Final Report

TO

IOWA STATE HIGHWAY COMMISSION

SOIL STABILIZATION WITH CEMENT AND LIME

Iowa Highway Research Board Project HR-82
Iowa Engineering Experiment Station Project 449-S
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SUMMARY OF THE FINAL REPORT

Soil-cement and soil-lime research during two years 1961-63 was reported in a series of 22 Progress Reports and Special Reports which have been submitted. Some of the conclusions from these reports are as follows:

1. The Iowa freeze-thaw test, intended to be realistic for Iowa conditions, is apparently reliable for a loessial soil-cement in Iowa, with very substantial savings in cement content (see p. 2, this report).

2. The AASHO-ASTM standard soil-cement freeze-thaw test can be abbreviated by use of fewer samples (see p. 4, this report) or fewer cycles (p. 5).

3. The optimum moisture content for strength of sandy soil-cement is 2.5 - 5.5% lower than that for maximum density (p. 5).

4. A 75% sand-25% clay mix is near an optimum blend for maximum strength of soil-cement (p. 5).

5. Up to 1% linear shrinkage of soil-cement occurs during drying, and is mainly due to presence of montmorillonitic clay (p. 6).

6. Long-term compressive strength of soil-cement can be predicted from a semi-logarithmic plot (p. 6-7).

7. Fly ash can be used as a partial replacement for cement in granular soil-cement, and delays the setting reactions (p. 7).

8. Lime is an effective addition to clayey soil-cement, which at high pH becomes deficient in lime (p. 8).

9. Other trace chemicals increase strength and durability of soil-cement but offer no economic advantage (p. 8, 9).

10. The lime retention point of C-horizon loess and till soils varies from 2 to 4%, depending on the clay content and geologic age (p. 10). Iowan and older tills and gumbotil give lower strengths with lime.

11. The best lime for cementation is soft-burned monohydrate dolomitic with appreciable silica and alumina impurities (p. 12) or a hydraulic lime (p. 13). Dolomitic lime strength relates to crystallite size of the MgO.

12. Calcitic lime is best for altering P.I. (p. 13, 14).

13. Cement increases both cohesion and angle of friction of soils (p. 14). Cohesion increases with increasing cement content, but angle of friction relates mainly to the kind of soil (p. 16).

14. A 75% sand-25% loess soil blend variously stabilized with cement, lime, lime-local fly ash, lime-Chicago fly ash, and cationic chemical is performing satisfactorily in a test road (p. 17-18).

15. A clayey soil (Webster series) stabilized with cement, lime, and lime-fly ash contents below usual recommended minimum requirements has performed satisfactorily for load carrying, but the surface has deteriorated as a result of construction and shrinkage problems (p. 18-19).

16. Three to 6% lime + 10 to 25% fly ash are required to stabilize granular soils; 5 to 9% lime and 10 to 25% fly ash are optimum for clayey soils (p. 20). Friable loess is most effectively stabilized with cement (p. 21).

17. Some fly ash needs no added lime, but reacts with water to give sufficient strength for embankments, bases, or subbases (p. 22).

18. Dolomitic lime gives highest strength at temperatures up to 90°F, but at higher temperatures calcitic lime is much the better (p. 23).

The above represent more important conclusions from this research. Other related conclusions are presented in the body of this Final Report, on the indicated pages. For data and methods used, see the source progress reports (Appendix A).

INTRODUCTION AND OBJECTIVES

The IHRB Project HR-82 was established to continue research started under Project HR-1. In particular, it was proposed to study:

1. Soil-cement mix design in connection with sections of variable cement content in primary highway 37 in western Iowa,
2. Factors affecting shrinkage cracking of soil-cement,
3. Strength-maturity relationships in soil-cement,
4. Improvement of soil-cement with additives,
5. Correlations between cement requirements and soil series,
6. Pulverization requirements for soil-lime and soil-cement,
7. Development of an improved lime for soil stabilization,
8. Structural properties (cohesion, angle of internal friction, moduli of rupture and deformation, Poisson's ratio) of soil-lime and soil-cement.
9. Soil-cement and soil-lime test roads.

The research and Final Report were delayed through the untimely death of the project director, Donald T. Davidson, about half-way through the project, late in 1962. As might be expected with such a broad set of research subjects, some were not pursued, whereas others not listed or even thought of at the time of the proposal were followed because they appeared to hold promise.

All of the studies pursued have been reported through a series of Progress Reports listed in Appendix A. The purpose of this Final Report is to summarize these findings.

SOIL-CEMENT RESEARCH

1. Mix Design

A. Test road based on the Iowa Freeze-Thaw Test. This work was done jointly with HR-81, Physical Test Methods, and was reported under that project. An abstract from "Development of a freeze-thaw test for the design of soil-cement" by K. P. George and Donald T. Davidson, follows:

> A laboratory test for evaluating the durability of stabilized fine grained soils subjected to repeated freeze-thaw cycles has been developed. Two in. by 2 in. diameter test specimens molded in Iowa State Compaction Apparatus are used. The specimens are kept frozen from top with free water available at bottom. Winter climatic conditions such as a freezing temperature, availability of free water, and a proper temperature gradient. Climatic data and freeze-thaw calculations showed that 10 cycles of freezing and thawing are sufficiently severe for testing base courses for use in Iowa. The criteria used were the unconfined compressive strength, and the index of resistance to the effect of freezing defined as the ratio of the unconfined compressive strength of the freeze-thaw specimens to that of the immersed control specimens.
>
> Laboratory test results are correlated with those of field trial sections of soil-cement base courses. Based on the performance of the test sections in which the cement content was the variable an adequate soil and cement combination was chosen. The laboratory test results of the above soil-cement, are proposed as tentative criteria for the design of soil-cement for base courses. From the results of one year study of the experimental pavement sections, 7 percent cement seems to be adequate for making durable soil-cement though standard tests warranted 11 percent cement admixture.

