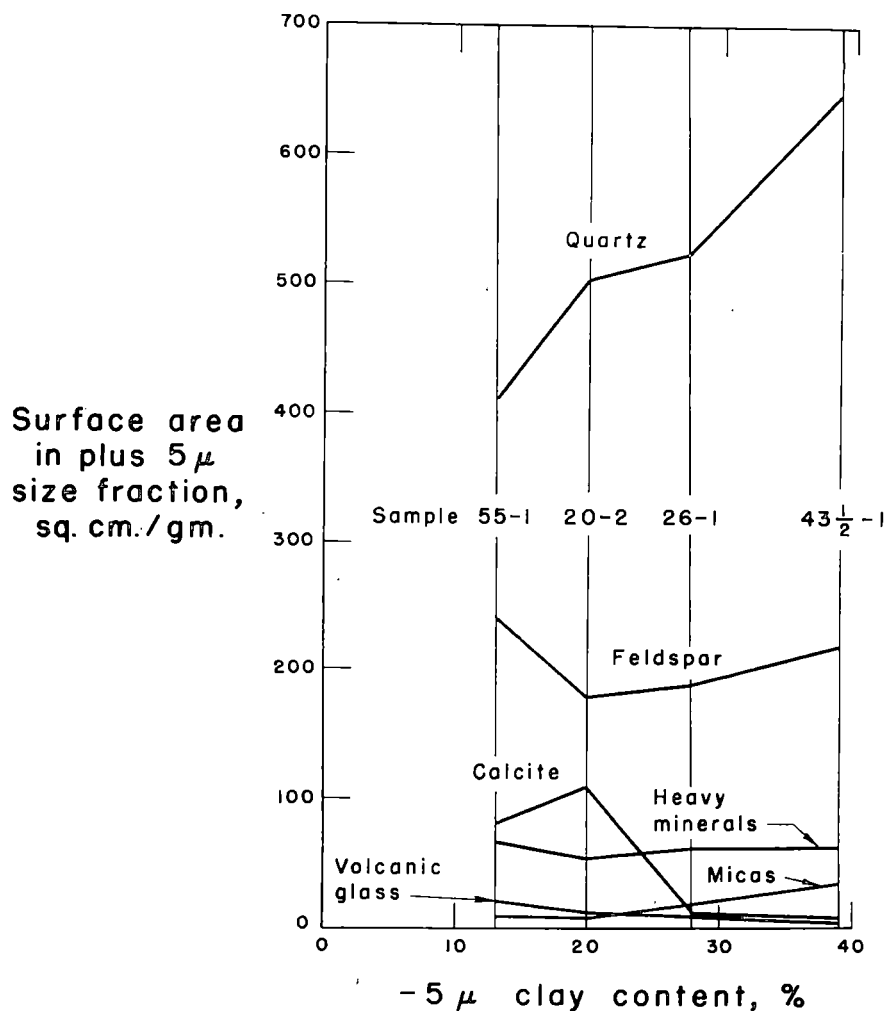


Fig. 22. Mineral surface areas in the plus 5 micron size fraction as related to the minus 5 micron clay content.

test, displays some major differences from the other samples: it has the highest calcite (CaCO_3) and lowest feldspar areas, and it has a rather high quartz area in relation to its clay content.

While it is possible that the variations in weathering strength gain for different loess samples are related to reactions which affect the setting of the cement paste, the strength of the cement bonds to the loess grains appears to be the major factor, especially since loess grains are mostly clay coated. One effect of high clay content is to reduce the effective non-clay surface areas available for cementing, and it is highly possible that the effective quartz surface area approaches an optimum in sample 20-2. This

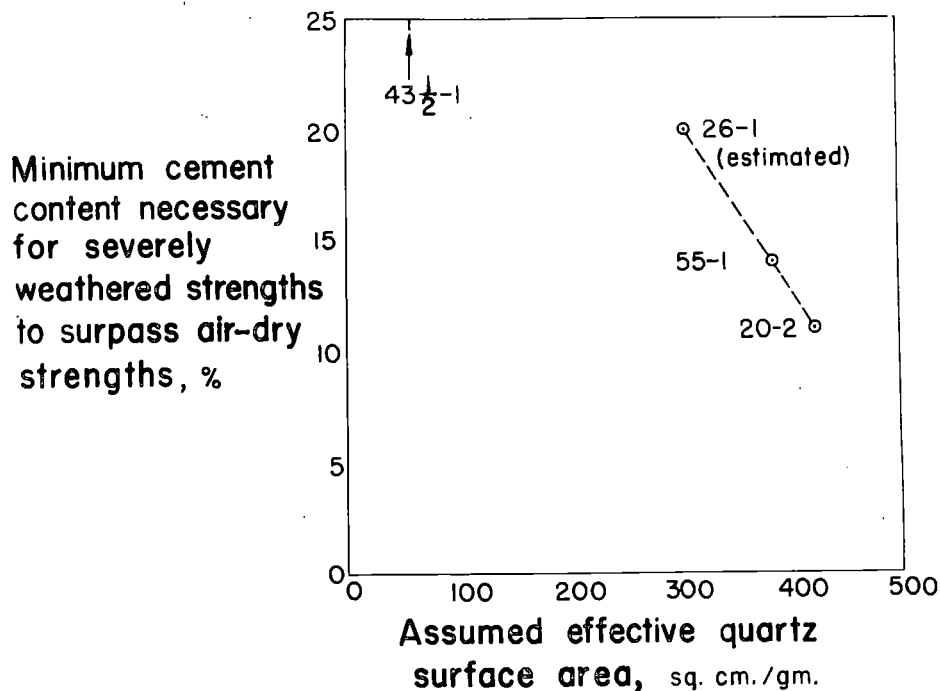


Fig. 23. Cement contents at which severely weathered strengths equal air-dry strengths (figure 16) as related to an effective surface area calculated for quartz.

is illustrated in figure 23, where a cube function of clay content has been subtracted from the quartz surface areas. Such a relationship has the scientific status of a guess, but it may point out the correct trend. Calcite is another major variable which will be investigated, perhaps by leaching some sample 20-2 loess and testing for a strength gain on curing. Testing to determine accurate reference curing curves is now under way.

Soil Cement With Treatments Or Admixtures

Monoionic Treatments

Loess sample 20-2 was treated to obtain a monoionic soil material²⁰. In the treatments used the loess is first treated with HCl and washed to obtain a hydrogen clay, and the various metallic hydroxides added either in solution or colloidal suspension and time allowed for the reaction to take place²⁴. The effects of these treatments on Portland cement stabilization of sample 20-2 are summarized in table IX. The most notable effect is that of iron. This may be due to replacement of the exchangeable cations by iron, or quite possibly by an excess of iron hydroxide either coating the loess grains and making a poor bond, or coating the cement clinker grains and retarding the set^{2, p. 479}.

TABLE IX. EFFECTS OF SOME MONOIONIC TREATMENTS
ON PORTLAND CEMENT STABILIZED LOESS

(Based on data from exploratory tests²⁰)

Cation Used in Treating Natural Soil	Effect of Treatment on Properties of Soil Cement Mixtures
Aluminum	Effect not obvious
Iron	Large decrease in strength
Potassium	Slight decrease in strength
Sodium	Slight decrease in strength

TABLE X. EFFECTS OF VARIOUS ADMIXTURES
ON PORTLAND CEMENT STABILIZED LOESS

(Based on data from exploratory tests²⁰)

Admixture* Added to Soil-Cement Mixture	Range of Admixture Tested, Percent†	Effect of Admixture on Soil-Cement Mixture
Calcium chloride	0.1 -6.0	Increase in rate of hardening
Aluminum chloride	0.2 -1.0	Effect not obvious
Ferric chloride	0.2 -1.0	Effect not obvious
Lime, hydrated	0.1 -2.0	Effect not obvious
Fly ash	0.2 -7.0	Effect not obvious
A calcium salt of vinyl acetate maleic acid polymer	0.02-0.05	Effect not obvious
Silicone A	0.05-0.25	Effect not obvious
Silicone B	0.1 -0.5	Effect not obvious
Sodium methyl siliconate	0.5 -2.5	Increase in immersed strength
Ethyl sodium silanolate	0.05-0.5	Effect not obvious
A fatty amine acetate	0.2 -3.0	Effect not obvious
Vinsol resin, pulverized	0.02-1.00	Increase in immersed strength
Paraffin	1	Effect not obvious
A commercial waterproofing agent	1 -4	Increase in immersed strength
Commercial admixture A	0.02-0.30	Effect not obvious
Commercial admixture B	0.01-0.15	Effect not obvious
Commercial admixture C	0.04-0.15	Effect not obvious
Commercial admixture D	0.04-0.60	Effect not obvious
Bentonite	0.2 -2.0	Effect not obvious

*Source and commercial name of admixtures are given in Appendix D.

†Percentage of admixtures tested are expressed as percent of
oven-dried weight of soil.

As has been pointed out^{11, p. 143}, the treatment to obtain a hydrogen clay
may result in partial decomposition of the clay mineral and movement of

aluminum ions to exchange positions. The aluminum then would remain at the exchange position through the subsequent hydroxide treatment, and a monoionic clay would not be obtained.

Admixtures

A number of additives to soil cement have been investigated²⁰. The effects of these additives on Portland cement mixtures with samples 20-2, 26-1, and 43 $\frac{1}{2}$ -1 are summarized in table X. Major changes were noted only with the addition of calcium chloride, which increased the rate of hardening, and with sodium methyl silicate (a silicone), powdered Vinsol resin, and an asphalt emulsion sold commercially as a waterproofing agent for concrete. The silicone, the resin, and the asphalt emulsion all resulted in higher strengths of immersed specimens, probably due to waterproofing. The waterproofing effect may be considerably aided by the adsorptive power of clay mineral coatings for organic complexes.

The effects of calcium chloride are illustrated by data on samples 20-2 and 43 $\frac{1}{2}$ -1. The addition of 2 percent calcium chloride to sample 43 $\frac{1}{2}$ -1 increased 7 day and 45 day strengths about proportionally, indicating an overall strength gain instead of an acceleration effect (figure 24). The same

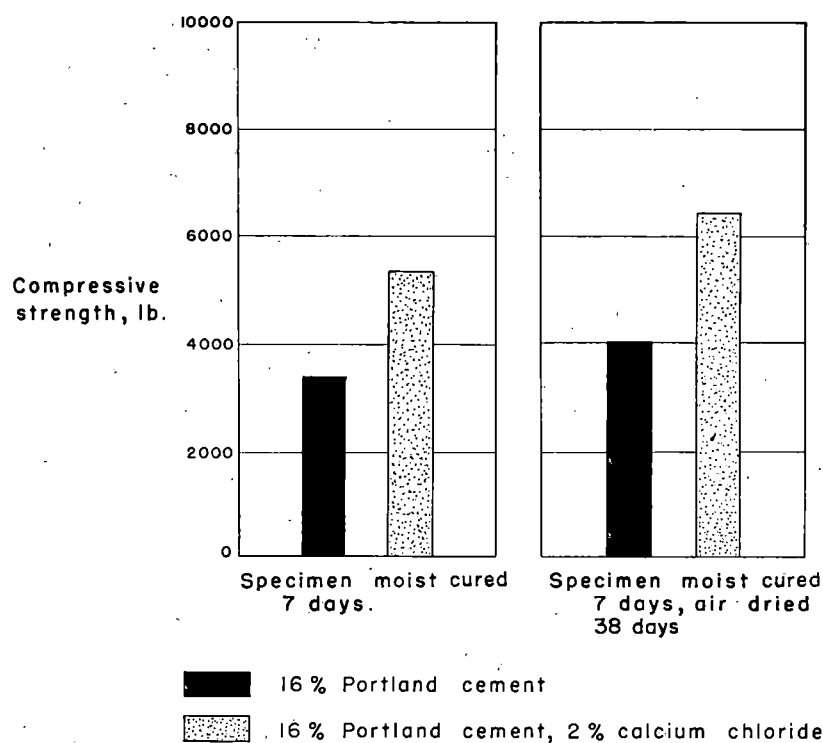


Fig. 24. Effect of calcium chloride on the compressive strength of soil cement with Sample 43 $\frac{1}{2}$ -1. Specimens were dried 1 day at 160° F. before testing.

proportional increase is also shown in specimens subjected to the C. A. A. weathering test. Whether the strength gain is due to an improvement in the character of the clay minerals, of the cement gel, or of the bonding action is not yet known.

The addition of calcium chloride to sample 20-2 with Portland cement results in somewhat different trends than those mentioned above (figure 25). The addition of 4 percent calcium chloride increased 7 day strengths,

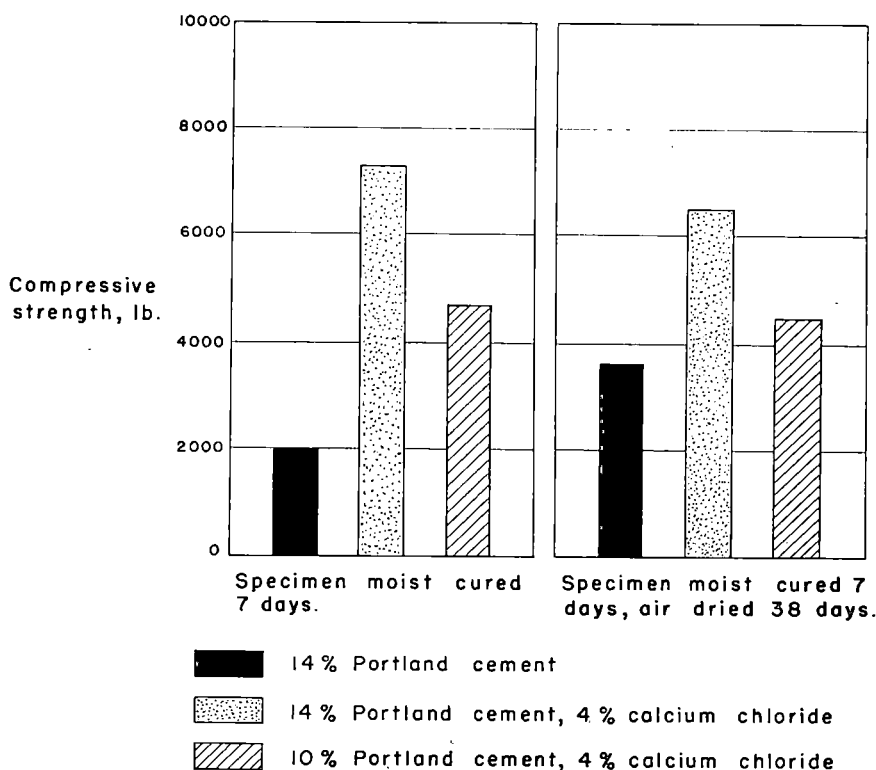


Fig. 25. Effect of calcium chloride on the compressive strength of soil cement with Sample 20-2. Specimens were dried 1 day at 160° F. before testing.

but there was no further gain in strength with 38 days of additional curing. This would indicate that the major effect with sample 20-2 is one of acceleration. Specimens without calcium chloride and subjected to the C. A. A. weathering test showed a high strength gain, as has been discussed. With calcium chloride added, the specimens gave much lower strengths after severe weathering, indicating that the acceleration in cure may have been at the expense of the high strength eventually obtained with cement alone. The effects of additions of smaller amounts of calcium chloride are now being studied in this relation.

SUMMARY STATEMENT

Petrographic information on a soil material is essential for an understanding of stabilization involving cementing reactions, and methods have been presented by which petrography may be applied to stabilization problems. Possible explanations for various questions involving stabilization of loess with Portland cement alone and with admixtures have been suggested. The validity of these interpretations will be determined by experimental work in progress. When reactions between cement and the ingredients of soil are thus more fully understood, further work to find improvements may be carried on more efficiently. In other words, the approach might be labeled Big Think and Little Do. This can grow into Big Do. It is preferable to the ever-popular Big Do and Little Think, which is equivalent to the proverbial shot-in-the-dark and may result in a large expenditure of ammunition for benefits obtained.

REFERENCES CITED

1. Ally, S. R. W. Stabilization of southwestern Iowa loess with Portland cement. M. S. thesis, Iowa State University Library. 1953.
2. Bogue, R. H. The chemistry of Portland cement. Reinhold Pub. Co., New York. 1947.
3. Chu, T. Y., Davidson, D. T., and Sheeler, J. B. Mathematical analysis of a layer extraction method for separating clay-size material from soils. Second National Clay Minerals Conference. 1953.
4. Clare, K. E. Some chemical tests for engineering purposes. Roads and Road Construction. 27:43-49, 83-86. February/March, 1949.
5. Davidson, D. T. and Chu, T. Y. Dispersion of loess for mechanical analysis. Hwy. Res. Bd. Proc. 30:500-510. 1951.
6. Davidson, D. T., Handy, R. L. and Chu, T. Y. Depth studies in the Wisconsin loess in southwestern Iowa: I. Particle size and in-place density. Iowa Acad. Sci. Proc. 60:333-353. 1953.
7. Davidson, D. T., and Handy, R. L. Property variations in the Peorian loess of southwestern Iowa. Iowa Acad. Sci. Proc. 59:248-265. 1952.
8. Davidson, D. T., and Handy, R. L. Studies of the clay fraction of southwestern Iowa loess. Proceedings, Second National Clay Minerals Conference. 1953.
9. Davidson, D. T., and Sheeler, J. B. Cation exchange capacity of the clay fraction of loess in southwestern Iowa. Iowa Acad. Sci. Proc. 60:354-361. 1953.
10. Davidson, D. T., and Sheeler, J. B. Cation exchange capacity of loess and its relation to engineering properties. A.S.T.M. Spec. Tech. Pub. 142. 1952.
11. Grim, R. E. Clay mineralogy. McGraw-Hill Book Co., Inc., New York. 1953.
12. Groves, A. W. Silicate analysis. Second Ed. George Allen & Unwin, Ltd., London. 1951.
13. Handy, R. L. Petrography of selected southwestern Iowa loess samples. M. S. thesis. Iowa State University Library. 1953.
14. Handy, R. L., and Davidson, D. T. A pipette method to supplement the hydrometer test for particle-size determination in soils. Hwy. Res. Bd. Proc. 32:548-555. 1953.
15. Jeffries, C. D. A rapid method for the removal of free iron oxides in soil prior to petrographic analysis. Soil Sci. Soc. Am. Proc. 11:211-212. 1946.
16. Jeffries, C. D., and Jackson, M. L. Mineralogical analysis of soils. Soil Sci. Soc. Am. Proc. 68:57-73. 1949.
17. Krumbein, W. C. Measurement and geological significance of sedimentary particles. Jour. Sed. Pet. 11:64-72. 1941.
18. Krumbein, W. C., and Pettijohn, F. J. Manual of sedimentary petrography. Appleton-Century-Crofts, Inc., New York. 1938.
19. Mielenze, R. C., and King, M. E. Identification of clay minerals by staining tests. A.S.T.M. Proc. 51:1213-1233. 1951.

20. Nicholls, R. L. Preliminary investigations for the chemical stabilization of loess in southwestern Iowa. M. S. thesis. Iowa State University Library. 1952.
21. Procedures for testing soils, A.S.T.M., Philadelphia, Pa. 1950.
22. Rittenhouse, Gordon. A visual method of estimating two dimensional sphericity. Jour. Sed. Pet. 13:79-81. 1943.
23. A summary report on soil stabilization by the use of chemical admixtures. Tech. Development Note No. 136, Civil Aeronautics Administration. February, 1951.
24. Winterkorn, H. F., Gibbs, H. J., and Rollie, G. Surface chemical factors of importance in the hardening of soils by means of Portland cement. Hwy. Res. Bd. Proc. 22:385-414. 1942.

APPENDIX A

A RISING CURRENT ELUTRIATOR FOR FRACTIONATING SILTS

Separation of soils and sediments into size fractions prior to analysis is an important petrographic technique resulting in more accurate and more complete mineral composition data. Coarse materials are usually separated by sieving, and materials too fine to sieve are separated by sedimentation procedures.

A rising current elutriator is a separation device consisting of a vertical tube in which the sample is placed. Through this tube a fluid, usually

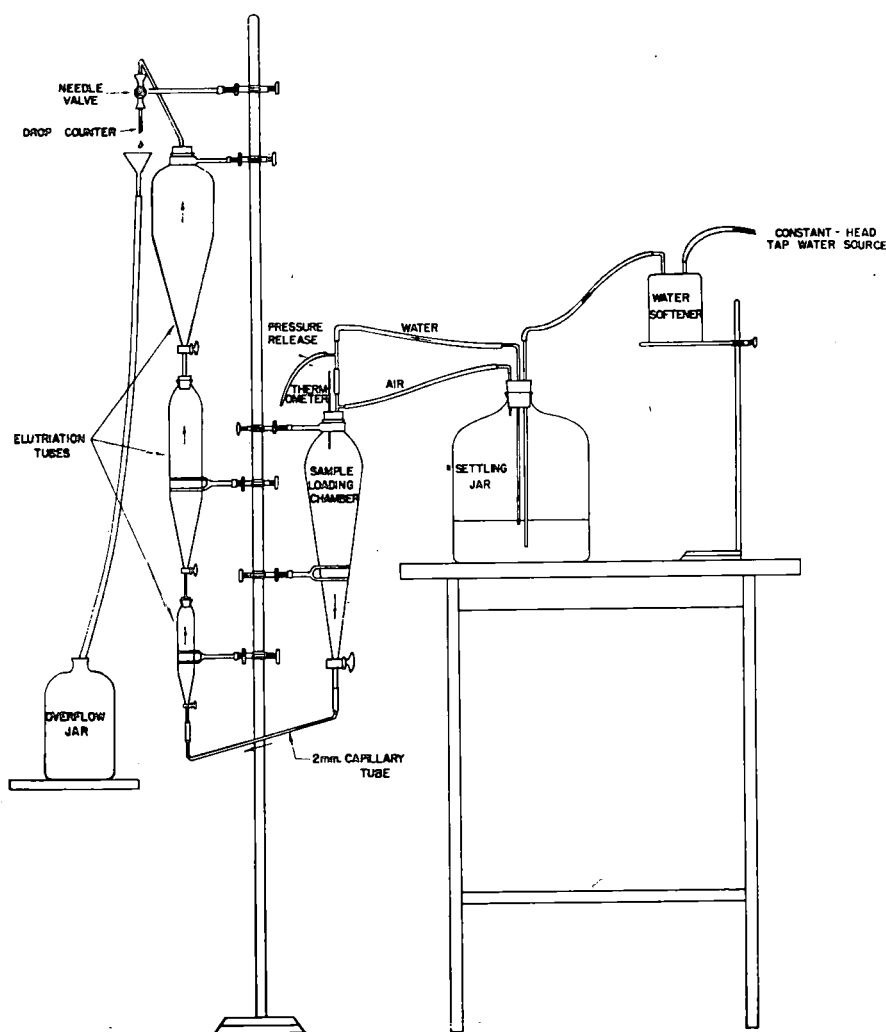


Fig. 26. Rising-current elutriator for the size separation of fine materials.

water or air, flows upward at a measured velocity. Particles in the sample which are large enough and heavy enough to settle faster than the velocity of the upcurrent remain in the elutriator; smaller particles are washed or blown out at the top. The particle size at which the separation occurs may be varied by regulating the velocity and viscosity of the suspending medium.

A multiple tube water elutriator (figure 26) was used to fractionate silts in the loess. Successive tubes have double diameters, decreasing the water velocity by a factor of $\frac{1}{4}$. According to Stokes' Law, the settling velocity of a sphere is proportional to the square of its radius, $V = Kr^2$. Since at the critical particle size in each tube the up-current equals the settling velocity, decreasing the settling velocity by $\frac{1}{4}$ means

$$V' = \frac{V}{4} = Kr'^2 = \frac{Kr^2}{4}$$

$$r' = \frac{r}{2}.$$

That is, doubling the tube diameter results in halving the particle size at which separation will occur. In the present study three tubes were used, and the water velocity was regulated so that material coarser than 20 microns diameter was retained in the first tube. This automatically resulted in material 10 to 20 microns being retained in the second tube, material 5 to 10 microns being retained in the third tube, and minus 5 micron clay being carried out in the overflow.

Dispersion of Sample

Because of flocculation, water elutriation has been reported as unsuccessful for separating materials finer than 10 microns, and various stirring devices have been built into the elutriation tubes¹⁸. In the present study the loess was first dispersed as for a mechanical analysis, using a high-speed stirrer and sodium metaphosphate. Because the first tube in the elutriator is small in diameter and would have to be disproportionately long to accommodate the dispersed sample, a sample loading chamber (figure 26) was added to the apparatus.

The use of tap water in elutriation caused flocculation to occur in the third chamber and prevented complete separation of the minus 5 micron clay. Distilled water also caused flocculation, probably because of dilution of the dispersing agent. The use of tap water with a small zeolite water softener was successful, the sodium in the softened water being sufficient to maintain dispersion. A settling jar was then necessary to prevent solid impurities from the water softener from entering the sample.

Apparatus

The three elutriation tubes are made from glass stock 15/16 in., 17/8 in., and 33/4 in. inside diameter and were patterned somewhat after those of Kopecky and Anderson. The length of the taper on the tubes is about twice the inside diameter to prevent turbulence and to promote an even cross-section velocity. The tubes are arranged in a vertical column to prevent plugging of the connecting tubing. The sample charger is a 1000 ml. separatory funnel. It is connected to the first chamber by an inclined tube of capillary size to hold the velocity high and discourage plugging.

A 5 or 6 ft. constant pressure head measured above the overflow is sufficient for elutriation. Flow is regulated with a needle valve located in the overflow line to maintain pressure throughout the system and to hold air in the water in solution. Otherwise air bubbles may restrict flow and cause a stoppage.

Procedure

(1). About 20 grams of soil free from material larger than 1 mm. diameter and preferably all passing the No. 325 sieve is dispersed as for a mechanical analysis, using a proportional amount of dispersing agent. If necessary, the material may be first sieved to prevent clogging the elutriator.

(2). The water softener is recharged if necessary, the elutriator is filled with water, and the system is checked for leaks or pressure failure.

(3). The input head is blocked with a hose clamp and the sample is flushed into the loading chamber. Pressure is again applied and hose clamps are so arranged that air from the settling bottle is forced into the sample loading chamber. When the chamber is almost empty, the hose clamps are changed to force water from the settling bottle into the loading chamber. The loading chamber now serves only as a passage for water into the elutriator.

(4). The temperature of the inflowing water is noted on the thermometer mounted in the sample loading chamber. The rate of flow, which is regulated by means of the needle valve, may be calibrated in number of drops in a given time.

(5). Elutriation is continued until the overflow runs clear. The three stopcocks on the three elutriation tubes are then turned off simultaneously. The pressure is turned off, and the tubes are disassembled to remove the samples.

(6). A complete elutriation requires about 16 hours and about 3 gallons of overflow. If at any time a pressure failure occurs, the separated materials in the tubes will settle into the lower tubes, and a longer time will be required. The process may be interrupted at any time by turning the three tube stopcocks, but it is usually more satisfactory to continue the process without interruption to avoid difficulties in restarting. The elutriator tends

to slow down rather than to speed up after adjustment, due to air coming out of solution at the needle valve. The velocity must therefore be checked occasionally.

Calculations

The velocity of flow may be calculated as in the following example from Stokes' Law:

$$V = \frac{2 (d_1 - d_2) g r^2}{9\eta} = \frac{L}{T},$$

where V is the settling velocity of the particles in cm. per sec., g is the acceleration of gravity, r is the particle radius in cm., η is the viscosity of the settling medium, d_1 and d_2 are the specific gravities of the particles and the medium, respectively, and L is the settling distance in time T . In elutriation the time is measured with a stopwatch for a given volume of overflow. If the overflow is 10 ml., the settling distance in the large tube with radius $r_e = 17/8$ in. is

$$L = \frac{10}{r_e^2 r} = \frac{10}{71.1} = 0.1408 \text{ cm.}$$

The time T for a 10 ml. overflow is then

$$T = \frac{9\eta (0.1408)}{2 (d_1 - d_2) 980 r^2}$$

If the separation in the large tube is to be made at 5 microns, the particle radius $r = 0.0025$ mm. At 68°F. , $\eta = 0.01009$ poise. If $d_1 = 2.65$,

$$T = \frac{9(0.01009) (0.1408)}{2(2.65 - 1.00) (980) (0.0025)^2}$$

$T = 63.1$ seconds for 10 ml. overflow.

For convenience in timing, the rate of overflow may be converted to time necessary for 5 drops, and suitable graphs relating overflow to temperature may be prepared.

APPENDIX B

CENTRIFUGAL SEPARATION OF HEAVY FROM LIGHT MINERALS

The separation of minerals into light and heavy fractions by immersing grains in bromoform (sp. gr. 2.87) is a useful technique in mineral identification. Bromoform separation of silts presents special problems, such as the necessity for speeding separations by centrifuging.

Apparatus

Inner and outer centrifuge tubes (figure 27) are used¹⁸. The outer tube is a 40 ml. double thickness Pyrex centrifuge tube to withstand breakage.

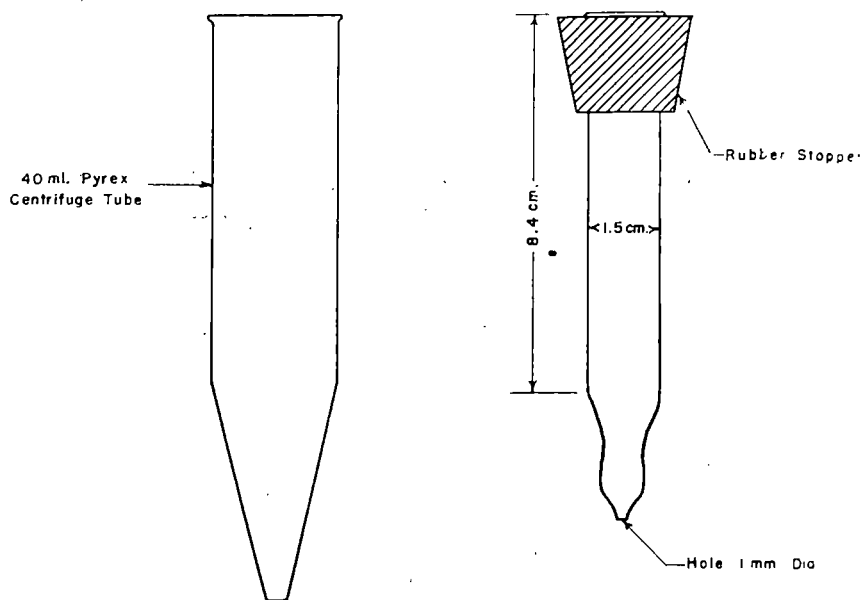


Fig. 27. Centrifuge tube apparatus for the bromoform separation of silts into heavy and light minerals.

Procedure

- (1). A thoroughly oven-dried (110°C.) size fraction obtained by sieving or elutriation is quartered to obtain a representative sample. The fine fractions require further prolonged drying at 150-200°C. to prevent flocculation in the bromoform.
- (2). The outer centrifuge tube is filled about half full with bromoform and the inner tube is inserted. About 1 gram of sample is placed in the inner tube and stirred. The assembled apparatus is stoppered and centrifuged

at speeds not to exceed 1500 R.P.M. to lessen breakage. After sufficient centrifuging heavy minerals will have settled through the hole in the inner tube into the outer tube. The sample in the inner tube is stirred and centrifuged three times, or until no more heavy particles settle out.

(3). The mineral separates are rinsed into filtering crucibles with bromoform, and the bromoform is filtered off with the aid of a partial vacuum. The bromoform is saved for future separations.

(4). Grains in the filtering crucibles are rinsed with acetone, oven-dried at 110°C., brushed out, and weighed on an analytic balance. Heavy mineral percentages may then be calculated. As the separation is seldom perfect, the percentage may be corrected after microscopic examination of the light fraction.

APPENDIX C

DERIVATION OF AN EXPRESSION FOR THE SURFACE AREA OF GRAINS IN A SIZE FRACTION

Surface areas of various minerals in a soil material may be calculated to aid in interpretation of stabilization data, since this emphasizes the finer, more active material.

The basic assumption used in the derivation of Stokes' Law is also applied here with the particles assumed to be spherical. Abrading is not common in silt-size material; so sphericities do not vary greatly between size fractions or between samples, and the error is more or less constant.

The mass of a spherical particle is

$$M = \frac{\pi D^3 P}{6}$$

where D is its diameter in cm. and P its density in grams per cubic cm.

In one gram there would be $\frac{6}{\pi D^3 P}$ particles, each with a surface area of πD^2 . The surface area in one gram of particles is therefore

$$\begin{aligned} S &= \frac{6}{\pi D^3 P} \times \pi D^2 \\ &= \frac{6}{DP} \end{aligned}$$

If D is in microns, S will be square meters per gram.

In standard histograms the distribution of particles may be considered to be uniform throughout the size range of each bar (figure 28). The narrower the bars of the histogram, the more accurate the assumption in

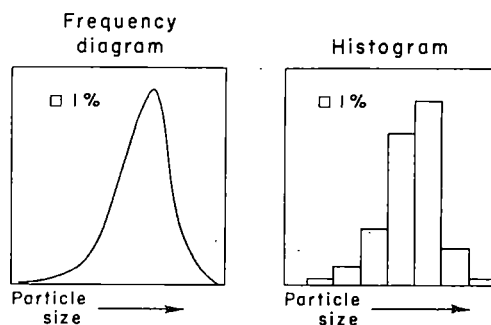


Fig. 28. Assumption of a uniform distribution of grain sizes in a size fraction. At left is the true representation of a soil; the graph at the right shows the assumption made.

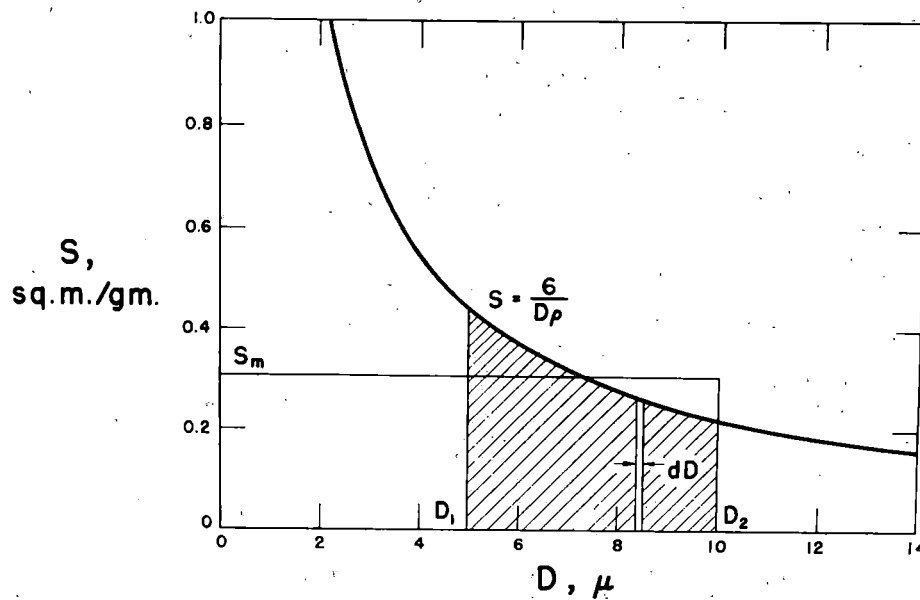


Fig. 29. Relationship between specific surface and particle diameter, showing integration to obtain the mean surface area of a size fraction.

the relationship between specific surface and particle diameter (figure 29), if D_1 and D_2 are the limits of the size fraction, S_m is the mean specific surface of the fraction.

$$\begin{aligned}
 S_m (D_2 - D_1) &= \int_{D_1}^{D_2} S dD \\
 &= -\frac{6}{P} \int_{D_1}^{D_2} \frac{1}{D} dD \\
 &= -\frac{6}{P} \ln \frac{D_2}{D_1} \cdot \\
 S_m &= \frac{6 \ln D_2/D_1}{P (D_2 - D_1)}.
 \end{aligned}$$

Example: With a 10 to 20 micron size fraction of loess with a density of 2.70 gm. per cu. cm.

$$\begin{aligned}
 \text{Sm} &= \frac{6 \ln \left(\frac{20}{10} \right)}{2.70 (20 - 10)} \\
 &= 0.154 \text{ sq. m./gm.} \\
 &= 1540 \text{ sq. cm./gm.}
 \end{aligned}$$

The surface areas thus calculated for the various size fractions separated in the loess are given in table XI.

TABLE XI. SURFACE AREAS OF GRAINS
AS RELATED TO PARTICLE SIZE

Particle Diameter, microns	Surface Area in 1 gm. of Material, sq meters
0.2- 0.5	67,900
0.5- 1.0	30,800
1.0- 2.0	15,400
2.0- 5.0	6,790
5.0- 10	3,080
10 - 20	1,540
20 - 44	714
44 - 74	384
74 -115	237

APPENDIX D

SOURCE OF ADMIXTURES USED IN PORTLAND CEMENT STABILIZATION OF LOESS

MATERIAL	SOURCE
Portland cement, Type I	Hawkeye Portland Cement Company, Des Moines, Iowa
Lime, hydrated	Linwood Stone Products Company, Buffalo, Iowa
Fly ash	Louisville Gas and Electric Co., Louisville, Kentucky
A calcium salt of vinyl acetatemaleic acid polymer, known as "Krilium No. 6 (CRD-186)"	Monsanto Chemical Company, St. Louis, Missouri
Silicone A, known as Linde silicone SF99	Linde Air Products Company, Tonawanda Laboratory, Tonawanda, N. Y.
Silicone B, known as Linde silicone C25	Same as above
Sodium methyl silicate	General Electric Company, Chemical Division, Waterford, N. Y.
A fatty amine acetate, known as "Armac T"	Armour and Company Chicago, Illinois
Vinsol resin, pulverized	Hercules Powder Company Wilmington, Delaware
A commercial waterproofing agent known as "Hydropel"	American Bitumuls Company, San Francisco, California
Commercial admixture A, known as "Pozzolith No. 2"	Master Builders Company, Cleveland, Ohio
Commercial admixture B, known as "Pozzolith No. 8"	Same as above
Commercial admixture C, known as "Stearolith"	Same as above
Commercial admixture D, known as "Omicron Motarproofing"	Same as above

**PORTLAND CEMENT CONTENTS REQUIRED
TO STABILIZE EASTERN AND WESTERN IOWA LOESS**

by

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D. T. Davidson, Professor, Civil Engineering

(Iowa Academy Science Proceedings 64:276-313. 1957.)

INTRODUCTION

Because of present and predicted future shortages of road-building aggregates, the Iowa State Highway Commission has for several years sponsored research programs to find satisfactory substitutes. A major part of these investigations have been to investigate possible chemical treatments to waterproof and harden natural soils. In areas of most critical aggregate shortages in Iowa, loess, a fine silt soil, is often the major surficial material. During successive project years different loess soil areas in Iowa have been studied, first to determine petrographic and engineering properties of the soils and second to examine systematically various soil stabilizers with the object of selecting the most promising through laboratory tests. Considering the extremely wide variety of chemicals tried and the various stabilization principles involved, it is significant that one treatment has remained consistently near the head of the list — that of stabilizing soil by adding water and Portland cement. Compacted mixtures of cement and water and soil, termed *soil cement*, have been used as road base materials since about 1935, and many roads using this material have long and successful service records. The growth in nation-wide utilization of soil cement has been most rapid in recent years; but perhaps as important is that the advent of soil cement marked the beginning of modern chemical soil stabilization, and field and laboratory procedures adopted for soil cement have strongly influenced the investigations of other chemicals.

Much of the popularity of soil cement is related to the development of satisfactory design criteria by the Portland Cement Association, or P.C.A. Early in the history of soil cement, exhaustive laboratory and field tests were carried out to find correlations necessary to predict field performance. Eventually on the basis of laboratory tests it was possible to estimate the minimum amount of cement required to stabilize a given soil. These laboratory procedures, somewhat modified, are still in use. They define cement requirements mainly on the basis of strength and resistance to artificial

weathering (wet-dry and freeze-thaw). For sandy soils, a short cut procedure utilizing particle size and compressive strength data has been evolved⁹. However, for most soils the cement requirements must still be determined through rather lengthy laboratory tests. Recent efforts by the P.C.A. have been aimed at obtaining satisfactory correlations with other data, and especially with agricultural soil series¹⁰. In connection with this a cooperative program was inaugurated with the Iowa Engineering Experiment Station whereby samples representing Iowa soil series were sent to the P.C.A. for an evaluation of minimum cement requirements. It was believed that with careful field sampling, correlations between cement requirements and other field and laboratory data might be worked out.

OBJECTIVES

Objectives of this program were to find the cement contents required to stabilize various horizons of major upland soil series in typical loess areas in Iowa (figure 1).

Preliminary work in those areas has shown that engineering properties are closely related to clay content³, and clay content varies systematically

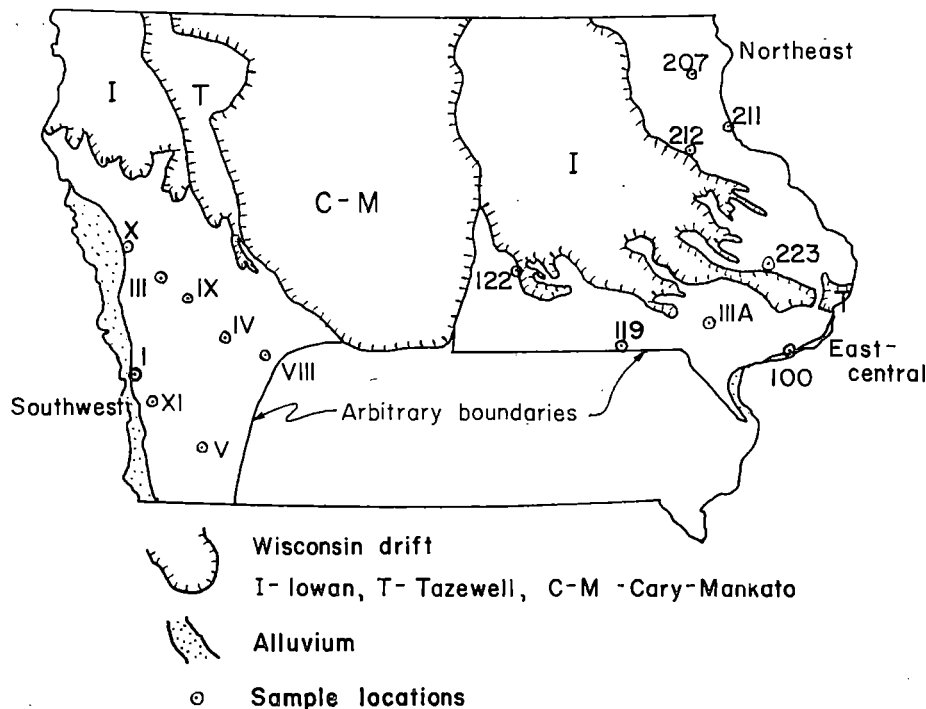


Fig. 1. Sample locations in the three loess study areas in Iowa.

over each area^{2, 11, 12}. Soil classification experts have long recognized this, and each soil series in a loess area must include a range in soils. It was therefore decided in this investigation to include a minimum of two sample locations for each soil series; and the locations were selected to show variability within a soil series. It was believed that in this way the results would show if the soil series is a reliable criterion for estimating cement requirement. Should these correlations fail, an alternative was provided; that of possible correlations to such basic property data as mineral composition or grain size.

METHODS AND APPROACH

Sampling

Experience in investigating loess sections has shown that soil horizons can be identified satisfactorily in the field by color, structure, and texture or "feel"; and this procedure was followed. Sampling sections were chosen from old sample sites whenever possible so that data already available would show if these sections were representative. Since it was desired to sample completely through the sections whenever possible, and the thickness of the loess in some areas, particularly in western Iowa, severely limited site selection, quarry faces and deep roadcuts were used.

At each location the samples were made composite with respect to depth; that is, a location might provide a composite A horizon sample, a composite B horizon sample, and so on through to the base of the loess. Since in some soil series certain horizons are missing, the samples were identified by code numbers beginning with the uppermost sample. For example, an A horizon sample may be numbered 100-1c. The "c" appended to the number indicates a composite sample and automatically instructs the laboratory men to empty the bags and mix the sample. The first number is a location number which for convenience has been coded as follow: 0 to 99 and I to XX, southwest Iowa; 100 to 199, east-central Iowa; 200 to 299, northeast Iowa. Other areas now under investigation are coded in a like manner, but samples from those areas are not included in the present investigations.

Studies of loess profiles have shown that weathering is in the following sequence: oxidation, leaching of carbonates, and soil profile development¹⁶. Therefore the normal sequence in a loess profile, beginning at the bottom, is (a) unoxidized, calcareous loess, gray in color, usually ending at the water table;

- (b) oxidized, calcareous loess, tan in color;
- (c) oxidized, leached loess, in appearance similar to that below, but not reactive to dilute hydrochloric acid;
- (d) B horizon, higher in clay and often with a blocky structure;
- (e) A horizon or topsoil, lower in clay than the B horizon and usually darker

in color due to the presence of humic organic matter.

Soil series, western Iowa

Soil series in western Iowa follow a pattern related to the thickness of the loess. Near the Missouri River where the loess is thickest the rate of erosion has exceeded that of soil profile development, and oxidized, calcareous loess is exposed at the surface of the ground. This is designated in the Hamburg soil series. The Hamburg is transitional to the Ida Series, which is very similar and is represented in the same area. The Ida has a faint, calcareous A horizon, typically about a foot thick and differentiated by its brown color. The Monona soil series is the next transition and represents increased weathering over the Ida; in Monona soils leaching has occurred, and there is the development of a faint B horizon, usually extending to the depth of the leaching. Farther east the leaching and horizon differentiation are more prominent, and the Marshall Series¹⁷ is characteristic of much of southwest Iowa (figure 2).