B. An abbreviated ASTM-AASHO Freeze-Thaw Test (1)*. A statistical study was made to see if the number of test mixes and/or number of cycles

*Numbers in parentheses refer to reports listed in Appendix A.

for test could be reduced. Conclusions were as follows:

> This investigation indicates that the freeze-thaw loss of soil-cement mixtures follows certain approximately predictable paths. An approximate logarithmic relationship was found to exist between the cement content and the freeze-thaw loss of a soil-cement mixture. This relationship is useful for determining approximately the cement content which will produce the allowable freeze-thaw loss. Freeze-thaw tests with two cement contents will establish the relationship. When more than two cement contents are used, the relationship will obviate any outliers which might exist in the data, reducing the error inherent in this type of subjective testing.
>
> The logarithmic relationships for A-2, A-3, and A-4 soil-cement mixtures were found, approximately, to intersect at a common point. It is conjectured that all granular soil-cement mixtures follow this rule. This can be of great value when properly applied. A granular soil for which the cement content (below 10%) is approximately known would require a freeze-thaw test with one cement content to establish the relationship and determine, to within reasonable approximation, the requirement cement content.
>
> The slope of the logarithmic relationship was found independent of the number of freeze-thaw cycles. This introduces the possibility of conducting the freeze-thaw test at a reduced number of cycles.
>
> By the use of the above methods the time and labor involved in the conduct of the freeze-thaw test can be greatly reduced, though a detailed analysis of the precision to be expected from these methods has not as yet been conducted. The accurate determination of the cement content required to produce a specified freeze-thaw loss will result in more economical mix design of soil-cement mixtures.

Based on these results a tentative abbreviated test is proposed:*

1. For a more accurate method of selecting the required cement content using the present

*L. J. Circeo, "Abbreviated freeze-thaw test procedures for soil-cement mixtures," Ph.D. thesis, ISU Library, 1963, Appendix B.

method of freeze-thaw testing:

a. Plot the cement contents (% by weight) against the freeze-thaw losses (% by weight) on logarithmic paper;

b. Draw the best straight line through these points;

c. From this line, select the cement content corresponding to the maximum allowable freeze-thaw loss. Observation of the relationships will determine whether an increment of cement should be added to arrive at the cement requirement of the soil.

2. If the soil classifies as A-1, A-2, A-3, or A-4 and the cement requirement is below 10% and is approximately known;

a. Conduct the standard freeze-thaw test at the approximate cement content;

b. If the freeze-thaw loss is below 50% and above the allowable loss, plot the freeze-thaw loss and cement content on logarithmic paper;

c. Connect this point with the common intersection point (12.6% cement, 2.4% freeze-thaw loss);

d. From this line, select the cement content corresponding to the maximum allowable freeze-thaw loss. Alternately a graph similar to Figure 4 will accomplish steps b, c and d.

e. The above cement content may be revised, knowing $S_c = \pm\ 0.65\%$ cement, and keeping in mind that A-1, A-2 and A-3 soils generally predict on the safe side whereas A-4 soils generally have an equal distribution of safe and unsafe predictions.

f. If the freeze-thaw loss is above 50%, a higher cement content should be tested; if below the allowable loss, good judgment will determine whether to use this cement content or to retest at a lower cement content.

3. To determine the required cement content after 6 cycles of freeze-thaw testing:

   a. Follow the standard freeze-thaw test method up to 6 cycles of freeze-thaw testing;

   b. Plot the cement contents against the freeze-thaw losses on logarithmic paper;

   c. Draw the best straight line through these points;

   d. Select the cement content conforming to the following criteria for maximum permissible soil-cement losses by brushing:

      Soil groups A-1, A-2 and A-3, not over 6.0%

      Soil groups A-4 and A-5, not over 3.3%

      Soil groups A-6 and A-7, not over 2.8%

   e. Knowing the standard deviation (Table 6), determine a cement content which should adequately stabilize the soil.

4. To check the reliability of the results obtained by using either abbreviated method, compare to results obtained for each soil by the standard freeze-thaw test. Eventually it might be advisable to alter the criteria to obtain more valid results.

C. Optimum moisture content for strength (2). Test results showed that optimum moisture content for maximum density is not necessarily the optimum for maximum strength; sand should be compacted 2.5 to 5.5% on the dry side, probably for better water-cement ratio, whereas montmorillonitic clays are best compacted slightly on the wet side. A 75% sand-25% clay soil is near an optimum blend for maximum strength of soil-cement.