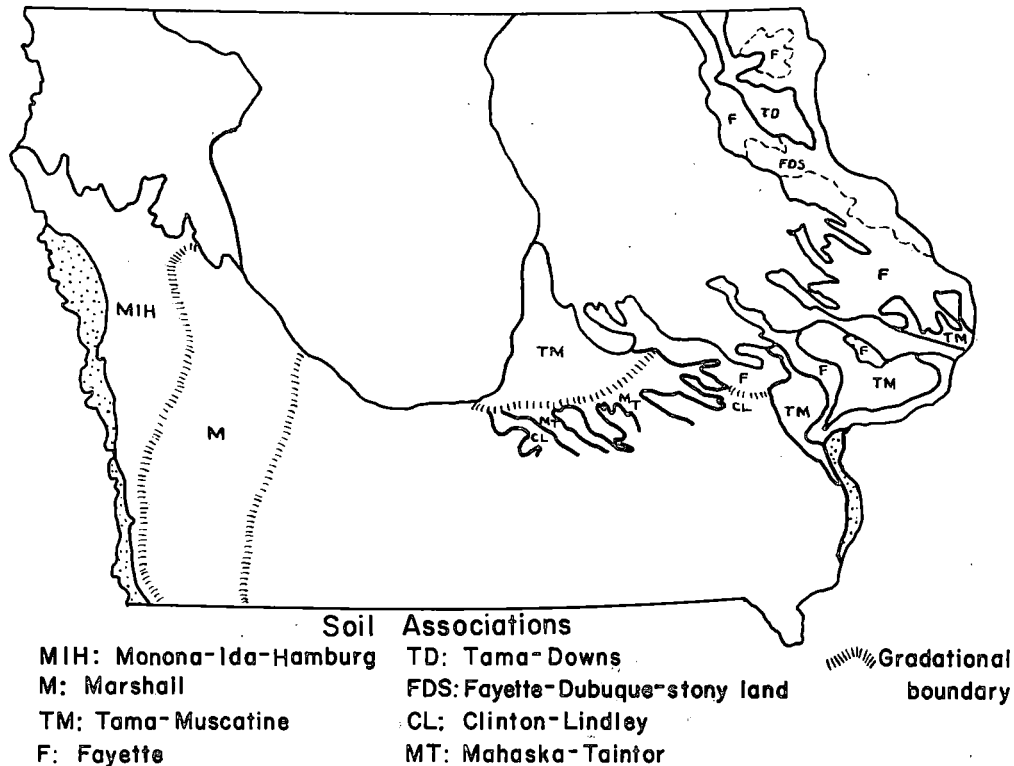


Fig. 2. Major upland soil series in the loess area studied⁸.

Because the C horizon is more important in soil engineering than in agronomy, special attention is warranted. The C horizon is usually defined

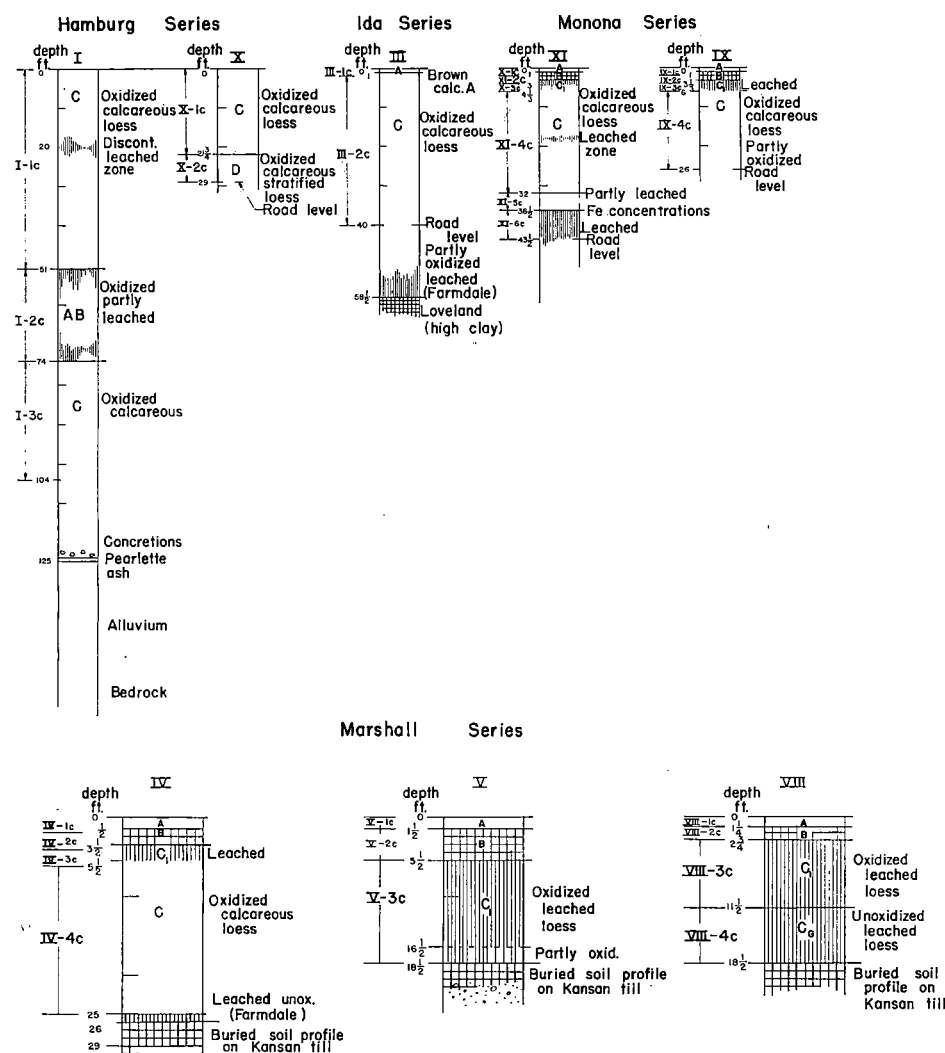


Fig. 3. Sample sections in western Iowa.

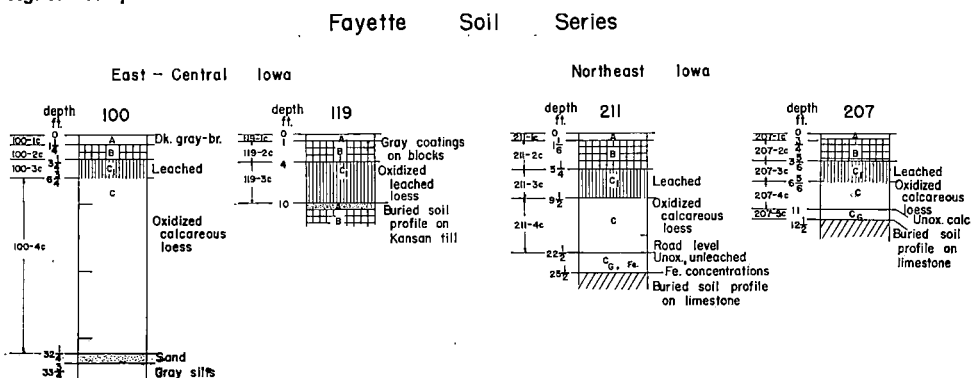


Fig. 4. Sample sections in the Fayette series in eastern Iowa.

as the parent material for the soil profile, and subdivisions of the C based on oxidation or leaching are not of direct concern to the agronomist. Therefore the horizon nomenclature is not well adapted to the changes in the C. The leached C, transitional to the B, is usually labeled the C_1 horizon. Exact location of the boundary between the B and C horizons is largely a matter of judgment. Herein the oxidized, calcareous C horizon is called simply the C horizon, and the unoxidized portion is referred to the C_G , although objections may be raised because G normally implies deoxidation or gleying. However, a true gley horizon usually carries only the letter G, so there is no direct conflict or overlapping of terms. Concretion zones and iron-enriched zones where present are designated C_{Ca} and C_{Fe} , respectively, as is standard practice. Underlying materials which differ from the soil profile parent material are designated by D.

Locations of sample sections are indicated in figure 1 and are listed in the Appendix in table I. Diagrammatic section descriptions of all sections are shown in figures 3, 4, and 5.

Soil series, eastern Iowa

In east-central and northeast Iowa higher annual precipitation has contributed to somewhat greater soil profile development. In western Iowa a-zonal soils such as the Hamburg are fairly common; in eastern Iowa zonal soils dominate the landscape. The Tama series is the approximate eastern Iowa equivalent of the Marshall, both being prairie soils or brunizems. They are believed to differ primarily in having formed on loess which came from different sources. Less well drained prairie soils in eastern Iowa come under the Muscatine series, and frequently the water table is immediately below the B horizon. The Fayette series is a grey-brown podzolic soil with

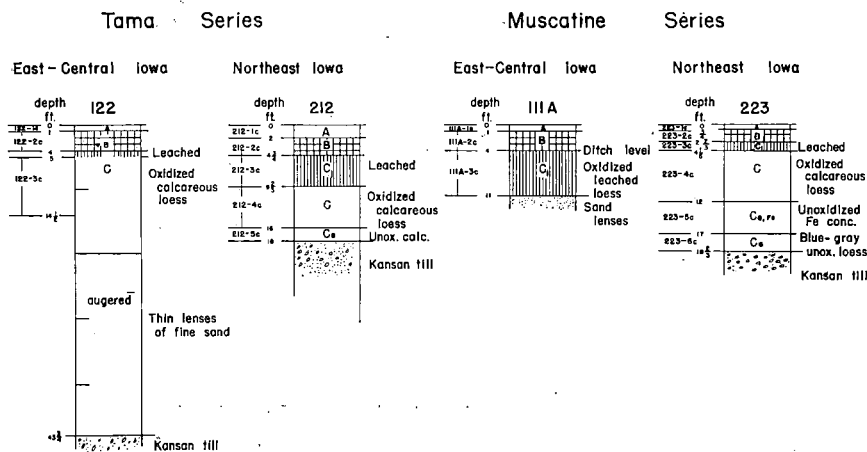


Fig. 5. Sample sections in the Tama and Muscatine series in eastern Iowa.

a profile somewhat similar to that in western Iowa, although coarsest loess is much less extensive⁸. Loess with high dolomite content is found

locally in Iowa along the Mississippi River, and on the basis of mineral composition correlates more closely with the loess in Illinois than with that in Iowa¹². In recognition of this, a dolomitic loess section (No. 100) is one of those selected in this study. Because of the widespread zonal soil development, the characteristics of eastern Iowa soil profiles are not so dependent on parent material as in western Iowa; and series names are used in northeast and east-central Iowa, although mineral analyses in these areas also show distinct differences believed related to sources of the loessal parent material⁸.

Laboratory Testing Procedure

Testing of soils to determine cement requirements, while a relatively simple procedure, requires extensive laboratory facilities for a large testing program. Up until now this has proved a main deterrent to large scale testing of Iowa soils to determine cement requirement. It is through the cooperation of the Soil Cement Bureau, Portland Cement Association, that the testing here reported became possible. In the cooperative study, sampling and testing to determine basic soil properties were carried out by the Iowa Engineering Experiment Station in Ames. Samples were then shipped to the Portland Cement Association for soil cement tests in their Skokie, Illinois, laboratory; and finally there was a mutual interchange of data.

Basic Property tests

Sufficient laboratory tests were run on all samples for classification according to the American Association of State Highway Officials system (A.A.S.H.O.) Designation: M145-49 (10). These tests and methods are as follows:

Mechanical analysis. Hydrometer method using an air-jet stirrer and with sodium metaphosphate as the dispersing agent¹.

Plasticity index. Method of test according to A.S.T.M. Designation: D427-39¹⁴.

Other tests were run where they were needed. These tests will be discussed where introduced.

Soil cement tests

The procedures in testing to determine cement requirements are as follows¹⁸:

Moisture-density test. This is a standardized procedure to determine the optimum water content in a compacted soil or soil cement mixture. Samples are mixed and molded with varying moisture content but with the same compactive effort. At first water acts as a lubricant and increases the density obtained, but above a certain moisture content so many voids become

filled with water that further compaction is impossible. Addition of water above this point gives a decrease in dry density. The water content which gives the highest density is defined as the optimum moisture content and is expressed as a percentage of the oven dry weight of the soil. This moisture content must be determined for each soil and is used in the soil cement

TABLE I. LOCATIONS OF SAMPLING SECTIONS

Sample No.	Area*	County	Location Township	Section	Remarks	Other Designations
I	SW	Pott.	T76N, R44W	35, NW Cor.	Active quarry	Crescent City Sec.
X	SW	Monona	T84N, R44W	20, NE Cor.	S roadcut	
III	SW	Monona	T82N, R42W	14, SE $\frac{1}{4}$ SW $\frac{1}{4}$	N roadcut	Soldier Sec.; Loc. 24
XI	SW	Pott.	T74N, R43W	11, NW $\frac{1}{4}$	S roadcut	
IX	SW	Shelby	T81N, R40W	18, NW $\frac{1}{4}$ NW $\frac{1}{4}$	N roadcut	
IV	SW	Shelby	T79N, R38W	16, SE $\frac{1}{4}$ SW $\frac{1}{4}$	N roadcut	Harlan Sec.
V	SW	Montgomery	T71N, R38W	17, SE $\frac{1}{4}$ SW $\frac{1}{4}$	Gravel pit	Red Oak Sec.
VIII	SW	Audubon	T78N, R35W	34, NW $\frac{1}{4}$	E roadcut	
100	E-C	Scott	T77N, R2E	13, N $\frac{1}{2}$ SW $\frac{1}{4}$	Active quarry	Buffalo Sec.
119	E-C	Iowa	T78N, R10W	31, NE $\frac{1}{4}$ NW $\frac{1}{4}$	S roadcut	N. English Sec.
211	NE	Clayton	T92N, R2W	16, SE Cor.	S roadcut	
207	NE	Allamakee	T97N, R5W	23, NE $\frac{1}{4}$ SE $\frac{1}{4}$	N roadcut	
122	E-C	Marshall	T83N, R17W	3, NE $\frac{1}{4}$ SE $\frac{1}{4}$	Abandoned quarry	Quarry Sec.
212	NE	Clayton	T91N, R5W	27, SE $\frac{1}{4}$ SW $\frac{1}{4}$	NE roadcut	
111A	E-C	Muscatine	T78N, R3W	8, SE $\frac{1}{4}$	N roadcut	
223	NE	Clinton	T83N, R1E	26, NE $\frac{1}{4}$ NE $\frac{1}{4}$	SW roadcut	

* SW, southwest Iowa; E-C, east-central Iowa; NE, northeast Iowa.

tests. The test is designed to correlate with field construction practice, and the densities obtained in the laboratory often form a basis for specifications in the field.

Wet-dry test. An artificial weathering procedure has been outlined to test the durability of soil cement mixtures. After 7 days moist curing, soil cement specimens are alternately immersed in water, dried, and brushed with a coarse wire brush to remove loose material. After 12 cycles the specimens are weighed to determine soil cement loss.

Freeze-thaw test. A second artificial weathering procedure involves alternate freezing and thawing of 7 day cured soil cement specimens. During thawing, specimens are placed on wet felt pads so that they may absorb water. After 12 cycles of freezing, thawing, and brushing, the specimens are weighed to determine soil cement loss. Standard 4 inch diameter, 4.6 inch high specimens are used in both wet-dry and freeze-thaw tests.

Compressive strength test. Compressive strengths of soil cement specimens are determined after moist curing 2, 7 and 28 days, to determine rate of hardening. Usually a soil cement mixture with a 7 day compressive strength of 300 psi or more will pass the wet-dry and freeze-thaw tests. Compressive strength specimens are soaked in water prior to testing. Specimens 2 inches in diameter and 2 inches high were used for this study.

Criteria for soil cement construction. The above soil cement tests are run with a number of cement contents for each soil. The minimum cement content for construction must then satisfy wet-dry, freeze-thaw, and compressive strength requirements: During the wet-dry and freeze-thaw tests the soil cement loss should not exceed 10 percent for an A-4 soil or 7 percent for A-6 and A-7 soils. Compressive strengths should increase both with age and with increasing cement contents; if strengths do not increase, this indicates a poorly reacting soil and is a danger signal.

RESULTS

Property Tests

Results from mechanical analyses are related to the soil cement test data (Tables II, III). The mechanical analyses confirmed previous field identifications of soil series and profile horizons¹⁹.

Plasticity index results (tables IV, V) show that the plasticity index, or PI, is related to clay content (figure 6). Plasticity indices for B and C horizon samples show approximately the same relation to clay content, but A horizon samples tend to have a slightly lower PI, probably because of the flocculating influence of humic organic matter. In figure 6, for which

TABLE II. PARTICLE SIZE DATA FOR WESTERN IOWA SAMPLES

Soil Series	Horizon	Sample No.	% sand (2-0.074 mm)	% silt (0.074- 0.005 mm)	% clay		0.001 mm	U.S.D.A. textural classi- fication
Hamburg	C	I-1c	3.2	80.3	16.5	14.3	13.3	silt loam
	AB*	-2c	6.2	70.9	22.9	19.9	18.2	silt loam
	C	-3c	8.2	78.2	13.7	12.2	11.4	silt loam
Hamburg	C	X-1c	0.9	80.6	18.5	15.6	14.0	silt loam
	D	-2c	0.7	83.3	16.0	12.8	11.0	silt loam
Ida	A	III-1c†	0.0	67.7	32.3	27.0	24.5	silt loam
	C	-2c	0.5	75.0	24.5	20.0	18.0	silt loam
Monona	A	XI-1c†	0.1	82.5	17.4	25.2	13.7	silt loam
	B	-2c	0.4	68.7	30.9	24.4	21.6	silt loam
	C ₁	-3c	0.4	73.2	26.4	22.0	21.0	silt loam
	C	-4c	0.6	74.8	24.7	18.2	18.0	silt loam
	C _{Fe}	-5c	0.3	73.3	21.4	16.8	15.9	silt loam
	C ₁	-6c	0.2	79.2	20.6	16.6	15.6	silt loam
Monona	A	IX-1c†	0.7	65.7	33.6	28.3	26.2	si. cl. lo.
	B	-2c†	0.5	68.3	31.2	25.9	22.6	silt loam
	C ₁	-3c	0.5	70.1	29.4	23.8	20.9	silt loam
	C	-4c	0.7	74.3	25.0	19.4	17.5	silt loam
Marshall	A ₃	IV-1c†	0.8	59.3	39.9	34.0	30.0	si. cl. lo.
	B	-2c†	0.4	65.2	34.4	28.4	25.5	si. cl. lo.
	C ₁	-3c	0.3	68.2	31.5	25.4	22.0	silt loam
	C	-4c	0.4	72.6	27.0	22.5	19.8	silt loam
Marshall	A	V-1c†	0.5	64.7	34.8	28.4	24.9	silt loam
	B	-2c†	0.3	60.4	39.3	33.0	30.4	si. cl. lo.
	C ₁	-3c	0.4	66.6	33.0	26.9	23.9	silt loam
Marshall	A	VIII-1c†	0.4	58.3	41.3	34.3	29.9	si. cl. lo.
	B	-2c†	0.4	54.8	44.8	37.6	33.2	si. cl. lo.
	C ₁	-3c	0.4	63.6	36.0	29.3	26.0	silt loam
	C _G	-4c	0.8	66.6	32.6	26.2	23.0	silt loam

* Buried (fossil) profile

† Treated with 30 percent H₂O₂ to prevent flocculation during grain size analysis

TABLE III. PARTICLE SIZE DATA FOR EASTERN IOWA SAMPLES

Area and soil series	Horizon	Sample No.	% sand (2-0.074 mm)	% silt (0.074- 0.005 mm)	0.005 mm	% clay 0.002 mm	0.001 mm	U.S.D.A. textural classi- fication
E-C Iowa Fayette	A	100-1c*	2.1	62.6	35.4	27.8	23.0	si. cl. lo.
	B	-2c	0.1	60.9	39.0	32.7	29.0	si. cl. lo.
	C ₁	-3c	1.0	78.2	20.8	17.5	15.1	silt loam
	C	-4c	8.3	79.4	12.3	10.0	8.3	silt
E-C Iowa Fayette	A	119-1c*	1.2	64.8	34.0	26.0	21.0	silt loam
	B	-2c	0.7	56.6	42.7	32.6	25.6	si. cl. lo.
	C ₁	-3c	3.4	62.9	34.7	31.1	30.6	si. cl. lo.
NE Iowa Fayette	A	211-1c*	2.0	77.8	20.1	13.8	10.3	silt loam
	B	-2c	0.8	65.2	34.0	25.5	19.8	silt loam
	C ₁	-3c	0.5	67.8	31.7	23.4	17.8	silt loam
	C	-4c	0.7	78.2	21.1	14.6	10.4	silt loam
NE Iowa Fayette	A	207-1c	1.7	75.1	23.1	17.0	14.1	silt loam
	B	-2c	0.4	68.9	30.7	26.0	24.5	silt loam
	C ₁	-3c	0.5	64.3	35.2	30.1	28.3	si. cl. lo.
	C	-4c	0.4	76.7	22.9	18.3	17.2	silt loam

TABLE III. CONTINUED

	C _G	-5c	0.3	77.5	22.2	16.9	16.8	silt loam
E-C Iowa	A	122-1c	2.3	71.5	26.2	21.8	20.0	silt loam
Tama	B	-2c	2.4	68.6	29.0	25.5	24.5	silt loam
	C	-3c	5.0	77.6	17.4	15.8	15.4	silt loam
NE Iowa	A	212-1c	3.4	71.6	25.0	17.7	12.9	silt loam
Tama	B	-2c	2.3	74.9	32.2	28.8	28.3	si. cl. lo.
	C ₁	-3c	3.1	71.4	25.5	22.1	21.3	silt loam
	C	-4c	1.2	66.6	22.8	19.8	19.4	silt loam
	C _G	-5c	2.4	74.5	23.1	15.2	9.3	silt loam
E-C Iowa	A	111A-1c	3.3	64.7	32.0	26.0	24.4	silt loam
Muscatine	B	-2c	2.1	57.6	39.3	32.8	30.0	si. cl. lo.
	C ₁	-3c	0.8	69.4	29.8	24.4	23.8	silt loam
NE Iowa	A	223-1c	0.8	67.6	31.6	26.2	23.2	silt loam
Muscatine	B	-2c	0.7	63.9	35.4	33.2	32.6	si. cl. lo.
	C ₁	-3c	0.3	69.0	30.7	28.1	27.3	si. cl. lo.
	C	-4c	0.8	78.6	20.6	18.7	18.2	silt loam
	C _{G Fe}	-5c	0.9	78.1	21.0	19.3	19.0	silt loam
	C _G	-6c	1.4	76.3	22.3	18.8	18.3	silt loam

*Treated with 30 percent H₂O₂ to prevent flocculation during grain size analysis.

TABLE IV. ENGINEERING CLASSIFICATION OF WESTERN IOWA SAMPLES

Soil Series	Horizon	Sample No.	Liquid limit, %	Plasticity Plastic limit, %	Plasticity Index	AASHTO soil class
Hamburg	C	I-1c	30.3	25.1	5.2	A-4(8)
	AB	-2c	31.8	22.4	9.4	A-4(8)
	C	-3c	27.3	24.7	2.6	A-4(8)
Hamburg	C	X-1c	32.1	22.0	10.1	A-4(8)
	D	-2c	33.9	23.0	10.9	A-6(8)
Ida	A	III-1c	46.1	25.9	20.2	A-7-6(13)
	C	-2c	35.2	23.4	11.8	A-6(8)
Monona	A	XI-1c	42.9	23.4	19.5	A-7-6(13)
	B	-2c	45.8	22.3	23.5	A-7-6(15)
	C ₁	-3c	39.9	22.9	17.0	A-6(11)
	C	-4c	33.5	23.7	9.8	A-4(8)
	C _{Fe}	-5c	35.7	23.8	11.9	A-6(8)
	C ₁	-6c	34.6	23.8	10.8	A-6(8)
Monona	A	IX-1c	44.7	23.3	21.4	A-7-6(14)
	B	-2c	41.8	21.5	20.3	A-7-6(13)
	C ₁	-3c	41.2	21.5	19.7	A-7-6(12)
	C	-4c	37.9	21.7	16.2	A-6(11)
Marshall	A _s	IV-1c	45.8	22.7	23.1	A-7-6(14)
	B	-2c	46.0	20.1	25.9	A-7-6(16)
	C ₁	-3c	41.7	20.7	21.0	A-7-6(13)
	C	-4c	38.0	21.2	26.8	A-6(11)
Marshall	A	V-1c	42.6	22.9	19.7	A-7-6(12)
	B	-2c	48.0	20.1	27.9	A-7-6(17)
	C ₁	-3c	39.6	18.3	21.3	A-6(13)
Marshall	A	VIII-1c	49.2	21.6	27.6	A-7-6(17)
	B	-2c	56.3	23.1	33.2	A-7-6(19)
	C ₁	-3c	43.6	21.1	22.5	A-7-6(14)
	C _G	-4c	40.4	20.7	19.7	A-6(12)

TABLE V. ENGINEERING CLASSIFICATION OF EASTERN IOWA SAMPLES

Area and soil series	Horizon	Sample No.	Liquid limit, %	Plasticity Plastic limit, %	Plasticity index	AASHTO soil class
E-C Iowa Fayette	A	100-1c	41.0	23.3	17.7	A-7-6(9)
	B	-2c	54.1	20.3	33.8	A-7-6(14)
	C ₁	-3c	30.0	20.9	9.1	A-4(8)
	C	-4c	25.5	19.2	6.3	A-4(8)
E-C Iowa Fayette	A	119-1c	36.9	24.0	12.9	A-6(7)
	B	-2c	51.8	21.8	30.0	A-7-6(14)
	C ₁	-3c	38.1	18.2	19.9	A-6(10)
NE Iowa Fayette	A	211-1c	30.0	22.5	7.5	A-4(8)
	B	-2c	43.4	21.9	21.5	A-7-6(11)
	C ₁	-3c	45.8	21.9	23.9	A-7-6(13)
	C	-4c	28.9	20.7	8.2	A-4(8)
NE Iowa Fayette	A	207-1c	33.3	29.0	4.3	A-4(8)
	B	-2c	38.0	23.0	15.0	A-6(9)
	C ₁	-3c	41.7	22.4	19.3	A-7-6(10)
	C	-4c	30.2	21.8	8.4	A-4(8)
	C _G	-5c	28.6	21.9	6.7	A-4(8)
E-C Iowa Tama	A	122-1c	32.9	24.0	8.9	A-4(8)
	B	-2c	33.9	21.2	12.7	A-6(9)
	C	-3c	25.4	23.6	1.8	A-4(8)
NE Iowa Tama	A	212-1c	35.7	24.0	11.7	A-6(8)
	B	-2c	47.7	22.0	25.7	A-7-6(16)
	C ₁	-3c	39.1	21.8	17.3	A-6(10)
	C	-4c	32.8	22.1	10.7	A-6(7)
	C _G	-5c	29.6	20.8	8.8	A-4(8)
E-C Iowa Muscatine	A	111A-1c	39.2	26.2	13.0	A-6(9)
	B	-2c	39.1	24.0	15.1	A-6(10)
	C ₁	-3c	30.8	21.8	9.0	A-4(8)
NE Iowa Muscatine	A	223-1c	40.7	23.5	17.2	A-7-6(10)
	B	-2c	45.5	20.0	25.5	A-7-6(13)
	C ₁	-3c	37.4	21.5	15.9	A-6(9)
	C	-4c	26.6	23.0	3.6	A-4(8)
	C _{G Fe}	-5c	26.8	20.4	6.4	A-4(8)
	C _G	-6c	28.2	19.1	9.1	A-4(8)

the equation was obtained from western Iowa C horizon loess samples, four A horizon samples fall above the line and eight come below it. It was necessary to treat the A horizon sample with hydrogen peroxide for removal of organic matter to prevent flocculation during mechanical analysis. It is therefore expected that A horizon samples will tend to compact to lower density and will therefore require more cement.

Part of the scatter in points is undoubtedly due to the relatively low accuracy of the PI tests. Plasticity indices are ordinarily accurate and reproducible to within 2 or 3 percent, a large personal factor being involved. Clay contents measured by the hydrometer method are considered accurate to within 1 or 2 percent.

The engineering classification of the samples represented graphically shows the relatively small but inconsistent variation in plastic limit (figure 7). Calculation of the standard deviation of the plastic limit from an aver-

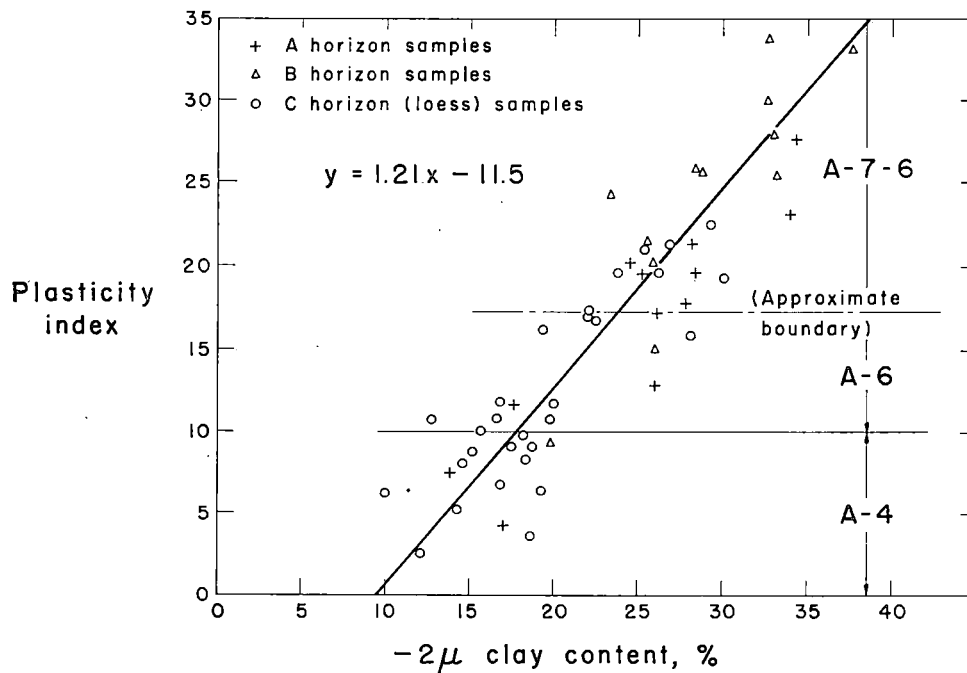


Fig. 6. Relation of plasticity index to clay content.

age value of 22.0 percent gives a probable error of approximately 1 percent, indicating that there is a 50 percent chance that any one plastic limit will fall between 21 and 23 percent, regardless of liquid limit or clay content^{3, p. 203}.

Soil Cement Tests

The criteria for selecting adequate cement contents to stabilize a soil vary depending on the engineering classification of a soil.

Soil cement losses during 12 cycles of either the wet-dry test or the freeze-thaw test should not exceed 10 percent for an A-4 soil or 7 percent for A-6 and A-7 soils. In addition, compressive strengths should increase both with age and with increasing cement contents. Based on past experience, mixes which meet these specifications will probably be suitable for road base course construction. The sliding scale used to determine the minimum cement content is in recognition of the severe nature of the weathering tests, particularly with sandy or friable silty soils. Brushing to remove loose materials is recognized as a vigorous requirement for these normally poorly cohesive soils. Although the severity of the weathering tests has been criticized, the tests are on the safe side.

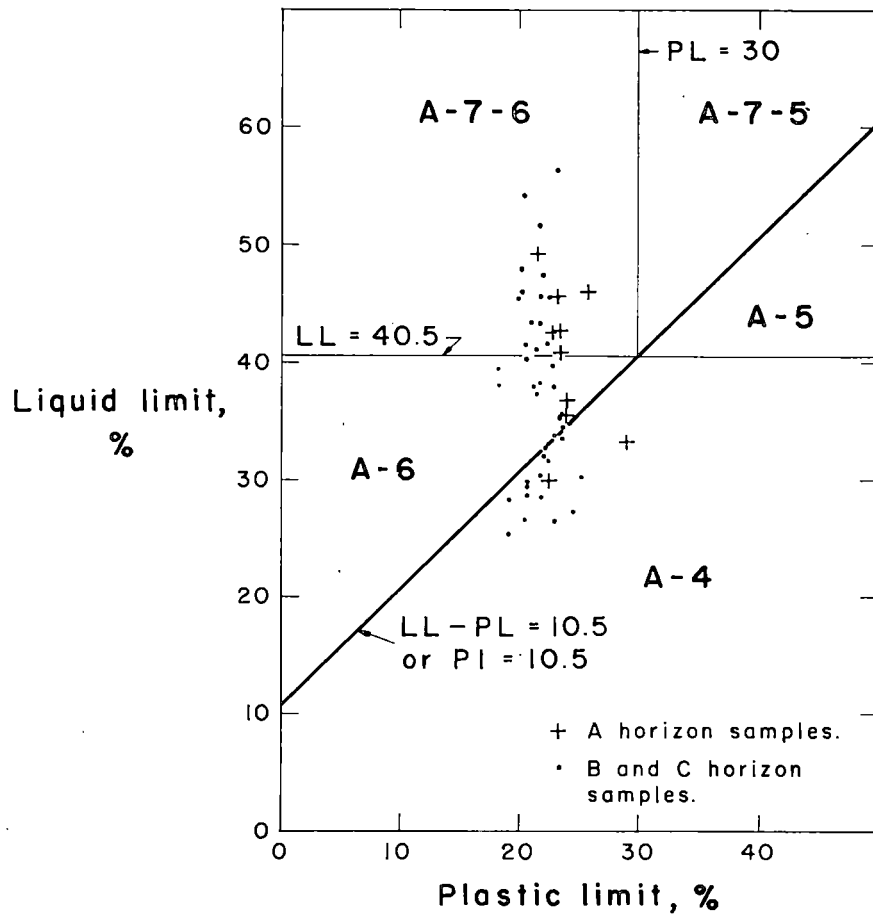


Fig. 7. Relation between liquid limit, plastic limit, and A.A.S.H.O. engineering classification of the loess soils.

Optimum moisture, maximum density

Moisture density relationships were determined for each sample, and the optimum moisture content was evaluated and used in subsequent molding of specimens (figure 8). The addition of Portland cement to a soil usually causes additional flocculation and lowers the compactibility. Moisture density tests on raw soil are of less interest than tests on soil cement mixtures, therefore tests are run with a cement content which is the estimated cement requirement based on AASHO soil group. At present an A-4 soil is ordinarily tested with 10 percent cement by weight, an A-6 soil is tested with 12 percent, and an A-7 soil with 13 percent. Tests must be run quickly, before the cement has a chance to set up. Cement hydration during mixing causes a further decrease in density and an increase in op-

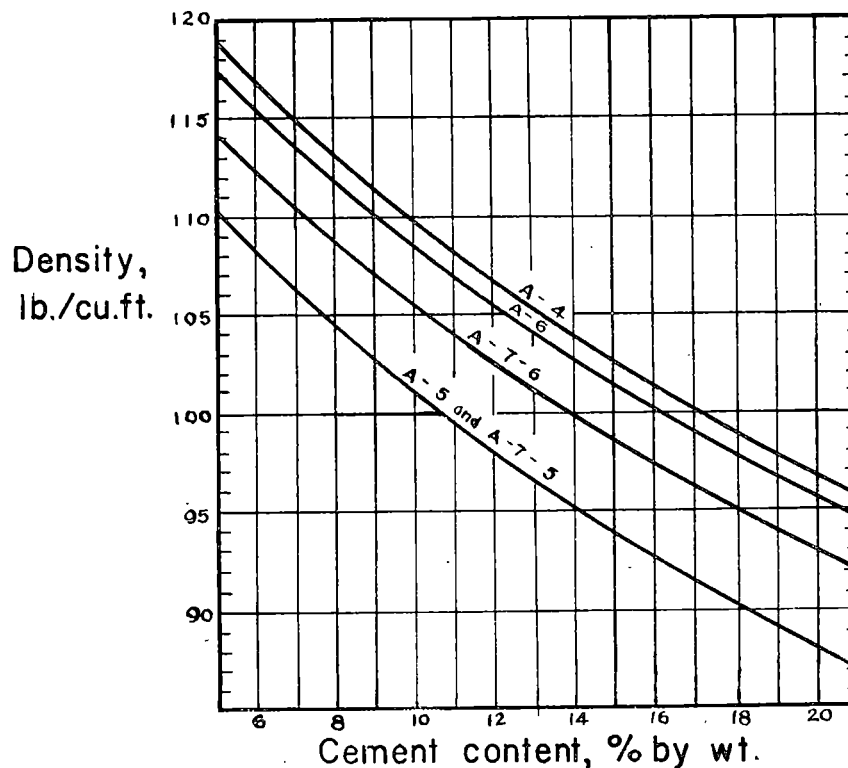


Fig. 8. Relation of average cement requirements to compacted density and A.A.S.H.O. soil class. Reproduced from Portland Cement Association, "Soil-cement Laboratory Handbook"¹³.

timum moisture (tables X, XI).

Wet-dry tests

With only a few exceptions the soil cement losses during 12 cycles of wetting and drying were exceeded by freeze-thaw losses and therefore were not critical (tables VI and VII). The exceptions are soils for which the

TABLE VI. FREEZE-THAW AND WET-DRY LOSSES FOR WESTERN IOWA SOIL CEMENT*

Soil series	Hori- zon	Sample No.	Cement content, percent by volume						Allow- able loss, %	Ce- ment req., vol., %
			10	12	14	16	18	20		
Hamburg	C	I-1c	18	4(3)	3				10	12
	AB	-2c	32	6(3)	5				10	12
	C	-3c	8	8(3)	4				10	12
Hamburg	C	X-1c	17	14(10)	5				10	14
	D	-2c	9	6(7)	5				7	12
Ida	A	III-1c			40	15(3)	14	5	7	20
	C	-2c	52	40(6)	22	18	17		7	20

TABLE VI. CONTINUED

Monona	A	XI-1c			22	7(3)	7		7	18
	B	-2c		12	6(14)	3			7	16
	C ₁	-3c	55	45(5)	23	18	18		7	20*
	C	-4c	48	37(3)	17	19	14	10		20*
	C _{Fe}	-5c	82	64	37	27	23		7	20*
	C ₁	-6c	100	36(3)	19	19	13		7	20*
Monona	A	IX-1c			34	26(4)	4		7	18
	B	-2c	46	36(6)	27	6			7	16
	C ₁	-3c	45	25(1)	24	6			7	16
	C	-4c		50(9)	18	2			7	16
Marshall	A ₃	IV-1c			29	23(7)	3	2	7	18
	B	-2c	76	33(4)	4	3			7	14
	C ₁	-3c		70(6)	36	16	7		7	18
	C	-4c	40	24(7)	12				7	16
Marshall	A	V-1c			59	37(3)	6		7	18
	B	-2c	33	12(8)	3	3			7	14
	C ₁	-3c	60	45(6)	14	6			7	16
Marshall	A	VIII-1c			23	19(12)	4		7	18
	B	-2c	40	33(7)	13				7	16
	C ₁	-3c	62	56(5)	34	7			7	16
	C _G	-4c	12	5(4)	5				7	14

* Wet-dry soil cement losses are shown in parentheses.

freeze-thaw losses are exceptionally low; they are better discussed in that connection.

Compressive strength

The 2, 7, and 28 day compressive strengths were determined after final evaluation of the required cement content. The data show a sporadic compressive strength gain in a few of the samples (tables VIII and IX). All western Iowa samples show satisfactory strength gains with increasing age. In eastern Iowa, however, many of the A horizon samples show lower strength at 7 than at 2 days, and most have relatively low strength after 28 days. Humic materials in Portland cement concrete cause a "flash set" which disturbs the cement structure and causes a considerable loss of mechanical strength. It would appear that the same kind of reaction occurs here. The reaction in concrete is believed to be a flocculation which reduces the availability of gypsum previously added to Portland cement as a retarder. Ordinarily the action of gypsum is to form insoluble calcium aluminate sulfate at the surface of the unhydrated tricalcium aluminate grains, retarding their rate of hydration⁴, p. 1239 ff. The deleterious effect of humus in the A horizons of Fayette, Tama, and Muscatine soils might possibly be offset by the use of additional gypsum in the cement, but because of the ease of stripping the relatively thin A horizons, gypsum treatment would be of doubtful value. For this reason, and because of the higher cement contents indicated by freeze-thaw tests, it is recommended that these A horizons be stripped and not used in soil cement.

TABLE VII. FREEZE-THAW AND WET-DRY LOSSES FOR EASTERN IOWA SOIL CEMENT, PERCENT*

Area and soil series	Horizon	Sample no.	Cement content, percent by weight																							Allowable loss, %	Cement re-quirement, %	
			9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	by wt.	by vol.							
E-C Iowa Fayette	A	100-1c				10			5(5)			3								7	14.0	13.5						
	B	-2c			34		28(15)		8		4		3							7	15.5	14.5						
	C ₁	-3c		25		19(4)		13		5										10	15.0	14.5						
	C ₁	-4c	8		3(5)		3													10	9.0	9.5						
E-C Iowa Fayette	A	119-1c							51			18(3)			3					7	20.0	17.0						
	B	-2c					6			6(4)		6								7	16.0	14.5						
	C ₁	-3c			38		12(6)		6											7	15.0	14.5						
NE Iowa Fayette	A	211-1c			44			35(4)			33			20			20			10	23+							
	B	-2c			(9)								63		32					7	21+							
	C ₁	-3c			(7)				75		32		3							7	18.5	17.5						
	C	-4c		17			6(5)		4											10	11.0	11.5						
NE Iowa Fayette	A	207-1c				65			37(3)			23			18			1		10	23.0	19.5						
	B	-2c				46		42(7)		26		4		5						7	17.5	16.5						
	C ₁	-3c					(6)					45			22			2		7	23.5	20.5						
	C	-4c			59		12(8)		7											10	14.0	14.0						
	C _G	-5c	22		20(6)		6													10	12.5	13.0						
E-C Iowa Tama	A	122-1c								13			4(2)			2				10	17.0	17.0						
	B	-2c				6		5(3)		4		4								7	12.0	12.5						
	C	-3c				3		3(2)		3		2								10	12.0	12.5						
NE Iowa Tama	A	212-1c					45			30(3)			4							7	19.0	17.0						
	B	-2c		83		26(4)		11												7	15.0	15.0						
	C ₁	-3c	63		31(5)		25													7	15.0	14.5						
	C	-4c	27		22(5)		5													7	13.0	13.0						
	C _G	-5c	23		14(8)		4													10	12.0	12.0						
E-C Iowa Muscatine	A	111A-1c				100			100(5)			100			100					7	21+							
	B	-2c			32			10(10)			4			4						7	15.5	14.5						
	C ₁	-3c			34		8(4)		4		4									10	13.0	13.5						
NE Iowa Muscatine	A	223-1c				12			5(5)			4								7	13.0	14.0						
	B	-2c				17		16(5)		6										7	16.0	14.5						
	C ₁	-3c		36		17(4)		16		1		1								7	15.0	14.5						
	C	-4c		15		8(5)		17												10	12.0	12.0						
	C _{G, Fe}	-5c		25(4)		18		3		3										10	13.0	13.5						
	C _G	-6c	40		15(8)			3												10	12.0	12.0						

* Wet-dry soil cement losses are shown in parentheses

TABLE VIII. COMPREHENSIVE STRENGTHS OF EASTERN IOWA SOIL CEMENT

Area and soil series	Horizon	Sample No.	Cem. Cont., % by wt.	Comprehensive Strength, psi		
				2	7	28 day
E-C Iowa Fayette	A	100-1c	14.0	287	239	503
	B	-2c	15.5	334	420	436
	C ₁	-3c	15.0	290	318	474
	C	-4c	9.0	201	287	363
E-C Iowa Fayette	A	119-1c	20.0	169	229	261
	B	-2c	16.0	160	204	375
	C ₁	-3c	15.0	275	299	408
NE Iowa Fayette	A	211-1c	-----	-----	-----	-----
	B	-2c	-----	-----	-----	-----
	C ₁	-3c	18.5	318	382	487
	C	-4c	11.0	236	344	452
NE Iowa Fayette	A	207-1c	23.0	239	165	360
	B	-2c	17.5	242	318	494
	C ₁	-3c	23.5	303	357	600
	C	-4c	14.0	337	541	840
	C _G	-5c	12.5	424	478	815
E-C Iowa Tama	A	122-1c	17.0	245	300	
	B	-2c	12.0	185	300	
	C	-3c	12.0	290	446	
NE Iowa Tama	A	212-1c	19.0	204	143	280
	B	-2c	15.0	194	264	366
	C ₁	-3c	15.0	245	306	572
	C	-4c	13.0	404	420	655
	C _G	-5c	12.0	401	541	713
E-C Iowa	A	111A-1c	-----	-----	-----	-----
	B	-2c	15.5	160	280	
	C ₁	-3c	13.0	222	382	
NE Iowa Muscatine	A	223-1c	13.0	268	251	299
	B	-2c	16.0	280	337	401
	C ₁	-3c	15.0	286	271	608
	C	-4c	12.0	356	455	446
	C _{G Fe}	-5c	13.0	343	445	748
	C _G	-6c	12.0	337	325	502

TABLE IX. COMPREHENSIVE STRENGTHS FOR WESTERN IOWA SOIL CEMENT

Soil series	Horizon	Sample No.	Cem. Content., % by vol.	Comprehensive strength, psi		
				2	7	28 day
Hamburg	C	I-1c	12	286	420	560
	AB	-2c	12	347	528	542
	C	-3c	12	344	388	636
Hamburg	C	X-1c	14	242	484	725
	D	-2c	12	236	248	489
Ida	A	III-1c	20	414	458	554
	C	-2c	18*	341	535	572
Monona	A	XI-1c	18	286	363	363
	B	-2c	16	280	420	432
	C ₁	-3c	16†	306	471	667
	C	-4c	16†	280	509	719
	C _{Fe}	-5c	16†	382	395	566
	C ₁	-6c	16†	274	446	630

TABLE IX. CONTINUED

Monona	A	IX-1c	18	286	388	407
	B	-2c	16	318	388	489
	C ₁	-3c	16	382	503	521
	C	-4c	16	414	477	620
Marshall	A _s	IV-1c	18	239	318	318
	B	-2c	14	286	337	623
	C ₁	-3c	18	363	471	471
	C	-4c	16	337	509	879
Marshall	A	V-1c	18	286	325	375
	B	-2c	14	267	318	343
	C ₁	-3c	16	-----	-----	-----
Marshall	A	VIII-1c	18	331	388	388
	B	-2c	16	255	331	716
	C ₁	-3c	16	267	420	420
	C _G	-4c	14	223	356	534

* Freeze-thaw cement requirement 20%

† Freeze-thaw cement requirement over 20%

Freeze-thaw test

Freeze-thaw loss was the deciding factor for cement content in nearly all of the loess soil samples (tables VI, VII). Freeze-thaw losses of some soils were approximately as expected; in others they were abnormally high. Cement contents necessary to reduce freeze-thaw losses to within specified limits exceeded 20 percent for some samples, indicating that Portland cement stabilization would be uneconomical for these soils. Samples which exhibited excessive freeze-thaw losses were from the Ida and Monona series in western Iowa and from the Fayette series in eastern Iowa; but there is a danger in accepting this as a valid correlation. For example the Ida samples give excessive freeze-thaw losses, but the Hamburg samples do not. The Ida series differs from the Hamburg only by development of a faint, unleached A horizon, probably because of a slightly lower erosion rate. The series difference is more closely related to topography than to C horizon loess properties, and both series may be found on the same hill. The soil series may not form a reliable criterion in these exceptional cases.