2. Shrinkage of Soil-Cement (3)*

Linear shrinkage of 2- by 2-in. diameter molded soil-cement specimens was measured at prescribed intervals during curing. Four soils were used: a standard graded Ottawa sand with no clay, an Iowa dune sand and an Iowa loess silt with 2.8% and 16% montmorillonitic clay, respectively, and a North Carolina clay with 30% kaolinitic clay.

Effects of varying the cement content, initial water content, and curing method were evaluated.

Results show no relation between total shrinkage and cement content in the ranges investigated. The initial water content had some effect on shrinkage of the silt and the clay, but not the sands; compaction below the optimum moisture content gave slightly less shrinkage. Montmorillonitic clay in a mix greatly increased total shrinkage, kaolinitic clay less so, and total linear shrinkages ran as high as one percent. Shrinkage occurred mainly on drying, and prolonged curing before drying slightly increased total shrinkage.

3. Strength-Maturity (4)

A statistical study indicates that long-term compressive strengths of soil-cement may be predicted from short-term strength gains:

Soil-cement was observed to increase in unconfined compressive strength with time of curing with a better than random correlation in both a semi-logarithmic and logarithmic manner. The best relationship for granular soil-cement is semi-logarithmic; silty and clayey soil-cement exhibit the best relationship logarithmically. These correlations were found to exist, independently of changes in:

a. Cement content
b. Time of curing up to 5 years
c. Curing temperature
d. Size of the test specimen
e. Type of soil
f. Immersion of test specimen before testing.

*This research was also described in Soil Research Lab Brief 449.1.

These relationships can be used to predict the compressive strength of soil-cement. The strength-age relationship can be determined from data obtained in standard laboratory tests. A semi-logarithmic relationship tends best to predict future compressive strengths for all soil types. Compressive strength can be predicted both graphically and by equation with a reasonable degree of accuracy.

The slope of the strength-age relationship was found to be affected by the physical and chemical properties of the soil, the cement content, and certain chemical additives. Thus it is evident that the slope of the strength-age relationship can be used as an indicator of the quality of a soil-cement mixture. Also the effect of additives can be better evaluated by using this relationship.

4. Improvement With Additives (5, 6, 7, 8, 9, 10)

Use of additives with soil-cement received intensive research, in attempts to reduce cost and improve compressive strength of the product. Results are as follows:

A. Fly ash and/or sodium carbonate in soil-cement (5).

In this investigation, three soils - a dune sand, a friable loess and an artificial sand-loess mixture - were studied. Three fly ashes from three different sources were used. The cement was Type I and the sodium carbonate was reagent grade.

It was found that fly ash could be used as an additive to, or as a replacement for, cement in friable soil-cement mixtures. The smaller the loss on ignition and the finer the particle size of the fly ash, the more useful it is as an additive or replacement: however these criteria are not in themselves sufficient to fully differenciate between the varying qualities of the fly ashes. For each fly ash there appears to be an optimum ratio of cement to fly ash. The advantages of fly ash are mainly reflected in long term strengths. The addition of fly ash tends to retard the setting-up of soil-cement mixtures, thus allowing more time for mixing and compacting. The beneficial effects of the addition of sodium carbonate are most noticeable after short curing periods. Sodium carbonate can be detrimental over a long period of time to soil-cement and soil-cement-fly ash mixtures containing low cement contents.

B. Lime additive to soil-cement (6). We may note that is the above study fly ash was tested only with fairly granular soils, since clayey soils tend to adsorb and remove lime from the system. A parallel study was therefore to investigate the effects of more lime:

> Although lime as a secondary additive to soil-cement mixture has been investigated before, the effectiveness of the addition has not been thoroughly explained. The present research is an attempt to fill this gap.
>
> Five soils were studied. Though all contained montmorillonite as the dominant clay mineral, they varied texturally from friable loess to high clay gumbotil. Various amounts of lime and cement were used, and the compressive strengths of compacted specimens were determined after 7, 28 and 84 days humid curing and 1 day immersion in distilled water. The results obtained indicate that there is an optimum amount of lime which gives the maximum strength for a fixed amount of cement.
>
> The increase of strength with addition of lime was higher for soils with high clay content and much higher when noncalcareous soils of similar gradation were used.

C. Trace chemicals for soil-cement Discovery (7, 8). A study of trace chemical additives (NaOH; Na, Ca, and Mg sulfates, $CaCl_2$; MgO; sodium carbonate and orthosilicate), to soil-cement is reported in detail in (7) and in abbreviated form in (8). Particularly informative is the inclusion of triaxial test data on soil cement.

> The 7 day and 28 day cured, one day immersed, unconfined compressive strengths of specimens which had been compacted to near standard Proctor density at optimum moisture content indicated that organic top soils benefitted from the incorporation of sulfates when the soils were acidic and low in clay content. With increasing clay content and an alkaline environment the addition of calcium and magnesium ions in general gave high strengths. The B and C horizon clay soils containing cement seemed to respond very favorably to additives of lime, sodium hydroxide, or sodium carbonate, the latter only with soils having near neutral pH.

Stabilized soil mixes which attained a 7 day unconfined compressive strength of 250 psi or more were further evaluated in the Iowa freeze-thaw and wet-dry durability tests. The results of these tests verified the strength beneficiation derived from adding the chemicals to soil-cement mixtures. Also, they provided data that suggested the establishment of a functional relationship between the 14 day unconfined compressive strength and the strength at the end of 10 cycles of freeze-thaw to which the stabilized soil mixes were subjected.