For convenience in analysis a freeze-thaw sensitivity factor may be defined. By determining cement requirements for many soils the P.C.A. has a graph (for estimating probable cement requirements) which relates cement requirement to compacted density and AASHO soil class (figure 8). The difference between the values from the graph and the actual cement requirements is taken as an index of freeze-thaw sensitivity, since loess specimens which required additional cement all failed in the freeze-thaw. Use of a freeze-thaw sensitivity serves to minimize the effects of density and soil class variables. The freeze-thaw sensitivity of the samples ranges from minus 2 to over 10 (table X).

TABLE X. SOIL CEMENT RESULTS AND FREEZE-THAW SENSITIVITY OF WESTERN IOWA SAMPLES

Soil series	Horizon	Sample No.	Opt. M.C., %	Est. dens., pcf	Est. cem. req., wt. %	Recommended cem. cont., % by wt.	Recommended cem. cont., % by vol.	Freeze-thaw sensitivity
Hamburg	C	I-1c	17.9	102.9	14.8	12.2	12	-2.6
	AB	-2c	16.5	107.8	11.2	11.7	12	0.5
	C	-3c	15.8	107.7	11.3	11.7	12	0.4
Hamburg	C	X-1c	18.5	103.0	14.8	14.0	14	-0.8
	D	-2c	19.0	102.3	14.3	12.4	12	-1.9
Ida	A	III-1c	19.5	99.4	14.4	23.3	20	8.9
	C	-2c	18.5	100.0	16.0	23.2	20	7.2
Monona	A	XI-1c	22.5	98.5	15.0	20.8	18	5.8
	B	-2c	22.0	98.7	15.1	18.0	16	2.9
	C ₁	-3c	18.0	105.0	12.3	21.8	20	9.5
	C	-4c	18.6	102.0	15.4	22.6	20	7.2
	C _{Fe}	-5c	19.3	101.3	15.0	21.3	20	6.3
	C ₁	-6c	18.3	102.0	14.6	22.6	20	8.0
Monona	A	IX-1c	21.0	98.6	15.0	20.7	18	5.7
	B	-2c	18.3	103.2	11.5	17.0	16	5.5
	C ₁	-3c	19.0	103.3	11.5	17.0	16	5.5
	C	-4c	18.7	103.8	13.1	16.9	16	3.8
Marshall	A ₃	IV-1c	23.3	94.5	18.3	21.8	18	3.5
	B	-2c	18.8	102.3	12.3	14.8	14	2.5
	C ₁	-3c	18.8	103.0	11.8	19.6	18	7.8
	C	-4c	19.5	99.6	16.3	17.7	16	1.4
Marshall	A	X-1c	21.5	98.3	15.2	20.8	18	5.6
	B	-2c	21.5	99.0	14.3	15.3	14	1.0
	C ₁	-3c	18.7	104.2	12.6	16.8	16	4.2
Marshall	A	VIII-1c	21.3	98.4	15.0	20.8	18	5.8
	B	-2c	22.0	98.8	14.6	17.9	16	3.3
	C ₁	-3c	18.7	103.3	11.5	17.0	16	5.5
	C _G	-4c	21.3	98.4	17.5	15.4	14	2.1

DISCUSSION

Relation to Soil Series

Western Iowa

The soil cement test results for western Iowa may be summarized under the following soil series:

Hamburg (5 samples). Compacted density 102 to 108 pcf, optimum moisture 16 to 19 percent, cement requirement usually 12 percent. These results are considered quite favorable, and the samples reacted as expected.

Ida A and C horizons (2 samples). Compacted density around 100 pcf, optimum moisture 18 to 20 percent, cement requirement 20 percent. The freeze-thaw sensitivity of these samples is very high, requiring 7 to 9 percent additional cement over that previously estimated.

Monona C horizon (6 samples). Compacted density 101 to 105 pcf, optimum moisture usually between 18 to 19 percent. Cement requirements and freeze-thaw sensitivity erratic, the friable (A-4 and A-6) Monona reacting similarly to the Ida, and the more plastic Monona (usually A-7-6) being more like the Marshall. Freeze-thaw sensitivity very high to medium.

Monona and Marshall A horizons (5 samples). Compacted density around 98.5 pcf, optimum moisture 21 to 23 percent, cement requirement 18 percent. The high cement requirement is at least partly due to the lower compacted density. Freeze-thaw sensitivity is medium.

Monona and Marshall B horizons (5 samples). Compacted density usually 99 to 103 pcf, optimum moisture 18 to 22 percent, cement requirement 14 to 16 percent. Freeze-thaw sensitivity low or medium.

Marshall C horizon (5 samples). Compacted density usually 100 to 104 pcf, optimum moisture about 19 percent. Cement requirement 16 to 18 percent. Freeze-thaw sensitivity medium. The cement requirement is 2 percent lower for material beneath the water table.

Summary: Western Iowa. In western Iowa the very coarse loess which is usually in the Hamburg series responds quite favorably to treatment with cement, the required amount being commonly 12 percent. However, the critical and somewhat unpredictable nature of the freeze-thaw resistance of coarse loess indicate that cement requirements should be checked prior to acceptance of a material for soil cement construction. Finer loesses and

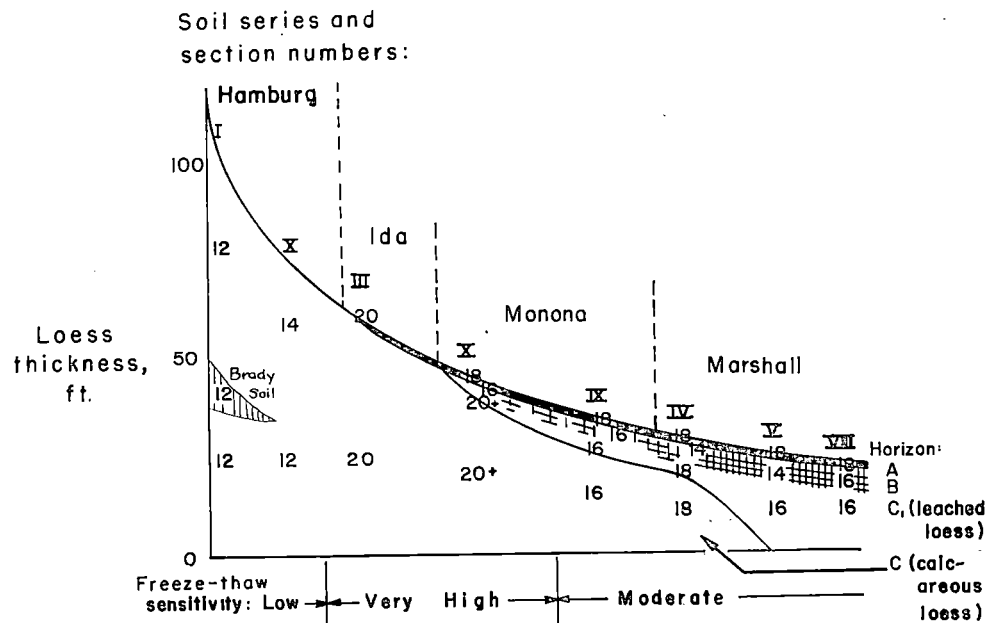


Fig. 9. Cement requirements for western Iowa loess and loessal soils. Numbers indicate cement percentages by volume.

loessal soils are more predictable but are less economical to stabilize (figure 9).

Eastern Iowa

Soil cement test results for eastern Iowa are summarized under the following soil series:

Fayette A horizon (4 samples). Compacted density 96 to 103 pcf, optimum moisture content 17 to 22 percent. Cement requirement 13.5 percent and up, depending in part on the density. The density tends to be low due to the influence of organic matter. Some samples show an interrupted compressive strength gain on curing, probably due to deleterious organic matter. Use of Fayette A horizon in soil cement therefore is not recommended.

Fayette B horizon and leached C horizon (8 samples). Compacted density 100 to 105 pcf, optimum moisture content 16.5 to 22 percent. Cement requirement 14.5 percent in east-central Iowa, much higher in northeast Iowa. The high cement requirements are mainly a result of freeze-thaw sensitivity.

Fayette calcareous C horizon (3 samples). Compacted density, 106 to 109 pcf, optimum moisture content 16.5 to 18 percent. Cement requirement 9.5 to 14 percent, averaging 6.3 percent less than that for the overlying leached C horizon. The average density is about 5 pcf greater, which is about two-thirds sufficient to explain the cement requirement difference (figure 8). The sand content is not consistently higher in the calcareous than in the leached loess. However the clay content is consistently lower, undoubtedly due to the transitional nature of the B and C horizons. The calcareous samples contain 8 to 12 percent less 5 micron clay and would be in the critical frost sensitive range in western Iowa (figure 9); yet freeze-thaw loss is not excessive. In these samples a lower clay content allows better compaction and a reduction in cement. The single unoxidized sample reacts much like those which are calcareous and oxidized; it has low clay, high density, and low cement requirement.

Summary: Fayette series. In northeast Iowa Fayette A, B and leached C horizons are highly frost susceptible and unsatisfactory for soil cement. In east-central Iowa the Fayette A horizon is unsatisfactory, but the B and C horizons can be stabilized with approximately 14 to 15 percent cement. In both east-central and northeast Iowa the Fayette calcareous C horizon may be stabilized with from 10 to 14 percent cement; if it were not for the excessive overburden it would be advantageous to use this lower material. The depth of leaching in the loess of eastern Iowa is usually 7 or 8 feet; the thickness of essentially uneroded loess is 10 to 40 feet. Coarse loess requires less cement.

Tama A horizon and Muscatine A horizon (4 samples). Compacted density may be very low, 90 to 103 pcf. Optimum moisture content usually 18 to 20 percent. Cement requirements erratic and largely influenced by density.

Compressive strength shows an interrupted gain. The use of these A horizons ordinarily is not recommended in soil cement.

Tama B and leached C horizon (3 samples). Compacted density 105 to 107 pcf, optimum moisture content 17 to 18 percent. Cement requirement 12 to 15 percent, depending on the texture of the parent material. Coarse-textured loess requires less cement. Freeze-thaw sensitivity moderate.

Tama calcareous C horizon (3 samples). Compacted density 106 to 108 pcf, optimum moisture content 16 to 17 percent. The cement requirement is 12 to 13 percent; freeze-thaw sensitivity is moderate.

Muscatine B and leached C horizon (4 samples). Compacted density 100 pcf in the B, 105 to 109 pcf in the C. Optimum moisture content 18 to 20 percent. Cement requirement 13.5 to 14.5 percent, freeze-thaw sensitivity moderate.

Muscatine calcareous C horizon (3 samples). Compacted density 107 to 110 pcf, optimum moisture content 15 to 17 percent. Cement requirement 12 percent and freeze-thaw sensitivity low except in material enriched in secondary iron. The loess sample with secondary iron has a cement requirement of 13.5 percent and moderate freeze-thaw sensitivity.

Summary: Tama and Muscatine series. Portland cement stabilization would be most economical with coarse-textured C horizon loess, for which the cement requirement is 12 or 13 percent. A higher clay content either in the B or C horizons requires additional cement, up to a maximum of about 15 percent. Iron oxide enriched zones may require somewhat more cement than comparable zones without high enrichment.

Analysis

After the results were compiled cement requirements were related to compacted density, percent air voids, moisture content, clay content, the various plasticity limits, sand content, . . . : The only conclusion which could be drawn was that this was a very knotty problem. Cement requirements correlated in a general way with each of these variables, but relating it to any single variable gave a considerable scattering of points. The cement requirement obviously was affected by more than one variable. Such mixing of dependent variables naturally contributes a generous amount of confusion to the analysis, but this is now considered more or less routine in soils investigations and will not be further dwelled upon.

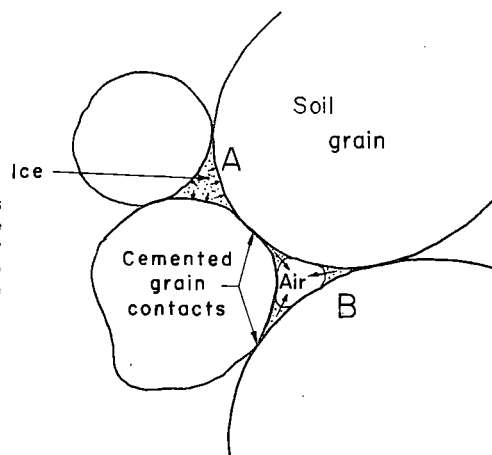
Freeze-thaw

The critical test for nearly all samples was the freeze-thaw test. First of all weight loss, not strength loss, is the deciding factor for soil cement. Supplementary observations of severe freeze-thaw failures in samples molded at various densities suggested the mechanism for these failures.

It is widely recognized that water expands on freezing and can exert large pressures — pressures which certainly exceed the relatively low ten-

tile strength of soil cement or concrete. Air voids ordinarily present in soil cement probably provide spaces for ice expansion and act to reduce the pressure (figure 10). Pressure in the air voids will more or less follow the

Fig. 10. Role of saturation in the disruptive forces exerted by ice. In void A if there is no leakage during freezing, ice pressure will bear directly against soil grains and force them apart. In void B the air is compressible and provides room for ice expansion.



familiar relationship $PV = nRT$, but pressure in a saturated void will build up much more rapidly with a protracted change in volume. Saturation therefore becomes a critical factor.

In the laboratory testing it was observed that specimens with abnormally high freeze-thaw losses fail by scaling. A surface layer of the specimen forms into loose flakes or scales during freezing, and after subsequent thawing these are brushed off. Additional freeze-thaw cycles then loosen another shell and cause it to be lost. This progressive destruction continues to the end of the test. Some specimens which, according to compressive strength, should have been stabilized suffered a 100 percent freeze-thaw loss.

Supplementary investigations using specimens with low cement contents and varying density showed that specimens compacted to high density exhibited tensile cracking and partial loss of strength, as expected from ice crystal expansion. Specimens less well compacted showed excessive scaling and other significant signs of distress, including formation of frost blisters and ice lenses in the outer portions of the specimens. These suggested very strongly that scaling might be related to water movement and saturation of voids near the outer margins of the specimens during freezing. Moisture measurements made on sections of frozen specimens showed higher moisture contents in the outer shell.

Moisture movement during freezing was suggested some time ago on the basis of field observations²¹. Explanations of ice lens growth in hydrated cement paste have also been made¹³. The distress in cement paste is believed due to hydraulic pressure from growing capillary ice forcing water out through the surrounding paste. The low permeability of cement paste aids this buildup of pressure. Contributing to the ice formation is water coming out of individual particles of cement gel. The water thus moves in two directions, out of the gel to the capillary voids, for thermodynamic reasons, and then out of the filled voids through the paste to unsaturated air voids, for purely physical reasons. Air entrainment in concrete reduces the pressure buildup by introducing thousands of tiny nuclei for ice formation and pressure relief. The shorter distance through the gel to the air voids reduces the hydraulic pressure.

In soil cement the cement gel is much less important than in concrete. Hydraulic pressure in the cement gel may be a factor, but permeability is high in the surrounding soil, and the major mechanism causing freeze-thaw loss appears to be direct ice pressure. The amount of pressure largely depends on the degree of saturation of the air voids (figure 10). This would suggest that voids in the outside of specimen are saturated due to moisture movement before and during freezing. Thermal osmosis occurs even without freezing¹⁵, but it is greatly hastened by the large vapor pressure reduction associated with freezing.

The differential volume change results both in shearing off the outer shell and in loss of strength within the shell due to failure by tension. Brushing of specimens which fail in this manner may not be so severe as commonly supposed, since the circumferential crack commonly observed in a failure specimen may act as a barrier to capillary movement outward during the next cycle; the moisture buildup and freeze-thaw failure would then be in the next inner shell.

A possible complicating factor in this analysis is the lowering of the freezing point of water due to pressure. However, the minimum temperature at which water can remain liquid is -22°C .,²² and this is under a pressure of about 29,200 psi, which is far in excess of any containing force that could be developed in soil cement.

Probably more important in lowering the freezing point is the influence of dissolved salts. Salts will tend to be isolated as water freezes out, and concentrated salt solutions may remain in the ice as inclusions.

Progressive freezing undoubtedly occurs, partly as a result of ion concentration but mainly because heat must be conducted away from the freezing solution. As the temperature in a void is lowered, it is questionable where freezing would begin. The crystal structure believed to be in water adsorbed on the basal plane in montmorillonite⁵ would probably be a good starting point. The thermal conductivity of minerals is several times that of water, so cooling would proceed mainly through the mineral grains. It

therefore appears that freezing probably extends from the soil grains out into the void. Thus the first freezing would tend to clog the pores and contain the remaining water so that it will exert pressure during expansion. Otherwise, if the central pore water froze first, the marginal pore water would be free to escape. The same conclusion can be reached by calculating adsorptive pressures²². That is, under high pressures water freezes even at 40 or 50° C. and so would remain "frozen" on the surface of clay. Decreasing the temperature allows freezing at lower pressures farther out from the clay. An objection to this approach may be that as pressure is further decreased, the freezing point of water continues down until it is below 0° C. Then there would be a zone around a clay particle where water would not freeze so readily. Water would freeze closer to the clay and farther from the clay and leave the intermediate zone liquid. This assumption is based on measurements on free water, and it is doubtful if such a condition would be found in the neighborhood of a clay crystal surface.

Summary for the mechanism of freeze thaw

The above analysis would suggest that permeability and rate of freezing are two major variables affecting freeze-thaw loss. While a specimen is being frozen the temperature gradient draws capillary water to the outside, saturating the outer pores. In the meantime freezing in these pores extends outward from the surfaces of the clay. If pores are plugged by ice the final water to freeze will be trapped and can exert expansive pressure. If not, the pressure is lost. It therefore appears that two conditions are necessary

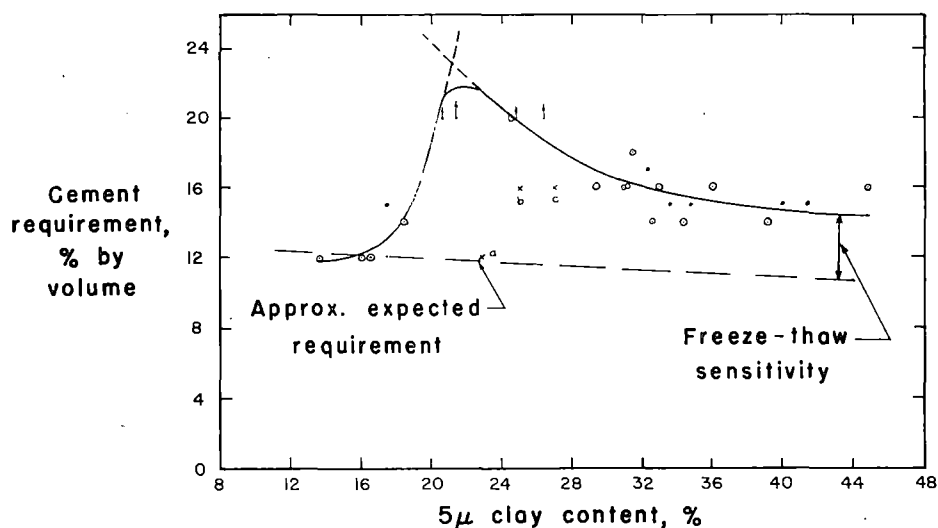


Fig. 11. Relation of cement requirement to clay content of western Iowa samples. A horizon requirements, less 3 percent, are shown by dots. Arrows indicate where cement requirements were so high they were not finally determined; these samples showed extreme freeze-thaw sensitivity. Non-correlative samples are Brady soil, a, and basal loess samples b and c.

for high freeze-thaw loss: these are a high permeability, so that sufficient water can move outward to saturate the pores during freezing. Increasing the clay content would reduce this permeability and gradually lower the freeze-thaw loss. The second condition is for trapping the final water; if pores are so large that ice does not quickly clog the pores, pressure will be lost. Water expands only 9 percent on freezing, so relatively little water movement would be required to relieve the pressure.

TABLE XI. SOIL CEMENT RESULTS AND FROST SENSITIVITY OF EASTERN IOWA SAMPLES

Area and soil series	Horizon	Sample No.	Opt. M.C., %	Est. dens., pcf	Est. cem. req., wt. %	Recommended cem. cont., %		Frost sensitivity
						by wt.	by vol.	
E-C Iowa	A	100-1c	19.3	102.7	12.0	14.0	13.5	2.0
	B	-2c	18.7	101.5	12.6	15.5	14.5	2.9
	C ₁	-3c	17.0	105.4	12.9	15.0	14.5	2.1
	C	-4c	15.3	109.2	10.0	9.0	9.5	1.0
E-C Iowa	A	119-1c	22.1	96.1	19.7	20.0	17.0	0.3
	B	-2c	21.7	100.1	14.0	16.0	14.5	2.0
	C ₁	-3c	19.8	103.5	13.5	15.0	14.5	1.5
NE Iowa Fayette	A	211-1c	17.3	102.0	15.5	23	20	7.5
	B	-2c	16.5	104.0	11.0	21	19	10
	C ₁	-3c	17.8	104.3	10.8	18.5	17.5	8.3
	C	-4c	16.2	106.6	12.1	11.0	11.5	-0.9
NE Iowa Fayette	A	207-1c	18.9	100.0	17.0	23.0	19.5	6.0
	B	-2c	19.2	102.7	14.0	17.5	16.5	3.5
	C ₁	-3c	18.1	101.3	12.7	23.5	20.5	10.8
	C	-4c	16.6	108.1	11.0	14.0	14.0	3.0
	C _g	-5c	15.8	109.6	10.0	12.5	13.0	2.5
E-C Iowa Tama	A	122-1c	18.4	102.8	14.9	17.0	17.0	2.1
	B	-2c	17.5	105.2	8.9	12.0	12.0	3.1
	C	-3c	16.0	107.8	8.9	12.0	12.0	3.1
NE Iowa	A	212-1c	19.2	99.8	16.2	19.0	17.0	2.8
	B	-2c	18.0	104.8	10.5	15.0	15.0	4.5
	C ₁	-3c	17.5	106.7	11.2	15.0	14.5	3.8
	C	-4c	17.3	106.0	11.5	13.0	13.0	1.5
	C _g	-5c	15.7	107.9	11.2	12.0	12.0	0.8
E-C Iowa	A	111A-1c	24.3	91.3	21	21	21	----
	B	-2c	20.2	99.8	14.0	15.5	14.5	1.5
	C ₁	-3c	16.7	108.9	10.5	13.0	13.5	2.5
NE Iowa Muscatine	A	223-1c	19.7	99.6	14.2	13.0	14.0	-1.2
	B	-2c	18.5	100.1	13.8	16.0	14.5	2.2
	C ₁	-3c	18.0	105.1	12.0	15.0	14.5	3.0
	C	-4c	16.5	106.8	12.0	12.0	12.0	0
	C _{g, Fe}	-5c	15.2	110.4	9.5	13.0	13.5	3.5
	C _g	-6c	17.3	107.6	11.3	12.0	12.0	0.7

Application to western Iowa loess

Coarse loess is not frost susceptible because moisture is not so easily trapped during freezing (figure 11). With increased clay the moisture can be trapped, and freeze-thaw becomes critical. Further increasing the clay content reduces permeability so that moisture movement and freeze-thaw

loss are progressively less.

Application to eastern Iowa loess

The eastern Iowa cement requirement curve (figure 12) shows a

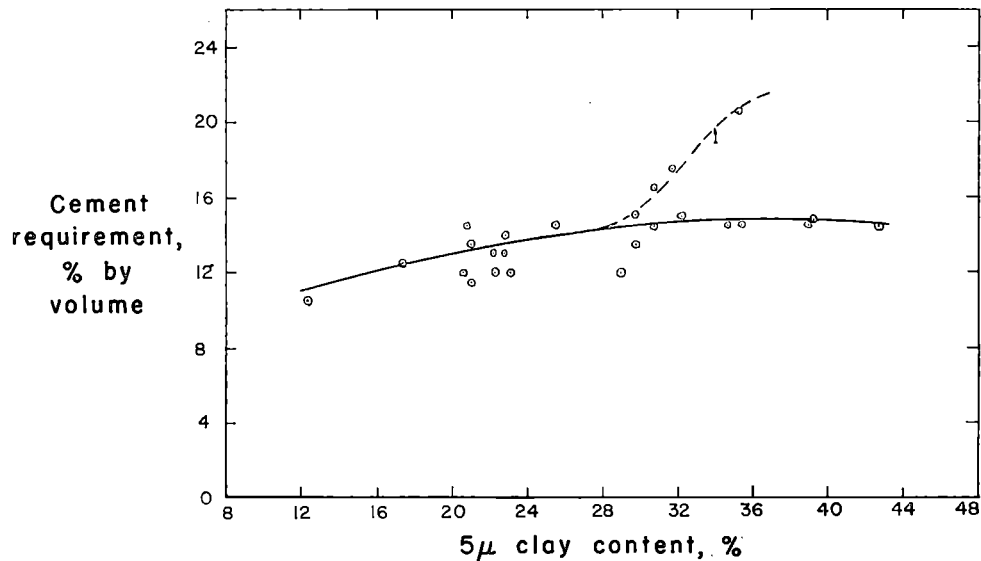


Fig. 12. Relation of cement requirement to clay content of eastern Iowa B and C horizon samples. Samples with excessive requirements are from the Fayette series in northeastern Iowa.

freeze-thaw sensitivity related to clay content. However, there are some differences between this curve and the one for western Iowa samples. All eastern Iowa samples show at least a moderate freeze-thaw sensitivity; their cement requirements are higher than expected. The average difference is about 3 percent, and there is no decrease with low percent clay. There is also a lack of extreme freeze-thaw sensitivity in the neighborhood of 20 to 28 percent clay, which was the sensitive range for loess in western Iowa. A third difference in that high freeze-thaw sensitivity is shown by several samples in the range 30 to 36 percent clay. All four of these samples are from B and leached C horizons of the Fayette series in northeast Iowa.

The freeze-thaw sensitivity of eastern and western Iowa loess does not correlate directly to differences in compacted density. However, on the average the eastern Iowa samples tend to compact to higher density, than those from western Iowa, the average compacted densities for B and C horizon samples being 105 and 102 pcf, respectively. There is little difference in average percent sand or percent clay, and the ranges covered are about the same. These density data duplicate trends already found for other loess samples from eastern and western Iowa⁸. Explanations proposed then were based on microscopic studies which showed a difference in the character of the clay. Variations in grain shape and composition were not believed

enough to explain the compactive difference. According to microscopic observations clay occurs more as coatings in loess in eastern Iowa than in western Iowa. Clay could therefore be more effective in compaction by acting as a lubricant between grains. Clay which does not occur as coatings occurs as aggregates, and aggregates are not so readily compacted.

A difference in clay occurrence could help to explain the freeze-thaw data. Clay occurring as coatings becomes concentrated around grain contact areas during mixing, but clay as aggregates does not do this so well⁶. Clay as coatings may therefore be more effective in lowering the permeability of compacted specimens. In western Iowa about 28 percent clay was necessary to lower permeability and reduce freeze-thaw loss. In eastern Iowa less clay may be necessary; the freeze-thaw loss is thus reduced but not eliminated throughout the clay content range.

The lack of a freeze-thaw sensitive peak in the range 20 to 28 percent clay may thus be accounted for, but the sensitivity characteristics in the range 30 to 36 percent clay remain a mystery. Only certain samples show this high cement requirement; other eastern Iowa samples with practically identical particle size gradations show only moderate susceptibility to freeze-thaw (figure 12). There is no consistent relation to plasticity, compressive strength, density, or other measured variables. The only constancy is that the four excessively sensitive samples are all from northeast Iowa Fayette B and C horizons. It is possible there is a difference in organic matter or coatings which would explain the high frost susceptibility of these samples, but no data are available to verify this.

CONCLUSIONS

Cement requirements of Iowa loess and loessal soils are imperfectly related to soil series due to erratic susceptibility to freeze-thaw. A theory to explain abnormal freeze-thaw loss is proposed, and freeze-thaw sensitivity is correlated to clay content and clay occurrence as coatings and as aggregates. Excessive freeze-thaw loss appears to be due to scaling caused by void saturation from moisture movement outward in the molded cylinders during freezing. The same process would occur in a road, but moisture movement would be only toward the upper surface. Perhaps freeze-thaw loss is prevented in coarse loess by the ice failing to plug the pores quickly during freezing. In all areas studied, coarse C horizon loess therefore would be the most economical to stabilize. The cement requirement for this material is usually about 12 percent. Finer loesses and B horizon materials often have reduced freeze-thaw loss due to low permeability, but the cement requirements are usually 14 to 18 percent. These requirements are fairly closely related to soil series. Other materials because of high freeze-thaw sensitivity would be completely unsatisfactory for soil cement, although with some of these materials the cement requirement may be reduced by

greater compaction. Another possible solution suggested by the freeze-thaw mechanism is to reduce the freeze-thaw sensitivity by admixing sand. This possibility has not yet been checked. Critical susceptibility to freeze-thaw is evidenced by medium-coarse textured loess in western Iowa and by A and B horizons in the Fayette series in northeastern Iowa. A horizons in eastern Iowa often require excessive cement due to poor compactibility, and some eastern Iowa A horizons react unfavorably with cement. Use of cement with these materials is not recommended.

TABLE XII. CORRESPONDING IOWA AND P.C.A.
SAMPLE NUMBERS

Western Iowa		Eastern Iowa	
I.E.E.S.	P.C.A.	I.E.E.S.	P.C.A.
I-1c	515	100-1c	548
-2c	516	-2c	549
-3c	517	-3c	550
X-1c	520	-4c	551
-2c	521	119-1c	552
III-1c	518	-2c	553
-2c	519	-3c	554
XI-1c	522	211-1c	537
-2c	523	-2c	538
-3c	524	-3c	539
-4c	525	-4c	540
-5c	526	207-1c	528
-6c	527	-2c	529
IX-1c	511	-3c	530
-2c	512	-4c	531
-3c	513	-5c	532
-4c	514	122-1c	
IV-1c	500	-2c	
-2c	501	-3c	
-3c	502	212-1c	533
-4c	503	-2c	534
V-1c	504	-3c	535
-2c	505	-4c	536
-3c	506	-5c	541
VIII-1c	507	111A-1c	
-2c	508	-2c	
-3c	509	-3c	
-4c	510	223-1c	542
		-2c	543
		-3c	544
		-4c	545
		-5c	546
		-6c	547

REFERENCES CITED

1. Chu, T. Y., and Davidson, D. T. Simplified air-jet apparatus for mechanical analysis of soils. Hwy. Res. Bd. Proc. 32:541-547. 1953.
2. Davidson, D. T., and Handy, R. L. Property variations in the Peorian loess of southwestern Iowa. Iowa Acad. Sci. Proc. 59:248-265. 1952.
3. Davidson, D. T., and Handy, R. L. Studies of the clay fraction of southwestern Iowa loess. Iowa Eng. Exp. Sta. Eng. Rept. No. 22. 1954.
4. Eitel, Wilhelm. The physical chemistry of the silicates. The University of Chicago Press, Chicago. 1954.

5. Grim, R. E. Clay mineralogy. McGraw-Hill Book Co., New York. 1953.
6. Grim, R. E., and Cuthbert, F. L. The bonding action of clays. Part I.—Clays in green molding sand. Ill. Engr. Exp. Sta. Bul. 357. 1945.
7. Handy, R. L., Davidson, D. T., and Chu, T. Y. Effect of petrographic variations of southwestern Iowa loess on stabilization with Portland cement. Iowa Engr. Exp. Sta. Engr. Rept. 22, 1954. Hwy. Res. Bd. Bul. 98:1-20. 1955.
8. Handy, R. L., Lyon, C. A. and Davidson, D. T. Comparisons of petrographic and engineering properties of loess in southwest, east-central and northeast Iowa. Iowa Acad. Sci. Proc. 62:279-297. 1955.
9. Leadabrand, J. A. and Norling, L. T. Soil-cement test-data correlation in determining cement factors for sandy soils. Hwy. Res. Bd. Bul. 69:29-44. 1953.
10. Leadabrand, J. A. Norling, L. T. and Hurless, A. C. Soil series as a basis for determining cement requirements for soil-cement construction. Hwy. Res. Bd. Bul. 148. 1956.
11. Lyon, C. A. Petrography of four northeastern Iowa loess samples. M. S. thesis. Iowa State University Library. 1955.
12. Lyon, C. A., Handy, R. L. and Davidson, D. T. Property variations in the Wisconsin loess of east-central Iowa. Iowa Academy Sci. Proc. 61:291-312. 1954.
13. Powers, T. C., and Helmuth, R. A. Theory of volume changes in hardened Portland cement paste during freezing. Hwy. Res. Bd. Proc. 32:285-297. 1953.
14. Procedures for testing soils. Am. Soc. for Testing Materials, Philadelphia, Pa. 1950.
15. Rollins, Ralph. Movement of soil moisture under a thermal gradient. Ph.D. thesis. Iowa State University Library. 1954.
16. Scholtes, W. H., Ruhe, R. V. and Riecken, F. F. Use of the morphology of buried soil profiles in the Pleistocene of Iowa. Iowa Acad. Sci. Proc. 58:295-306. 1951.
17. Simonson, R. W., Riecken, F. F. and Smith, G. D. Understanding Iowa soils. Wm. C. Brown Co., Dubuque, Iowa. 1952.
18. Soil cement laboratory handbook. Portland Cement Association, Chicago. 1956.
19. Soil survey manual. U.S.D.A. Handbook No. 18. U. S. Department of Agriculture, Washington, D. C. 1951.
20. Standard specifications for highway materials and methods of sampling and testing, Part I. Am. Assoc. of St. Hwy. Officials, Washington, D. C. 1950.
21. Taber, Stephen. The mechanics of frost heaving. Jour. Geol. 38:303-317. 1930.
22. Winterkorn, Hans. The science of soil stabilization. Hwy. Res. Bd. Bul. 108: 1-24, 1955.

USE OF FLY ASH WITH PORTLAND CEMENT FOR STABILIZATION OF SOILS

by

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ABSTRACT

The results of a laboratory investigation of soil stabilization with Portland cement and fly ash are presented. The fly ash was used as a partial replacement for Portland cement or as an additive to mixtures already meeting the requirements of soil cement.

INTRODUCTION

One of the most common methods of soil stabilization in use today is with Portland cement. In this method pulverized soil is mixed with a predetermined amount of cement (water is added during mixing if the moisture content is less than required for compaction) and the mixture is shaped, compacted and moist-cured. The resulting product is *soil cement*, this term implying that the mixture is designed to meet specifications of strength and durability established by the Portland Cement Association⁸. Soil cement, properly designed and constructed, has a world-wide record of satisfactory field performance as a base course material for roads and airfields.

Despite the commendable performance record of soil cement, there is still room for improvement in its properties and in its economy of use, particularly with silty and clayey soils. Property improvements to be desired include decreased shrinkage and permeability and increased resistance to freezing and thawing. A reduction of the cement requirement without sacrificing needed strength and durability is desirable from the standpoint of both cost and the limited availability of cement in many areas during the last few years. The possibility of using fly ash to improve the properties and/or economy of soil cement was suggested by the extensive use of fly ash in concrete for these purposes.

Fly ash in concrete

Fly ash is the most commonly used commercial pozzolan. It is collected in large quantities from the smoke in power plants burning powdered coal.

Being a waste product fly ash is cheap, which explains the widespread interest in utilizing it in concrete, especially as a partial replacement for the more expensive Portland cement. Fly ash contributes to strength in concrete by reacting with the lime and alkalies liberated by the hydrating cement to produce a gel, perhaps similar to the gel formed by the hydration of Portland cement. Since the pozzolanic cementation develops more slowly than cementation from Portland cement hydration, 28 days or longer may be required to compensate for the initial strength loss in concrete due to replacing part of the cement with fly ash; the strength eventually may exceed that of concrete without fly ash^{2, 3, 5, 9}. According to published reports^{2, 3, 5, 9} the following benefits to properties of concrete, particularly mass concrete, may be obtained when fly ash is used to replace a portion of either the cement or sand: improved durability, workability and resistance to sulfate attack; decreased permeability, shrinkage, bleeding, evolution of heat and segregation of aggregates; reduced expansion from the reaction between alkalies of the cement and certain types of aggregates. Some of these benefits are desirable for soil cement.

Purpose of investigation

Although the use of fly ash in Portland cement concrete has been extensively investigated, there is little published material available on its use in soil cement other than the brief report on the limited studies made by the West Virginia State Road Commission¹. The purpose of the present laboratory investigation was to explore the possibility of benefiting Portland cement stabilization of sandy, silty and clayey soils by using fly ash either as a partial replacement for Portland cement or as an additive to the soil cement mixture. Unconfined compressive strength and resistance to freezing and thawing were used as the principal criteria of improvement.

MATERIALS USED

Soils

A description and the properties of the four soils used in the investigation are given in tables I and II. The samples are typical of major fine grained soil types in Iowa. The most detailed studies were with the friable loess; the plastic loess, alluvial clay and dune sand were used to obtain some test results with different textural types.

Portland cement and fly ash

Fresh samples of Portland cement and fly ash were used. Chemical composition and physical property data are given in table III.

Portland cement. The cement was marketed as Type I, the type commonly employed in soil cement construction. It may be classed as medium alkali cement (equiv. $\text{Na}_2\text{O} = 0.49\%$); the tricalcium silicate content of the

TABLE I. THE SOILS USED

	Friable loess (Lab. No. 20-2(V))	Plastic loess (Lab. No. 44A-1)	Alluvial clay (Lab. No. A1-1)	Dune sand (Lab. No. S-6-2)
Location	Harrison County SW Iowa	Page County, SW Iowa	Woodbury County, W Iowa	Benton County, E Iowa
Geological description	Wisconsin age friable loess, oxidized. Thick- ness over 100 ft.	Wisconsin age plastic loess, oxidized. Total thickness 15-20 ft.	Recent back- swamp clay from Missouri River. Thickness undetermined.	Wisconsin age eolian sand, fine-grained, oxidized. Thick- ness over 20 ft.
Soil series	Hamburg	Marshall	Luton	Carrington
Horizon	C	C	A-C	C
Sampling depth	39-40 ft.	4-5 ft.	0-3 ft.	1½-16½ ft.

TABLE II. PROPERTIES OF SOILS USED

	Friable loess	Plastic loess	Alluvial clay	Dune sand
Textural composition, %*				
Gravel (>2.0 mm)	0	0	0	0
Sand (2.0-0.074 mm)	0.4	0.2	1.5	95.8
Silt (74-5μ)	82.6	58.0	24.2	1.2
Clay (>5μ)	17.0	41.8	74.3	3.0
Colloids (>1μ)	12.3	31.0	55.1	2.9
Predominant clay mineral†	Montmoril- lonite and illite	Montmoril- lonite and illite	Montmoril- lonite and illite	Montmoril- lonite and illite
Probable predominant exchangeable cation	Calcium	Calcium	Calcium	Calcium
Specific gravity, 25°C/4°C	2.68	2.72	2.65	2.65
Chemical properties				
Cat. ex. cap., m.e./100 gm‡	13.4	28.2	39.4	1.5
Carbonates, § %	10.2	0.8	2.3	1.4
pH	7.8	6.2	7.3	7.4
Organic matter, %	0.2	0.5	1.7	0.17
Physical properties				
Liquid limit, %	32.9	53.1	71.0	91.0
Plastic limit, %	21.1	25.7	24.5	---
Plasticity index	11.8	27.4	46.5	N.P.
Shrinkage limit, %	28.3	19.9	10.2	---
Centrifuge moist. equiv, %	15.2	21.3	38.4	---
Classification				
Textural‡	Silty clay loam	Silty clay	Clay	Sand
Engineering (AASHO)	A-4(8)	A-7-6(18)	A-7-6(20)	A-3(0)

*Dispersed by air-jet with sodium metaphosphate dispersing agent.

†From differential thermal analysis of fraction passing No. 200 sieve.

‡Fraction passing No. 40 sieve.

§From differential thermal analysis.

+Textural classification is based on former Bureau of Public Roads system^{17, p. 18} except that sand and silt sizes are separated on No. 200 sieve (0.074 mm).

TABLE III. CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES
OF THE PORTLAND CEMENT AND FLY ASH

	Portland cement* (Type I)	Fly ash†
Chemical composition, %		
Silicon dioxide	21.8	41.9
Aluminum oxide	4.9	22.5
Ferric oxide	2.7	25.8
Calcium oxide	64.3	2.7
Magnesium oxide	2.2	1.0
Sulfur trioxide	2.2	0.8
Loss on ignition	1.0	3.6
Sodium oxide	0.21	0.3
Potassium oxide	0.41	---
Total equiv. alkalies as Na ₂ O	0.49	---
Insoluble residue	0.3	---
Free calcium oxide	1.0	---
Computed compound composition, %		
Tricalcium silicate	53.0	---
Dicalcium silicate	---	---
Tricalcium aluminate	8.3	---
Physical properties		
Specific gravity	---	2.61
Specific surface (Wagner), sq cm/g	1816	---
Specific surface (Blaine), sq cm/g	---	2720
Passing No. 325 sieve, %	---	88.7
Autoclave expansion, %	0.114	---
Time of setting (Gillmore test)		
Initial, hr.	3.0	---
Final, hr.	6.5	---
Compressive strength (1:2.75 mortar)		
At 3 days, psi	1815	---
At 7 days, psi	2525	---
At 28 days, psi	4000	---
Mortar air content, %	5.0	---

*Hawkeye Portland Cement Company, Des Moines, Iowa.

†Detroit Edison Company, St. Clair Power Plant,
Detroit (St. Clair), Michigan.

cement was 53%. Tricalcium silicate content is related to the amount of lime liberated during cement hydration, the more tricalcium silicate the more lime that should be available to react with a pozzolan. Type I and Type II cements contain more tricalcium silicate than Type IV. A larger replacement of cement by a pozzolan may be made when Type I or Type II cement is used than when Type IV is used⁴. Evidence was found that the alkali in the cement of cement fly ash mortars accelerates the pozzolanic reaction at earlier ages, but at later ages the amount of tricalcium silicate in the cement governs the benefits derived from the addition of fly ash to the mortar³.

Fly ash. The most reliable criteria for judging the quality of fly ash for use as a pozzolan in concrete appear to be the loss on ignition of the fly ash and the fineness of the fly ash as measured by the amount passing the No. 325 sieve³. The St. Clair Power Plant fly ash is representative of what is considered good quality fly ash.

METHODS USED

Cement requirement

The minimum percentage of Portland cement required for each of the soils to meet PCA criteria for soil cement was determined by the ASTM standard test procedures (ASTM Designations: D558-44, D559-44, D560-44).

Mixing and molding

Soil cement and fly ash mixes were proportioned and mixed dry; then optimum water content for maximum standard Proctor density was added and the material were machine mixed for 4 minutes.

Two inch diameter by 2 in. high specimens for unconfined compressive strength tests were prepared at approximate standard Proctor density with a double plunger drop-hammer molding apparatus. Four inch diameter by 4.6 in. high specimens for freezing and thawing tests were prepared with the standard Proctor compaction apparatus.

Curing

The specimens were double wrapped in waxed paper and aluminum foil to better preserve moisture and to prevent entry of carbon dioxide from the air. Curing for periods of 7, 28 and 120 days was done in a moist curing room at $70^{\circ} \pm 3^{\circ}$ F and a relative humidity of not less than 90%.

Unconfined compressive strength test

At the end of the 7, 28 or 120 day curing periods 2 in. by 2 in. specimens were unwrapped, immersed in distilled water for 24 hours and then tested for unconfined compressive strength using a load travel rate of 0.10 in. per minute. Tests were run in triplicate and average strengths reported in psi; no correction was made for the ht/diam. ratio which was one.

Freezing and thawing test

Seven and 28 day cured 4 in. by 4.6 in. specimens were used in the freezing and thawing test, which was conducted according to the ASTM standard procedure (ASTM Designation: D560-44) with the following modification: duplicate specimens were used for the loss on brushing measurements, and volume change was not determined.

FLY ASH AS AN ADDITIVE TO SOIL CEMENT

As an additive to soil cement, fly ash in the amounts used may be considered mainly a replacement for the soil, with the cement content remaining nearly constant. The extent to which this is true is shown by the upper abscissa scales in figures 1, 2, 3, 4, where on a total mix dry weight basis the maximum replacements of cement by fly ash are only 0.8% (friable

loess) to 1.6% (alluvial clay). Thus the lower abscissa scales, where both cement and fly ash contents are expressed as percentages of the soil dry weight, can be used to obtain an indication of the effect on strength and durability of varying fly ash as an additive when the Portland cement content is the minimum requirement for soil cement. The minimum cement requirements were 9% for the friable loess, 20 % for the plastic loess, 21% for the alluvial clay and 11% for the dune sand, all percentages being of the soil dry weight.

Effect on unconfined compressive strength

Friable loess. Adding fly ash to friable loess cement resulted in strength gains of about 10% after 7 and 28 days curing, but no gain due to fly ash

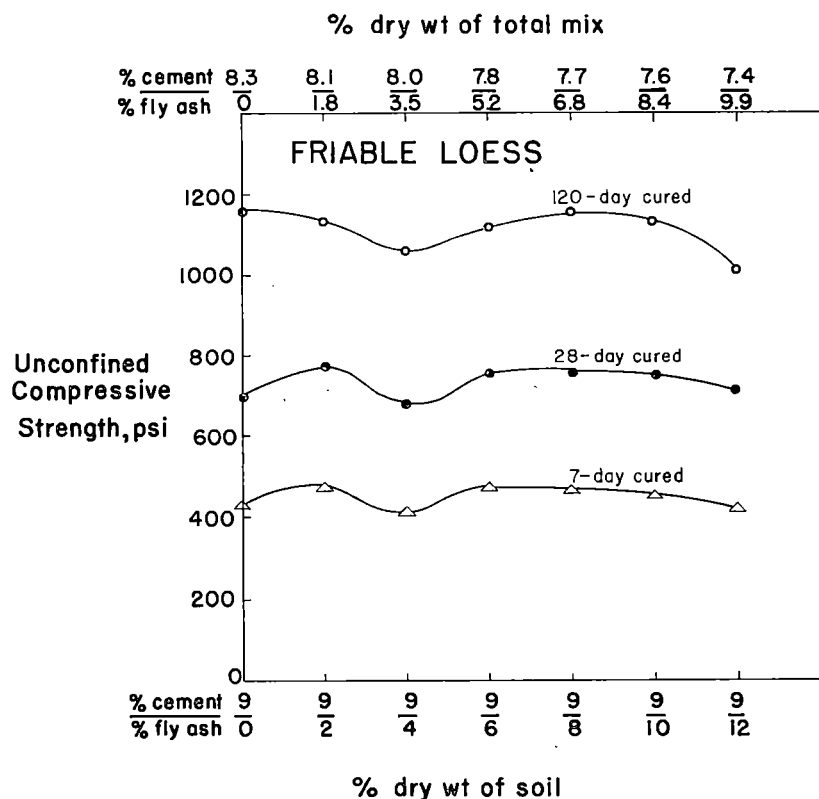


Fig. 1. Effect of fly ash additives to friable loess cement on immersed unconfined compressive strength, when the Portland cement content is near the minimum requirement for soil cement.

was apparent at 120 days (figure 1). No additional benefit to strength was obtained with more than 2% fly ash. The reason for the strength decrease with 4% fly ash, which occurred at all ages, is not known; but the decreases

with 10% and 12% fly ash probably reflect decreasing Portland cement content (see upper abscissa scale).

The strength gains are attributed to cementation products resulting from the pozzolanic reactions between the fly ash and the lime and alkalies liberated by the hydrating Portland cement, as discussed previously. With friable loess and the amount of cement used, evidently only a small amount of fly ash (about 2%) is needed to obtain maximum strength gain from pozzolanic reactions. No other benefits to friable loess cement from the use

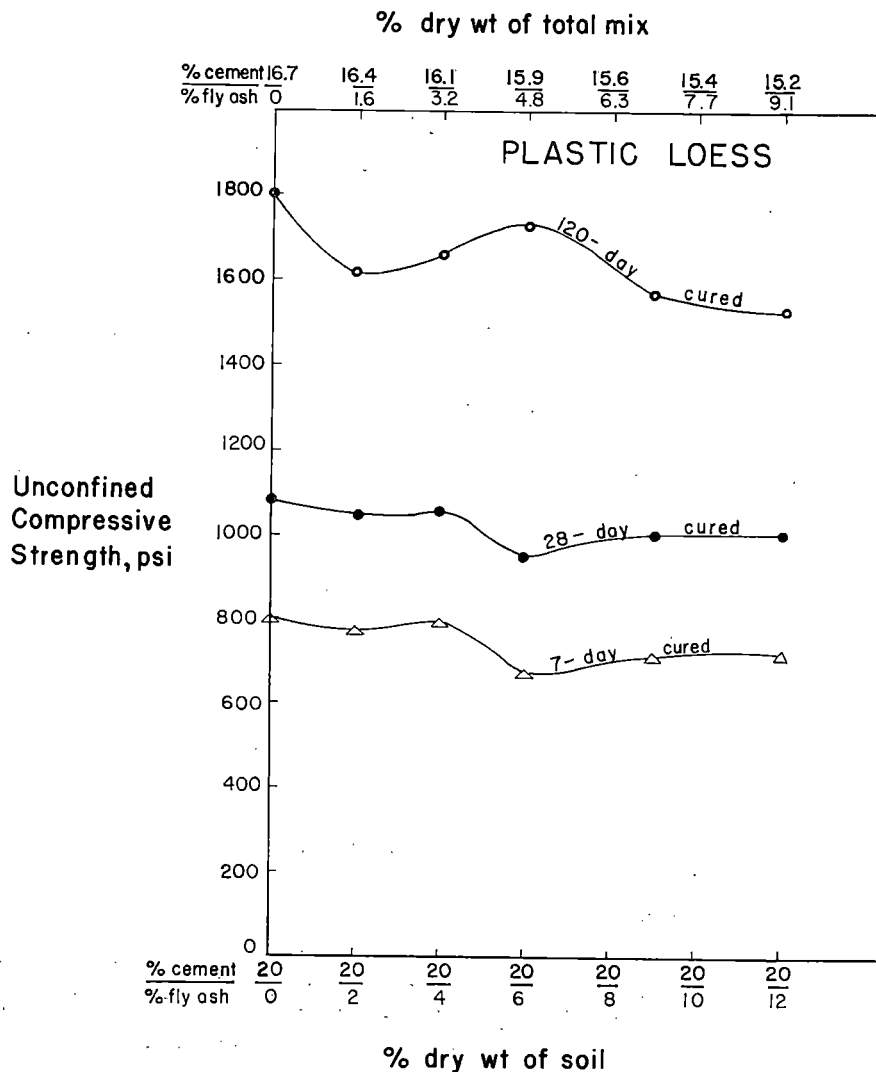


Fig. 2. Effect of fly ash additives to plastic loess cement on immersed unconfined compressive strength, when the Portland cement content is near the minimum requirement for soil cement.

of fly ash as an additive were observed. Compacted density was not significantly changed by the amounts of fly ash used.

Plastic loess. There was no indication of pozzolanic action in the plastic loess, cement, and fly ash mixes at 7, 28 or 120 days (figure 2). The slight decrease of 7 and 28 day strengths with increasing fly ash content may be due either to the lubricating action of the predominantly spherical fly ash particles or to the decreasing cement content (see upper abscissa scale) or to both effects. The 120 day strength data generally show the same trend as the 7 and 28 day, but the decrease in strength is considerably greater. The reason for the apparent irregularities in the curves is not known; they are not due to variation in compacted density, which was very slight.

Alluvial clay. The strength gains attributable to fly ash additives to alluvial clay cement are mainly due to reduction of shrinkage during curing (figure 3). This benefit was especially evident for 120 day cured speci-

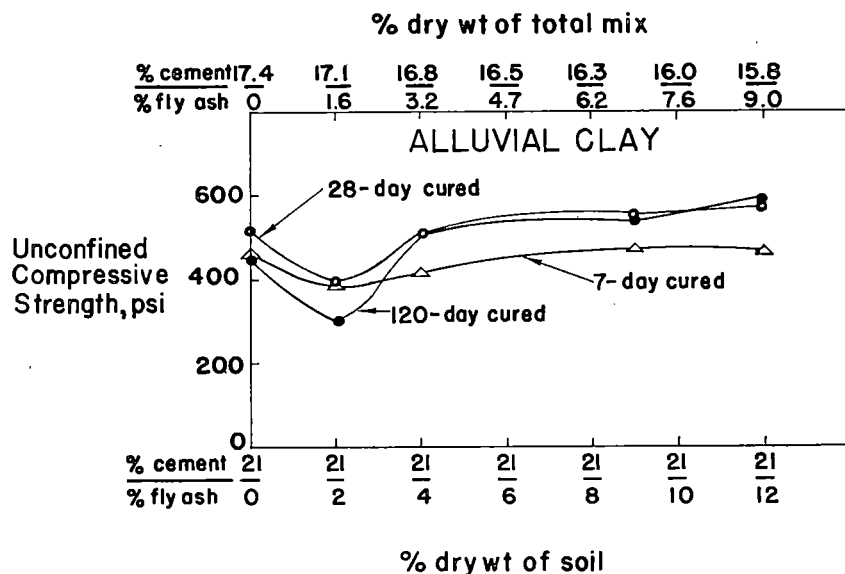


Fig. 3. Effect of fly ash additives to alluvial clay cement on immersed unconfined compressive strength, when the Portland cement content is near the minimum requirement for soil cement.

mens; those containing no fly ash were badly cracked, which is the reason the zero fly ash strength is lower at 120 days than at 7 and 28 days. Four percent or more of fly ash reduced cracking of 120 day cured specimens, and those containing 9% and 12% fly ash showed no surface cracks. As with friable loess and plastic loess, the fly ash additives to alluvial clay and cement did not cause significant variation in compacted density.

Dune sand. The most encouraging results with fly ash as an additive

were obtained with dune sand cement (figure 4). At 120 days the gain in strength with 4% to 6% fly ash was about 28% greater than the strength without fly ash. The beneficial effects of fly ash in the dune sand cement are attributed to two related factors: first, the fly ash acted as a filler—

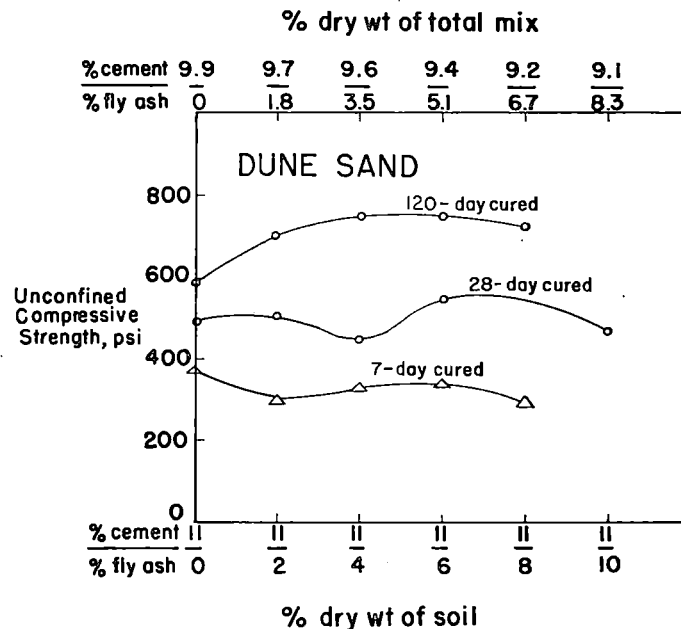


Fig. 4. Effect of fly ash additives to dune sand cement on immersed unconfined compressive strength, when the Portland cement content is near the minimum requirement for soil cement.

6% increased the compacted density from 114.9 to 117.2 pcf; second, the fly ash acted as a pozzolan and the resulting cementation was made more effective by the improvement in grain contact areas. At 7 days the lubricating quality of the fly ash evidently overshadowed the beneficial effects, resulting in a net decrease in strength, but at 28 days the benefits appear and continue to increase up to 120 days.

Comparison of benefits. The different results obtained with the four soils indicate that soil texture has an important effect on the benefits from fly ash as an additive in soil cement. Although this investigation was not extensive enough to obtain a correlation between beneficial pozzolanic activity and the clay content of soil, there is evidence that such a relationship exists. In the two high clay content soils, plastic loess (41.8% 5 micron clay) and alluvial clay (74.3% 5 micron clay), there was no sign of beneficial pozzolanic reactions between fly ash and hydration products of Portland cement, presumably because of clay coatings on the fly ash or fixation

of lime by clay or a combination of both effects. In the friable loess (17% 5 micron clay) and in the dune sand (3% 5 micron clay), sufficient lime and alkalies from the hydrating Portland cement were available to react with from 2% to 6% fly ash; the best strength gains due to pozzolanic reactions were obtained with the dune sand, probably because of its low clay content.

The other beneficial effects of fly ash additives in soil cement, reduction of shrinkage cracking in the alluvial clay mixes and improvement of gradation in the dune sand mixes, are also important, particularly to ultimate strength.

Influence of cement content. The friable loess was used to check on the beneficial effect of fly ash additives when the Portland cement content is above and below that required for soil cement, in this case 9%. At 7 days there is definite indication of increased pozzolanic action for cement contents higher than 9%: for 15% cement the strength gain due to fly ash reached a maximum of 53% with 4% fly ash, as compared with the 40% gain for 12% cement with 2% fly ash, and the 10% gain for 9% cement with 2% fly ash (figure 5A). For cement contents less than 9% there was

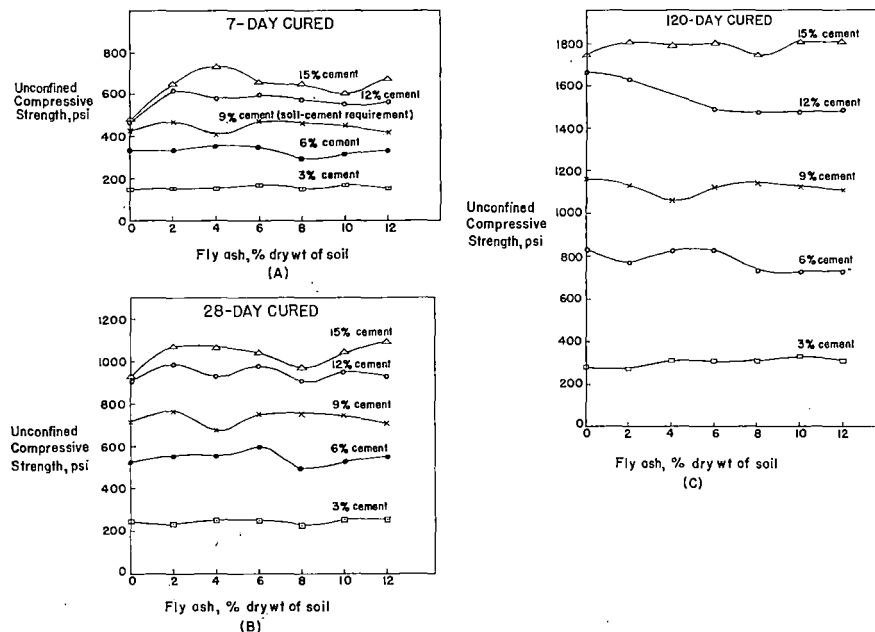


Fig. 5: Effect of fly ash additives to friable loess cement on immersed unconfined compressive strength, when the Portland cement content is above and below the minimum requirement for soil cement.

little or no indication of pozzolanic activity. Thus it appears that with the friable loess and the Type I Portland cement used, at least 9% cement is needed to provide sufficient lime and alkalies for significant pozzolanic re-

actions with fly ash at 7 days. The use of larger amounts of cement resulted in the formation of more reaction products as evidenced by the greater strength gains.

The 28 day strength curves (figure 5B) generally display the same trends as the 7 day curves, but the strength gains from pozzolanic action are less. At 120 days (figure 5C) there is little or no remaining evidence of benefit to strength from pozzolanic action. The apparent decrease of

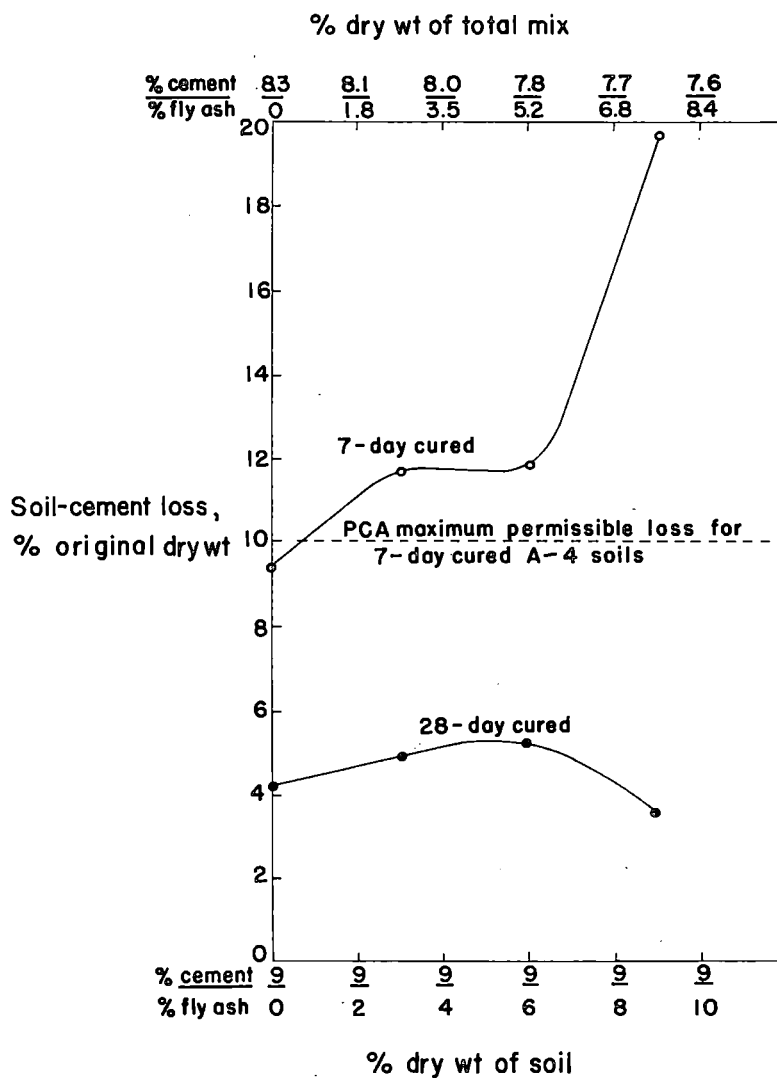


Fig. 6. Effect of fly ash additives to friable loess cement on 12-cycle freeze thaw resistance, when Portland cement content is near the minimum requirement for soil cement.

pozzolanic activity with increased curing time is contrary to expectations; it will be recalled that the opposite trend was obtained in the experiments with dune sand. It may be that there was no reduction of pozzolanic activity at 28 and 120 days, as would appear from the data, but rather that there was interference of some sort with the normal Portland cement hydration process. This of course is just a guess.

Effect on freeze-thaw resistance

Although it is known that a relationship exists between the unconfined compressive strength and freeze thaw resistance of soil cement, there is always the possibility that an additive to soil cement, such as fly ash, will produce unexpected results. As a check on this, the effect of fly ash on the freeze thaw resistance of soil cement was studied with the friable loess. To save on testing time, only the soil cement weight loss with brushing part of the standard freeze thaw test procedure was conducted.

According to the PCA criteria for soil cement, the maximum permissible friable loess cement loss in weight during 12 cycles of freezing and thawing, with brushing after each cycle, is 10% of the original dry weight of the test specimen. The addition of fly ash to friable loess cement increased the 12 cycle weight losses of 7 day cured specimens to above the maximum permissible value; fly ash contents greater than 6% appear especially detrimental, probably because of the lubricating action of the fly ash and the consequent lowered resistance to brushing (figure 6).

If the interpretation of a lubrication effect is correct, it would mean that the brushing test is relatively more severe for soil, cement, and fly ash mixtures than for soil cement, and the results should be weighed accordingly. Brushing of course does not correspond to any expected field usage of soil, cement, and fly ash in base course construction, since resistance to abrasion is not required.

The weight losses of 28 day cured specimens, both with and without fly ash, were considerably lower than the 7 day maximum allowable loss. Also, on the basis of the 28 day data, fly ash additives to friable loess cement appear to be much less detrimental to freeze-thaw resistance, possibly because the increased pozzolanic activity with longer curing compensated for some of the fly ash lubrication effects.

FLY ASH AS A PARTIAL REPLACEMENT FOR PORTLAND CEMENT

This part of the investigation was made to determine the feasibility of using fly ash as a partial replacement or substitute for Portland cement in soil cement. The replacement of cement with fly ash is expressed in two different ways (figures 7, 8, 9, 10, 11). The bottom abscissa scales show the

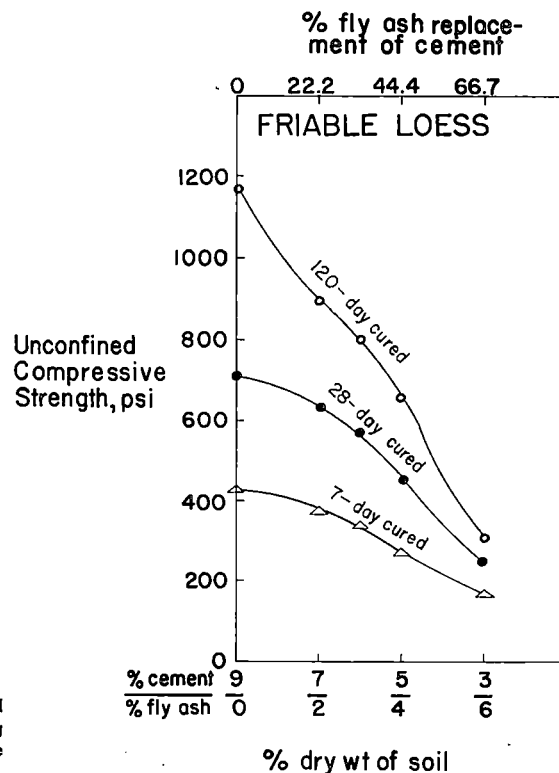


Fig. 7. Effect on immersed unconfined compressive strength of partially replacing Portland cement with fly ash in friable loess cement.

relative percentages of cement and fly ash on the basis of the dry weight of the soil; the top scales express the fly ash replacement of cement as a percentage of the cement requirement for soil cement.

Effect on unconfined compressive strength

Even a cursory examination of the data trends (figures 7, 8, 9, 10) shows that cementation from pozzolanic reaction products does not compensate for that lost due to the reduction of Portland cement content. Apparently not enough lime and alkalies are available for beneficial pozzolanic reactions with fly ash when the cement content is below that for soil cement; this conclusion is also supported by the previously discussed data (figure 5). It is possible that replacements smaller than those tried might cause only slight loss of strength, but this possibility is of little practical interest, since it seems doubtful that fly ash would be used in the field in quantities less than 2% of the dry soil weight.

The only definite benefit from fly ash as a replacement for Portland cement was observed with the 120 day cured alluvial clay, cement, and fly ash specimens which showed an increase in strength due to less shrinkage cracking (figure 9).

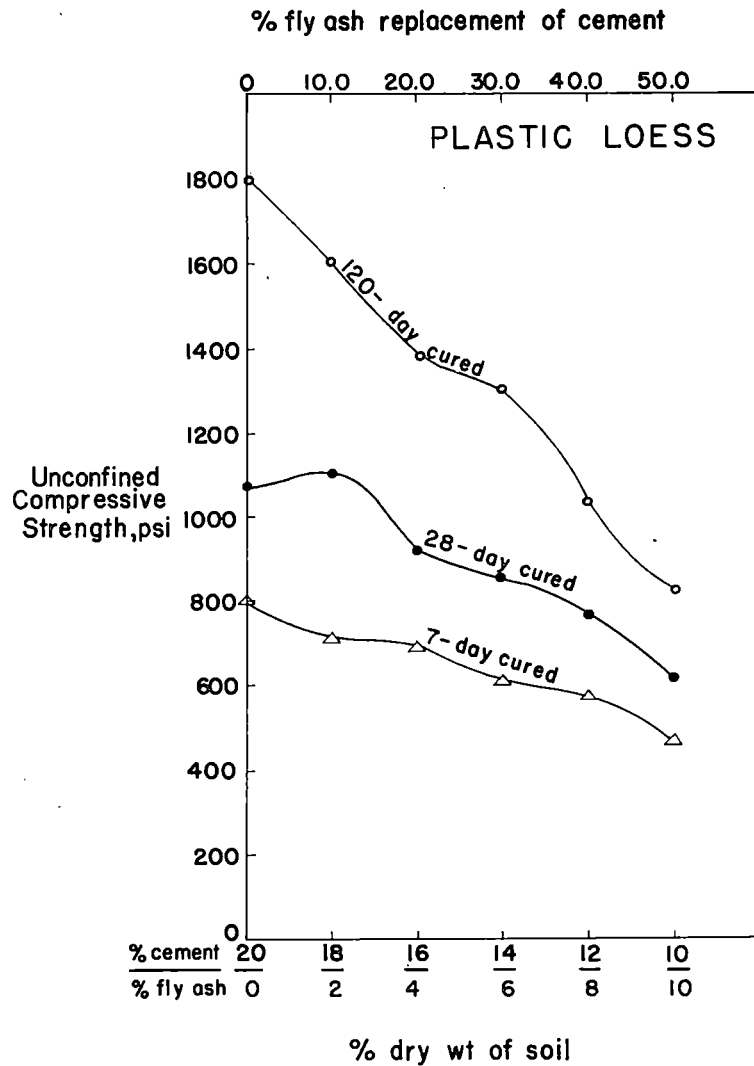


Fig. 8. Effect on immersed unconfined strength of partially replacing Portland cement with fly ash in plastic loess cement.

Effect on freeze thaw resistance

The question naturally arises, how strong does soil cement have to be? Maybe some strength reduction is permissible providing resistance to freezing and thawing is satisfactory?

The answer for one soil, the friable loess, is that freeze-thaw resistance at both 7 and 28 days is drastically decreased by even small replacements of cement by fly ash (figure 11).

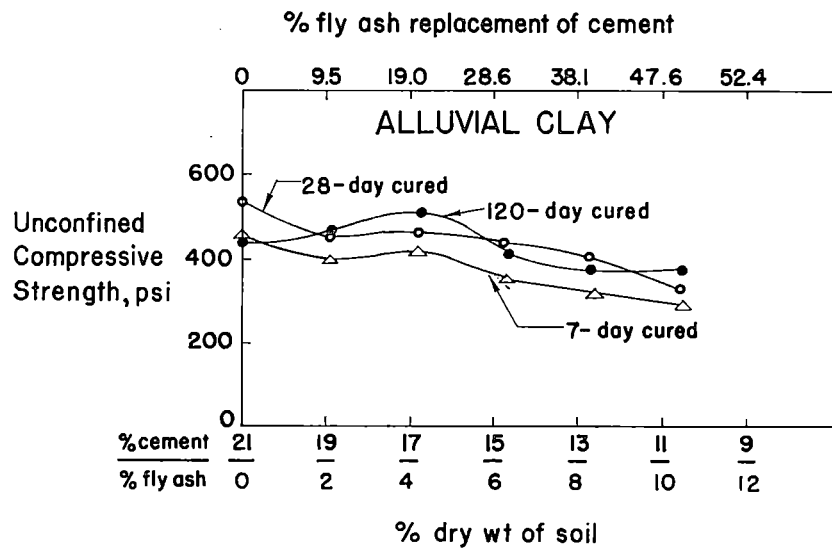


Fig. 9. Effect on immersed unconfined compressive strength of partially replacing Portland cement with fly ash in alluvial clay cement.

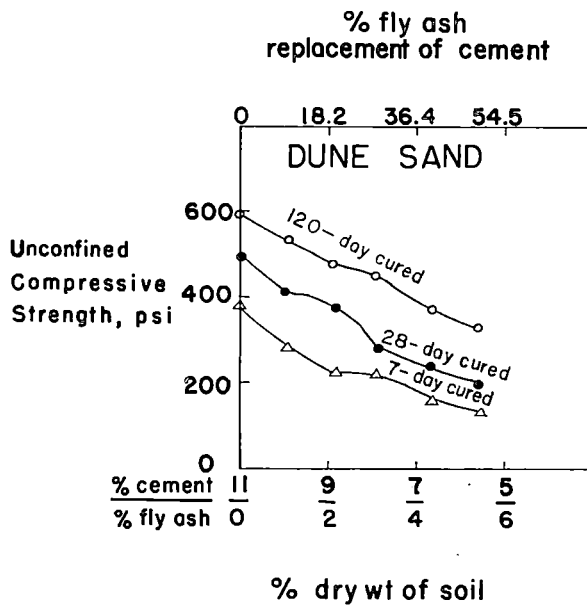


Fig. 10. Effect on immersed unconfined compressive strength of partially replacing Portland cement with fly ash in dune sand cement.

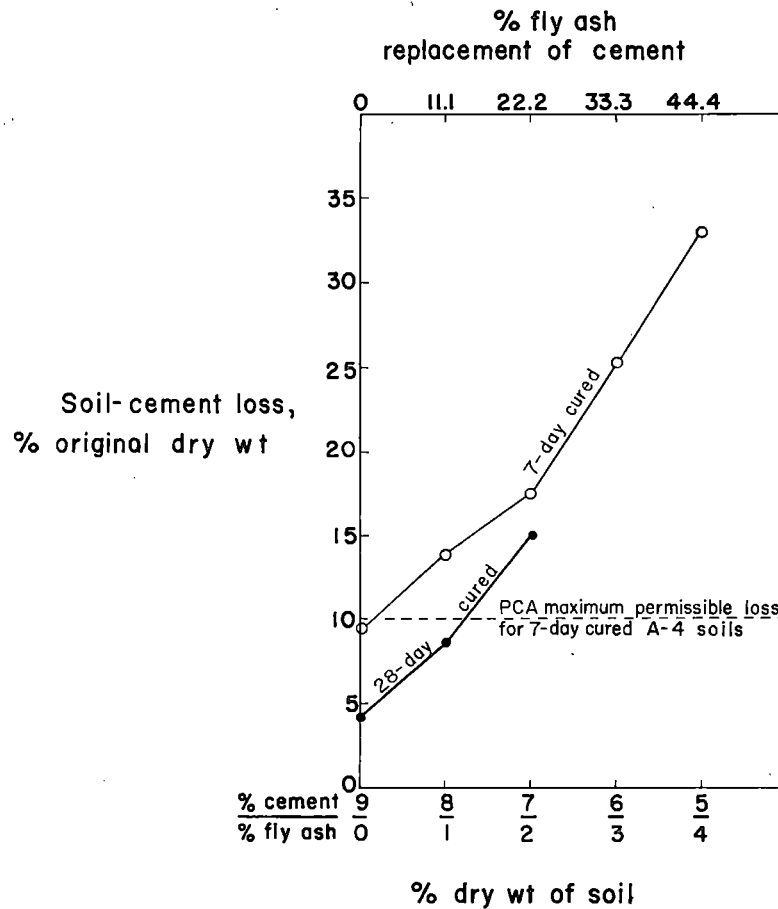


Fig. 11. Effect on 12 cycle freeze-thaw resistance of partially replacing Portland cement with fly ash in friable loess cement.

CONCLUSION

In conclusion it would seem that for use in soil stabilization with Portland cement, fly ash is more promising as an additive than as a replacement for part of the Portland cement.

The greatest benefits from fly ash as an additive in soil cement appear to be obtainable with poorly graded, low clay content soils such as dune sand, in which improvement in strength is the result of more surface contact areas and complementary cementation from pozzolanic reaction products.

Fly ash, both as an additive and as a partial replacement for cement, was observed to reduce shrinkage cracking during curing of Portland cement stabilized highly plastic clay soil. Whether sand or other relatively inert material would have been equally effective was not determined.

REFERENCES CITED

1. Baker, F. F. Discussion. In Minnick, L. J. and Miller, R. H. Lime-fly ash compositions for use in highway construction. pp. 498-499. Proc. Highway Research Board. 30:489-502. 1950.
2. Blanks, R. L. Fly ash as a pozzolan. Jour. Am. Concrete Inst. 21 (No. 9): 701-707. 1950.
3. Brink, R. H. and Halstead, W. J. Studies relating to the testing of fly ash for use in concrete. Proc. Am. Soc. Testing Mats. 56:1161-1214. 1956.
4. Davis, R. E. A review of pozzolanic materials and their use in concrete. ASTM STP No. 99, p. 3. Am. Soc. Testing Mats. Philadelphia, Pa. 1949.
5. Davis, R. E., Davis, H. E. and Kelly, J. W. Weathering resistance of concrete containing fly ash cements. Jour. Am. Concrete Inst. 12 (No. 3):281-293. 1949.
6. 1955 Book of ASTM Standards, Part 3, p. 201. Am. Soc. for Testing Materials, Philadelphia. 1955.
7. Principles of highway construction as applied to airports, flight strips, and other landing areas for aircraft. U. S. Public Roads Adm., Washington, D. C. 1943.
8. Soil cement laboratory handbook. Portland Cement Association. Chicago. 1956.
9. Timms, A. G. and Grieb, W. E. Use of fly ash in concrete. Proc., Am. Soc. Testing Mats. 56:1139-1160. 1956.

CEMENTATION OF SOIL MINERALS WITH PORTLAND CEMENT OR ALKALIS

by

R. L. Handy, Associate Professor, Civil Engineering

(Highway Research Board Bulletin 198. 1958.)

ABSTRACT

Although cementation of mineral surfaces has obvious importance in coarse graded mixtures such as concrete, surface reactions become even more important in finer grained mixtures such as soil cement because of the far greater surface areas involved.

Unexpected long-term cementation of certain soil cement mixtures has led to a hypothesis of hardening involving not only changes in the hydrating cement gel, but also changes within the surface layer of the mineral grains. The hypothesis follows Weyl's proposals of polarization and readjustment of ions near the surface of a solid to compensate partly for the unbalance in forces at that surface. Theoretically, such polarization and distortion screening should reduce the potential of a surface for chemisorption, or chemical bonding to other ions.

Once a mineral comes in close contact with an inorganic cementitious gel, bonds developing between the mineral surface and the gel should tend to reduce the unbalance in forces at the mineral surface. Because the cause of initial polarization is less, the screening to reduce surface energy may reasonably be expected to become less. Reduced polarization then allows improved chemical bonding at the surface of the mineral, which in turn allows a further reduction in screening. Thus a bond should show a gradual increase in strength over a period of time.

The data show a logarithmic relationship between compressive strength of soil cement and curing time. The relative polarizability of various minerals and pozzolans in general correlates with the rate of strength gain and response to high temperature curing. Reactions are enhanced by use of alkalis which aid readjustment of the screened zones.

INTRODUCTION

Cementation can be imagined as a combination of mechanical bonding of the cement to rough mineral surfaces, plus chemical bonds developing

between the cement and the mineral surfaces. The latter process becomes more important as materials become finer grained—surfaces tend to be smoother, and more surface area is available. Portland cement stabilization of fine grained soils thus emphasizes the chemical aspect, although answers obtained here would be expected to apply to a lesser extent in the cementation of coarse materials.

The present paper offers a hypothesis whose only pretense is perhaps to be reasonable in context, albeit rather evasive in proof.

BONDING IN MINERALS

Minerals are crystalline; they have an orderly internal arrangement of atoms. The bonding between atoms is primarily ionic in character, though there is covalence, or electron sharing. Purely ionically bonded atoms retain their respective electrons and are attracted electrostatically because of the net plus and minus charges. These are not true bonds in the strict sense of the word; they are forces. Adjacent oppositely charged ions may be said to screen each other, since they act to balance out each other's forces.

Evidence shows that these two types of bonds, ionic and covalent, are transitional, and both can be in any one linkage. Pauling¹² working with halides, developed expressions relating the percentage of ionic character in a bond to the "electronegativity" of elements making up that bond. Electronegativity is the ability of atoms in a molecule to attract electrons. Electronegativities show a close relation to position of the element in the Periodic Table (table I, figure 1). The greater the difference in electronegativity be-

TABLE I. ELECTRONEGATIVES OF ELEMENTS¹²

Element	Electronegativity
H	2.1
C	2.5
O	3.5
Na	0.9
Mg	1.2
Al	1.5
Si	1.8
P	2.1
S	2.5
Cl	3.0
K	0.8
Ca	1.0
Fe	1.7

TABLE II.

Bond	Percent ionic characters*
K - O	84
Na -	82
Ca - O	79
Mg - O	73
Al - O	63
Fe - O	56
Si - O	51
H - O	39
C - O	22

* $P = 1 - e - \frac{1}{4}(X_A - X_B)^2 \cdot 100$.
A modified treatment³, gives $P = 16(X_A - X_B) + 3.5(X_A - X_B)^2$.
Neither relationship is perfect because of difficulties in evaluating effects of resonance.

tween two elements, the greater the percentage of ionic character in their bond.

A measure of ionic vs. covalent bonding, as well as actual positions of atoms, is obtained by plotting electron densities from various crystal planes

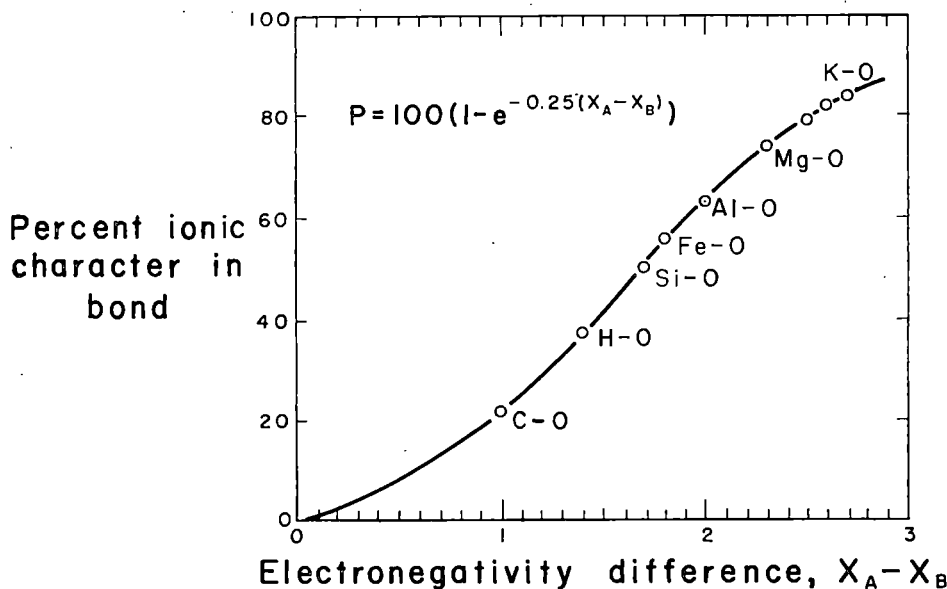


Fig. 1. Percent ionic character in bonds. Calculated after Pauling¹.

by techniques involving three dimensional Fourier analysis of X-ray diffraction intensities. In an ionic crystal such as sodium chloride the electron density falls to zero between adjacent positive and negative ions. In a covalent crystal such as diamond the electron density between adjacent atoms does not fall so low (about 1.7 per cubic Ångström in the case of diamond). In intermediate crystals the minimum electron density is intermediate⁵.

For the most part the percentages of ionic character in various bonds occurring in minerals have not been measured, and one must rely on the relationship of Pauling to obtain average values (figure 1). Calculated values important in minerals are as follows.

Of these only H-O and C-O are predominantly covalent in character. These occur as distinctive units in minerals, H-O as OH or in H₂O; C-O as CO₃ groups in the carbonate minerals. The Si-O bond is borderline.

So far the picture is relatively simple, and calculation of ionic character is uncomplicated if one anion and one cation combine to make up a molecule. But minerals often contain several kinds of cations, for example orthoclase feldspar, KAlSi₃O₈, and anions are usually shared by two or more cations. Pauling's theories have been applied to mineral stability, by calculating the average electronegativity of all cations and adding a correction "bridging factor" for sharing of the O ions⁶. Such a simplification is practical because in most minerals all cations are bonded to oxygen.

In discussing bond type, Pauling refers to "polarization," or electron shell deformation effects. Covalent bonds occur only when polarizability of

the participant atoms allows the electron swarms to be distorted.

POLARIZATION AND SCREENING OF MINERAL SURFACES

Mineral grain interiors are essentially ions captured in a three-dimensional network of electrical forces. At a surface the continuity is interrupted and force patterns are disrupted. Surface tension is one result; the partial reorientation causes attractive forces to be diverted into the plane of the surface.

In a solid, several mechanisms may operate to reduce the energy in a surface. One of these, sorption of ions and molecules, is the goal of cementation. A second mechanism is polarization of the surface ions, or distortion of their electron swarms¹⁶ (figure 2b). Unbalanced forces are represented

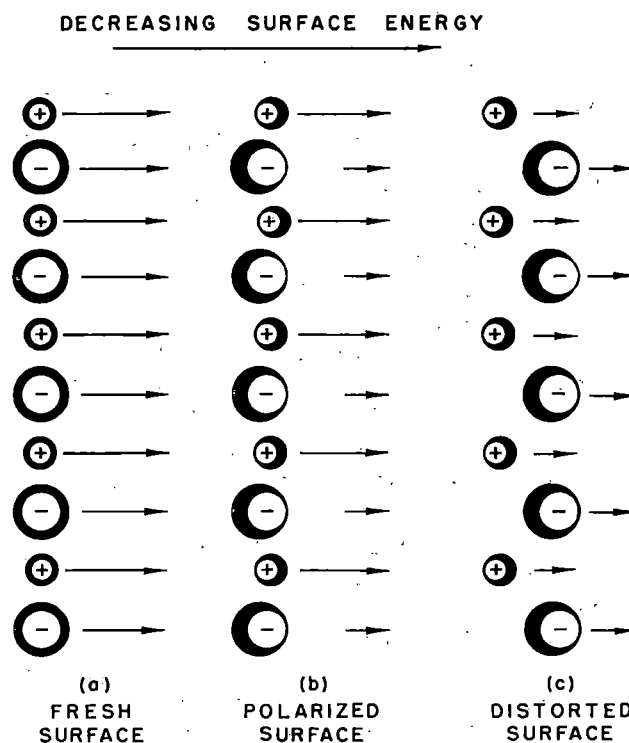


Fig. 2. Polarization (b) and distortion screening (c) in a 100 NaCl surface. After Weyl⁴.

by arrows in the figure; and polarization tends to reduce the unbalance. Polarization is believed to be more pronounced in anions than in cations because of the larger diameter of electron swarms about anions. Thus polarization tends to create a negatively charged surface on a crystal. The extent to which polarization will take place varies depending on the nature of the ions and coordination of the bond. Large ions polarize more easily; small

ions not at all.

A third process suggested for reducing surface energy is distortion of the surface layer, the larger ions becoming slightly displaced and tending to "screen" the smaller cations. This would result in the formation of an electrical double layer in the surface of a mineral, the outer layer being negative (figure 2c). The difference from polarization is mainly one of degree, in that distortion in the surface layer also disturbs the force pattern of ions deeper in the crystal, and distortion screening effects probably extend a finite depth before dying out. The distortion mechanism may be analogous to the formation of an "amorphous" Beilby layer in metals.

A fourth mechanism important in stabilization of colloids is the formation of an electrical double layer by predominant adsorption of anions to screen the exposed cations. The process is here considered as part of chemisorption.

Comparison of mechanisms

Polarization of surface ions. Of the above surface phenomena, polarization would be expected to take place on the crystal surfaces containing large ions having readily polarizable electron swarms. Polarization involving only the surface ions probably takes place rather quickly. Screening should be most effective when the number of cations is small compared to the number of polarizable anions, since cations can then be screened more easily. Polarization would presumably be decreased by covalent bonding tending to tighten the electron swarms around the affected ions. Analysis of these factors suggests that silicates in general are only faintly polarizable in their surface layers.

Structural screening. That surface ions are limited in their adjustment by the ions underneath does not mean that screening cannot occur; it means that ions underneath must move also. Eventually a surface zone of distortion may develop, with each successive layer of ions less out of place than the next one above. The sum of these distortions may add up to an effective screening. X-ray diffraction of fine quartz powders reveals a strongly distorted zone extending 0.3 to 0.5 micron in from the surface. That these adjustments take time is evidenced by the fact that freshly ground quartz is chemically very active; it can lower the pH of water to below 5, presumably by adsorption of OH ions to cover unscreened Si^{+4} sides, and it can cause silicosis in man. The affinity of fresh quartz surfaces for anions is further indicated by presence of ozone in the grinding mill; O_2 covalent bonds are broken to supply oxygen ions and give a byproduct of $\text{O} + \text{O}_2 = \text{O}_3^{16}$. Quartz which has aged a while is apparently less reactive and probably less dangerous.

For reasons discussed later, quartz probably has an unusually high amount of surface zone distortion, and it is interesting to note the relation between quartz weathering and particle size. Quartz with its screened sur-

face is ordinarily rather resistant to weathering, more so than the feldspars, yet in the clay size range the relative positions of quartz and feldspars are reversed°. Probably in fine particles the distortion effects fading in from one side of a crystal are met by similar effects trying to fade in from the other. The result is less effective screening and a surface more susceptible to attack.