D. Trace chemicals for soil-cement. Economic aspects (9, 10).

Optimum amounts of several trace chemicals were determined and prices determined and compared to the cost of incorporating more cement:

> Three chemical additives were used with portland cement to stabilize sandy, silty and clayey soils.
>
> The results of a study made to determine the effect of the chemical additives on the unconfined compressive strength of the stabilized soils are presented. The chemicals, used were sodium silicate, sodium hydroxide and sodium carbonate. A cost analysis of soil-cement with and without chemical additives and a modified version of the British standard freeze-thaw test are also included.
>
> The use of selected chemical additives in small amounts with soil-cement mixtures results in significant strength increases over soil-cement with equal portland cement content but no chemical additive. Nevertheless the use of chemical additives in soil-cement may not be economical under normal conditions.

Another rather frank appraisal of this work is ref. (10):

> Trace chemical additives to soil-cement are a definite aid and may be required with poorly reacting soils such as podzolic sands. Although chemicals also benefit normally reacting soils in soil-cement, the same benefit ordinarily can be obtained more economically by use of more cement. An indirect benefit from the research has been to give information on reaction mechanisms, suggesting more fruitful studies in the future.

SOIL-LIME RESEARCH

5. Lime Requirements of Iowa Soils (11)

As originally proposed we were to continue correlation studies of cement requirement to soils series; instead, we decided to find out whether such correlations also exist regarding optimum lime content. Results are as follows (11):

> 1. Additions of lime increase the plastic limits of Iowa soils up to the lime retention point, even though the total increase in plastic limit may be small or the leveling off of plastic limit values after the lime retention point is reached may not be as apparent in some soils as in others.
>
> 2. Lime retention occurs in the loess C horizon soils of Iowa in the 2 to 4 percent lime range, the amount required being proportional to the amount of clay size material in the soil and independent of carbonate content of the soil. The range of lime retention for loess A and B horizons is 1 to 3 percent, with no definite relation to clay content.
>
> 3. Lime retention occurs in till C horizon soils of Iowa in the 2 to 3 percent lime range, and appears to be interrelated to particle size and geological age. The range of lime retention in till A horizons is 0 to 4 percent.
>
> 4. Iowa loess B and C horizon soils exhibited marked strength gains with the addition of lime in amounts above the lime retention point. The strength gain was inversely proportional to the clay content. Loess A horizon soils had small strength gains, not directly related to clay content or other single variables.
>
> 5. The gumbotil and till C horizon Iowa soils treated with lime can be placed in two general strength categories on the basis of geological age. Relatively younger tills had far better maximum strengths than the Iowan and older tills and gumbotil. Till A horizon soils gave generally low strengths.

6. It would appear that loess C horizon soils of Iowa would better fit a soil-lime design system for road construction based on particle size distribution than one based on soil series. Till C horizon soils of Iowa would seem to best fit into a design system based on geological age. However, it would seem that modification to fit into a system based on soil series would be possible for both groups with further study.

7. Much further work would be needed to fit the loess A and B horizon soils, till A and B horizon soils and alluvial soils of Iowa into a soil-lime stabilization design system for road construction purposes.

6. <u>Pulverization Requirements</u>

Not pursued under this project. (This subject was studied later, after termination of HR-82, by means of X-ray analysis, and is reported under Project HR-106).

7. <u>Development of a "Super" Lime (12, 13, 14)</u>

A. <u>Comparisons of commercial limes. Cementation (12)</u>. Tests of relative effectiveness of various commercially available limes showed more variation in dolomitic than calcitic limes:

1. Strengths of soil-lime test specimens using various commercial dolomitic monohydrate limes show significant variations.

a. Some factors influencing the strength obtained with dolomitic limes are: type of kiln used in calcination, firing conditions of the kiln, amount of silicon dioxide and sesquioxides in the lime, cyrstallite size of MgO, carbonate and $Mg(OH)_2$ content of the lime.

b. Limes from rotary kilns produce higher strengths than limes from shaft kilns. The data also indicates that rotary kiln limes are more uniform in strength production than shaft kiln limes.

c. An optimum calcining condition for the production of lime for soil stabilization is indicated by a <u>calcining index</u> between 0 and 1000, with the units $\sqrt{\text{hours}}$ (^{o}F). The <u>calcining index</u> is defined as the square root of calcining time, in hours, multiplied by the difference of the actual calcining temperature and the theoretical decomposition temperature in ^{o}F. This optimum calcining condition indicates that a well-decomposed lime is better for use in soil stabilization than hard-burned lime.

d. Strengths increase with an increase in silicon dioxide and sesquioxide content of the lime.

e. The crystallite size of magnesium oxide influences the strength characteristics of soil-lime mixtures; generally, the finer the MgO crystallite size, the higher the strength. Calcium hydroxide crystallites are much smaller than MgO crystallites and do not show a significant effect on the strength obtained.

f. Limes containing appreciable amounts of carbonate and/or $Mg(OH)_2$ produce lower strengths. Proper processing and storing is advisable.