Chemisorption. Adsorption of ions takes place to satisfy bonding energies unshielded by either polarization of surface ions or the deeper structural screening. Even mild chemisorption reduces the surface energy. For example, a polar liquid such as water will temporarily satisfy some of the surface forces and cause a reorientation, reducing surface tension and decreasing the scratch hardness of many silicate minerals. That is why quartz grinds more easily when wet with water and glass scribes more easily if the cutter is wet with water. The adsorption of OH ions also contributes to solubility by reducing surface tension of the quartz. Quartz and silica glass are much more soluble in alkaline than in neutral or acid solutions.

ALKALI REACTIONS

Alkali reaction proceed most rapidly with amorphous or glassy materials such as opal, opaline chert, and volcanic ash¹³. The reactions are not generally recognized as proceeding with quartz. This serves to emphasize an important point: a structurally screened surface zone is not randomly constituted as is a glass. The random bonding in a glass contributes to "weak places" which make the surface highly susceptible to attack. Screening distortions, however, increase the resistance to attack. Though screening would also be expected in a glass, reducing the suitability for reaction, because of the disorganized internal structure, screening may not shield cations symmetrically, as in crystals.

CEMENTATION

Portland cement is an alkaline substance. Na₂O and K₂O are often present in minor amounts, the amounts being limited to reduce alkali reactions with bad aggregates. Since Ca(OH)₂ is released on hydration, hydroxyl ions are available for immediate bonding to quartz. Polarization of the O ion may weaken the O-H bond and thus possibly result in the loss of a hydrogen. OH ions exchange for O ions in the surface of quartz, the displaced O ions being then bonded to the H⁺. OH ions in this position are pre-

sumably more polarizable. The picture is then $-\overset{|}{\underset{|}{\text{Si}}}-\overset{|}{\underset{|}{\text{O}}}-\overset{|}{\underset{|}{\text{Si}}}-$ distorted to

$\overset{|}{\underset{|}{\text{O}}}-\overset{|}{\underset{|}{\text{Si}}}-\overset{|}{\underset{|}{\text{O}}}-\overset{|}{\underset{|}{\text{Si}}}-$ as oxygens move out. Adsorption to complete the screening

is either $\begin{array}{c} \text{Si} \quad \text{Si} \\ \diagdown \quad \diagup \\ \text{O} \quad \text{O} \\ \diagup \quad \diagdown \\ \text{H} \quad \text{H} \\ \diagdown \quad \diagup \\ \text{O} \quad \text{O} \end{array}$ or a direct adsorption of OH onto partially covered Si, $\begin{array}{c} \text{Si} \quad \text{Si} \\ \diagdown \quad \diagup \\ \text{OH} \quad \text{OH} \\ \diagup \quad \diagdown \\ \text{O} \quad \text{O} \end{array}$

A theory of hydration has been developed to show how a quartz surface might assume the configuration of a feldspar or mica, thereby increasing the probability of intergrowth with those minerals⁴.

A theory has been suggested in a study of bonding with cement pastes that cement gel develops spontaneously on a mineral surface, bonding to the exposed oxygens, growing by polymerization of the SiO_4 groups, and incorporating free calcium ions into the linked SiO_4 superstructure^{10, 11}. Bonding thus depends on the number of surface oxygens either in the ionic or covalent state. Early bond strength is related to the effective number of oxygen ions, and later bond strength to the degree of covalent bonding of oxygens. Covalent linkages strengthen as a result of the continuing polymerization.

This theory would at first suggest that structural displacement screening would improve early cementation by increasing the exposed area of oxygen ions. But an unscreened or partially screened surface will immediately become coated by oxygens or OH ions from solution. Neither of these factors enter into the theory except indirectly, since both screening and effective ion calculations depend on kind and number of internal cations.

ADJUSTMENTS FOLLOWING CEMENTATION

The strength of soil cement and concrete continues to gain through years, although data on mortars show that cement hydration has essentially stopped after about 24 months². There is some relationship between strength of a Portland cement stabilized silt and time, with strengths reaching almost 3000 psi³. The increase in slope (the exponent on t) between 6 and 10 percent cement is significant, but the change from 10 to 14 percent cement is rather small. This suggests that above a certain minimum content of cement the hardening does not depend on changes in the gel but reflects increased bonding to the mineral crystals. If the gel alone were affected, there should be a closer relationship between slope and cement content. Also, the failures appear to involve breaks from the grain surfaces, not breaks through the grains, as sometimes occur in coarse aggregates in concrete.

It appears that, as cementation proceeds, screening by polarization and distortion may change. Development of new bonds on an ionic surface should logically cause an immediate reorganization of the force pattern,

the amount of the reorganization depending on the strength and number of cementation bonds. The net effect should be to reduce the surface disruption that caused screening and to cause structural adjustments which would increase cementation by providing a more satisfactory atomic surface pattern. Should a previous nonstoichiometric surface adsorption be involved, diffusion of cations through the cement gel could make up the valence deficiency. The increased bond strength might then cause a further change in screening, which would give a further boost to bond strength. There may be an interdependence whose effect is to put a time lag in the strengthening of cementation bonds.

The time necessary for such hypothetical adjustments to take place is not known. If the polarization effects were only "skin-deep" (figure 3b),

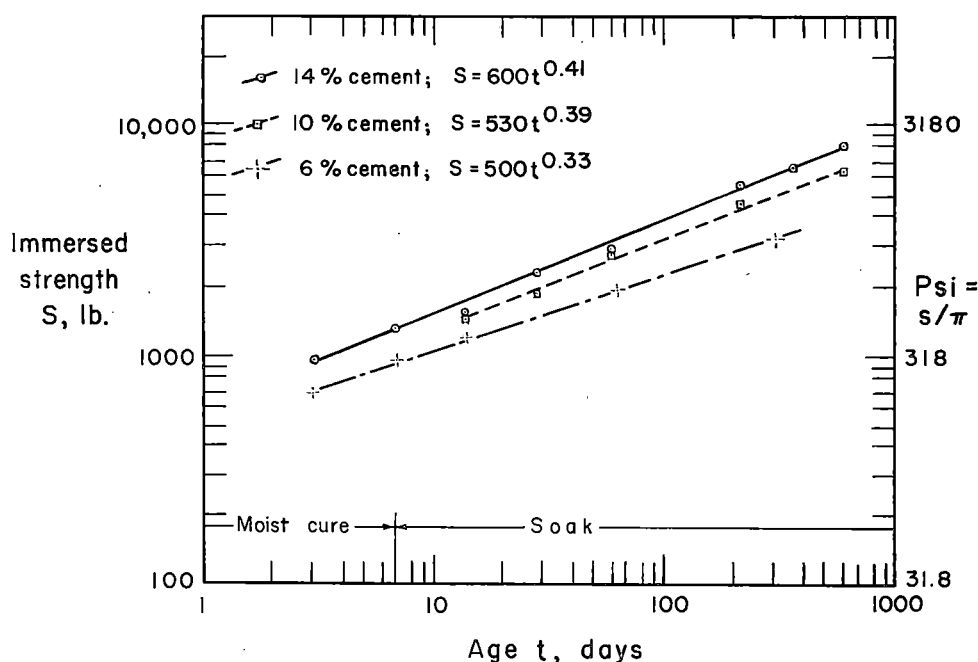


Fig. 3. Relation between time and strength of 2" x 2" diameter soil cement cylinders with Iowa loess sample 20-2. Samples were continuously soaked after initial 7 days moist curing.

adjustments should be almost immediate, since they involve only the surface electron swarms. But if screening involves distortions extending tens or hundreds of ions into a crystal, with distortion of each successive layer depending on unbalanced forces set up by distortions in the last, time may become important.

The time required for adjustments to improve cementation should be longer than the time for structural screening of a fresh surface. Original

screening was caused by a sharp discontinuity at the surface, but the opposing forces of cementation are at first comparatively weak. Since their weak force pattern must be mirrored by an adjustment in screening before a stronger pattern can develop, the lag in time may be considerable. The long-term effect is a slow relaxation of screening and an increase in bond strength.

ACTIVATION

Heat

The previous discussions suggest that quartz, with its deep surface zone distortions, may be a bit slow in developing the fullest cementation bond strength. One way to hasten readjustments in the surface zone may be by use of heat. Data show a high strength gain of quartz mortars after autoclaving at 150°C (table III). The same is true for mortars made with

TABLE III. TENSILE STRENGTHS OF MORTAR BRIQUETS IN PSI.
MINERALS CONSTITUTE 1:4 BY VOLUME¹⁵

Aggregate	Formula	52 hour moist cure	24 hour moist cure, 24 hour autoclave 150°C, broken at 52 hr.	52 hour moist cure, 14 months soak
Rose quartz	SiO ₂	92	515	340
Smoky quartz	SiO ₂	84	540	360
Milky quartz	SiO ₂	85	575	410
		87	545	370
Microcline	KAlSi ₃ O ₈	90	105	450
Plagioclase (Labradorite)	NaAlSi ₃ O ₈ + CaAl ₂ Si ₂ O ₈	111	210	405
Marble	CaCO ₃	78	90	370
Magnesite	MgCO ₃	155	585	730

quartzite, flint, or chert, and for mortars made with highly quartz-bearing igneous rocks. Lime and quartz become reactive at 150°C and new reaction products are formed¹⁵. The full strength apparently is not fully developed after 14 months with normal temperature curing. These strengths are used as a standard for the comparison of mortars made with other minerals.

Alkali

The solubility of quartz in alkalis suggests a solution for the troublesome surface layer. Treatment of loess with a solution of NaOH alone gave considerable strength, probably by incorporation of the surface layer of quartz into a gel which would borrow exchangeable calcium from the clay. Note that strengths came early (figure 4), and there is no latent strength gain as from reorganization within the mineral surface layers.

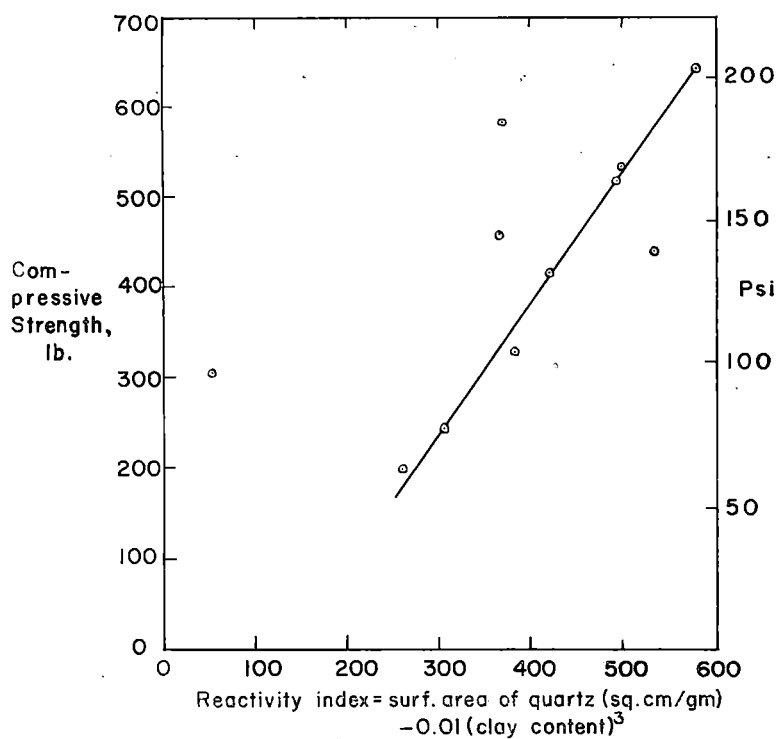


Fig. 4. Strength of 2" x 2" diameter loess specimens compacted to standard Proctor and with various normality NaOH solutions substituted for added water (15%). Continuous moist cure, with 24 hour immersion prior to testing.

Treatment with strong alkali should improve the reactions of quartz with alkaline stabilizers such as lime or Portland cement. Unpublished research shows early strengths may be raised 15 to 400 percent by use of strong alkalis. Petrographic data have been related to alkali reactivity of Iowa loess¹, and while the correlation with quartz surface area is imperfect (figure 5), there does seem to be a relationship. The other major minerals in loess are feldspars and carbonates. The equation for Reactivity Index is from earlier research⁸.

RELATIONS TO KINDS OF MINERALS

Feldspars and quartz

Quartz is about 50 percent ionically bonded and comparatively well screened by distortion in the surface layer. Feldspars, which are tectosilicates built on a three-dimensional framework, as is quartz, contain Al^{+3} substituted for some of the Si^{+4} , the valence deficiency then being made up by Na^{+} , or Ca^{++} . The result is preferred directional bonding leading to cleav-

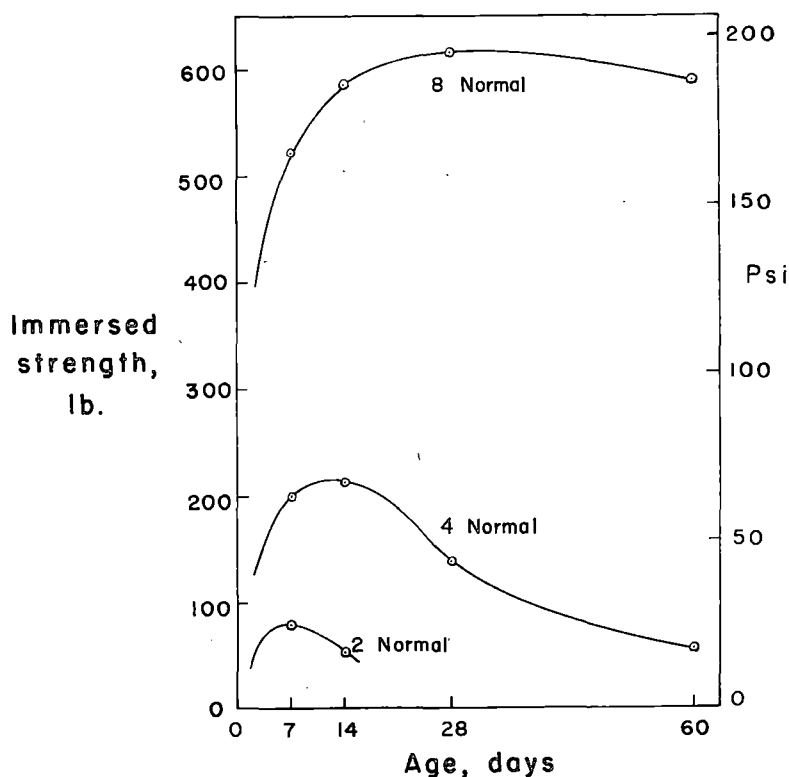


Fig. 5. Compressive strength of 8N NaOH treated 2" x 2" cylinders molded with various loess samples. Quartz surface area measured microscopically on material coarser than 5 microns.

age, and a net increase in the number of cations and in the ionic character of the bonding. The inherent cleavage directions signify a relatively lower surface energy along these planes, since less energy is required to make a new surface. Cleavage probably takes place because of the comparatively weaker ionic bonding, especially since the nearby Si-O bonds may be strengthened by unsymmetrical polarization of the oxygen ions, giving a better Si-O covalent bond¹⁴. In general the most stable silicate minerals are those with the most covalence.

The surface of a feldspar would be expected to contain metallic cations screened by polarization, especially since the cations, particularly potassium, are somewhat polarizable themselves.* Polarization of the surface ions should offer little hindrance to cementation compared with the deeper

*The radius of Na^+ and Ca^{++} ions is about 1\AA ; that of K is about 1.33\AA . Larger ions are the more polarizable. For comparison the radius of O is 1.4\AA . Si^{+4} , on the other hand, has a radius of only 0.4\AA . Al^{+3} has a radius of 0.5\AA . Figures are from Lange, Handbook of Chemistry, 8th ed. 1952.

more lasting distortions found in quartz. Such structural adjustments are probably less pronounced in feldspars because of the lower surface energy to start with, better polarization of the surface layer, and lower average valence on the cations, amounting to a deconcentration of charge. From this analysis one would expect

- (a) moderate early cementation bond strength, less than the potential in quartz because of the reduced but asymmetrical covalent bonding.
- (b) no special reactivity at high temperatures,
- (c) a long-term strength gain unrelated to relaxation of distortion screening, and
- (d) no benefit from dissolution of the surface layer other than to clean the grains.

Carbonates

Calcite, CaCO_3 , is another step in the same direction as feldspars. Calcite contains covalent CO_3 groups occurring in planes and bonded to one another by ionic O-Ca-O bonds. Because of polarization of the oxygen ions bonded to C, the Ca-O bonds are rather weak, and calcite is softer and more soluble than most silicates. It also has very good cleavage. Screening at a surface would be expected to be nil; therefore cementation bond strength should develop rapidly and show little high temperature improvement (table III). From the standpoint of removing screened zones there should be little advantage in chemical treatment. High long-term strengths (table III) are unexplained, but they are believed unrelated to screening.

Magnesite, MgCO_3 , was found to be reactive on autoclaving, whether incorporated in mortar as a pure mineral or in the rock dolomite, $\text{MgCa}(\text{CO}_3)_2^{15}$; and solubility was suggested as a factor. $\text{Mg}(\text{OH})_2$ is less soluble than MgCO_3 , resulting in dissolution of the carbonate and precipitation of the hydroxide, probably as brucite. Highest strength was found after long curing (table III).

Clay minerals

Clay minerals and micas are platy crystals classified as phyllosilicates. Clay flakes are so thin (7-10Å) as to prevent satisfactory structural screening, and the electrical effects observed on clay are attributed to this¹⁶. Adsorption of OH ions on the unscreened sites would serve to make the clays negative. However, isomorphous substitutions add to negativity of many clay minerals.

Cations within the clay mineral are automatically partly screened by their positions in tetrahedral and octahedral layers. Three-layer clays such as illite have predominantly O^- ions in their surfaces, and two-layer minerals such as kaolinite contain both O^- and OH^- . The average bond type

within the crystal approximates that of quartz or feldspars,* but this may be of little direct importance because of the variety of bonds occurring. The exceptionally good cleavage representing weak surface forces is more of a barrier to bonding than in feldspars and calcite, and there are no surface adjustments to give slow improvement. This disregards hydration and the flocculation by excess calcium from the cement. Flocculation takes place quickly but is a comparatively weak bond. Probably more important are long-term chemical changes within the clay minerals brought on as a result of the change in the environment. Clay minerals are quite susceptible to such modification.

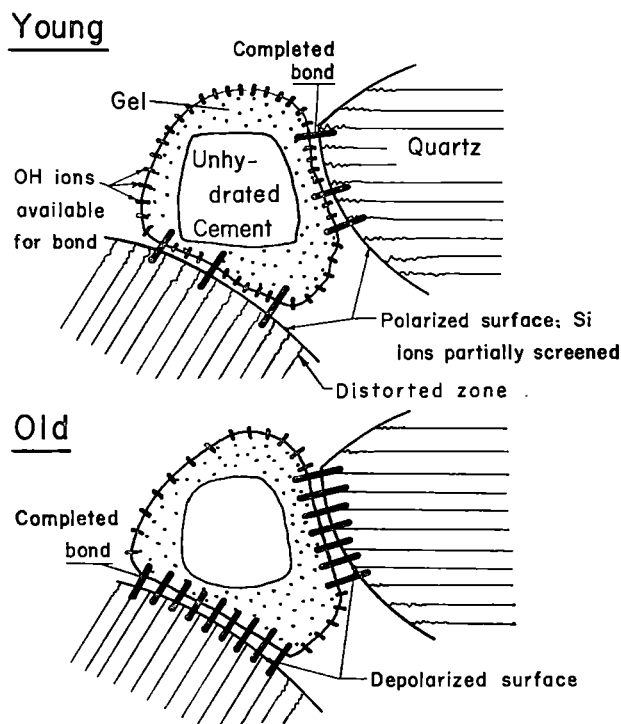


Fig. 6. Diagrammatic representation of a theory of cementation. Early cementation bonding is weak due to distortion polarization of the quartz surface. However, the early chemical bonding causes distortion to slowly disappear. This in turn allows even greater chemical bonding.

Amorphous materials. Glasses deserve close attention because of their usefulness as pozzolans. Natural glasses and fly ash vary in composition,

*Using Pauling's relationship and electronegativities from table I, Orthoclase, KAlSi_3O_8 , gives $X_B = (0.8 + 1.5 + 3 \times 1.8) \frac{1}{6} = 1.54$. Kaolinite, $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2 \cdot \text{H}_2\text{O}$ gives $X_B = (2 \times 1.5 + 1.8 + 2 \times 2.1) \frac{1}{6} = 1.8$. Muscovite, $\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$ gives $X_B = (2 \times 0.8 + 6 \times 1.5 + 6 \times 1.8 + 4 \times 2.1) \frac{1}{18} = 1.66$.

but are essentially mixtures of Al_2O_3 , SiO_2 , and Fe_2O_3 , plus lesser amounts of other oxides. The bonding is therefore mainly ionic and probably variable according to localized coordination conditions. As already discussed, screening probably occurs but is imperfect because of randomness of the inner structure. However, one would expect the reactivity of pozzolans to be enhanced by alkalis or by heat because this would expose disorganized glass. The effect of heat on curing of fly ash, an artificial pozzolan, is shown in table IV. Benefits would be expected to be greatest in pozzolans highest in

TABLE IV. UNCONFINED COMPRESSIVE STRENGTHS OF COMPACTED LIME AND FLY ASH MIXTURES. 92% FLY ASH, 8% LIME¹⁷

Fly ash No. 10	Loss on ignition	Compressive strength, psi			
		20°C cure		60°C cure	
		7 days	45 days	7 days	45 days
	3%	240	2250	2250	2700
11	28%	40	190	420	570
12	10%	50	950	1200	1550
15	17%	120	900	1100	1250

silica, as the higher valence on silicon means fewer cations to be screened than if the cations are Al^{+3} or Fe^{+3} . The composition varies so much from grain to grain that almost any fly ash should be benefited—each grain of fly ash represents the composition of a parent mineral grain in coal; there is very little combination and averaging of the product during burning.

SUMMARY

A hypothesis is advanced to explain long-term strength gains in soil cement by readjustments within the mineral surface, tending to improve chemical bonding. The hypothesis is extended to pozzolans and representative minerals in soils and in concrete, and offers an explanation of activation of silica by heat and by alkalis.

REFERENCES CITED

1. Anderson, Reuben L., Jr. Pozzolanic reactivity of loess. M.S. thesis. Iowa State University Library. 1956.
2. Bogue, R. H., and Lerch, William. Hydration of Portland cement compounds. *Ind. and Engr. Chem.* 26:837-847. 1934.
3. Coulson, Charles Alfred. Valence. Oxford University Press, London. 1952.
4. Devore, George W. Surface chemistry as a chemical control on mineral association. *Jour. Geol.* 64:31-55. 1956.
5. Eitel, Wilhelm. The physical chemistry of the silicates. University of Chicago Press, Chicago, Illinois. 1954.
6. Gruner, J. W. Silicates and their reaction energies. *American Mineralogist* 35:137-148. 1950.
7. Handy, Richard L. Stabilization of Iowa loess with Portland cement. Ph.D. Thesis. Iowa State University Library. 1956.
8. Handy, R. L., Davidson, D. T., and

- Chu, T. Y. Effect of petrographic variations of southwestern Iowa loess on stabilization with Portland cement. Hwy. Res. Bd. Bul. 98:1-20. 1955.
9. Jackson, M. L., Tyler, S. A., Willis, A. L., Bourbeau, G. A., and Pennington, R. P. Weathering sequence of clay size minerals in soils and sediments. Jour. Phys. & Coll. Chem. 52:1237-1260. 1948.
 10. Munger, Elmer C. Bond between Portland cement paste and aggregate. Ph.D. Thesis. Iowa State University Library. 1957.
 11. Munger, Elmer C. Discussion to "Effect of chemical nature of aggregate on strength of steam-cured Portland cement mortars," by T. Thorvaldson, Proc. Am. Conc. Inst. 52:1405-1408. 1956.
 12. Pauling, Linus. The nature of the chemical bond. 2nd ed. Cornell University Press, Ithaca, New York. 1942.
 13. Pike, Robert G., Hubbard, Donald, and Insley, Herbert. Mechanisms of alkali-aggregate reaction. Proc. Am. Conc. Inst. 52:13-34. 1955.
 14. Ramberg, Hans. Relative stabilities of some simple silicates as related to the polarization of the oxygen ions. Am. Min. 39:256-271. 1954.
 15. Thorvaldson, T. Effect of chemical nature of aggregate on strength of steam cured Portland cement mortars. Proc. Am. Conc. Inst. 52:771-780, 1403-1413. 1955-56.
 16. Weyl, W. A. Wetting of solids as influenced by the polarizability of surface ions. In Gomer, Robert and Smith, Eds. Structure and properties of solid surfaces. pp. 147-181. University of Chicago Press, Chicago. 1953.
 17. Davidson, D. T., Sheeler, J. B., and Delbridge, N. G., Jr. Reactivity of four types of fly ash with lime. Hwy. Res. Bd. Bulletin 193. 1958.

**COMPARISON OF TYPE I AND TYPE III
PORTLAND CEMENTS FOR SOIL STABILIZATION**

by

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(Highway Research Board Bulletin 267. 1960.)

ABSTRACT

Test data are presented which indicate the possibility of significant economic and structural advantages in using Type III high early strength Portland cement instead of Type I normal Portland cement for soil cement road construction. The data also indicate that high alkali content in Type I cement may be beneficial to the strength of cement treated soil if the soil contains a relatively high proportion of clay free quartz surfaces.

Test methods and criteria for evaluating the strength and durability of cement treated fine grained soils are presented and discussed. The minimum Type I and Type III cement requirements for soil cement indicated by these methods for the sandy, silty and clayey soils studied were surprisingly low.

INTRODUCTION

Soil cement is defined as a hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, Portland cement and water. Durability and compressive strength are the common criteria for hardness. The standard for hardness varies¹⁴. Soil cement has an excellent record of successful field service in base courses of roads, airfields, parking lots and similar applications. It has some structural advantages, and it is often cheaper than equivalent untreated granular base materials. An increase of these advantages would further increase the popularity of soil cement.

Same Possibilities for Improving Soil Cement

Two types of Portland cement available on the market for general use in soil cement are Type I normal cement and Type III high early strength cement, as given in ASTM Standard Specifications for Portland Cements, C 150-56². Type I cement is usually used in soil cement, probably because it

is usually most readily available and is slightly lower priced than Type III cement. However, if the cement requirement for soil cement is significantly lower with Type III than with Type I, a possibility suggested previously, there could be an economic advantage in using Type III cement^{5, 6, 10, 17}.

Soil cement requires a definite curing period prior to the construction of additional base or wearing courses. This curing period is normally seven days when Type I cement is used. Since curing time affects total construction time, a reduction in curing time made possible by use of Type III cement could be advantageous.

Recent work (at Iowa State^{11, 12, 22} and at M.I.T.^{15, 16}) indicates that the use of small amounts of alkali additives in soil cement may accelerate the rate of hardening. This suggests that the alkali content of Portland cement may have a significant effect on the strength of soil cement, a possibility which apparently has not been investigated previously.

Objectives of the Investigation

This report presents the results of a laboratory investigation to obtain more information on the advantages of Type III cement over Type I cement for soil cement road construction, particularly in Iowa. A second objective was to determine whether alkali content is an important compositional variable in Portland cement used in soil cement.

PROPERTIES OF MATERIALS USED

Soils

The three soils used in the investigation, a sandy, a silty and a clayey soil, are typical of widespread and readily available materials for stabilized road construction in Iowa (table I). The sand loess mix was sampled from the blended material used in the soil cement base course of primary system Iowa highway 117, constructed in 1957.

Portland Cements

The three Type I cements and two Type III cements used in the investigation designated Ia, Ib, Ic, (table II) meet the requirements for the ASTM specifications (C 150-56) for Type I Portland cement; those designated IIIa and IIIb meet ASTM requirements for Type III Portland cement².

The three Type I cements differed mainly in their total alkali content (as Na_2O), which was the desired variable. Cement Ia had low alkali content, cement Ib had medium alkali content, and cement Ic had high alkali content. The 7 and 28 day compressive strengths obtained in 1-2.75 graded Ottawa sand mortars are similar. The difference in 1 day mortar strengths seems to correlate with small variations in fineness and calculated C_3S content.

The two Type III cements were quite similar and had medium alkali contents, although cement IIIa had a slightly lower alkali content than cement IIIb. They were much finer than the Type I cements and in mortars gave higher compressive strengths at ages up to 28 days. Type III cements had higher C_3S contents and lower C_2S contents than the Type I cements. Sulphur trioxide (gypsum) content was not considered a significant variable in this investigation, since the gypsum content of each cement was adjusted to about optimum for setting and strength properties of the cement paste.

METHODS OF PREPARING AND TESTING SPECIMENS

Mixing

The mixing of materials was done mainly with a Hobart Model C-100 Mixer. Proper proportions of cement and air dry soil, based on the oven dry weight of the soil, were placed in the mixing bowl, were blended briefly by hand, and then were dry mixed by machine for one minute. The materials were mixed for another minute while a predetermined amount of distilled water was added. The mixing bowl was scraped, and the materials were hand mixed for approximately one minute to break up any clods which might have formed. The mixture was given a final machine blending for one minute.

Molding

Test specimens were prepared by use of the molding apparatus (figure 1). The specimens had a diameter of 2 inches and a height of 2 ± 0.005 inches. This specimen size also is used for compressive strengths tests by the Portland Cement Association when the soil contains no plus No. 4 material¹⁹. A 2 inch by 2 inch specimen can be compacted to uniform density in one layer with no cleavage planes.

The amount of mixture needed for a specimen was placed in the calibrated cylinder which rested on the temporary support. The mixture was given one blow with the 5 pound hammer, the temporary support was removed, and the mixture was given an additional four blows. The molding cylinder was inverted and the specimen was given five additional blows. The resulting specimen was extruded and weighed to the nearest 0.1 gram; then the height was measured to the nearest 0.001 inch. When the molding is done on a wooden table, the ten blows with the 5 pound hammer dropping 12 inches gives a compactive effort approximately equal to standard ASTM (Proctor) compactive effort (ASTM Method D 558-57²).

Moisture, Density, Strength Relationships

The purpose of the moisture density and moisture strength relationship tests was to determine the optimum moisture contents for molding cement treated soil specimens for subsequent immersed strength and freeze

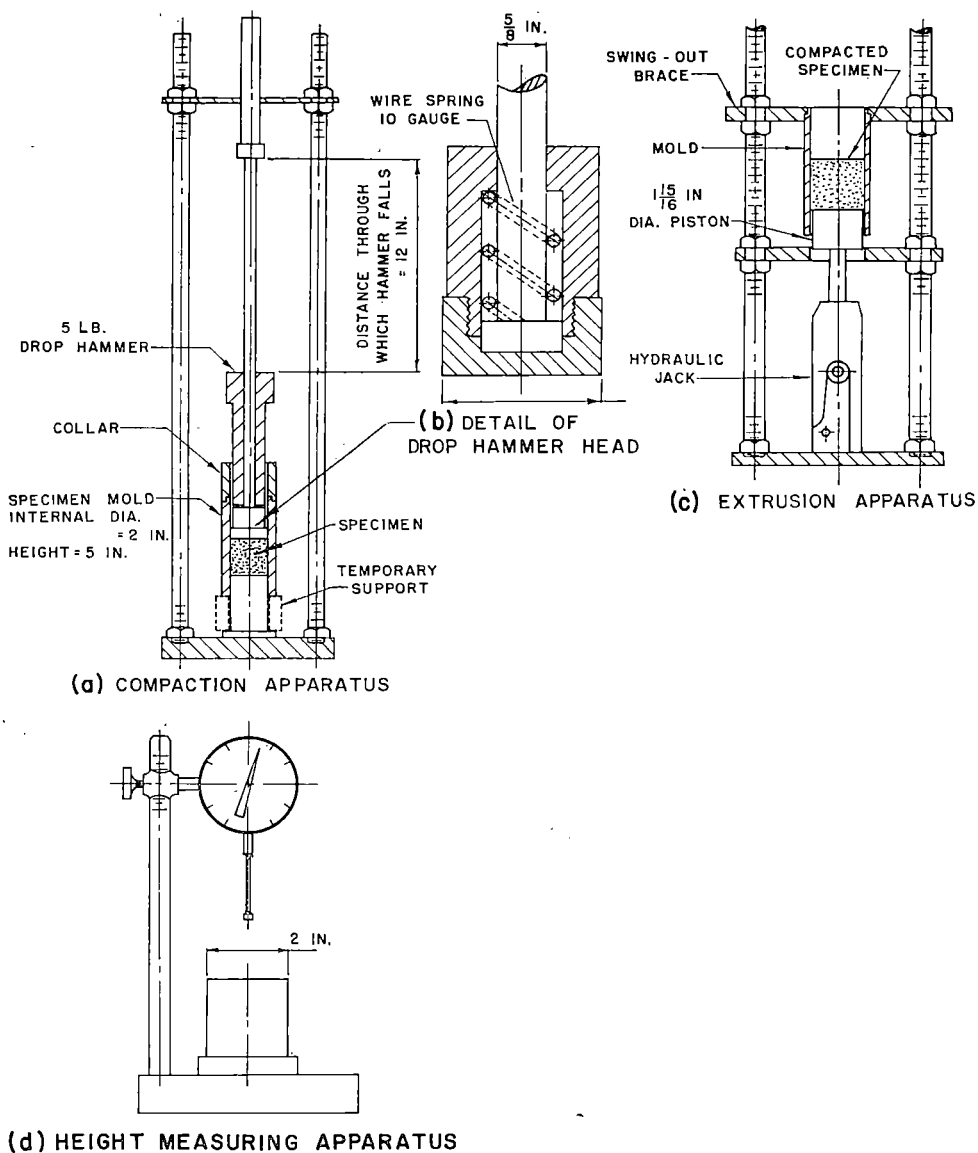


Fig. 1. Apparatus used for molding 2 inch high by 2 inch diameter test specimens.

thaw tests. The tests were performed with the three soils. Each cement in varying amounts was used with each soil.

Sufficient soil for ten specimens was dry mixed with the desired amount of Portland cement. Enough of the mixture to mold two specimens was mixed with the required amount of water to obtain a moisture content on the dry side of optimum moisture. Two specimens were molded, measured

and weighed, and two samples of the unmolded mixture were taken for moisture content determinations. The procedure was repeated four more times, with the moisture content of the mixture increased approximately 2% for each repetition.

The molded specimens of varying moisture content were cured for 7 days, were immersed in water for 24 hours, and then were tested for unconfined compressive strength.

Average values of dry density (at time of molding) and immersed strength were calculated for each moisture content. These data enabled comparisons to be made of the optimum moisture requirements for maxi-

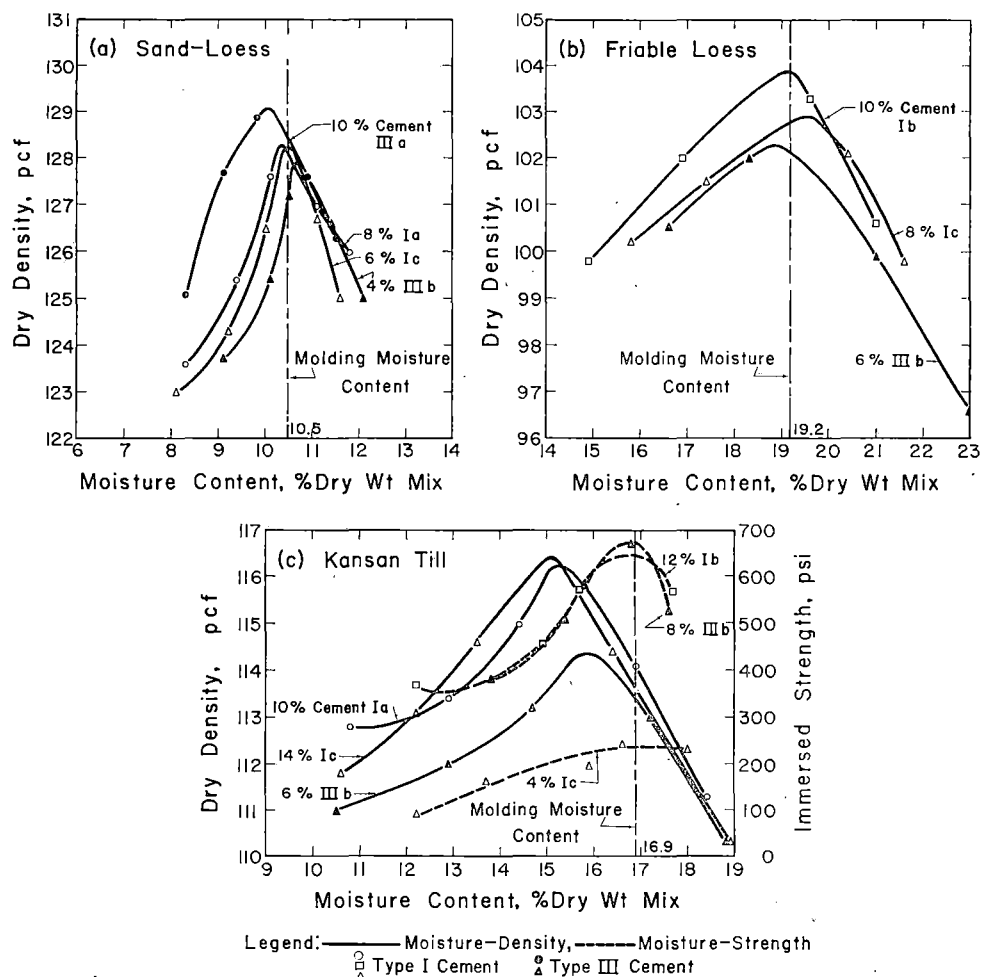


Fig. 2. Typical moisture-density and moisture-strength curves for the Type I and Type III cement-treated soil-mixtures studied. The molding moisture content indicated for each soil is the selected "optimum" for mixtures of the soil and Type I or Type III cement.

imum dry density and maximum immersed strength obtained from curves such as those for cement treated Kansan till mixtures (figure 2). The optimum moisture contents for maximum dry density and maximum immersed strength were nearly identical for cement treated sand loess and friable loess mixtures; therefore only typical moisture density curves are shown. For cement treated Kansan till mixtures, optimum moisture for maximum immersed strength was about $11\frac{1}{2}\%$ greater, based on the oven dry weight of the mixture, than optimum moisture for maximum dry density (figure 2). Similar results have been found for clays¹⁷. The type of Portland cement did not significantly affect optimum moisture contents or maximum density, which agrees with previous findings¹⁰. Generally, an increase in cement content caused an increase of maximum density but only a slight decrease of optimum moisture contents. Therefore it was possible to select a single molding moisture content for each soil.

The moisture density relations obtained by this method agree closely with those obtained by standard ASTM Method D 558-57².

Curing

After they were molded, specimens for immersed strength or freeze thaw resistance tests were wrapped in waxed paper sealed with cellophane tape and were placed in a moist curing room for designated periods. The desired constants for the curing room were a temperature of $70 \pm 5^\circ\text{F}$, and a relative humidity of $95 \pm 5\%$. However, the temperature was known to deviate from the desired constant, particularly in the summer, when it was higher, and in the winter, when it was lower.

Immersed Strength and Freeze Thaw Testing

Unconfined compressive strength after curing and 24 hours immersion. For each mixture, sufficient soil for nine specimens was dry mixed with the desired amount of Portland cement. Enough water to bring the mixture to optimum moisture was added. After moist mixing, nine specimens were molded, and sealed in waxed paper, to reduce moisture loss and absorption of CO_2 during curing, and then were placed in the humidity room.

Three specimens were cured for 2 days, three for 7 days and three for 28 days. At the end of each curing period, the specimens, with waxed paper removed, were immersed in distilled water at room temperature for 24 hours. Immediately after being removed from the water bath, the specimens were tested for unconfined compressive strength. The maximum load to break a specimen, with a load travel rate of 0.1 inch per minute, was taken as the compressive strength. Average values, based on the three specimens, are reported. With very few exceptions, the difference between the individual values and the average value did not exceed 10% of the average value.

Freeze thaw resistance. The freeze thaw test used to evaluate selected cement treated soil mixtures is a modification of the British Standard Test¹⁸. The modifications are as follows: use 2 inch by 2 inch instead of 2 inch by 4 inch test specimens, use waxed paper sealed with cellophane tape instead of paraffin to reduce moisture evaporation from specimens during curing, and use a resin-base paint (plax) instead of tar as the seal coat on the tops of specimens (figure 6, Appendix A).

Two identical specimens were molded for each mixture and the curing period was studied. (Specimens of cement treated sand loess were cured for 2 and 7 days, specimens of cement treated friable loess and Kansan till were cured for 7 days only.) One specimen was designated the control specimen and the other the freeze thaw specimen. After moist curing, the flat top surface of each specimen was sprayed with the resin base paint to a thickness of approximately 1 mm. Then the control specimen was immersed for 15 days in distilled water at a temperature of $77 \pm 4^\circ\text{F}$; the freeze thaw specimen was immersed for one day, then it was subjected to the 14 cycles of freeze thaw (14 days) (Appendix A). The unconfined compressive strengths in psi of the control (immersed) specimen (p_c) and the freeze thaw specimen (p_f) were then determined. The index of the resistance to the effect of freezing (R_f) was calculated from the formula:

$$R_f = \frac{100p_f}{p_c} \text{ (percent)}$$

The modified British freeze thaw test is thought to simulate field freeze thaw conditions better than the brushing test^{2, 19}. The modified British test is simpler, faster and requires less soil and additive materials than the ASTM test; these advantages are particularly important when a large number of specimens are to be evaluated. The use of the modified British test is limited to fine grained soils which pass the No. 4 sieve.

TEST RESULTS AND INTERPRETATIONS

Unconfined Compressive Strength After Curing and 24 Hours Immersion

The purpose of these immersed strength tests was to obtain a comparison of the relative strength gain from the use of the Type I and Type III cements in mixtures with each of the three soils. Plots of immersed strength versus cement content, for each soil, cement type, and curing period were drawn (figure 3). And plots of immersed strength versus curing time for each soil, cement type, and cement content were also drawn (figure 4). Cement contents are expressed as percentages of the oven dry weight of the soils.

Sand Loess. Type III cements gave higher strengths than Type I cements at all cement contents except 4% cement IIIb, which gave approximately the same strength as the same amount of the three Type I cements (figures

3, 4). Generally the rate of strength gain with increasing cement content

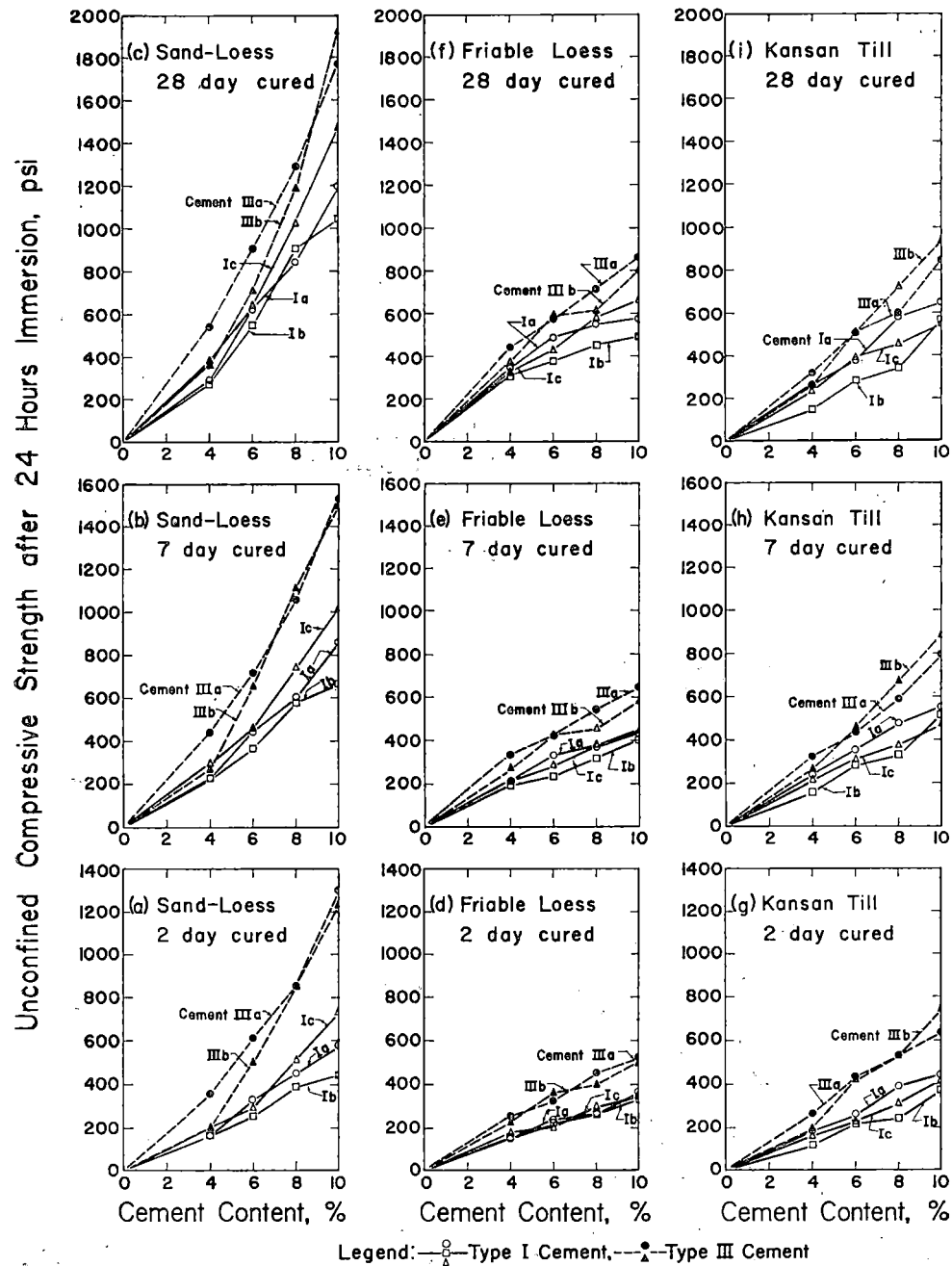


Fig. 3. Immersed strength versus cement content, for each soil, cement type and curing period studied. Cement contents are percentages of the oven-dry weight of the soils.

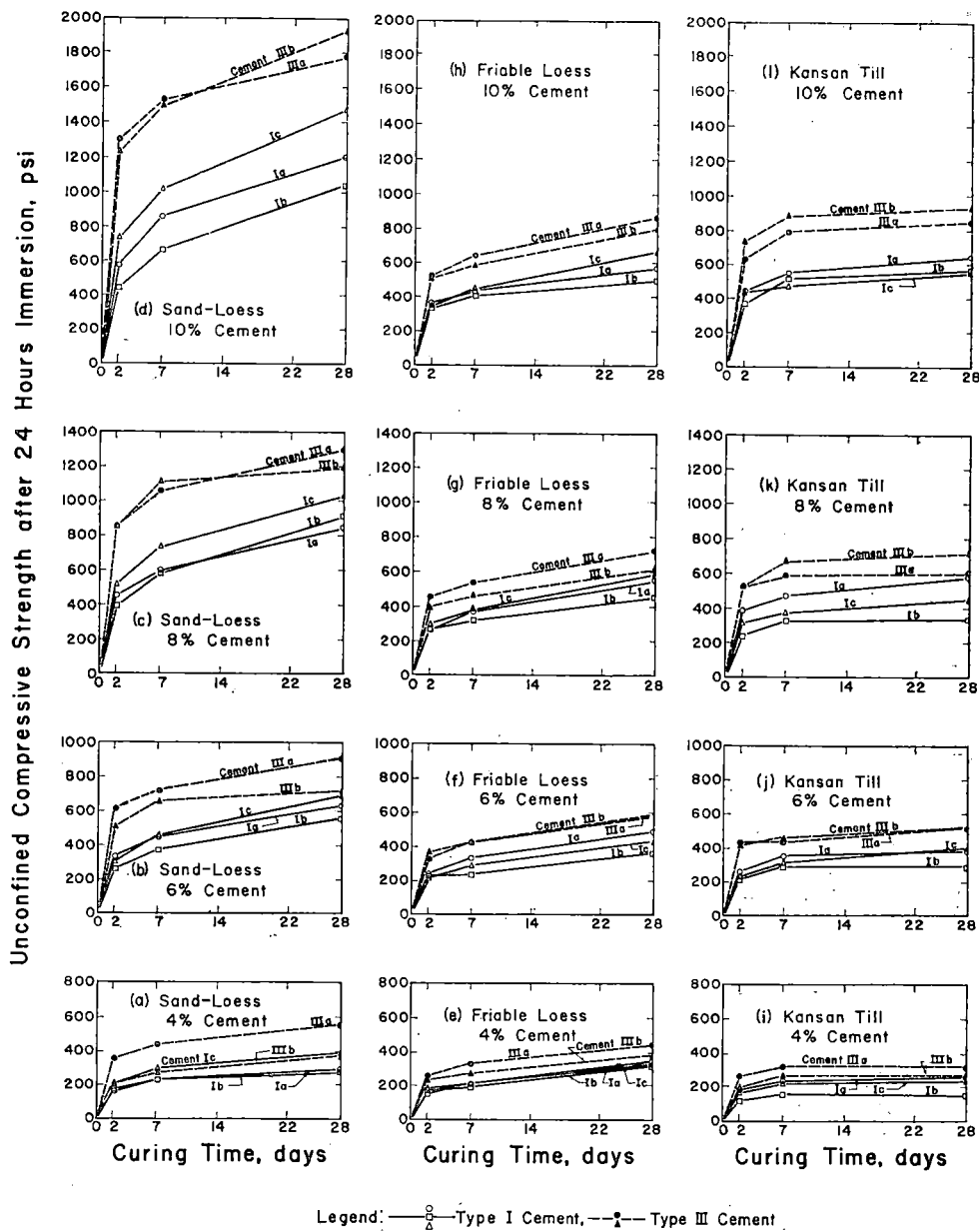


Fig. 4. Immersed strength versus curing time, for each soil, cement type and cement content studied. Cement contents are percentages of the oven-dry weight of the soils.

was greater with Type III than with Type I cements, the strength difference being more pronounced after curing periods of 2 and 7 days than after 28 days.

TABLE I. PROPERTIES OF SOILS

Property	Sand and loess (Colfax mix)*	Friable loess (20-2-VII)*	Kansan till (409-12C)*
Geological description:	Mix of approximately 82% waste sand from hydraulic dredging operations and 18% Wisconsin age loess, oxidized, calcareous, medium plastic	Wisconsin age loess, oxidized, calcareous, friable	Kansan-age glacial till, oxidized, calcareous, plastic
Sampling location:	Jasper Co., Iowa	Harrison Co., Iowa	Ringgold Co., Iowa
Soil series:	Loess: Tama	Hamburg	Shelby (Burchard)
Horizon:	Loess: C	C	C
Sampling depth, ft.:	Sand. Stock pile Loess: Borrow pit	35-36	4½-10½
Textural composition,† %:			
Gravel (> 2 mm)	0.0	0.0	0.0
Sand (2.0 — 0.074 mm)	70.7	0.4	31.5
Silt (0.074 — 0.005 mm)	22.3	80.0	30.0
Clay (< 0.005 mm)	7.0	19.6	38.5
Colloids (< 0.001 mm)	6.0	14.5	31.0
Atterberg limits‡:			
Liquid limit, %	18.9	30.8	42.4
Plastic limit, %	16.4	24.6	20.5
Plasticity index, %	2.5	6.2	21.9
Classification:			
Textural§	Sandy loam	Silty loam	Clay
Engineering (AASHO)¶	A-2-4	A-4(8)	A-7-6(12)
Chemical:			
Cation exchange capacity,‡ m.e./100 g	11.0	13.4	29.5
Carbonates,** %	11.6	10.2	4.9
pH††	8.0	8.7	8.25
Organic matter,‡‡ %	0.16	0.17	0.17
Non-clay mineral composition,§§ %:			
Aggregates (silicious)	36.3	---	---
Quartz	50.5	56.0	60.2
Feldspars	9.0	21.1	21.1
Calcite	3.8	13.7	---
Others	0.3	9.2	18.7
Clay mineral composition:			
Predominant clay mineral¶¶	Montmorillonite	Montmorillonite	Montmorillonite
Clay coatings on surfaces of grains > 0.005 mm££	Light to moderate (15-35%)	Moderate (20-80%)	Extensive (75-100%)

* Soil Research Laboratory sample designation.

† ASTM Method D 422-54T (2).

‡ ASTM Methods D 423-54T and D 424-54T (2).

§ Triangular chart developed by U. S. Bureau of Public Roads (12).

¶ AASHO Method M-145-49 (13).

£ Ammonium acetate (pH = 7) method on soil fraction < 0.42 mm (No. 40 sieve).

**Versenate method for total calcium.

††Glass electrode method using suspension of 15 g soil in 30 cc distilled water.

‡‡Potassium bichromate method.

§§Petrographic microscopical analysis.

¶¶X-ray diffraction analysis.

££Estimated, based on microscopic examination of random grains > 0.005 mm.

The higher early strengths up to 28 days obtained with Type III cements probably can be attributed to their fineness and C_3S contents. Since it is finer ground than Type I cement, Type III cement has a considerably larger surface area which serves to accelerate the hydration process and give a better distribution of gel. Also C_3S , abundant in Type III cements, is the component of Portland cement which contributes most to early strength³. As expected, the rate of strength gain of cement treated soil generally increases with an increase in amount of Type III cement, and strengths are higher than with equal amounts of Type I (figure 3).

Strength gain from C_3S begins to diminish after curing periods of 28 days, and C_2S becomes chiefly responsible for strength gain thereafter³. Type I cement contains considerably more C_2S than Type III cement, and it seems probable that Type I strength curves would intercept Type III curves at some curing time beyond 28 days (figure 4).

Among the three Type I cements, cement Ic produced highest strengths, which was particularly evident at 10% cement content after 28 days curing. Properties of the cement (table II) suggest the comparatively high alkali content may be the reason for the better performance, since the C_3S content was lower than, and the cement fineness was about the same as in cement Ia. Cement Ia, the low alkali cement, generally rated second best, but the medium alkali content Ib was coarser and contained less C_3S than cement Ia, which probably subtracted from the benefits derived from alkali reactions. The mineralogical properties of the sand loess (table I) are considered conducive to benefits from alkali reactions in that this soil contains a relatively large amount of quartz; and clay coatings on grain surfaces are comparatively light. Studies of the use of alkali additives to improve cement treated soil have shown that greatest benefits to strength are obtained with soils having a relatively large proportion of uncoated quartz surfaces^{11, 15, 22}.

At the lower cement contents cement IIIa, the finest ground Type III cement, gave much higher strengths than cement IIIb, though cement IIIb had slightly higher alkali and C_3S contents. However, its slightly higher alkali and C_3S contents may explain why the performance of cement IIIb improved as cement content increased. At 8% cement the two Type III cements gave similar strengths after 2 and 7 days curing. At 10% cement, cement IIIb gave higher strengths than cement IIIa, the difference being greatest (about 200 psi) after 28 days curing.

If an immersed strength of about 300 psi after 7 days curing is taken as indicative of satisfactory quality soil cement prepared from the sand loess (as suggested by the Soil Cement Bureau, Portland Cement Association), selection of cement contents that give this strength by interpolating from the curves of the best Type I and Type III cements (figure 3b) indicates that about 3% cement IIIa is equivalent to 4% cement Ic, making

possible a 22% reduction in the cost of Portland cement*. If construction requirements necessitated an immersed strength of 300 psi after only 2 days curing (figure 3a), about 3% cement IIIa is equivalent to about 6% cement Ic, a 44% saving in price.

Friable loess. In mixtures with the friable loess, the Type III cements gave the highest immersed strengths after all curing periods (figures 3d, e, f and 4e, f, g, h). The occurrence previously noted with the sand loess, greater strength differences between the Type III and Type I cements with increasing cement content, is evident although not as marked. In general the strengths obtained were considerably below those obtained with the sand loess. This probably is largely due to the greater surface area of the friable loess. An increased soil surface area without a proportional increase of cement may result in a less perfect distribution and functioning of cement gel on grain surfaces, and consequently lower strengths.

Comparisons of strengths obtained with cements Ia and Ic, low and high alkali cements, respectively, show little evidence of alkali reactions benefiting strength. Generally these two cements gave similar strengths. Cement Ib gave the lowest strengths, except after 2 days curing, when all three Type I cements produced about the same strengths. The only indication of beneficial alkali reactions is that cement Ic gave appreciably higher strength than cement Ia at 10% cement content after 28 days curing. This suggests that due to a smaller amount of uncoated quartz surface (table I) the alkali reactions did not occur as readily as in the sand and loess mixture and that for the alkali reactions to have an appreciable effect required a relatively high concentration of alkalis and a fairly long curing period.

As with sand loess, cement IIIa usually gave higher strengths than cement IIIb, presumably because fineness was the major cement property variable (table II) affecting strength.

Assuming that an immersed strength of 275 psi after 7 days curing is indicative of satisfactory quality, soil cement prepared from the friable loess, as suggested by the Soil Cement Bureau, Portland Cement Association, 3% cement IIIa could be used instead of 5% cement Ia with a 35% saving in the cost of cement (figure 3c). A similar comparison after 2 days curing (figure 3d) indicates that for an immersed strength of 275 psi, 4% cement IIIa is about equivalent to 8% cement Ic, and 44% cheaper.

Kansan till. Kansan age glacial till contains approximately equal amounts of sand, silt, and clay sized particles (table I); hence it has a better gradation than friable loess, which is approximately 80% silt and 20% clay. This may account for the higher immersed strengths obtained with some of the cement treated Kansan till mixtures. The Type III cements again

*4-3 = 1% less Type III cement needed, based on dry weight of soil. Assuming Type III cement costs 1.13 times as much as Type I cement, the percentage saving in the cost of cement by using Type III cement is: $(1 \div 4) (100 \div 1.13) = 22\%$.

TABLE II. PROPERTIES OF THE TYPE I AND TYPE II PORTLAND CEMENTS*

Cement designation: Cement type	Ia†(13)‡ I	Ib†(21)‡ I	Ic†(14)‡ I	IIIa†(31)‡ III	IIIb†(33)‡ III
Major oxide composition, %:					
Silicon dioxide (SiO ₂)	22.18	23.71	22.17	20.36	20.03
Aluminum oxide (Al ₂ O ₃)	4.70	3.97	4.62	4.96	5.08
Ferric oxide (Fe ₂ O ₃)	2.12	3.21	3.03	2.11	2.52
Calcium oxide (CaO)	64.22	63.98	62.86	63.28	63.81
Magnesium oxide (MgO)	1.07	1.18	2.37	3.20	1.38
Sulphur trioxide (SO ₃)	1.62	1.24	1.73	2.23	2.31
Sodium oxide (Na ₂ O)	0.04	0.22	0.06	0.23	0.21
Potassium oxide (K ₂ O)	0.19	0.40	1.30	0.22	0.44
Free calcium oxide (CaO)	1.61	0.65	0.19	1.45	1.83
Total equivalent alkali content as Na ₂ O	0.17	0.48	0.92	0.37	0.50
Calculated potential compound composition, %:					
Tricalcium silicate (C ₃ S)	53.6	45.4	47.1	60.1	63.2
Dicalcium silicate (C ₂ S)	23.2	33.7	28.1	13.0	9.8
Tricalcium aluminate (C ₃ A)	8.9	5.1	7.1	9.6	9.2
Tetracalcium aluminoferrite (C ₄ AF)	6.4	9.8	9.2	6.4	7.7
Physical properties:					
Fineness, turbidimeter (Wagner), sq cm/g	1660	1630	1880	2800	2530
Fineness, air permeability (Blaine), sq cm/g	3430	2890	3420	5800	5270
Compressive strength of 1-2.75 mortars, ASTM Method C 109					
1 day, psi	720	380	690	1820	2010
3 day, psi	1560	1380	1730	4000	4180
7 day, psi	2350	2450	2880	5630	5910
28 day, psi	4140	4330	4330	7010	6340

*Cements and property data furnished by Portland Cement Association.

†Designation used in this report.

‡Portland Cement Association's designation.

gave higher strengths than the Type I cements, the difference being greatest at the higher cement contents (figures 3g, h, i and 4i, j, k, l).

Strengths obtained with the Type I cements do not correlate with the alkali contents of the cements, indicating no significant benefits to strength from alkali reactions. This seems reasonable in that quartz surfaces in Kansan till were heavily coated with clay particles. Cement Ia generally gave the highest strengths, possibly due to its relatively high C₃S and free CaO contents. An appreciable amount of free CaO in Portland cement may improve the gel production process or provide additional cementation compounds by reacting with soil grain surfaces. The occurrence of the latter might also improve the chemical bonding of cement gel to grain surfaces. Previous work with Kansan till in soil lime mixtures indicates that it contains minerals which are exceptionally reactive with Ca(OH)₂¹⁷.

Cement IIIa gave higher strengths than cement IIIb when the cement content was 4%. At 6% cement the two Type III cements gave similar strengths; at higher cement contents, cement IIIb generally gave highest strengths. Cement IIIb had slightly higher free CaO, alkali and C₃S con-

tents than cement IIIa, and the cumulative beneficial effects from the extra amounts of these components may account for the improved performance of cement IIIb at the higher cement contents.

An immersed strength of 250 psi after 7 days curing may be indicative of satisfactory soil cement prepared from the Kansan till. Three percent of cement IIIa is equivalent to 4% cement Ia, and the use of cement IIIa would reduce the cement cost by about 22% (figure 3h). Using the same strength criterion with the curves for 2 days curing (figure 3g) shows that either 4% cement IIIa or 6% Ia would produce satisfactory soil cement. The use of the Type III cement would reduce the cement cost about 25%.

Conclusion. The immersed strength test results for the cement treated sandy, silty and clayey soils indicate the possibility of significant economic and structural advantages from using Type III high early strength Portland cement instead of Type I normal Portland cement for either normal or emergency soil cement construction. A high alkali content in Portland cement appears to be beneficial to the strength of cement treated soil only when the soil has a relatively high proportion of quartz whose surfaces are uncoated with clay minerals.

Freeze Thaw Resistance

The modified British test (Appendix A) was used to determine whether the soils stabilized with Type III Portland cement were as resistant to freeze thaw deterioration as when stabilized with Type I Portland cement. The Type I and Type III cements used with each soil were the ones that generally had given the best results in the study of unconfined compressive strengths after curing and 24 hours immersion. The results of the freeze thaw study show the effect of increasing cement content (% oven dry weight of soil) on the unconfined compressive strengths of the control (cured + 15 days immersed) specimens and the freeze thaw (cured + 1 day immersed + 14 cycles of freezing and thawing) specimens (figure 5). Also shown is the effect of cement content on the index of the resistance to the effect of freezing (R_f), the ratio of the freeze thaw specimen strength (p_f) to the control specimen strength (p_c), expressed as a percentage.

General comparison of Type I and Type III cements. Almost without exception mixtures with the Type III cement had much higher control and freeze thaw specimen strengths than similarly proportioned mixtures with Type I cement. The strength differences were sometimes as much as 300 psi, clearly indicating the superior durability of the 2 day and 7 day cured specimens containing the Type III cement. The reason is probably the greater surface area of Type III cement compared with that of Type I cement. This makes possible the attainment of higher strengths during the curing period, as previously discussed, and any hardening that occurs during immersion or during freezing and thawing cycles probably proceeds

at a greater rate.

With only two exceptions, the values of the index of the resistance to damage by freezing and thawing, R_f , were higher for mixtures containing the Type III cement. All the Type III curves reach a maximum at cement contents between 6% and 8% ; the Type I curves do likewise, except for the Kansan till, which had a minimum of 8% cement. The maximums occurred at cement contents where the slope of the control curves became greater than the slope of the freeze thaw curves. An explanation has been suggested for this phenomenon, but more experimental data are needed to confirm the hypothesis⁴.

Criteria for satisfactory freeze thaw resistance. Two criteria may be used as the basis for selecting minimum cement contents for durable soil cement from the data obtained in the modified British freeze thaw test. The first criterion is the R_f value, which must equal or exceed a specified value. The minimum R_f value used in England is 75%, and stabilized soils designed on this basis have given satisfactory performance under field conditions. In Iowa, a minimum R_f of 80% for soil cement has been tentatively adopted for use with the modified British test.

The second criterion used for stabilized base course design in Iowa is that the unconfined compressive strength of both the control specimen and the freeze thaw specimen must equal or exceed 250 psi. The value of 250 psi is still tentative, but calculated strength requirements of base courses indicate that this value is conservative^{4, 13, 22}.

Most modern design methods for flexible pavements are based on limiting vertical deformations in pavement components. The deformation can occur from compression of voids, shearing failure, or a combination of both. The compression of voids in a soil cement base should not cause a failure condition in a pavement because soil particles are compacted to or near a maximum density (usually standard ASTM for roads) and are cemented together during curing; the hardening mechanism continues for a number of years. Plate bearing tests indicate that the load required to produce 0.1 inch vertical deformation in soil cement (plastic gravelly clay with 6% cement) is about twice that required to produce the same deflection in crushed limestone, and two and a half times that required for the plastic gravelly clay unstabilized with cement⁷. Hence, failure of a soil cement base by deformation would probably be due to shearing failure; and, for laboratory mix design, the use of a safe minimum allowable unconfined compression strength, after adequately severe simulated weathering treatments, is considered a valid criterion of durability.

The suggested minimum unconfined compressive strength of 250 psi for laboratory specimens is purposely high to compensate for such uncertainties as:

- (1) Laboratory strengths may not be reproduced in the field at the same curing age. Studies have shown that field strengths may be 60% to 80% of laboratory

strengths.

(2) The shearing strength of soil cement in a base course may not be accurately evaluated by an unconfined compression test. An assumption of the shearing strength being one-half the unconfined compressive strength is probably on the safe side.

(3) A static load test may not give a true evaluation of soil cement performance under repeated dynamic loads. The fact that soil cement is known to gain in strength over a long period of time may be a compensating factor.

The modified British freeze thaw test is believed to be adequate for Iowa's climate. The field conditions for deleterious frost action are simulated in the test: a freezing temperature, a readily available source of water, a thermal gradient, and cycles of freezing and thawing. Depths of freezing during each freezing period, calculated by the modified Berggren formula¹, were 2.91, 1.83 and 1.94 inches, respectively, for the sand loess, the friable loess and the Kansan till. The actual depths of freezing of the 2 inch high specimens were not determined. However, the water in the containers at the end of a freezing period varied from 32°F with no ice crystals to 32°F with the water "mushy"; the water in containers with sand loess specimens usually contained the most ice crystals. Complete thawing is believed to have occurred during the thawing periods. From calculations of the number of freeze thaw cycles occurring at different depths in lime fly ash stabilized gravelly, sandy and clayey base courses at St. Clair, Michigan, during the 1956 winter⁸, the 14 cycles of freezing and thawing used in the modified British test probably simulate maximum winter conditions in Iowa in a soil cement base under a 2 to 3 inch bituminous wearing course. The test can be adapted to less severe winter conditions or different surface course thicknesses by simply varying the number of freeze thaw cycles.

Comparison of Type I and Type III cement requirements for soil cement. The test data indicate the questionable reliability of the first criterion, a minimum R_f of 80%, used without consideration of the second criterion, a minimum unconfined compressive strength of 250 psi after simulated weathering (figure 5). A possibility not illustrated by the data is that the first criterion could be satisfied without satisfying the second criterion. In interpolating or extrapolating for equivalent Type I and Type III minimum cement contents to satisfy both criteria, usually one or the other of the criteria governed the selection. The results indicate that an allowable reduction in cement content of 1%, based on the dry soil weight, is possible if the Type III cement is used instead of the Type I cement (table III). The consequent cost saving of Portland cement varies somewhat with the curing time taken as the basis of design and with the kind of soil stabilized, the saving being 15% for the 2 day cured sand, loess, and cement mixture, 18% for the 7 day cured sand, loess, and cement, 22% for the 7 day cured friable loess cement, and 18% for the 7 day cured Kansan till cement.

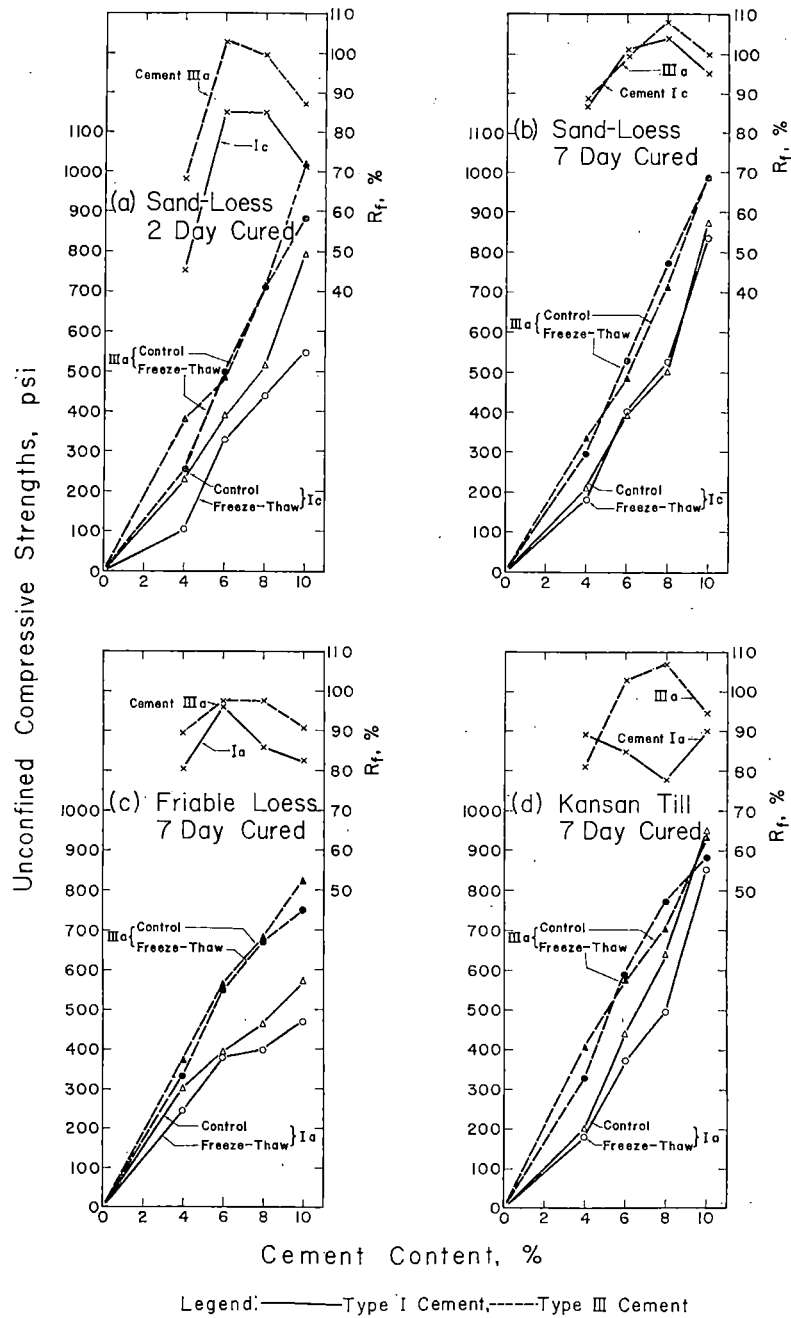


Fig. 5. Modified British freeze-thaw test results for selected Type I and Type III cement-treated soil mixtures, showing the effect of cement content on the unconfined compressive strengths of the control and freeze-thaw specimens, and on the index of the resistance to the effect of freezing (R_f). Cement contents are percentages of the oven-dry weight of the soils.

TABLE III. EQUIVALENT MINIMUM TYPE I AND TYPE III CEMENT REQUIREMENTS
FOR SOIL CEMENT BASE COURSES IN IOWA

Soil	Cement type and designation*	Minimum cement requirements, % oven-dry wt. soil			
		Based on 2 day curing		Based on 7 day curing	
		Using immersed strength test†	Using modified British test‡	Using immersed strength test†	Using modified British test‡
Sand loess	Ic	6	6	4	5
	IIIa	3	5	3	4
Friable loess	Ia	8	---	5	4
	IIIa	4	---	3	3
Kansan till	Ia	6	---	4	5
	IIIa	4	---	3	4

*Type refers to kind of cement—Type I or Type III; designation refers to sample number in Table 2.

†Specimens cured 2 or 7 days, immersed in water 24 hours, then tested for unconfined compressive strength. Minimum cement requirements were interpolated from figure 3, using PCA's suggested minimum immersed strength values for 7 day cured soil cement as a criterion of durability.

‡Specimens cured 2 or 7 days, then subjected to modified British freeze-thaw test (Appendix A). Minimum cement requirements interpolated or extrapolated from figure 5, using tentative Iowa durability criteria.

The minimum cement requirements are interpolated (figure 3), using the Portland Cement Association's suggested minimum strength values for soil cement after seven days curing and 24 hours immersion to indicate satisfactory freeze thaw durability. Since the PCA recommendations were based on uncompleted correlation studies of unconfined compression strength and standard ASTM method freeze thaw durability for fine grained cohesive soils, the cement requirements arrived at by the two methods show remarkably good agreement.

Conclusion. The indicated cement requirements of the three soils are surprisingly low for both Type I and Type III cements. If these low requirements are verified by planned field trials, the future of soil cement for low-cost road construction in Iowa looks bright. All test results point to probable economic or structural advantages, or both, from use of Type III cement.

ACKNOWLEDGMENT

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REFERENCES CITED

1. Aldrich, H. P., Jr. Frost penetration below highway and airfield pavements. low highway and airfield pavements. Highway Research Board Bulletin 135. 1956.
2. American Society for Testing Materials. 1958 Book of ASTM Standards, Part 4. Philadelphia, Pa. 1958.
3. Blanks, R. F. and Kennedy, H. L. The technology of cement and concrete, Volume I concrete materials. John Wiley & Sons, Inc. New York. 1955.
4. Bruns, L. D. Design and construction of base courses. Hwy. Res. Bd. Bul. 129. 1-9. 1956.
5. Clare, K. E. and Farrar, D. M. The use of cements of different fineness in soil cement mixtures. Magazine of Concrete Research. 8, No. 24:137-144. November, 1956.
6. Clare, K. E. and Pollard, A. E. Relationship between compressive strength and age for soils stabilized with four types of cement. Magazine of Concrete Research. 3:48. December, 1951.
7. Concrete paving design. Portland Cement Association, Chicago. 1951.
8. Davidson, D. T., Katti, R. K. and Handy, R. L. Field trials of soil-lime-fly ash paving at the Detroit Edison Company St. Clair Power Plant, St. Clair, Michigan. (Mimeo). 1958.
9. Davidson, D. T., Noguera, G. and Sheeler, J. B. Powder versus slurry application of lime for soil stabilization. ASTM Proceedings, 1959.
10. Felt, E. J. Factors influencing physical properties of soil cement mixtures. Hwy. Res. Bd. Bul. 108. 138-162. 1955.
11. Handy, R. L. Cementation of soil minerals with Portland cement or alkalis. Hwy. Res. Bd. Bul. 198. 55-64. 1958.
12. Handy, R. L. Stabilization of Iowa loess with Portland cement. Ph.D. thesis. Iowa State University Library. 1956.
13. Hicks, L. D. Design and construction of base courses. Hwy. Res. Bd. Bul. 129. 1-9. 1956.
14. Highway Research Board Committee on soil Portland cement stabilization. Definition of terms relating to soil Portland cement stabilization. Hwy. Res. Bd. Abstracts 29:28-29. June, 1959.
15. Lambe, T. W., Michaels, A. S. and Moh, Z. C. Improvement of soil cement with alkaline metal compounds. Hwy. Res. Bd. Bul. 241. 1959.
16. Lambe T. W. and Moh, Z. C. Improvement of strength of soil cement with additives. Hwy. Res. Bd. Bul. 183. 38-47. 1957.
17. Leyder, J. P. Stabilisation du sol au ciment. Centre De Recherches Routieres, Bruxelles. Rapport de recherche du 15 janvier 1957, pp. 1-164.
18. 1958 Yearbook. British Standards Institution. London, England, 1958.
19. Soil cement laboratory handbook. Portland Cement Association. London, England. 1958.
20. Spangler, M. G. Soil engineering. International Textbook Co., Scranton, Pa. 1951.
21. Standard specifications for highway materials and methods of sampling and testing, Part I specifications. The American Association of State Highway Officials. Washington, D. C. 1950.
22. Tawes, R. H. Improvement of soil cement with chemical additives. M.S. thesis, Iowa State University Library. 1959.

APPENDIX A

Modified British (B.S. 1924:1957) Freeze-Thaw Test

Scope

1. This method covers the determination of the change in the unconfined compressive strength of 2 inch high and 2 inch diameter specimens of stabilized fine grained soil when subjected to cycles of freezing and thawing under specified conditions. The test specimens are prepared as described under Methods of Preparing and Testing Specimens in this paper or as described in the Portland Cement Association's Soil Cement Laboratory Handbook¹⁴, p. 32.

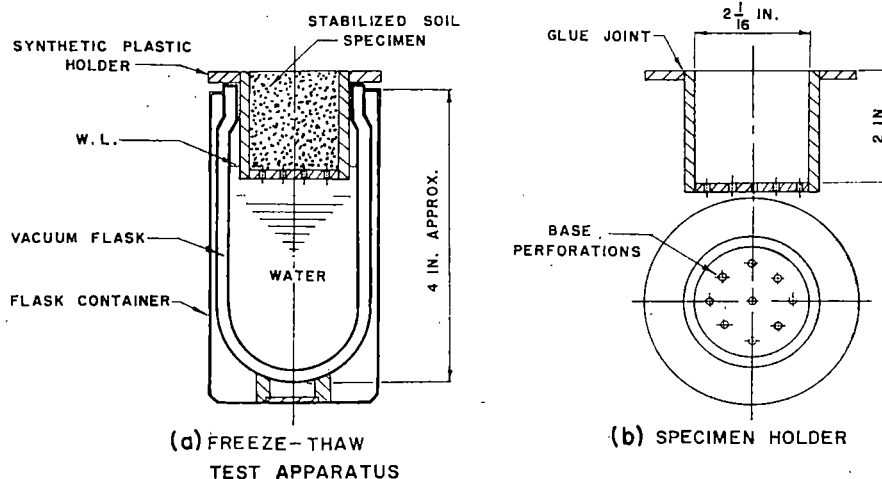


Fig. 6. Apparatus used in the modified British freeze-thaw test.

Apparatus

2. The apparatus required (figure 6) is as follows:

- a. A commercial vacuum flask having a neck with an internal diameter of approximately $2\frac{1}{2}$ inches and an internal depth of at least 4 inches.
- b. A specimen holder of low thermal conductivity and resistant to deformation under the test conditions, and capable of supporting a stabilized soil specimen 2 inches high and 2 inches in diameter within the vacuum flask, so that the upper flat surface of the specimen is flush with the top of the flask (figure 6). The base of the carrier shall be perforated in order to permit free access of water to the underside of the specimen.
- c. A refrigerated space within which is maintained a temperature of $-5 \pm 1^\circ\text{C}$ ($23 \pm 2^\circ\text{F}$), and which is large enough to contain the vacuum flask with its enclosed specimen. A thermometer mounted inside the refrigerated space.
- d. A supply of asphalt or resin base paint.
- e. A supply of self adhering membrane (the commercial product "Saran Wrap" was found very satisfactory).
- f. About 100 ml of distilled water, cooled to $8 \pm 2^\circ\text{C}$ ($46 \pm 4^\circ\text{F}$).

Preparation of Specimens for Test

3. For each determination two identical specimens 2 ± 0.05 inches high and 2 inches in diameter shall be prepared. (If greater accuracy is desired, four or six identical specimens may be prepared for each determination.)

Test Procedure

4. a. After the desired curing period any covering material on the specimens shall be removed, and both specimens shall be weighed. The method and length of curing will depend on the method of stabilization. If either specimen has lost more than 2 grams in weight during storage in a moist room maintained at a temperature of $21 \pm 1.7^\circ\text{C}$ ($70 \pm 3^\circ\text{F}$) and a relative humidity of at least 90%, both specimens shall be discarded. If dry curing is used to reduce the volatile content of specimens to a desired percentage of the original volatile content, the difference in weight between the specimens should not exceed 1 gram.

b. After weighing, a coating of asphalt or resin base paint, about 1 mm thick, shall be applied to the flat top surfaces of both specimens and allowed to dry. The specimens shall then be immersed in distilled water at $25 \pm 2^\circ\text{C}$ ($77 \pm 4^\circ\text{F}$).

c. After immersion for 24 hours one of the specimens shall be removed from the water and dried with blotting paper. A collar, $1\frac{1}{2}$ inches deep, of a self-adhering membrane ("Saran Wrap") shall be placed around the top of the specimen.

d. Sufficient water at a temperature of 8°C (46°F) shall be poured into the vacuum flask so that when the specimen dealt with in *c* above is inserted in the holder and the latter placed in the flask, the bottom $\frac{1}{4}$ inch of the specimen is immersed in water. The vacuum flask and its contents shall then be placed in the refrigerated space maintained at $-5 \pm 1^\circ\text{C}$ ($23 \pm 2^\circ\text{F}$) for a period of 16 hours.

e. The flask and contents shall be removed and thawed for a period of 8 hours at a temperature of $25 \pm 2^\circ\text{C}$ ($77 \pm 4^\circ\text{F}$). If, after thawing, the level of the water inside the vacuum flask has dropped so that it is no longer in contact with the base of the specimen, water at 8°C (46°F) shall be added to restore the level.

f. The procedure described in *d* and *e* above constitutes one cycle of freezing and thawing. Testing shall continue until the specimen has been subjected to 14 such cycles: the 8 hour thawing period may be extended to 66 hours for a maximum of 4 cycles of the total 14 cycles, if this is required for experimental convenience. (The number of cycles of freezing and thawing in the test should approximate the number of cycles that the stabilized soil will be subjected to in the road each winter. Thus 14 cycles may not be appropriate in all climates or for all components, base, subbase, subgrade, of roads.)

g. At the conclusion of the freezing and thawing cycles the thawed specimen shall be removed from the holder and, together with the second (control) specimen which has been stored in water during the entire period (15 days), shall be allowed to drain for 15 minutes. The heights of both specimens shall be measured.

h. The unconfined compressive strengths of the two specimens shall then be determined. Each specimen shall be placed centrally on the lower platen of the compression testing machine, and the load shall be applied to the ends of the specimen. The load shall be applied so that the rate of deformation is uniform and approximately 0.10 inch/minute. The maximum load in pounds exerted by the testing machine shall be noted and recorded (p_r for the freeze thaw specimen and p_e for the control specimen).

i. The moisture contents of representative samples of fragments taken from the interiors of the specimens shall be determined. In the case of soil stabilized with a fluid stabilizer, an additional representative sample of the fragments shall be set aside and their non-aqueous fluid stabilizer content(s) determined.

Calculations

5. a. The unconfined compressive strengths (p_r and p_e) of the two specimens shall be calculated from the formula:

$$p = 0.318 P \text{ (psi)}$$

where P = the maximum load recorded in pounds.

b. The index of the resistance to the effect of freezing (R_f) shall be calculated from the formula:

$$R_f = \frac{100p_r}{p_e} (\%)$$

Reporting of Results

6. The values of p_e , p_r and R_f shall be reported, the latter to the nearest 5%. The report shall also include relevant details of the composition of the stabilized soil mixture, the dry density at time of molding, and the moisture content and linear dimensional changes of specimens.

CEMENT REQUIREMENTS OF SELECTED SOIL SERIES IN IOWA

by

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ABSTRACT

Previous work has shown good correlation between cement requirements for soil cement and specific horizons in 43 agricultural soil series in several Great Plains States, Washington, and Idaho¹.

To check the validity of such correlations further and to expand the results to Iowa, a number of loess, sand and glacial till soil series were sampled in various horizons and tested. Instead of selecting modal samples from a series, many series are represented by modal samples and by extremes to provide a more rigorous test. Zonal great soil groups represented are Brunizem and Gray-Brown Podzolic. The dominant clay mineral is montmorillonite.

Cement requirement correlations ranged from good to poor. Reasons for poor correlations are that cement requirements for some fine-grained Iowa soils were abnormally high due to freeze-thaw sensitivity, and that some series are too broadly defined to distinguish adequately the sensitive from non-sensitive soils. Major differences relating to great soil group and B horizon structure were also found.

Investigations of Iowa fine sands showed good correlation of cement requirements with geologic origin, which is not reflected in the soil series designations on published soil maps. The sands are a valuable resource for use in soil cement.

CEMENT REQUIREMENTS OF SELECTED SOIL SERIES IN IOWA

Agricultural soil maps are useful to highway and foundation engineers, and recently the basic mapping unit, the soil series, has proved to be a reliable criterion for judging the amount of Portland cement needed to convert the soil to soil cement⁵. This correlation was demonstrated with samples from the different soil layers, or horizons, from each series. Samples were then tested to find the cement requirement. Results were checked by sampling the same series and horizons at several locations. Usually the re-

quirements remained constant, and the variation was never more than one percent of cement. Tests were conducted on A, B, and C horizon samples from 43 soil series in several Western states.

This led to the search for additional correlations, and application of the method to soils of Iowa. A variety of sandy, silty, and clayey soils were tested, representing glacial till, loess, and sand parent materials. In many series the sampling sites were selected to represent the extremes as well as the "average" or modal profiles, to provide a more severe test.

Published USDA county soil maps were helpful for series identification and sampling. Unfortunately most maps are old, and most series on the old maps have been re-defined. Therefore sampling is necessarily done by workers familiar with recent advances in soil mapping in a particular geographic area. This of course holds true whether sampling is for a research project or for an actual field use — whenever correlations are to be made with soil series.

Parent material

In approximately eighty-two percent of the area of Iowa the soils have developed in loess or in glacial drift, divided about equally between the two^a. The parent materials for soils over most of the remaining areas are alluvium.

Representative loessial and till soil series were selected for study. In addition four samples of upland glacio-fluvial and eolian sand were tested. Although a complete representation of Iowa series was impossible, the series most significant to engineers, for example those in hilltop positions where there is more likelihood of roadcuts and excavation of borrow, are represented. The loessial series are of interest because the loess parent material presents wide systematic textural variations believed related to distance from a source. This relation could be useful in correlation to cement requirement. Near major river valleys such as those of the Missouri, Mississippi, and Iowa, the loess is an A-4 silt with little or no soil profile. Fifty to eighty miles away the loess gradually changes to A-6 and then A-7-6 clay with a very strong soil profile (figure 1).

The Wisconsin age loess usually overlies Illinoian age (Loveland) loess or, more commonly, Kansan age glacial till which otherwise underlies the Loveland. Where loess is thin, the till outcrops on eroded valley slopes (figure 2) or may be intercepted by deeper roadcuts. In some roadcuts a tough, gray, clayey layer, aptly termed *gumbotil*, is found between the loess and glacial till. This is a paleosol, or ancient soil profile, weathered into the Kansan till during the long interval prior to loess deposition. An analogous paleosol is in the Loveland loess^a. Gumbotil is usually very high in montmorillonitic clay mineral and causes interesting problems, such as seepages, slumps, and tenaciously muddy roads. Color and morphology of the buried paleosol relate to pre-loess topography and erosion and are somewhat pre-

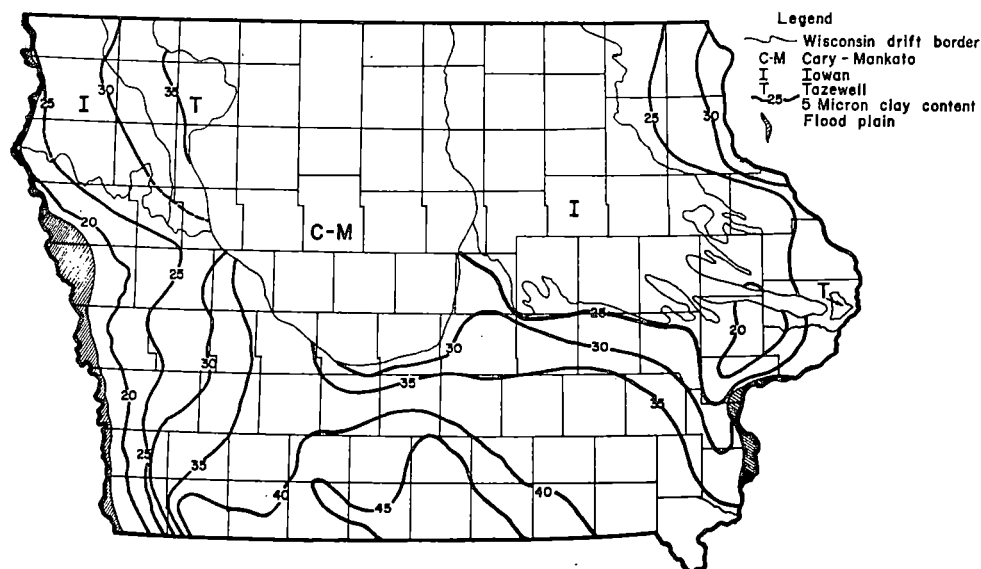


Fig. 1. Map showing Wisconsin drift borders and contoured 5 micron clay contents of C horizon loess.

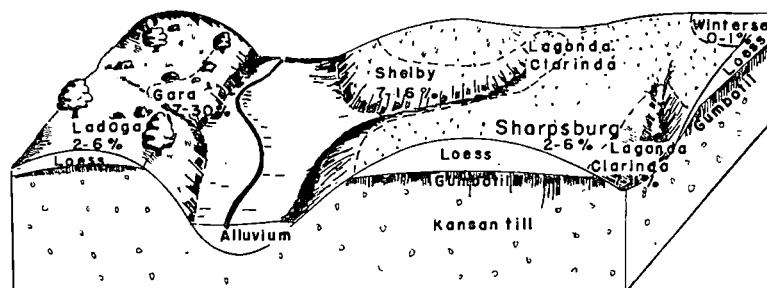


Fig. 2. Block diagram illustrating typical topographic occurrences of till and loess soils in the Shelby-Sharpsburg-Winterset soil association area, southwest Iowa. From *Understanding Iowa Soils*².

dictable from the present landscape⁷. For example, gumbotil is very clayey, thick, and gray colored in flat, uneroded upland position, where it is much like a modern planosol. In better drained positions it is reddish, thinner, and resembles a gray-brown podzolic.

Great soil groups

Two zonal great soil groups occur in Iowa, Brunizems (formerly called prairie soils), formed under grass, and gray-brown podzolic soils, formed under forest. Brunizems cover about 68 percent of the state and are the well-drained, dark-colored topsoils currently associated with an over-abun-

dance of corn. Gray-brown podzolics occur interspersed with the Brunizems but are more prominent in the eastern and southern parts of the state. The gray-browns are somewhat similar to Brunizems in clay content and profile, but are more acidic and have a distinctive gray-colored topsoil, or A horizon. Both groups show marked clay accumulation in the subsoil, or B horizon.

In southern Iowa, upland remnants of the Kansan till plain occur as wide flats which have been etched away at the margins to leave long, projecting interfluvies that mesh into the drainage pattern like fingers. Loess on these flat areas is usually poorly drained, partly because it is underlain by the impermeable gumbotil. As a consequence two intrazonal great soil groups are prominent:

Wiesenbodens (humic gley soils) are the poorly drained counterpart of Brunizems, occurring where profile development has been inhibited by high water table. They are characterized by a thick, very dark brown or black A horizon over a weak, gray colored B. With proper drainage they are excellent for agricultural use.