2. Calcitic hydrated limes produce lower strengths than dolomitic monohydrate limes, and do not show large variations among each other. The variables controlling the strength properties of calcitic limes are believed to be the $SiO_2 + Al_2O_3$ content, the calcining conditions, and the carbonate content.

3. Soils treated with dolomitic monohydrate limes show slightly higher standard A.A.S.H.O. density and lower optimum moisture content than when treated with calcitic hydrates limes.

4. Inasmuch as the optimum moisture content among various commercial limes investigated differed by as much as 2% from each other at any specific lime content and within the same type of lime, it seems advisable to determine the optimum moisture content of available limes before construction is begun.

5. At present, the most reliable tests for evaluating a dolomitic lime for use in soil stabilization seem to be the determination of crystallite size of MgO and the amount of $SiO_2 + R_2O_3$ in the lime.

B. <u>Lime vs. hydraulic lime vs. portland cement. Cementation (13)</u>.

Conclusions 2 and 6 above suggested advantage in using hydraulic lime. Therefore lime, hydraulic lime, and portland cement were tested under the same conditions with clayey and silty soils, and the results compared (13):

1. Lime is a more effective stabilizer for reducing the plasticity of a soil than cement.

2. Among the limes tested high-calcium hydrated lime rated first in lowering the plasticity. The other three types of limes, dolomitic monohydrate, dolomitic dihydrate, and high-calcium hydraulic hydrated, gave a similar performance.

3. Among the major constituents of hydrated limes, calcium hydroxide, followed by magnesium oxide, is mainly responsible for the lowering of plasticity. The influence of magnesium hydroxide is practically negligible.

4. The shrinkage properties of a soil was markedly reduced by the addition of different types of lime and cement. High-calcium hydrated lime showed slight advantage over the others at lower percentage of content.

5. Portland cement was found more effective in increasing soil strength upon curing, followed by dolomitic monohydrate, high-calcium hydraulic, high-calcium hydrated and dolomitic dihydrate limes in that order. For low additive levels, up to about 5%, and for curing periods of 28 days or longer some of the limes were as effective as cement in improving the strength of the soils tested.

6. Hydraulic lime can be used effectively in soil-lime stabilization. Hydraulic lime is equivalent to other types in reducing soil plasticity. It is also better in larger amounts and longer curing time than monohydraulic lime in producing strength.

7. Based on the trends found in this study, the best all-round stabilizer for clayey soils seems to be a "high-magnesium hydraulic monohydrate lime".

C. <u>Best lime for changing P.I.</u> In the above studies, lime acted as a cementing agent, i.e. increased soil strength. Where lime is used in smaller quantities only to alter soil plasticity (14):

1. There is practially no difference between different types or between the same types of hydrated limes for reducing soil plasticity, though

those limes may show significant difference in pozzolanic strength production characteristics.

2. The choice of hydrated limes for soil-lime stabilization should, therefore, be dictated by the relative price and pozzolanic strength characteristics of the lime.

3. In hydrated limes calcium hydroxide is the main component needed for modifying soil plasticity. Magnesium oxide shows a moderate effect, but magnesium hydroxide and calcium carbonate show practically no effect.

STRUCTURAL PROPERTIES AND TEST ROADS

8. Structural Properties of Soil-Cement and Soil-Lime (7, 8)

This subject was pursued in conjunction with studies of trace chemicals in soil-cement. Cement significantly increases both cohesion and angle of friction (8); effects of lime were not studied.

Table I. Shear components of raw and stabilized soils

Sample designation	Cohesion c, psi	Angle of internal friction ϕ, degrees
Iowa silt	10	15
Iowa silt +12% cement	20	37
Iowa silt + 12% cement + 2% $CaSO_4$	60	33
Iowa clay	10	14
Iowa clay + 12% cement	50	40
Iowa clay + 12% cement + 1% lime B	85	35
Wisconsin sand	5	17
Wisconsin sand + 12% cement	20	22
Wisconsin sand + 12% cement + 2% $MgSO_4$	130	27

Table I. (Cont.)

Illinois clay	20	22
Illinois clay + 12% cement	25	49
Illinois clay + 12% cement + 0.25% NaOH	30	47
Texas clay	25	20
Texas clay + 12% cement	30	49
Texas clay + 12% cement + 3% lime B	50	44
Michigan clay	25	21
Michigan clay + 12% cement	70	48
Michigan clay + 12% cement + 0.25% Na_2CO_3	110	41
North Carolina clay	25	20
North Carolina clay + 12% cement	50	28
North Carolina clay + 12% cement + 1.5% NaOH	80	24
Washington sand	5	35
Washington sand + 12% cement	85	45
Washington sand + 12% cement + 1.5% NaOH	100	48
Washington sand + 12% cement + 3% lime B	35	65

The modulus of rupture (flexural strength), diagonal shear strength, and unconfined compressive strength of various soil-cement mixtures with standard compaction are presented in an M.S. thesis by F. H. Tinoco, a copy of which is on file in the office of the Director of Research, Iowa State Highway Commission. Data are in Table II.

Table II.

Soil	Cement/content	Strength, psi* Flexural	Diagonal shear	Unconfined Comp.	Cohesion, psi	ϕ, ^{o}**
75% sand 25% loess	6	137	148	731	207	32
	9	151	210	882	244	32
	12	195	253	1127	312	32
	15	227	296	1288	352	33
Friable loess (silt)	6	65	83	303	98	30
	9	87	113	483	135	31
	12	127	155	598	178	29
	15	134	184	634	191	28
Plastic loess	6	27	54	234	58	37
	9	47	91	367	92	37
	12	66	129	513	131	36
	15	75	171	576	146	36

*Averages of three specimens.
**Mohr envelope in tension assumed to be a parabola.

9. Test Roads (15, 16)

A. Colfax, sand-loess. A number of new techniques and materials were tried in the Colfax test road. Performance of this road was and is excellent (15):

> This paper presents the methods of construction, and the evaluation of three years of field and laboratory observations of 6000 ft. of stabilized soil base and subbase courses of primary highway 117, Jasper County, Iowa. The six inch subbase test sections were constructed by using the in-place subgrade loessial soil materials stabilized with lime, lime-fly ash, and an organic cationic chemical known commercially as Arquad 2HT. The seven inch base course test sections were constructed using a sand-loess soil mixture stabilized with lime-fly ash, lime-fly ash-accelerating agent and type I Portland cement. The fly ash was obtained from two sources. Sodium carbonate and sodium chloride were used as accelerating agents in two sections of lime-fly ash base course. The surface course was three inches of an asphaltic concrete mix.
>
> The evaluation program of the test sections was divided into three phases: (a) laboratory analysis and development of project specifications prior to construction; (b) construction of base and subbase courses, accompanied by sampling and specimen molding of field mixed materials for laboratory testing; (c) field and laboratory testing, and evaluation of the test sections under existing traffic and weather conditions covering the first three years of performance.
>
> So far as possible, conventional construction practices were used: scarification, blading, spreading of stabilizing agent, single and multi-pass mixing, sheepsfoot and rubber tired compaction. Water, for standard Proctor optimum moisture content, was applied through the spray bar of the single pass mixer. The Arquad 2HT was applied in a water solution through the spray bar at a rate and water concentration necessary for desired optimum moisture content and chemical concentration in the soil.
>
> Performance evaluation was accomplished through testing of laboratory specimens, core samples, Benkelman beam tests, crack studies, weather information, traffic

volumes and road roughness measurements. Results indicate that the design of all sections of the test road has given three years of excellent service. The road has sustained severe freezing and moisture conditions and is in an equally excellent condition to the non-experimental sections of the road immediately adjacent which employ a 6 inch soil-aggregate subbase, 7 inch soil-cement base course and 3 inch asphaltic concrete surface course.

Appendixed to this paper are the results of soil-bacterial counts made on the Arquad 2HT in the treated subbase section. The results indicate that the presence of Arquad 2HT in the treated soil material has resulted in no net increase or decrease in the quantity of micro-organisms present at the time of the study, approximately three and one-half years after construction.

B. Webster County, clay. The Webster County test road was an attempt to stabilize a difficult soil with less than the usually recommended amount of portland cement with and without dolomitic lime pre-treatment, or with lime with and without a poor grade of fly ash. Performance has been borderline, mainly because of base course shrinkage causing loosening and loss of the surface treatment, and much of the road has been covered with 2 inches of hot mix. Also we not know that calcitic lime would have been better than dolomitic for the pre-treatment where only a plasticity reduction was desired. Conclusions from the construction phase were as follows (16):

1. Pulverization-gradation requirements of 80% of the total material to pass the No. 4 U.S. standard sieve prior to introduction of stabilizing agent were impossible to meet. Additional laboratory and field studies are needed to adequately define and specify minimum gradation requirements of Iowa soils prior to introduction of soil stabilizing agents. However, 60 to 70 percent passing the No. 4 sieve appears the maximum obtainable without lime or cement pretreatment for the type of soil material encountered on this project.

2. Introduction of 3% lime as a pretreatment agent for the soil materials, assisted in a reduction of plasticity, increase of friability and increase in pulverization-gradations obtainable. The 48 to 72 hour lime pretreatment period appeared adequate to produce the maximum practical field benefits. Laboratory pre-treatment studies indicated maximum benefits in about one hour. With further field evaluation it appears possible to reduce the length of pretreatment curing time to 24 hours or less.

3. Specified spread quantities of stabilizing agents were not obtained with the conventional cement spreader used during construction but in general were within a normal 10% tolerance.

4. The variation of control and in-place densities with respect to the engineering classification of the various base soils encountered, illustrated the need for an optimum moisture-maximum density test of field-mixed stabilized materials at every suspected soil change during construction.

5. The use of a standard Proctor penetrometer as a rapid means of in-place moisture and/or density measurements appeared of little practical value without further testing and development of test procedure.

6. As a means of comparison of uniformity of dry and wet mixing of the materials, trials of additional types of mixing equipment would have been desirable. The multi-pass mixers used on the project appeared to have difficulty in obtaining a uniform mixture of base material and in reaching the loose mixing depth required in the 8 inch compacted thickness sections.

7. For prevention of surface checking and softening due to penetration of the MC-0 prime during the minimum 7-day curing period, the constructed base material should be of a moisture content at, or about 1-2% above optimum moisture of the field mixed materials.

8. Spike tooth drags used in removal of tractor tread and compactor foot marks should follow the first pass of the compactor and be of a weight and length adequate to reach through the uncompacted material and scratch the surface of the compacted layer.