Somewhat similar to Wiesenbodens in position but not in profile are the planosols. Here the poor drainage, instead of inhibiting profile development by waterlogging, has enhanced profile development due to increased infiltration and intensified leaching. Planosols formed either under forest or under grass are acidic throughout their profile, and the A horizon has a distinctive ash gray (under grass) to white (under forest) layer, labelled the A₂ horizon. The B horizon is extremely high in clay. Planosols should logically make poor soil cement.

Series

Table I. Classification of major soil series in western, southern, and eastern Iowa.

Parent material	Great soil group				
	Regosol	Gray-brown podzolic	Brunizem (prairie soil)	Wiesenboden (humic gley)	Planosol Grass- Forest land
W. Iowa loess, coarse ↓ fine	Hamburg Ida		Monona* Marshall Sharpsburg	Minden Winterset	
E. Iowa loess, coarse ↓ fine		Fayette Clinton Weller	Downs Pershing	Tama Otley	Muscatine Mahaska Grundy Seymour
Kansan till, unweathered ↓ weathered	Steinauer		Burchard* Shelby Lagonda*	Garwin Taintor	Haig Edina Marion

* Series showing characteristics of more than one great soil group are indicated by position or by arrows. Series more or less central in a group are underlined.

The approximate eastern Iowa equivalent of the Sharpsburg, developed on moderately clayey, leached loess, is the Otley. However, the forested counterpart, the Clinton series, and the poorly drained counterparts, Mahaska and Taintor, are more abundant in this particular area.

In south-central Iowa the loess is progressively finer, and the Grundy and Weller series represent Brunizems and gray-browns, respectively. Somewhat more poorly drained and finer textured is the Seymour series, a Brunizem. Also abundant are the Haig and Edina representing planosol influences, but the B horizons are so thick and clayey they are not well suited for soil cement.

Series on till. Also in western, southern, and eastern Iowa are the till soil series (table I). The nomenclature is simplified because, except for younger till sheets in northern Iowa, the glacial till parent material does not vary systematically across the state. Most is Kansan in age, but a rim of Illinoian till is in the eastern part of the state.

On rapidly eroding slopes, the essentially unweathered calcareous till Regosol is now designated the Steinauer series. The Burchard series is a weak Brunizem leached only in the A and B horizons, analogous to the Monona series on loess. These series have been mapped as Shelby in the past. Shelby is now restricted to a well-developed Brunizem on leached till. The forested counterpart of the Shelby is the Lindley; an intergrade between the two is now mapped on Gara. Surficial outcrops of gumbotil are included on older soil maps with Shelby, but now may be mapped Clarinda, a Wiesenboden, or Lagonda, a planosolic Brunizem (figure 2).

PROCEDURE

Sampling

Most of the series tested were represented by samples from two to four sections, which were selected to represent not only the mode but also the range of each series. For example, the Marshall series was sampled at three locations, one near the center of the Marshall area and the others from near the edges, where the Marshall is transitional to the Monona on the west and the Sharpsburg on the east (figure 3).

Most sections are located in roadcuts or quarries. Sampling was done by trimming back to a fresh surface, then cutting a downslope channel to obtain accurate composite samples of each layer. Pedological A, B, C₁ (leached C), and C horizons were sampled after field identification by two or three experienced persons to minimize bias. Supplemental augering was done where necessary, and special zones in or under the C horizon were sampled separately.

Mapping and definitions of soil series is constantly changing as finer distinctions are made, and very few of the soil series could be accurately

identified merely from location on published USDA Soil Survey maps, many of which were prepared in Iowa in the 1920's. Each series was therefore re-identified and fitted into up-to-date nomenclature.

Testing

Particle size analyses were made by the hydrometer method using the Iowa State air-jet dispersion device and sodium metaphosphate as the dispersing agent². Plasticity index and classification tests were performed according to standard ASTM methods¹. Cement requirements were determined in the Portland Cement Association Laboratory in Skokie, Illinois, according to standard methods⁶. These include the following:

- (a) a moisture density test to determine maximum density and optimum moisture content for compaction,
- (b) wet dry and freeze thaw tests, 12 cycles each on separate specimens, to determine how much cement is required to hold loss of loosened surficial material to within permissible limits, and
- (c) compressive strength tests to show if setting reactions are proceeding properly; strength should increase both with increasing age and cement content.

Permissible weight losses during wet dry or freeze thaw tests are set at 10 percent for A-4 and 7 percent for A-6 and A-7 soils. Specimens are brushed between cycles to remove loose material.

RESULTS

Loess

Minimum cement requirements are indicated in figures 4 and 5 for various loessial soil series.

Hamburg. Four samples of coarse calcareous loess mapped in the Hamburg series required 12 percent cement, and one required 14 percent. A sample of a weak, leached paleosol identified as Brady soil⁸ shows no difference in cement requirement, the requirement still being 12 percent.

Ida. Samples of Ida A horizon and C horizon loess required 20 percent cement due to failure by excessive scaling in the freeze thaw test. This loess is apparently in a critical clay content range for failure during freezing and thawing; the critical range is indicated by the vertical dashed lines in the top graph of figure 6.

Monona. Samples of coarse Monona leached and calcareous C horizon loess required over 20 percent cement, and are also in the critical clay content range (top, figure 6). In the B horizon samples and in a finer C horizon sample, the higher clay content reduced the requirement to 16 percent. The A horizon requirement was 18 percent.

Marshall. Marshall C horizon samples required 16 to 18 percent cement,

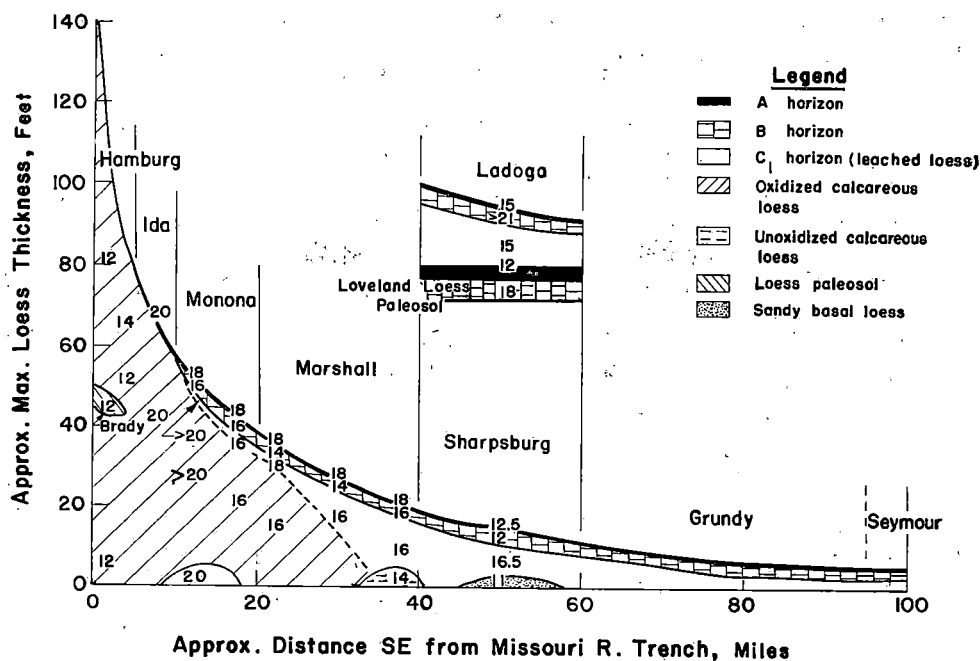


Fig. 4. Cement requirements of western Iowa loessal soils. As the loess thins it becomes finer, leached of carbonates, and weathered into heavier textured soil profile. Thickness and distance scales very approximate.

somewhat in the critical clay range. As in the Monona, the more clayey B horizon required less cement than the C, 14 to 16 percent, and all A horizon samples required 18 percent.

Sharpsburg. Sharpsburg C horizon loess is less critical for freeze-thaw loss, and the requirement was found to be 16.5 percent cement. The A and B horizons required only 12.5 and 12 percent, respectively, indicating the beneficial influence of clay. A sandy basal loess sample required 11 percent. The presence of either sand or clay is apparently effective at reducing cement requirement in these western Iowa Brunizems.

Ladoga. The gray brown podzolic equivalent of the Sharpsburg gives some interesting contrasting requirements in the A and B horizons. The gray brown A and B are bad actors compared with the Sharpsburg, and required 16 and over 21 percent cement, respectively. The C horizon was not affected, and required 16 percent cement. Possible influences of podzolization are discussed under Fayette.

Loveland loess and paleosol. Samples of plastic Loveland loess from underneath the Wisconsin loess at the section sampled for Ladoga have cement requirements not unlike the Weller (see below); 12 and 11.5 percent for the A and A₃ - B₁ horizons, and 18 percent for the clayey B₂.

Grundy. The Grundy continues trends initiated in the Sharpsburg:

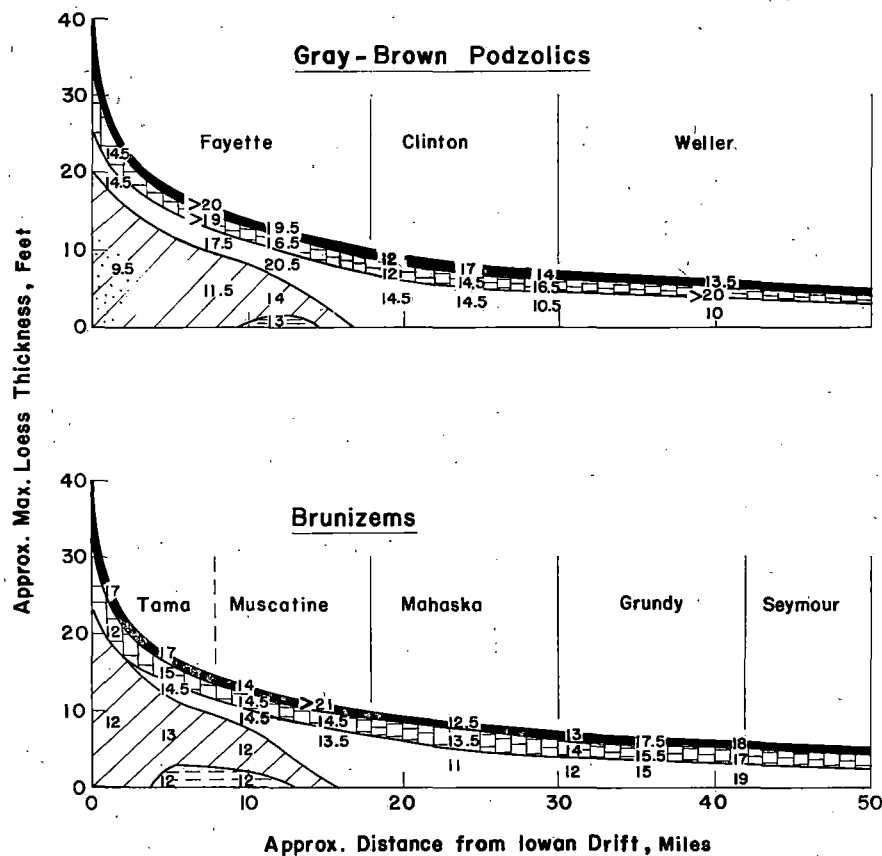


Fig. 5. Cement requirements of eastern and southern Iowa loessal soils. Legend is the same as in figure 4.

more clay, less sensitivity to freeze thaw, less cement. This trend reached a climax in the least clayey Grundy C horizon sample, which had a requirement of 12 percent. With more clay, however, failures began in the wet-dry test, and cement requirement mounted rapidly.

Tama. Thick eastern Iowa loess under the Tama series, a Brunizem, required 12 percent cement in the B and C horizons and 17 percent in the A, or very close to the Hamburg C and Monona A of western Iowa. Most interesting is that the C horizon Tama is not overly sensitive to freeze thaw, even though the clay content would put it in the critical range of the western Iowa samples (figure 6, middle graph).

Tama, Muscatine, Mahaska, Grundy. Some relationships are shown between intergrading eastern Iowa loessial Brunizem soil profiles and cement requirement, but the requirements do not necessarily coincide with series breaks (figure 4). For example, the C horizon loess requirement was 12 to

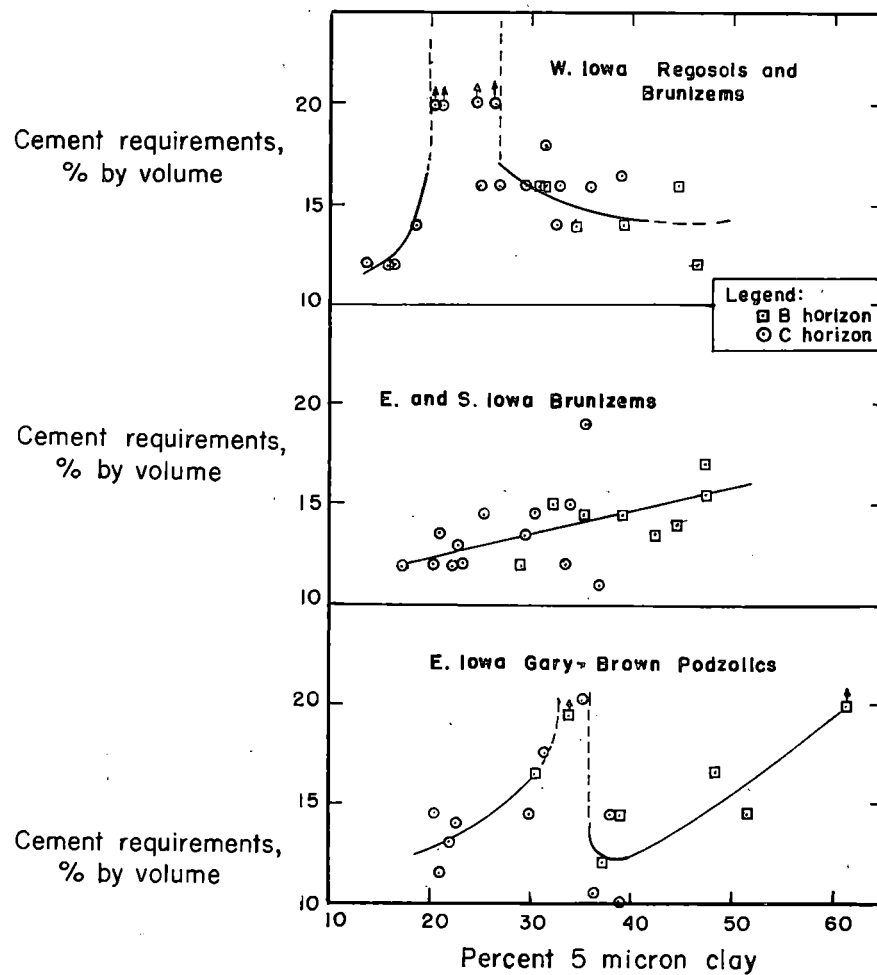


Fig. 6. Relations of cement requirement of Iowa loessial soils to 5 micron clay content.

13.5 percent cement in the Tama and Muscatine series, reached a low of 11 percent cement in the Mahaska, and climbed rapidly in the Grundy, from 12 to 17 percent, as losses in the wet-dry test became critical due to the high clay content. The major change in cement requirement thus took place within the confines of the Grundy. The cement requirements of the B horizons for these series was usually 1.0 to 2.5 percent higher than for the C. Requirement ranged from 13.5 to 15 percent to even higher in the already too clayey Grundy. The Edina series was not sampled, but it probably has cement requirements higher than the Grundy.

Fayette. Cement requirements of the Fayette series, the gray brown equivalent of the Tama (figure 4), are inconsistent, because the series is

too broadly defined to correlate adequately with some very critical freeze thaw losses. Coarse, sandy loess under the Fayette series required 9.5 percent cement in the C horizon and 14.5 percent in the C₁ and B. With more clay the B horizon became critically susceptible to freeze thaw, and the requirements jumped to 17.5 and 19 percent for the C₁ and B, respectively. Then in finer loess the C horizon became critical, requiring 20.5 percent, but the B horizon was over the hump.

This critical clay content range in the Fayette but not in the equivalent Brunizems (figure 6, lower and middle graphs) suggests a limited deleterious influence from podzolization. This is also true in the A horizon of the Fayette, which required 13.5 to 20 percent, averaging 17.7 percent for three samples. As previously mentioned, the Ladoga, a gray brown from western Iowa, also showed deleterious influence. However, the bad effect of forest vegetation does not carry over into the Clinton and Weller, which series are even more acidic than the Fayette. In the Fayette the pH is 4.5 to 5.1 in the A and B horizons; in the Weller it varies from about 3.8 to 4.5².

Perhaps the slightly different array of exchangeable cations or the traces of forest-derived organic matter could cause a structural effect in compacted samples, increasing capillary conductivity and causing excessive freeze thaw losses.

Clinton, Weller. The Clinton series is developed in finer loess than the Fayette and continues the trend toward lower cement requirement. In the coarser of the Clintons sampled, the C horizon requirement was 14.5 percent, and that in the higher clay B horizon was 12 percent. In the finest Clinton section and in the Weller section the C horizon reached an optimum for soil cement, 10.5 percent and 10 percent, respectively. However, as previously noted for the Grundy, the B is too clayey, and required 16.5 and over 20 percent, respectively, due to losses in the wet dry test. The unusually high requirement for the Weller B horizon could be partly due to theft of calcium from hydrating cement by the clay, since the natural base saturation is of the order of 50 to 60 percent.

Summary—loessial series. In western Iowa the cement requirement of coarse loess usually mapped in the Hamburg series is 12 percent. However, in slightly finer loess, freeze thaw losses suddenly become very critical, and cement requirements leap to over 20 percent. Loess mapped as Hamburg, Ida, or Monona and containing over 17 percent 5 micron clay should always be regarded as suspect. In the Marshall and Sharpsburg the cement requirements are steadily pushed down by the increase in clay content, until the requirement again reaches a low of 12 percent in the relatively heavy textured Sharpsburg B horizon.

Eastern Iowa Brunizems on loess do not show the same susceptibility to freeze thaw, and here in general more clay means that more cement is required. Best for stabilization are the Tama, Muscatine, Mahaska, and coarser Grundy C horizons, which require 11 to 13 percent cement. B hori-

zons take more cement, and the requirement jumps to 19 percent in the finer Grundy B and C horizons, where wet dry losses become critical.

The A horizons of most loessial Brunizems require 18 percent or more cement and should not be used. Exceptions may be the Sharpsburg and Mahaska, samples of which were stabilized with 12.5 percent cement.

Gray brown podzolics on loess show a critical sensitivity to the freeze thaw test, much like western Iowa Brunizems, but at higher clay contents. Cement requirements start low in the coarse Fayette, reach a peak in the medium Fayette B and the fine Fayette C, and fall off again in the Clinton. Then the clay content becomes too high in the Clinton and Weller B horizons, and failures occur in the wet dry test. The critical clay content range occurring in the Fayette probably is related to some influence of podzolization. This influence extends through the A, B, and C₁ horizons, but not into the calcareous C. Acidity alone does not explain it, since the acidity in the Clinton and Weller, which require less cement, is equal or greater.

Till

Cement requirements of till series are indicated in table II. Note that

TABLE II. CEMENT REQUIREMENTS OF SOIL SERIES ON KANSAN AND ILLINOIAN TILL

Horizon	Brunizems				Gray brown podzolic			
	Burchard	Shelby			Kansan till	Lindley	Ill. till	
A	13	14	12	....	10.5	8	....	....
B	13	15	14	....	13.5	16.5	15	12.5
C ₁	....	16	12	....	12.5	12.5	12.5	13
C _{ca}	13.5	....	....	....	....	....	....	....
C	17	11	15	11	13.5	12	....	....

the series correlation is not good, probably because series definitions and variability of the parent material are too broad. Calcareous C horizon Kansan till mapped under the Shelby, Lindley, and Burchard series was usually stabilized with 11 to 13.5 percent cement, but one sample required 15 percent and another 17 percent because of high losses during the wet dry test, probably from deleterious expansions of the montmorillonitic clay. Although C horizon cement requirements do not plot well against clay content (lower half of figure 7) the clay content becomes critical when the amounts are greater than about 37 percent. Eight of the 13 calcareous and leached C horizon till samples with 5 micron clay contents of 37 percent or less may be stabilized with 11 to 13.5 percent cement. The average requirement was about 12 percent. The five samples with over 37 percent clay required 13 to 17 percent cement, the average requirement being about 13 percent.

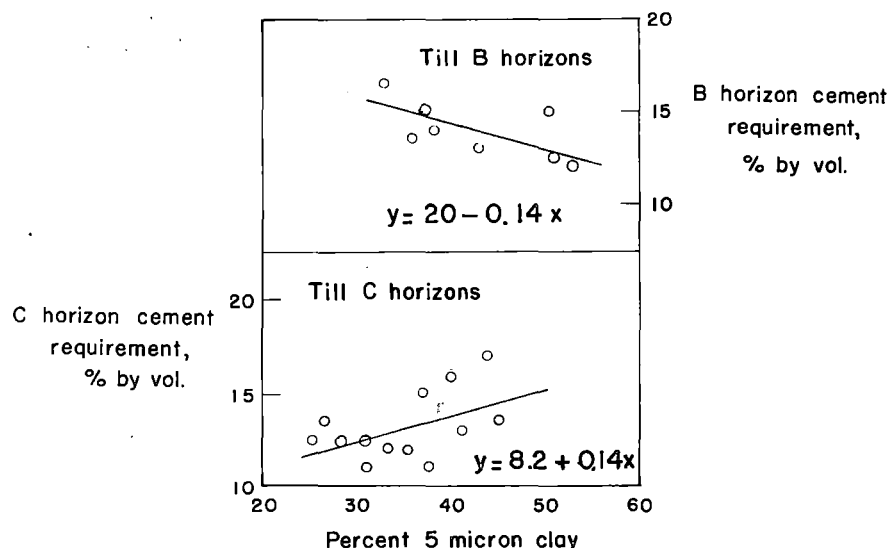


Fig. 7. Relations of cement requirement of Iowa till soils in 5 micron clay content.

If clay content is critical, one would expect till B horizons to require more cement, and most do. However, an inverse relationship exists (top half of figure 7), and the higher clay content B horizons tend to require less cement — several percent less than equivalent clay content C horizon samples. Furthermore, most B horizon samples failed in the freeze thaw test rather than the wet dry test, as did the C horizon samples with the same clay contents. This suggests an important contribution from the characteristic blocky structure of the B horizon, reducing volume change losses during wet to dry cycles. The compacted density of five B horizon samples with an average clay content of 37.8 percent is 106.2 pcf; of ten C horizon samples with a clay content of 37.5 percent, it is 110.8 pcf. The B horizon blockiness tends to reduce density, which may be directly or indirectly related to the increased resistance to wet dry volume change. Only the lowest clay content B horizon sample, a Lindley, failed during the wet dry test, and requirement was boosted to 16.5 percent. A gumbotil sample also showed benefit from having been a B horizon; although it contained 53 percent 5 micron montmorillonitic clay, the cement requirement was only 12 percent, and failure was by freeze thaw. Another gumbotil sample with 70 percent clay failed in the wet dry test and required 18 percent cement.

The A horizon Shelby and Burchard series required 12 to 14 percent cement, compared with only 8 to 10.5 percent for Lindley A horizons. As observed in loessial series, podzolization in the Lindley has no deleterious effect, but is beneficial in the A horizon because it reduces the clay content

to 15 or 20 percent and cuts the cement requirement. Unfortunately, Lindley A horizon soil is not abundant enough to provide a source for material; these results merely point out that A horizon material in the Lindley, Shelby, or Burchard series can beneficially be incorporated into soil cement.

Sand

Because of possible economic importance, upland sand deposits on and near the Iowan drift in eastern Iowa have in recent years been extensively mapped, sampled, and the engineering properties studied⁹ (figure 8). Four

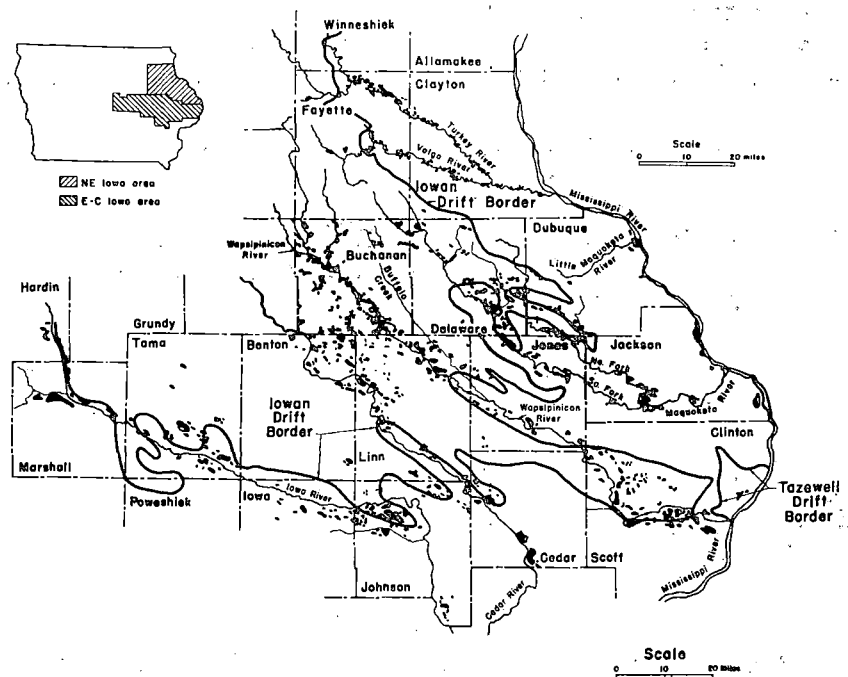


Fig. 8. Sand deposits in eastern Iowa.

representative deposits were sampled for soil cement tests. One sand, coarser than the rest, is fluvial in origin, i.e., deposited from water. The other three are finer and eolian, though one is rather coarse because of local derivation from sandy drift.

Because of difficulties in interpreting origin, the Iowa sands have been confusing for agricultural soil surveyors. As a result the sands are identified as belonging to a wide variety of series, such as Knox, Carrington, and Fayette. Although no attempt is made here to correlate cement requirement to modern series equivalents, on future soil maps the eolian Brunizem sands will probably be mapped as Hagener (formerly mapped as Thurman, Car-

rington, Lindley, Knox), and the gray brown podzolic equivalent will be the Chelsea (formerly mapped as Knox, Lindley, Sparta, Plainfield). Coarser eolian sands derived from local wind action on glacial drift will be mapped as Dickenson if a Brunizem (formerly Carrington, Shelby) or Lamont if a gray brown podzolic.

Many eastern Iowa sand deposits contain bands rich in clay and iron oxide minerals (figure 6). Most such bands lie nearly horizontal, but many dip, intersect one another, or are wavy. They are believed to be secondary in origin, perhaps miniature repeated B₂ horizons. One severely banded section was sampled separately for soil cement tests, to see if banding has any effect on cement requirement.

Results. Results of soil cement tests with the five sandy soils are shown in Table III. The fluvial sand required 7.5 percent cement; the eolian sands

TABLE III. CEMENT REQUIREMENTS OF EASTERN IOWA SANDS

Sample No.	Origin	% coarse sand (>0.42 mm)	Cement requirements, % by volume
S-31-1	Fluvial	24.9	7.5
S-28-4	Eolian (drift)	16.6	9.0
S-6-2	Eolian (banded)	6.2	8.5
S-6-2a	Eolian	3.2	9.0
S-57-4	Eolian	0.8	8.5

all required 8.5 to 9.0 percent, regardless of local derivation or secondary banding. The eastern Iowa sand deposits should be considered a valuable resource for use in soil cement.

CONCLUSIONS

Conclusions from the investigation may be stated as follows:

1. Not all soil series may be successfully correlated with cement requirement, particularly when requirements are high because of an unusual sensitivity.
2. Medium textured loess and loessial soils in the Ida, Monona, and Marshall series of western Iowa are critically susceptible to damage by freeze and thaw, probably due to high moisture mobility during freezing. However, this damage is reduced by increased contents of clay. Even more effective is the presence of sand.
3. Eastern Iowa Brunizems on loess do not show the critical susceptibility to freeze-thaw, but medium-textured gray brown podzolics, notably in the Fayette series, do. Perhaps differences in exchangeable cations or presence of traces of forest derived organic matter allow increased moisture movement during freezing.

4. Clay content reaches an optimum for freeze thaw resistance in fine textured loess or loessial B horizons. Then further increases in clay content accelerate wet-dry losses and raise the cement requirement. The optimum clay content is reached in the Clinton, Mahaska, and Sharpsburg B, and in the Clinton, Weller and Mahaska, Grundy C horizons. Weller B and Grundy, Seymour B and C horizons are too high in clay.
5. High clay contents in C horizon Kansan glacial till also accelerate wet-dry losses and increase the cement requirement. However, B horizon samples with the same clay content resist wet-dry losses and require less cement. The blocky structure in the B horizon of till series is of decided benefit.
6. Sand deposits common in eastern Iowa may be readily stabilized with 7.5 to 9.5 percent Portland cement. Cement requirement correlates with postulated origin and, when the areas are re-mapped, should correlate with soil series.

REFERENCES CITED

1. Procedures for testing soils. American Society for Testing Materials. Philadelphia, Pa. 1958.
2. Chu, T. Y. and Davidson, D. T. Simplified air-jet dispersion apparatus for mechanical analysis of soils. Hwy. Res. Bd. Proc. 32:541-547. 1953.
3. Daniels, R. B. and Handy, R. L. Suggested new type section for the Loveland loess in western Iowa. Jour. Geol. 67:114-119. 1959.
4. Handy, R. L. and Davidson, D. T. Evidence of multiple loess deposited in western Iowa. Iowa Acad. Sci. Proc. 63:470-476. 1956.
5. Leadabrand, J. S., Norling, L. T. and Hurless, A. C. Soil series as a basis for determining cement requirements for soil cement construction. Hwy. Res. Bd. Bul. 148. 1957.
6. Soil cement laboratory handbook. Portland Cement Association, Chicago. 1956.
7. Ruhe, R. V. Geomorphic surfaces and the nature of soils. Soil Science 82:441-456. 1956.
8. Simonson, R. W., Riecken, F. F. and Smith, G. D. Understanding Iowa Soils. Wm. C. Brown Co., Dubuque, Iowa. 1952.
9. Wickstrom, A. E. Fine sands in eastern Iowa. M.S. thesis. Iowa State University Library. 1957.

TABLE IV. TEST RESULTS FROM WESTERN IOWA LOESS SOILS

Series and Iowa No.	Horizon	Gradation				Consistency		Maximum density pcf	Optimum moisture, %	Required cement content, % by vol.
		Gravel, >2 mm	Sand, 0.074-2 mm	Silt 5-74 μ	Clay <5 μ	LL	PI			
W. Iowa Loess										
Hamburg I	C	0	3.2	80.3	16.5	30.3	5.2	102.9	17.9	12
	AB, Brady	0	6.2	70.9	22.9	31.8	9.4	107.8	16.5	12
	C	0	8.2	78.2	13.7	27.3	2.6	107.7	15.8	12*
Hamburg X	C	0	0.9	80.6	18.5	32.1	10.1	103.0	18.5	14
	D, Stratified	0	0.7	83.3	16.0	33.9	10.9	102.3	19.0	12
Ida III	A	0	0.0	67.7	32.3	46.1	20.2	99.4	19.5	20
	C	0	0.5	75.0	24.5	35.2	11.8	100.0	18.5	20
Monona XI	A	0	0.1	82.5	17.4	42.9	19.5	98.5	22.5	18
	B	0	0.4	68.7	30.9	45.8	23.5	98.7	22.0	16*
	C ₁	0	0.4	73.2	26.4	39.9	17.0	105.0	18.0	>20
	C	0	0.6	74.8	24.7	33.5	9.8	102.0	18.6	>20
	C, Fe-rich	0	0.3	78.3	21.4	35.7	11.9	101.3	19.3	>20
	C ₁	0	0.2	79.2	20.6	34.9	10.8	102.0	18.3	>20
Monona IX	A	0	0.7	65.7	33.6	44.7	21.4	98.6	21.0	18
	B	0	0.5	68.3	31.2	41.8	20.3	103.2	18.3	16
	C ₁	0	0.5	70.1	29.4	41.2	19.7	103.3	19.0	16
	C	0	0.7	74.3	25.0	57.9	16.2	103.8	18.7	16
Marshall IV	A _s	0	0.8	59.3	39.9	45.8	23.1	94.5	23.3	18
	B	0	0.4	65.2	34.4	46.0	25.9	102.3	18.8	14
	C ₁	0	0.3	68.2	31.5	41.7	21.0	103.0	18.8	18
	C	0	0.4	72.6	27.0	38.0	26.8	99.6	19.5	16
Marshall V	A	0	0.5	64.7	34.8	42.6	19.7	98.3	21.5	18
	B	0	0.3	60.4	39.3	48.0	27.9	99.0	21.5	14
	C ₁	0	0.4	66.6	33.0	39.6	21.3	104.2	18.7	16
Marshall VIII	A	0	0.4	58.3	41.3	49.2	27.6	98.4	21.3	18
	B	0	0.4	54.8	44.8	56.3	33.2	98.8	22.0	16
	C ₁	0	0.4	63.6	36.0	43.6	22.5	103.3	18.7	16
	C, unoxidized	0	0.8	66.6	32.6	40.4	19.7	98.4	21.3	14
Sharpsburg, 500	A	0	2.0	57.0	41.0	46.1	21.9	96.0	21.0	12.5
	B	0	1.0	52.5	46.5	55.1	33.6	95.5	22.7	12
	C ₁	0	1.0	60.0	39.0	47.7	26.1	100.0	22.0	16.5
	Sandy loess	0	15.0	55.0	30.0	35.5	16.4	112.3	13.5	11
Ladoga 502	A	0	2.3	63.9	33.8	35.6	13.9	102.5	17.1	15
	B	0	1.0	50.0	49.0	37.4	21.0	99.3	19.7	>21*
	C ₁	0	2.4	60.4	37.2	51.7	31.2	100.2	19.7	15
(Paleosol on	A _p	0	5.0	58.0	37.0	34.0	16.0	107.9	16.4	12
Loveland	B _{1p}	0	6.1	56.5	37.4	39.1	22.1	107.2	17.0	11.5
loess, 502)	B _{2p}	0	4.2	42.2	53.6	61.9	40.4	95.6	23.0	18*

*Wet-dry losses exceed losses from freeze-thaw.

TABLE V. TEST RESULTS FROM EASTERN AND SOUTHERN IOWA LOESS SOILS

Series and Iowa No.	Horizon	Gradation				Consistency LL	PI	Maximum density pcf	Optimum moisture, %	Required cement content % by vol.
		Gravel >2 mm	Sand 0.074-2 mm	Silt 5-74 μ	Clay <5 μ					
Gray-Brown Podzolics										
Fayette 100	A	0	2.1	62.6	35.4	41.0	17.7	102.7	19.3	13.5
	B	0	0.1	60.9	39.0	54.1	33.8	101.5	18.7	14.5
	C ₁	0	1.0	78.2	20.8	30.0	9.1	105.4	17.0	14.5
	Sandy loess	0	8.3	79.4	12.3	25.5	6.3	109.2	15.3	9.5
Fayette 211	A	0	2.0	77.8	20.1	30.0	7.5	102.0	17.3	>20
	B	0	0.8	65.2	34.0	43.4	21.5	104.0	16.5	>19
	C ₁	0	0.5	67.8	31.7	45.8	23.9	104.3	17.8	17.5
	C	0	0.7	78.2	21.1	28.9	8.2	106.6	16.2	11.5
Fayette 207	A	0	1.7	75.1	23.1	33.3	4.3	100.0	18.9	19.5
	B	0	0.4	68.9	30.7	38.0	15.0	102.7	19.2	16.5
	C ₁	0	0.5	64.3	35.2	41.7	19.3	101.3	18.1	20.5
	C	0	0.4	76.7	22.9	30.2	8.4	108.1	16.6	14
	C, unoxidized	0	0.3	77.5	22.2	28.6	6.7	109.6	15.8	13
Clinton 524	A	0	1.1	68.4	30.5	35.9	10.8	97.0	19.6	12
	B	0	0.7	61.8	37.4	43.9	22.4	98.8	20.0	12
	C ₁	0	0.3	69.7	30.0	36.2	15.9	103.7	19.0	14.5
Clinton 119	A	0	1.2	64.8	34.0	36.9	12.9	96.1	22.1	17
	B	0	0.7	56.6	42.7	51.8	30.0	100.1	21.7	14.5
	C ₁	0	3.4	62.9	34.7	38.1	19.9	103.5	19.8	14.5
Clinton 523	A	0	2.2	64.3	33.5	43.3	14.5	93.4	23.8	14
	B	0	2.8	58.0	39.5	48.5	24.1	98.3	19.5	16.5*
	C ₁	0	4.6	58.9	36.5	36.8	18.8	105.3	18.5	10.5
Weller 530	A	0	4.7	65.3	30.0	32.4	11.9	97.0	19.5	13.5
	B	0	1.8	46.4	51.8	61.9	40.0	95.3	22.0	>20*
	C ₁	0	4.8	55.2	40.0	39.1	21.4	104.3	19.6	10

TABLE V. CONTINUED

Series and Iowa No.	Horizon	Gradation			Clay <5 μ	Consistency		Maximum density pcf	Optimum moisture, %	Required cement content % by vol.
		Gravel >2 mm	Sand 0.074-2 mm	Silt 5-74 μ		LL	PI			
<i>Prunizems</i>										
Tama 122	A	0	2.3	71.5	26.2	32.9	8.9	102.8	18.4	17
	B	0	2.4	68.6	29.0	33.9	12.7	105.2	17.5	12
	C	0	5.0	77.6	17.4	25.4	1.8	107.8	16.0	12
Tama 212	A	0	3.4	71.6	25.0	35.7	11.7	99.8	19.2	17
	B	0	2.3	74.9	32.2	47.7	25.7	104.8	18.0	15
	C ₁	0	3.1	71.4	25.5	39.1	17.3	106.7	17.5	14.5
	C	0	1.2	66.6	22.8	32.8	10.7	106.0	17.3	13
	C unoxidized	0	2.4	74.5	23.1	29.6	8.8	107.9	15.7	12
Muscatine 223	A	0	0.8	67.6	31.6	40.7	17.2	99.6	19.7	14
	B	0	0.7	63.9	35.4	45.5	25.5	100.1	18.5	14.5
	C ₁	0	0.3	69.0	30.7	37.4	15.9	105.1	18.0	14.5
	C	0	0.8	78.6	20.6	26.6	3.6	106.8	16.5	12
	C, Fe rich	0	0.9	78.1	21.0	26.8	6.4	110.4	15.2	13.5
Muscatine 111A	C, unoxidized	0	1.4	76.3	22.3	28.2	9.1	107.6	17.3	12
	A	0	3.3	64.7	32.0	39.2	13.0	91.3	24.3	>21
	B	0	2.1	57.6	39.3	39.1	15.1	99.8	20.2	14.5
	C ₁	0	0.8	69.4	29.8	30.8	9.0	108.9	16.7	13.5
Mahaska 528	A	0	1.4	69.1	29.5	33.8	9.4	97.5	18.2	12.5
	B	0	0.7	57.8	42.5	49.5	26.2	102.0	20.5	13.5*
	C ₁	0	1.6	61.4	37.0	46.0	25.1	101.5	19.5	11
Grundy 529	A	0	2.5	62.5	35.0	34.3	14.1	97.5	21.4	13
	B	0	0.7	54.5	44.8	50.5	31.2	96.3	23.4	14*
	C ₁	0	0.5	65.8	33.6	38.0	20.2	104.0	17.8	12
Grundy 525	A	0	2.7	63.3	34.0	38.4	11.5	97.5	21.3	17.5
	B	0	0.9	51.8	47.4	52.5	27.6	93.5	22.5	15.5
	C ₁	0	0.4	65.6	34.0	38.8	19.1	101.3	19.5	15*
Grundy 541A	A	0	3.6	57.4	39.0	41.5	15.2	96.7	20.0	18
	B	0	1.5	51.0	47.5	55.2	29.9	96.6	22.5	17*
	C ₁	0	1.0	63.5	35.5	45.7	24.6	102.6	18.3	19*

*Wet-dry losses exceed losses from freeze-thaw.

TABLE VI. TEST RESULTS FROM KANSAN AND ILLINOIAN TILL SOILS

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Series and Iowa No.	Horizon	Gradation			Clay <5 μ	Consistency		Maximum Density pcf	Optimum moisture, %	Required cement content % by vol.
		Gravel, >2 mm	Sand 0.074-2 mm	Silt 5-74 μ		LL	PI			
<i>Brunizems</i>										
Burchard 411	A	3.0	30.0	30.5	36.5	43.3	20.3	100.5	18.7	13
	B	3.5	23.5	30.0	43.0	49.5	28.4	103.0	20.0	13
	C _{ca}	1.5	24.5	29.0	45.0	45.4	30.2	108.6	16.3	13.5
	C	3.0	24.5	28.5	44.0	41.1	25.7	108.1	16.0	17
Shelby 415	A	0.8	31.6	39.6	28.0	35.6	15.1	99.3	21.0	14
	B	2.7	29.2	30.9	37.2	47.4	29.4	103.0	19.3	15
	C ₁	2.3	23.4	34.3	40.0	45.8	28.6	99.7	22.0	16
	C	2.0	25.1	35.3	37.6	39.6	25.0	114.0	15.0	11
Shelby 416	A	8.0	36.5	29.5	26.0	38.4	14.6	104.6	17.3	12
	B	3.5	32.2	25.1	39.2	44.2	23.1	109.7	15.5	14
	C ₁	11.2	27.8	27.8	33.2	38.8	19.8	113.5	15.0	12
	C	1.3	32.6	29.1	37.0	38.2	23.1	112.5	15.5	15*
Shelby 425	C	2.5	35.6	30.9	31.0	29.0	12.0	117.8	13.0	11
<i>Gray-brown podzolics</i>										
Lindley 422	A	4.0	43.0	32.0	21.0	28.1	11.7	106.5	15.5	10.5
	B	1.2	37.1	25.2	36.5	39.3	23.0	108.3	15.7	13.5
	C ₁	6.2	41.3	27.0	25.5	33.0	20.0	116.3	13.7	12.5
	C	1.0	40.8	31.7	26.5	28.9	14.8	118.4	11.0	13.5*
Lindley 423	A	0	40.2	44.8	15.0	22.4	4.7	113.0	13.5	8
	B	0.4	41.6	25.0	33.0	39.6	22.8	107.0	16.5	16.5*
	C ₁	2.0	40.0	27.0	31.0	36.2	21.4	111.0	15.5	12.5
	C	0.8	28.7	35.0	35.5	40.9	22.6	113.1	14.2	12
Lindley 429A	B	1.2	30.7	17.7	50.4	35.6	18.5	101.0	21.0	15
	C ₁	2.0	41.5	28.1	28.4	27.6	12.9	113.6	14.1	12.5
Lindley 436 (Illinoian till)	B	5.0	19.0	25.0	51.0	56.5	35.3	107.4	18.0	12.5
	C ₁	1.0	26.0	32.0	41.0	56.2	35.7	109.3	14.5	13
<i>Paleosols</i>										
Gumbotil, 500-5C	B _p	5.0	21.5	21.0	52.5	41.0	24.0	101.9	20.9	12
Gumbotil, 528-4C	B _p	0.3	16.1	13.1	70.5	85.0	53.3	99.3	21.4	18*

*Wet-dry losses exceed losses from freeze-thaw.

TABLE VII. TEST RESULTS FOR EASTERN IOWA SANDS

Origin and Iowa No.	Horizon	Gradation				PI	Maximum density pcf	Optimum moisture, %	Required cement content, % by vol.
		coarse sand, 2-0.42 mm	Fine sand, 0.42- 0.74 mm	Silt, 5-74 μ	Clay <5 μ				
Fluvial† S-31-1	C ₁	37.0	59.2	1.6	2.2	NP	117.0	8.8	7.5
Eolian, local* S-28-4	C ₁	24.4	74.4	0.2	1.0	NP	110.6	9.5	9.0
Eolian* S-6-2	C ₁	9.1	87.7	1.7	1.5	NP	113.6	9.1	8.5
	B ₂ (band)	12.9	81.5	1.6	4.0	NP	116.0	9.5	9.0
Eolian† S-57-4	C ₁	1.7	86.9	8.6	2.8	NP	113.6	10.0	8.5

*Old series name indicates Brunizem.

†Old series name indicates Gray-brown podzolic.

**CHEMICAL TREATMENTS FOR SURFACE HARDENING
OF SOIL, CEMENT AND SOIL, LIME, AND FLY ASH**

by

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ABSTRACT

A bituminous wearing surface is nearly always used on base courses constructed of soil cement or soil, lime, and fly ash. A simpler expedient would be to treat the compacted roadbase chemically to increase hardness within the upper surface. Even if the hardened crust were inadequate as a wearing surface, it might alter freeze thaw susceptibility to allow a reduction in the thickness of bituminous surfacing and give a saving in cost.

Surface treatments investigated in the laboratory were calcium chloride, sodium hydroxide, sodium carbonate, and sodium silicate. Measured amounts of these solutions were sprinkled on the surfaces of molded 2 in. by 2 in. specimens confined in their molds. Solution amount, concentration, and time of application were varied. Other specimens were either moist cured or sprinkled with distilled water to provide a control. At the end of the treatment and curing period the specimens were tested for bearing capacity by the Iowa Bearing Value, essentially a miniature CBR. Bearing values were measured from plunger penetrations of up to $\frac{1}{2}$ in.