SOIL-LIME-FLY ASH

10. Soil-Lime-Fly Ash (17, 18, 19, 20, 21, 22)

Soil-lime-fly ash research was included in the original Proposal drafted by D. T. Davidson, and dropped at the request of the IHRB. Several of the studies already completed under HR-1 were reported under HR-82:

A. Lime-fly ash ratio (17):

> On the basis of the investigation conducted, the following conclusions are made:
>
> 1. There is no optimum amount or ratio of lime and fly ash for stabilizing all soils. The amount and proportions of lime and fly ash to use depend greatly on the kinds of fly ash and soil, and somewhat on the kind of lime. For granular soils the amount of lime should be between 3 and 6 percent; the amount of fly ash between 10 and 25 percent. For clayey soils the amount of lime should be between 5 and 9 percent, the amount of fly ash between 10 and 25 percent.
>
> 2. Dolomitic monohydrate lime generally gives better strengths in soil, lime and fly ash mixtures than calcitic hydrated lime in normal amounts and when cured at ambient temperatures.
>
> 3. At low lime contents, of around 3 percent, calcitic hydrated is more effective than dolomitic monohydrate for stabilizing clayey soils with or without fly ash; at higher lime contents, dolomitic monohydrate gives better strengths than calcitic hydrated.
>
> 4. The fly ashes used were beneficial to soil and lime mixtures for all soils except friable loess. With the friable loess, only a high quality fly ash was beneficial to loess and lime mixtures.
>
> 5. The moisture-density curves of montmorillonitic clay soils stabilized with lime are affected by the flocculating effects of lime. Sometimes the curves do not show a maximum density.

6. Portland cement is a very effective stabilizer for most soils. The strength gain of mixtures of soil and cement is rapid, and a large percentage of ultimate strength is developed in a relatively short time. But compacted soil, lime and fly ash mixtures gain strength slowly. Full strength may not be developed for several years. The comparison of soil and cement and soil, lime and fly ash test specimens should be made on the basis of 28 day curing. After this period, soil cement should have developed about 90 percent of the ultimate strength, and soil, lime and fly ash only about 50 percent, depending on the soil, lime and fly ash used.

7. Selected compositions of dune sand, lime and fly ash can compete in strength, freeze-thaw resistance, and cost with mixtures of the same soil and cement.

8. Friable loess is most effectively stabilized with cement. If lime is cheap and a good quality fly ash is available, lime or lime and fly ash may compete with cement for stabilizing friable loess.

9. Additions of fly ash are beneficial to gumbotil and lime mixtures. Selected gumbotil, lime and fly ash mixtures show good resistance to freezing and thawing, and may compete with gumbotil cement stabilization.

10. Additions of fly ash are beneficial to alluvial clay and lime mixtures. Lime fly ash stabilization of alluvial clay may compete economically and strengthwise with cement stabilization.

B. Fly ash for embankment material (18):

Seven Iowa fly ashes were evaluated as a construction material for embankments. Test specimens were molded at optimum moisture content for standard AASHO density and moist cured at 71°F for 28 and 120 days. Six of the fly ashes gave unconfined compressive strengths between 42 and 665 psi after 28 days curing plus one day immersion in water.

Test specimens were also steam cured in an autoclave to find a possible quick way to evaluate the strength producing characteristics of a fly ash. The strengths obtained after curing for one day in the autoclave give an indication of the strengths that may be obtained at one ordinary curing temperature for longer periods.

X-ray diffraction patterns of the fly ashes are included. The peaks show that the reactivity of the fly ashes without lime is related to the amount of free lime present in the fly ash.

The fly ashes tested could be used in the construction of embankments. Some of them developed enough strength to warrant their use in the construction of subbases and subgrades for roads. The low strengths obtained with some fly ashes may be improved, if needed, by the addition of lime.

C. Local fly ash, no lime, for subbases (19):

1. Some fly ashes possess cementitious qualities in themselves without addition of lime.

2. Some fly ashes can be used to stabilize soils. The soils that respond best are non-plastic coarse-grained soils, like gravel, sand, slag, etc. Strengths of 400 psi or more can be reached after 28 days curing with some combinations of soil and fly ash. These combinations are sufficient in strength to be used for the base courses of pavements.

D. Compaction characteristics of soil-lime-fly ash (20):

1. Maximum strength of soil-lime-fly ash mixtures is produced by a compaction moisture content which is not necessarily the optimum moisture content for maximum density. With sandy soils, the compaction moisture for maximum strength is to the dry side of the optimum moisture for maximum density. In soils having a high clay content, at least of the montmorillonite type, the compaction moisture is to the wet side. With other soils, such as a friable loess, maximum strength and maximum density may occur at the same compaction moisture.

2. The required compaction moisture content to produce maximum strength changes with the curing period; the longer the curing period the greater the compaction moisture content needed for maximum strength.

3. Increasing the compactive effort from standard Proctor to modified increases the strength of soil-lime-fly ash mixtures. The strength increase obtained is variable, from 50 to 160 percent.

4. If the materials are at high temperature at the time of mixing, the density and strength of clayey soil-lime-fly ash mixtures was lowered, as compared to mixing with cooled materials.