The soil, lime, and fly ash mixture was benefited most by application of sodium silicate solutions. The sodium silicate penetrates into the soil and probably reacts with calcium and magnesium ions from the lime to produce insoluble calcium and magnesium silicates. A single application of sodium silicate followed by continual moist curing approximately doubled the bearing strength, and sodium silicate treatment followed by daily applications of water increased bearing capacity in the surface layer about four times. The silicate crust also forms an effective seal against entry of surface water. From these results, a field test appears to be the next step. Similar results are to be expected for soil and lime.

Results with soil and cement were less spectacular, but by no means less interesting. Sodium silicate application followed by daily wetting with water again proved to be the best treatment; the improvement was between

20 percent and 90 percent over control strengths, depending on the soil. A sandy soil was most benefited. Daily wetting was in itself beneficial to the silty soil, and this alone increased the bearing strength about 30 percent over that from ordinary moist curing. However, daily sprinkling decreased the bearing strength of the stabilized sandy soil. A sodium silicate soil cement field test appears warranted, using sandy soil.

Soil cement, and more recently soil, lime, and fly ash mixtures are becoming important members in the engineer's list of materials for low-cost roads. Unfortunately both materials require a bituminous wearing surface, which often costs more than the soil stabilization. A beneficent alternative for light traffic uses would be to treat the stabilized soil chemically to increase strength in the upper layer of pavement.

TEST METHODS

A punch-type bearing test was used to measure surface hardness of the treated soil. The Iowa Bearing Value (IBV) test, essentially a miniature CBR, was selected because the small 2 in. diameter by 2 in. high specimen allows a considerable saving in time and labor. Tests were run in triplicate and the average bearing values are reported.

Stabilized soil cylinders slightly over 2 in. long were compacted to standard Proctor density inside of 5 in. long brass sleeves by means of a drop-hammer molding apparatus. Each sleeve was then slipped over a 3 in. high pedestal which pushed the soil cylinder into the upper 2 inches of the sleeve. The protruding soil specimen was then struck off level with a straightedge, giving a cut surface similar to that left on a stabilized soil road after trimming by a blade grader. The trimmed soil cylinder was pushed back to the other end of the sleeve so the walls of the sleeve might aid in retaining the curing solution.

Chemicals

Curing solutions of different chemicals were sprinkled on the cut soil surfaces in varying amounts, comparable with those obtained on a road with standard distributor equipment. Control specimens were sprinkled with corresponding amounts of distilled water. Laboratory sprinkling was done from a graduated burette from a height of 3 inches.

Curing

Starting the day after treatment, most of the treated and control specimens were daily sprinkled with distilled water in the amount of $\frac{1}{2}$ gal. per sq. yd., and allowed to dry at $80^{\circ}\text{F} \pm 5^{\circ}\text{F}$ in a relative humidity of 40 percent \pm 5 percent. Since specimens remained in the brass cylinders, only one end was exposed to open air.

For comparison, reference specimens not treated with chemicals were cured by wrapping in thin plastic (Saran Wrap) and storing at $70^{\circ}\text{F} \pm$

5°F in a relative humidity of 95 percent \pm 5 percent.

Testing

The $\frac{5}{8}$ in. diameter IBV plunger rod was pushed into a test specimen at a constant rate of 0.05 in. per min., and the load in pounds was recorded at every 0.02 in. of strain to 0.20 in., then at every 0.05 in. until the penetration reached 0.50 in. The IBV is the load in pounds when the plunger penetration is 0.08 in., or a little over $\frac{1}{16}$ in.¹ (The Iowa Bearing Value closely correlates with the California Bearing Ratio in the normal range for unstabilized soils. However, these correlations probably are not valid for stabilized soils. As a very rough guide, 0.08 in. IBV's of 1,000, 500, and 100 are approximately equivalent to 0.1 in. unsoaked CBR's of 200, 100, and 10 for unstabilized soils containing 50 percent to 80 percent sand.)

SOIL, LIME, AND FLY ASH

A sample of Detroit Edison Company St. Clair fly ash was used in the investigation. This fly ash has a specific surface of 2,720 sq. cm. per gm. and a 3.6 percent loss on ignition. Data show 11.3 percent retained on the No. 325 sieve. Except where otherwise specified, samples were molded with 22.5 percent fly ash and 2.5 percent monohydrate dolomitic lime, expressed as percents of the dry weight of the mix.

In the initial evaluation two soils were used, both having a fairly high permeability. One, an A-4(8) silt loam, is from the thick, friable loess deposits of western Iowa. The other is a 75:25 mixture of fine alluvial waste sand and medium textured loess, as used in a stabilized soil base course in primary highway 117 north of Colfax, Iowa (table I).

Treatment with Sodium Carbonate

Sodium carbonate has been found to be an effective accelerator for certain soil, lime and fly ash mixes, and it was decided to try this chemical in a curing solution. It is believed that sodium carbonate reacts with calcium from lime to precipitate calcium carbonate as a cement and simultaneously release sodium hydroxide, which acts to accelerate the pozzolanic reaction².

Sodium carbonate solutions of 5, 10 and 20 percent concentration were sprinkled to give various weights of chemical per sq. yd. (figure 1). Sprinkling was done after 0, 1, or 2 days preliminary moist curing. Thereafter each succeeding day the specimens were sprinkled with distilled water, and after 7 days they were tested.

The loess was not benefited by the sodium carbonate treatment, and bearing values were below those of the controls sprinkled with distilled water (figure 1a, b). General heaving and swelling were noticeable in the tops of specimens, indicating deleterious volume change from excess sodium carbonate. Furthermore, control strengths were below those from continu-

TABLE I. SOIL PROPERTIES

Material	Friable loess (No. 20-2V)	Sand	75:25 Sand loess Medium textured loess	Dune Sand (No. S-6-2)	Detroit clay	Kansan till (No. 409-12C)
Location	Harrison Co., Iowa	Jasper Co., Iowa	Jasper Co., Iowa	Benton Co., Iowa	Monroe Co., Mich.	Ringgold Co., Iowa
Soil series	Hamburg	—	Tama	Carrington (?)	—	Burchard
Great soil group	Lithosol	—	Brunizem	Brunizem	—	Brunizem
Sampling depth	80 ft.	—	5 ft - 40 ft.	1½ ft.-16½ ft.	—	4½ to 10½ ft.
Horizon or bed	C, oxidized, calcareous	Washed sand dredged from terrace of Des Moines River	C, oxidized, calcareous	C, oxidized, leached	C, oxidized, calcareous	C, oxidized, calcareous
Liquid limit	34%		18.9%	19%	47%	42%
Plastic limit	28%		16.4%	—	21%	20%
Plasticity index	6		2.5	N.P.	26	22
Gravel (>2 mm)	0%		0%	0%	0%	0%
Sand (2-0.074 mm)	0.3%		57.7	94.4	10.5	31.9
Silt (74 - 5μ)	82.7		30.2	1.6	14.1	28.9
Clay (<5μ)	17.0		12.1	4.0	75.4	39.2
Colloids (<1μ)	12.3		—	3.5	70.5	—
Textural classification	Silt loam		Sandy loam	Sand	Clay	Clay
AASHO classification	A-4(8)		A-4(1)	A-3(0)	A-7-6(15)	A-7-6(12)
Clay minerals	Montmorillon- ite and illite		Montmorillon- ite and illite	Montmorillon- ite and illite	Chlorite and illite	Montmorillon- ite and illite
Cation exchange cap., me/100 gm	13.4		11.0	—	19.0	29.5
Carbonate content	10.2%		11.6%	0%	0.9%	2.1%
pH	8.7		8.0	6.5	7.6	8.25
Organic matter content	0.17%		0.16%	0.04%	1.1%	0.17%
ASTM cement requirement, by weight	9%		8%	—	—	—
OMC for soil cement	17%		9.8%	—	—	—
Std. Proctor density	105 pcf		129 pcf	—	—	—
OMC for soil + 24% 1:7 lime fly ash	20%		11%			
Std. Proctor density	98 pcf		120 pcf			

Lime - Fly Ash Stabilized Soils

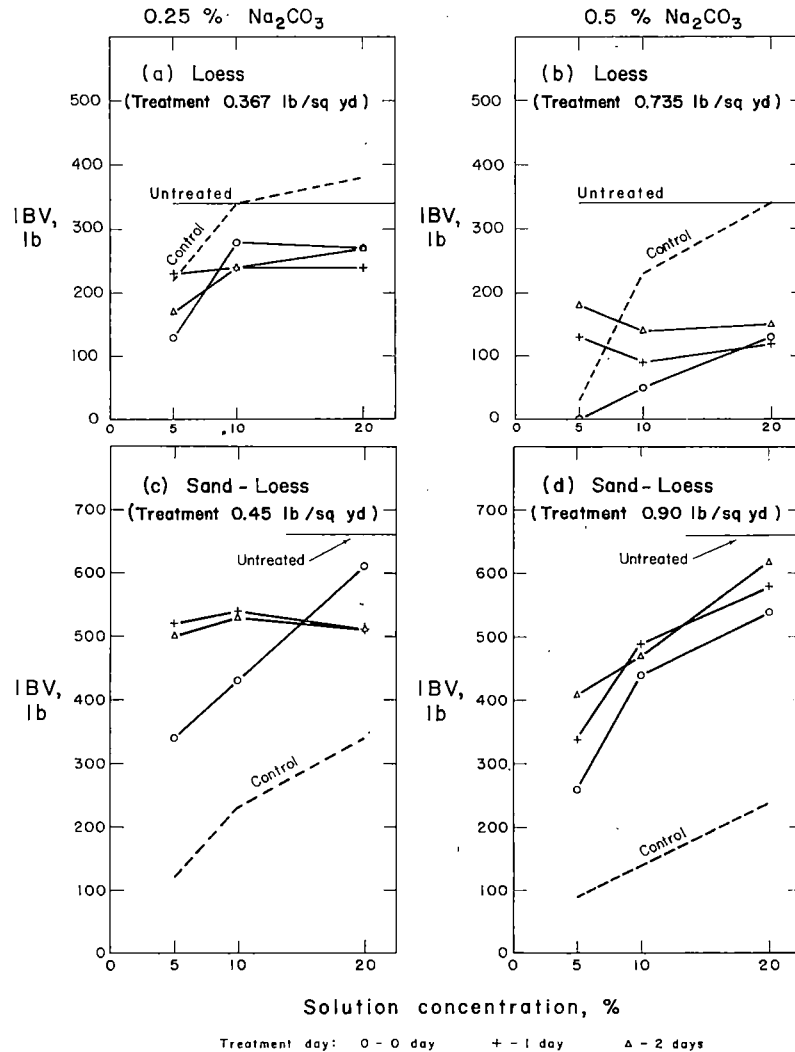


Fig. 1. Effects of sodium carbonate solutions on 7 day Iowa Bearing Values of soil, lime, and fly ash. Control specimens were sprinkled with distilled water; untreated specimens were simply moist cured. The 0.25 percent and 0.5 percent Na_2CO_3 figures refer to weight of the chemical compared to total dry weight of the specimen.

ous moist curing except when daily sprinkling was light, less than 0.4 gal. per sq. yd. (This amount represents control sprinkling with water to equal the amount of solution at a concentration of about 10 percent — in figure 1 stronger concentrations mean less water, indicating the deleterious effects of excess wetting.)

Lime - Fly Ash Stabilized Soils

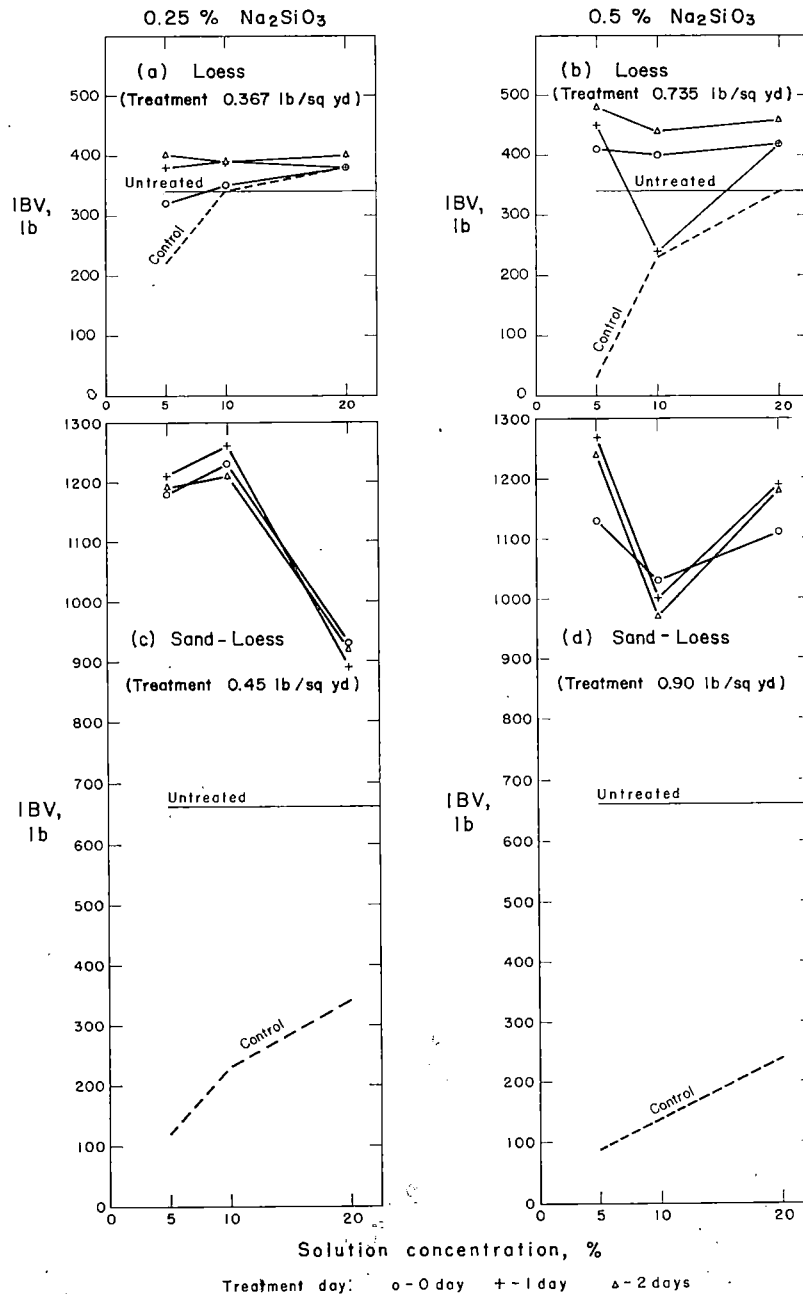


Fig. 2. Effects of sodium silicate solutions on 7 day IBV's of soil, lime, and fly ash. Results are particularly good with the sandy soil. A low solution concentration means more water is used to get the same application of chemical.

Sprinkling was particularly damaging to the surface of the stabilized sand and loess mixture, and IBV's fell from 650 in moist cured specimens to an average of about 200 in the controls sprinkled only with water. Sodium carbonate was beneficial, particularly when the chemical was added in high concentration; i.e., without much water (figure 1c, d), but bearing values still were not as high as with ordinary moist curing. It is concluded that while sodium carbonate contributes to bearing strength of sand and loess, the gain is often cancelled by the effect of wetting. Testing with this chemical was discontinued.

Treatment with Sodium Silicate

The second chemical tried reacts somewhat similarly to the action of sodium carbonate; that is, sodium silicate reacts with lime to precipitate calcium silicate and release sodium hydroxide. Tests were conducted similarly to those with sodium carbonate, and results were more encouraging. The IBV for stabilized loess was raised from 325 only to about 450, but for stabilized sand and loess it was raised from 650 to between 1,000 and 1,250 (figure 2c, d). The day of treatment was found to be not critical. Therefore in this and later investigations the curing solution was added immediately after molding at the time representing the greatest field convenience. Specimens were then sprinkled with water the second through the sixth days. This wet, dry treatment was found to give somewhat better strengths than continued moist curing after treatment.

Next, two kinds of sodium silicate were evaluated, one the metasilicate, Na_2SiO_3 , having an $\text{Na}_2\text{O}:\text{SiO}_2$ molar ratio of 1:1, and the other having a molar ratio of 1:3.25. Both amount and concentration of solution were varied. The loess soil 20-2V was used, because this previously gave poorest results. As more sodium silicate is used, bearing values go as high as 700, or approximately double (figure 3). The 1:3.25 silicate gave slightly higher strengths.

Age and Penetration. An important phase of the work was to discover the effects of sodium silicate at different depths and after longer curing times. A 20 percent solution of 1:3.25 silicate was sprinkled on the surface of stabilized sand and loess immediately after molding. This treatment was followed by 6 days of wet, dry treatment as before, then by air drying, as would be expected in the field.

Bearing values at different depths and ages show results that are particularly striking at 7 days, when the bearing value is triple even after a penetration of 0.50 in. (table II). At 0.08 in., the 7 day bearing value is increased eight-fold. After 28 days the effect is still strong at 0.08 in. and 0.02 in. penetration, but less marked at 0.50 in.

Soils. So far the testing has intentionally been with relatively permeable soils (table III). Both 1:1 and 1:3.25 silicates were used; the 1:1 is less viscous and should penetrate more. However, results with clayey soils were

Lime-Fly Ash Stabilized Loess Sodium Silicate, wet-dry cure

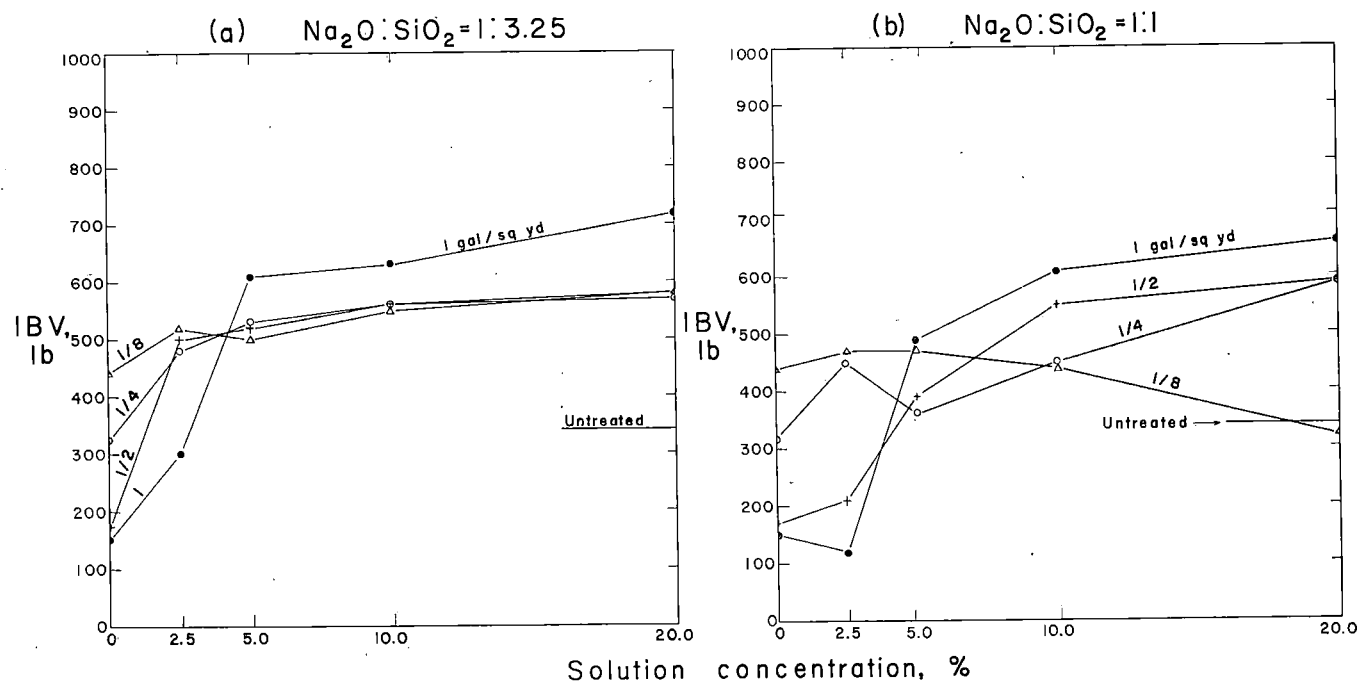


Fig. 3. Seven day IBV's for loess, lime and fly ash treated with two different kinds of sodium silicate solution. In (b) note the deleterious effect of too much wetting with low concentration of chemical.

TABLE II. EFFECT OF 1 GAL. PER SQ. YD. OF 20 PERCENT SODIUM SILICATE
(1:3.25) ON IBV OF LOESS, LIME, AND FLY ASH

Penetration depth, in.	Iowa Bearing Value, lb.					
	7 day		14 day		28 day	
	Control	Treated	Control	Treated	Control	Treated
0.08	180	1,570	300	2,010	730	2,860
0.20	650	2,490	1,260	3,250	3,020	4,570
0.50	1,560	4,650	4,580	5,950	7,010	8,270

TABLE III. EFFECT OF 1 GAL. PER SQ. YD. OF 20 PERCENT SODIUM SILICATE
(1:1 AND 1:3.25) ON IBV OF FOUR SOILS

Soil	Lime + fly ash, %	Lime: Fly ash ratio	Penetration depth, in.	7 day IBV, lb.*		
				Control	Treated 1:1	Treated 1:3.25
75:25 Sand loess [A-4(1)]	25	1:9	0.08	180	1,930	1,570
			0.20	650	2,940	2,490
			0.50	1,560	4,980	4,650
Dune sand [A-3]	25	1:5	0.08	290	1,640	1,970
			0.20	—	2,760	3,050
			0.50	—	4,690	5,010
Detroit clay [A-7-6(15)]	20	1:4	0.08	370	380	360
			0.20	630	540	540
			0.50	1,020	830	890
Kansan till [A-7-6(12)]	6 lime 0 fly ash	—	0.08	540	530	540
			0.20	850	750	—
			0.50	1,400	1,050	—

*Definite shear failures indicated by dash.

consistently poor, probably due to poor penetration. The choice of silicate ratio made little difference.

Lime. Different chemical classes of lime have proved satisfactory for soil stabilization, so there was a question which would react best with sodium silicate (table IV). With this soil the 1:1 Na₂O:SiO₂ appears best.

TABLE IV. EFFECT OF 1 GAL. PER SQ. YD. OF 20 PERCENT SODIUM SILICATE
(1:1 AND 1:3.25) ON IBV OF SAND LOESS STABILIZED WITH FLY ASH
AND TWO DIFFERENT KINDS OF LIME

Type of lime	Penetration, depth, in.	7 day IBV, lb.		
		Control	Treated 1:1	Treated 1:3.25
Dolomitic monohydrate [Ca(OH) ₂ + MgO]	0.08	180	1,930	1,570
	0.20	650	2,940	2,490
	0.50	1,560	4,980	4,650
Calcitic hydrate [Ca(OH) ₂]	0.08	140	1,370	680
	0.20	540	2,080	1,260
	0.50	1,760	3,420	2,640

Bearing values are about 50 percent higher for dolomitic monohydrate, $\text{Ca}(\text{OH})_2 + \text{MgO}$. By contrast the control samples show little difference in strengths with the two types of lime.

Lime to fly ash ratio. Theory suggests that because sodium silicate reacts with lime, the reaction might be benefited by a higher ratio of lime to fly ash. Dune sand stabilized with 25 percent lime fly ash in two ratios, 1:2 and 1:5 was treated with two types of sodium silicate.

TABLE V. EFFECT OF 1 GAL. PER SQ. YD. OF 20 PERCENT SODIUM SILICATE (1:1 AND 1:3.25) ON IBV OF DUNE SAND STABILIZED WITH TWO RATIOS OF LIME TO FLY ASH

Lime: Fly ash ratio (Total amount: 25% by weight)	Penetration depth, in.	Control	7 day IBV, lb.*	
			Treated 1:1	1:3.25
1:2	0.08	460	1,880	1,280
	0.20	810	2,200	1,910
	0.50	2,200	3,860	—
1:5	0.08	290	1,640	1,970
	0.20	—	2,760	3,050
	0.50	—	4,690	5,010

*Definite shear failures indicated by dash.

Contrary to this theory, the 1:5 lime to fly ash ratio gave best results (table V). However, shear failures of control specimens make the results difficult to evaluate. Insofar as sodium silicate surface treatment is concerned, the lime to fly ash ratio is not critical.

Surface seal. Sodium silicate treatment gave all appearances of sealing the soil, lime, and fly ash surface against further entry of water. In some cases $\frac{1}{4}$ gal. of water per sq. yd. failed to soak in during 24 hr. Equally as important, moisture retention within the specimens is improved (table VI), undoubtedly benefiting strength. A bituminous film would of course do likewise.

TABLE VI. MOISTURE CONTENTS OF SOIL, LIME AND FLY ASH AFTER 7 DAYS CURING WITH AND WITHOUT 1 GAL. PER SQ. YD. 20 PERCENT SOLUTION SODIUM SILICATE TREATMENT. ALL SPECIMENS RECEIVED A DAILY WETTING

Soil	Moisture content, %		
	Control (Water treatment)	Sodium Silicate 1:1	1:3.25
Loess	17.5	22.1	21.1
75:25 Sand loess	9.0	12.6	10.6
Dune sand	9.3	11.3	11.7

Cost. The current cost of sodium silicate is about 2 to 3 cents per lb. The cost of a 20 percent solution is thus in the neighborhood of 5 cents per gallon. The heaviest application investigated would therefore cost about 5 cents per sq. yd. In comparison, this is approximately equal to the cost of the asphalt in a single spray coat (0.3 gal per sq. yd.), to which must be added the cost of stone chips and rolling. Two asphaltic coats are usually used.

Summary.—Soil, lime, and fly ash. Of two types of curing solutions investigated for compacted soil, lime, and fly ash, sodium silicate appears best. Ratio of Na_2O to SiO_2 and ratio of lime to fly ash are not critical, and the treatment is only modestly sensitive to kind of lime. Good results are obtained only with permeable soils, in this case friable loess and a mixture of loess and sand. Laboratory data indicate that a satisfactory treatment may be 1 gal. of 20 percent solution per sq. yd. of road surface, which gives a three to eight fold increase in bearing strength. Field tests would appear to be justified.

SOIL CEMENT

For the investigation of surface treatments for soil cement, two soil samples, the friable loess and the 75:25 mixture of fine sand and medium textured loess, were stabilized with required amounts of Type I Portland cement (table 1), and then treated with various curing solutions, cured, and tested as before. For comparison, untreated samples were moist cured the same periods, and untreated control specimens were given a daily sprinkle with distilled water.

Treatment with Sodium Hydroxide

Previous investigators have reported soil cement strength benefits from sodium hydroxide, either as an additive³ or in a curing solution⁴.

The present investigation (figure 4) shows that surface treatment with sodium hydroxide solutions immediately after compaction usually gives best results, and this procedure was adopted. Data show that sodium hydroxide treatment followed by 7 days of moist curing only slightly benefited the 75:25 sand loess, but the loess, soil, cement shows a maximum gain from IBV 820 to an IBV near 1,250 (figure 4). This soil was selected for further study.

Further results show that when treatment is followed by moist curing the best treatment is a 5 or 10 percent NaOH solution sprayed at the rate of $\frac{1}{2}$ gal. per sq. yd. (figure 5). Treatment followed by daily wetting and drying gives better bearing strengths, the optimum treatment being about the same. Particularly interesting in this case is that wetting and drying with no sodium hydroxide treatment (0 percent concentration) was just as beneficial to the stabilized loess as wetting and drying after a treatment.

Cement Stabilized Soils

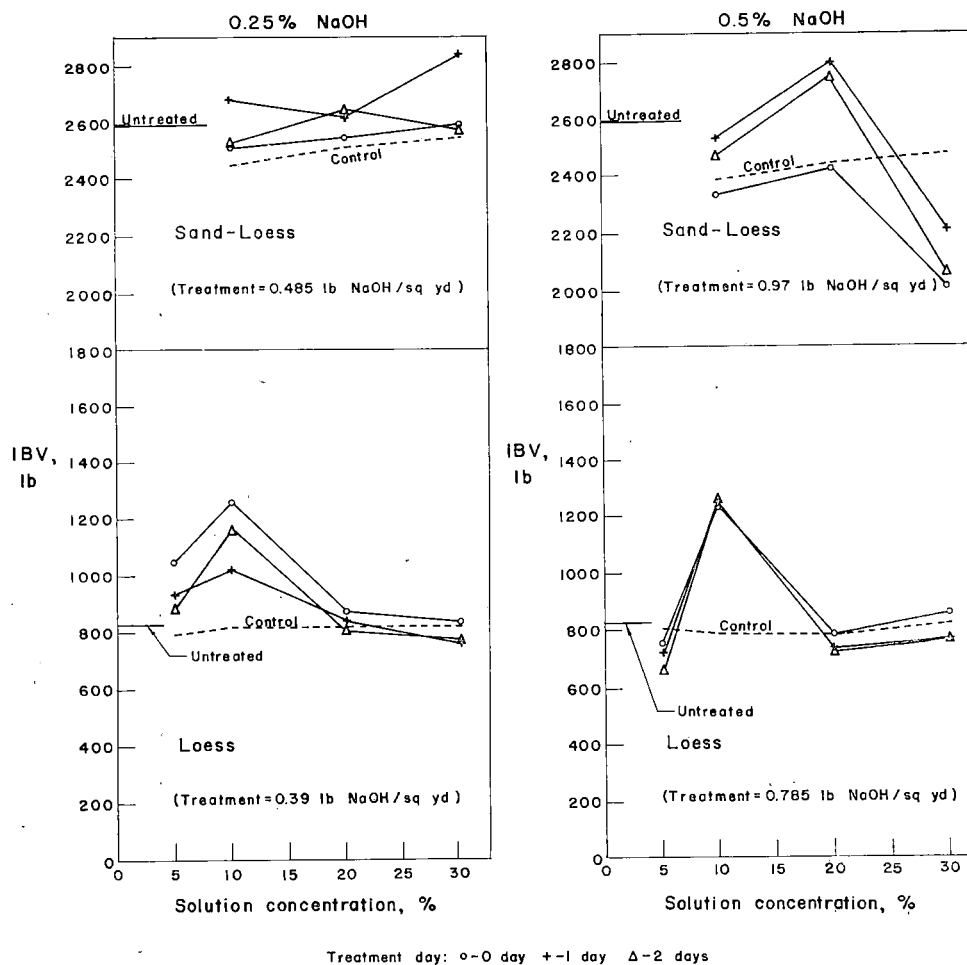


Fig. 4. Effects of sodium hydroxide solutions on 7 day IBV of two kinds of soil cement.

From the standpoint of surface hardness, wetting and drying with no chemical thus appears to be the best and certainly the most economical method for curing friable loess soil cement, and may give an increase in bearing strength in the neighborhood of 20 percent.

The previously measured high IBV of 1,250 for loess soil and cement was not repeated. Investigation revealed that the higher IBV was for an earlier loess sample, 20-2(IV), having a measurable pozzolanic activity⁴. Further, the later sampling for 20-2V was actually in error, and 20-2V is not truly representative of friable loess of western Iowa. However, the

Cement-Stabilized Loess

NaOH Treatment

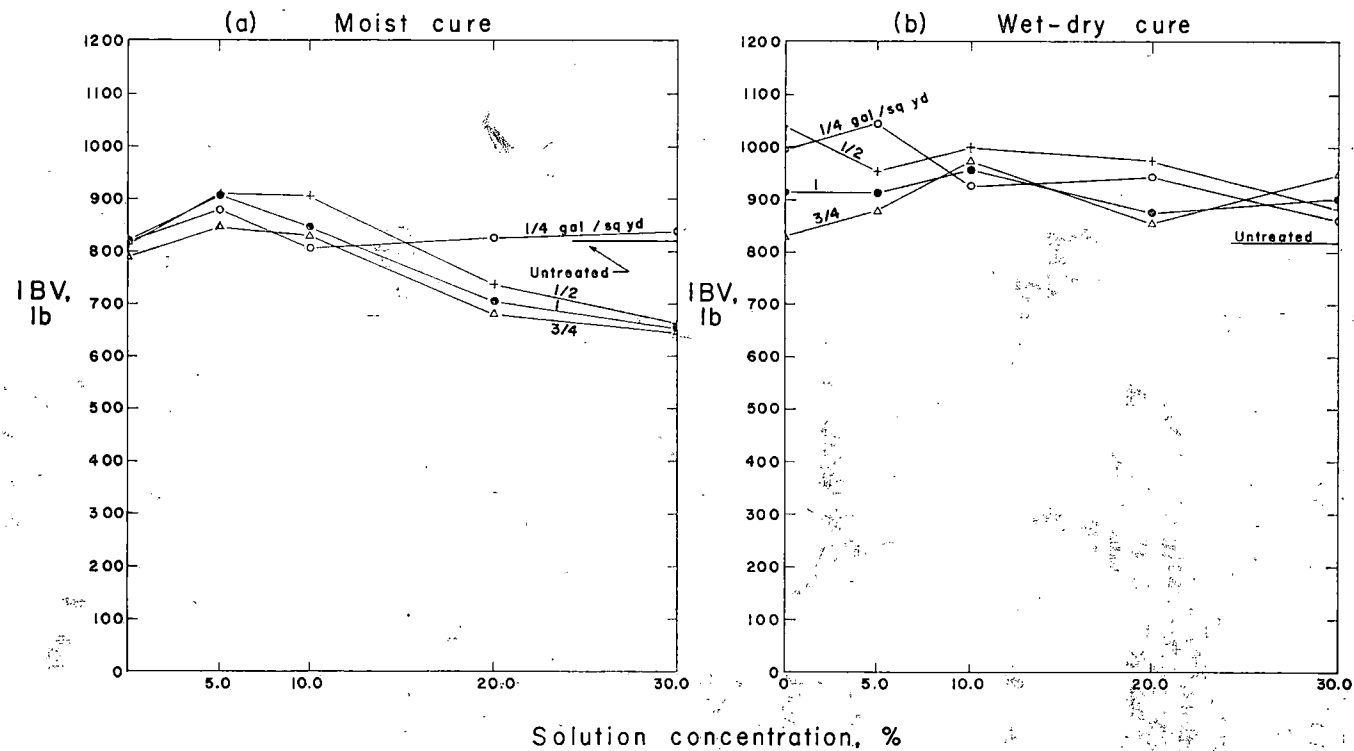


Fig. 5. Seven day IBV's for loess soil and cement treated with solutions of sodium hydroxide and either moist cured or wetted with water every succeeding day. From previous tests a 10 percent solution applied in the same amounts (0.425 and 0.85 gal per sq yd) should have given an IBV of 1,250 (figure 4). Inconsistency is explained in the text.

poorer results do establish that sodium hydroxide treatment is particularly sensitive to soil mineral composition.

The conclusion is that spraying on a 10 percent solution of sodium hydroxide at the rate of $\frac{1}{2}$ gal. per sq. yd. will boost the surface hardness of loess soil and cement as much as 50 percent, but this depends on the pozzolanic activity of the loess soil. With a poorly reacting soil — (and most would be poorly reacting) the benefit is less and may be equalled by merely wetting and drying every day for 7 days. Testing with this chemical was not continued.

Treatment with Sodium Metasilicate

The next chemical tried was sodium metasilicate. Cement stabilized

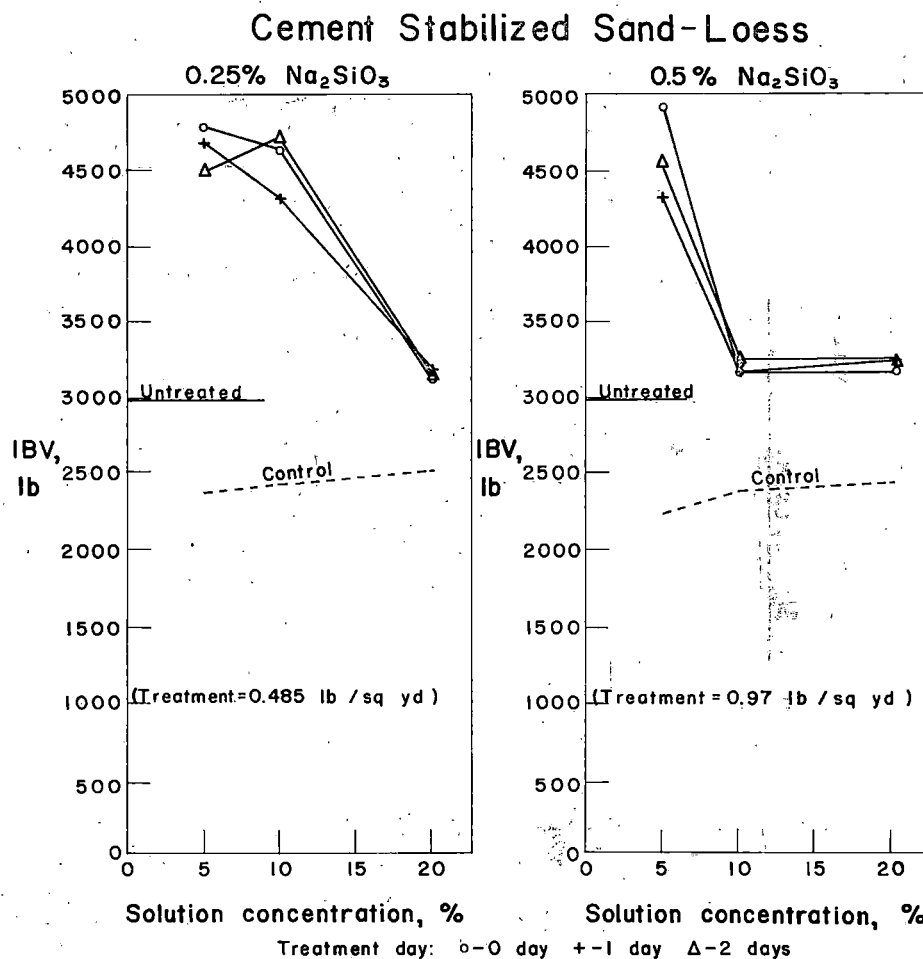


Fig. 6. Effects of sodium metasilicate solutions on 7 day IBV of sand, loess soil and cement. Control strengths after daily wetting with water are lower than strengths of untreated, moist cured specimens.

75:25 sand and loess was considerably benefited by this treatment, the IBV's being increased from 3,000 to a maximum near 4,900 (figure 6). Treatment with 5 percent solutions, immediately after compaction, proved best. With sandy soil, wetting and drying with plain water proved harmful, as shown by the low control IBV's. In the bearing values at different depths (table VII) the gain is still strong at a penetration depth of 0.5 in.

TABLE VII. EFFECTS OF 5 PERCENT SODIUM METASILICATE SOLUTIONS ON 7 DAY IBV OF MOIST CURED CEMENT STABILIZED SAND LOESS

Penetration depth, in.	Iowa Bearing Value, lb.			
	Na ₂ SiO ₃ Content			
	0% (control)*	0.25%†	0% (control)*	0.5%†
0.08	2,400	4,787	2,260	4,927
0.20	4,000	7,553	3,810	7,827
0.50	7,630	11,973	7,210	12,107

*Treated immediately after compaction with equal amount of distilled water.

†Percent of dry weight of specimen. 0.25 percent = 0.390 lb. per sq. yd. for loess, or 0.485 lb. per sq. yd. for sand loess. 0.5 percent chemical is double these figures.

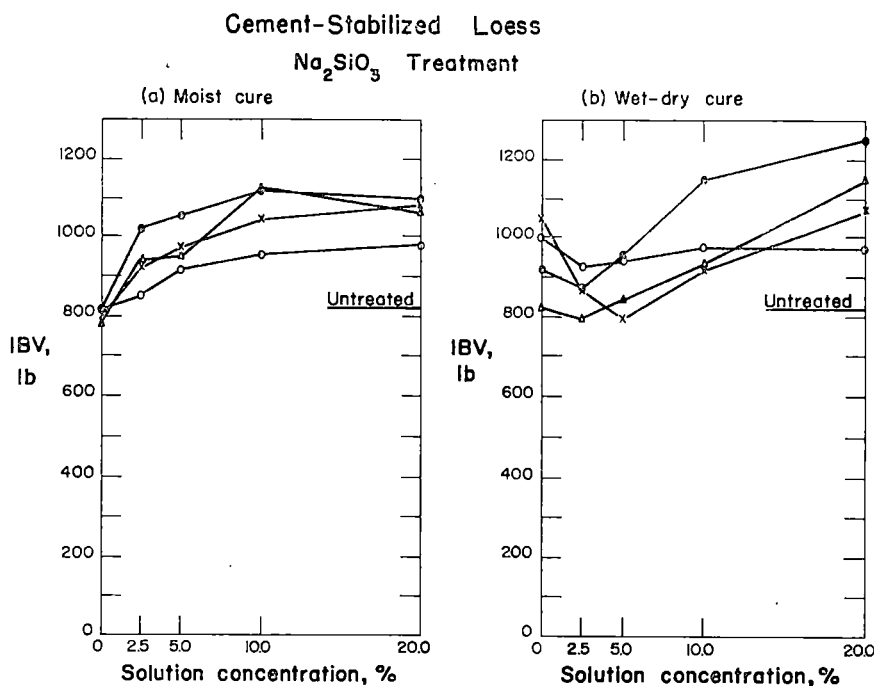


Fig. 7. Seven day IBV's for loess soil and cement treated with solutions of sodium metasilicate and either moist cured or wetted each succeeding day with 1/2 gal. per sq. yd. plain water.

Detailed studies with sodium metasilicate were conducted with loess soil and cement. Results indicate that stabilized loess is benefited by wetting

without any chemical, the IBV increasing from 820 to over 1,000 (figure 7b). However, if initial application of water exceeds $\frac{1}{2}$ gal. of water per sq. yd., bearing strengths are lowered. It will be recalled that after the first day the control specimens all received $\frac{1}{2}$ gal. of water per sq. yd. If moist curing is used, $\frac{3}{4}$ to 1 gal. of 10 percent sodium silicate solution per sq. yd. will increase the IBV to over 1,100. If wetting and drying are used, 1 gal. of 20 percent solution per sq. yd. raises the IBV to over 1,200, but this is not too much over that from spraying the road every day with the $\frac{1}{2}$ gal. per sq. yd. plain water.

Treatment with Calcium Chloride or Sodium Carbonate

Of the other chemicals tried, calcium chloride solutions give only a slight increase in the IBV of loess or sand, loess soil, and cement (table VIII). Solutions are best applied immediately after compaction, as applica-

TABLE VIII. EFFECT OF CALCIUM CHLORIDE SOLUTIONS ON 7 DAY IBV OF MOIST CURED SOIL CEMENT

Soil	Solution Concentration, %	0.08 in. Iowa Bearing Value, lb.			
		CaCl ₂ Content			
		0% (control)*	0.25%†	0% (control)*	0.5%†
Friable	10	820	867	790	965
loess	20	820	833	820	753
	30	820	785	820	747
75:25 sand:	10	2,443	2,837	2,390	2,840
loess	20	2,500	3,113	2,442	2,833
	30	2,535	2,747	2,483	2,693

*Treated immediately after compaction with equal amount of distilled water.

†Percent of dry weight of specimen. 0.25 percent = 0.390 lb. per sq. yd. for loess, or 0.485 lb. per sq. yd. for sand loess. 0.5 percent chemical is double these figures.

TABLE IX. EFFECT OF SODIUM CARBONATE SOLUTIONS ON 7 DAY IBV OF MOIST CURED LOESS SOIL CEMENT

Solution, Concentration, %	0.08 in. Iowa Bearing Value, lb.			
	Na ₂ CO ₃ Content			
	0% (Control)*	0.25%†	0% (Control)*	0.5%†
5	795	903	800	797
10	820	875	787	840
20	820	847	820	842

*Treated immediately after compaction with equal amount of distilled water.

†Percent of dry weight of specimen. 0.25 percent = 0.390 lb. per sq. yd. for loess, or 0.485 lb. per sq. yd. for sand loess. 0.5 percent chemical is double these figures.

tion after one or two days was in some instances deleterious. The mechanism may be one of accelerating the set.

Sodium carbonate solutions were erratically beneficial to loess soil and cement if applied immediately after compaction (table IX). Crystal growth probably has a deleterious effect, particularly if it takes place after the soil cement has time to set⁵.

Testing with chemicals was not continued.

Summary — Soil cement.

Comparison of treated to untreated wet-dry and moist-cure control specimens shows that a good way to cure cement stabilized friable loess (silt) soil is by wetting every day with $\frac{1}{2}$ gal. of water per sq. yd. Early sprinkling in excess of this should be avoided. One gal. per sq. yd. 20 percent sodium silicate raises the IBV about 35 to 50 percent.

With a permeable sand loess soil, wet dry treatments are somewhat deleterious to soil cement surface hardness and decrease bearing strength 5 to 10 percent, or roughly in proportion to the amount of water sprayed on. However, only a 5 percent solution of sodium metasilicate applied in the amount of $\frac{1}{2}$ gal. per sq. yd. will approximately double the bearing strength. A field test seems warranted.

Calcium chloride or sodium carbonate solutions are not particularly effective surface hardeners for soil cement.

REFERENCES

1. Davidson, D. T., Katti, R. K., Kallman, M. E., and Gurland, J., "Correlation of the California Bearing Ratio and the Iowa Bearing Value." ASTM Special Technical Publication STP No. 232, pp. 268-298. 1957.
2. Davidson, D. T., Mateos, M., and Katti, R. K., "Activation of the lime fly ash reaction by trace chemicals." HRB Bull. 231. 1959.
3. Lambe, T. W., and Moh, Z. C., "Improvement of soil cement with additives." HRB Bull. 183:38-47. 1957.
4. Handy, R. L., "A hypothesis of cementation of soil minerals with Portland cement or alkalis." HRB Bull. 198: 55-64. 1958.
5. Chadda, L. R., and Raj, H., "Role of detrimental salts in soil stabilization with and without cement—2. The effect of sodium carbonate." Indian Concrete Journal, 29:401-402. 1955.