5. Compaction should proceed as soon as possible after wet mixing of soil-lime-fly ash mixtures; otherwise density and strength may be substantially lowered. With clayey soils compaction should be completed not later than 4 hours after wet mixing; with sandy soils, compaction could be delayed until the day after wet mixing without appreciable loss of strength.

E. Pozzolanic activity and high-temperature curing of lime-fly ash (21, 22):

A quick test (21). Specimens made of lime and fly ash mixtures were cured in an autoclave (248^{o}F, 15 atm), and their strengths were compated with those obtained at ordinary curing temperatures. The strengths of the mixtures after steam curing for one day reflected the pozzolanic quality of the fly ash. Strength determined in this manner may be used as a criterion for a quick evaluation of the suitability of fly ash for use in concrete or lime-soil mixtures. Ranges of strength values after autoclave curing for one day, for fly ashes of good, medium, and poor quality, are given.

X-ray diffraction patterns of fly ashes indicate the crystalline minerals present in fly ashes are quartz, magnetite, mullite, hematite, corundum, calcium carbonate, anhydrite and calcium hydroxide.

Based on the results of another investigation (22):

1. Higher strengths are in general obtained with dolomitic monohydrate lime than with calcitic hydrated lime in sand-lime-fly ash mixtures for temperatures of curing up to about 90^{o}F.

2. Much higher strengths are obtained with calcitic hydrated lime than with dolomitic monohydrate lime in sand-lime-fly ash mixtures for temperatures of curing between 140 and 240^{o}F.

3. Soil stabilization with lime and fly ash should preferably be done in the early part of the summer to benefit during curing of the high summer temperature.

4. High loss on ignition appears to be a retardant of the lime-fly ash reaction for temperatures of curing higher than about 140^{o}F.

APPENDIX A

REPORTS SUBMITTED UNDER PROJECT HR-82 (449-S)

1. Circeo, L. J., Davidson, D. T. The relationship between cement content and freeze-thaw loss of soil-cement mixtures. Soil Research Lab Contr. No. 63-9.

2. Davidson, D. T., Pietre, G. L., Mateos, M. and Davidson, D. T. Moisture-density moisture-strength and compaction characteristics of cement-treated soil mixtures. SRL Contr. No. 62-7.

3. Nakayama H. and Handy, R. L. Factors influencing the shrinkage of soil-cement. SRL Contr. No. 64-2.

3a. Soil Research Lab. Shrinkage of soil cement. SRL Brief No. 449.1. 1964.

4. Circeo, L. J., Davidson, D. T. and David, H. T. Strength maturity relations of soil-cement admixtures. SRL Contr. No. 62-3.

5. O'Flaherty, C. A., Mateos, M. and Davidson, D. T. Fly ash and sodium carbonate as additives to soil-cement mixtures. SRL Contr. No. 62-6.

6. Pinto, Carlos, Davidson, D. T., and Laguros, J. G. Effect of lime on cement stabilization of montmorillonitic soils. SRL Contr. No. 62-8.

7. Laguros, J. G. and Davidson, D. T. Effect of chemicals on soil-cement stabilization. SRL Contr. No. 62-14.

8. Laguros, J. G. and Davidson, D. T. Effect of chemicals on soil-cement stabilization. SRL Contr. No. 63-8.

9. Mateos, M., Tawes, R. H. and Davidson, D. T. Effects of chemical additives on the strength of soil-cement mixtures. SRL Contr. No. 63-10.

10. Mateos, M. DISCUSSION to the paper "Soil stabilization with cement and sodium additives" by Za-Chieh Moh. SRL Contr. No. 63-11.

11. Pietsch, P. E. and Davidson, D. T. Effects of lime on plasticity and compressive strength of representative Iowa soils. SRL Contr. No. 62-2.

12. Wang, J. W. H., Davidson, D. T., Rosauer, E. A. and Mateos, M. Comparison of various commercial limes for soil stabilization. SRL Contr. No. 62-4.

13. Wang, J. W. H., Mateos, M. and Davidson, D. T. Comparative effects of hydraulic calcitic and dolomitic limes and cement in soil stabilization. SRL Contr. No. 63-3.

14. Wang, J. W. H. and Handy, R. L. Comparison of various commercial hydrated lime for reducing soil plasticity. SRL Contr. No. 64-4.

15. Hoover, J. M., Huffman, R. T. and Davidson, D. T. Soil stabilization field trials, primary highway 117, Jasper County, Iowa. SRL Contr. No. 62-1.

16. Hoover, J. M. Evaluation of experimental stabilized soil base construction, Webster County, Iowa. SRL Contr. No. 64-1.

17. Mateos, M. and Davidson, D. T. Lime fly ash proportions in soil-lime and fly ash mixtures some aspects of soil lime stabilization. SRL Contr. No. 62-9.

18. Mateos, M. and Davidson, D. T. Cementitious properties of some Iowa fly ashes without lime additive. SRL Contr. No. 62-15.

19. Mateos, M. Stabilization of soils with fly ash alone. SRL Contr. No. 63-21.

20. Mateos, M. and Davidson, D. T. Compaction characteristics of soil-lime fly ash mixtures. SRL Contr. No. 63-1.

21. Mateos, M. and Davidson, D. T. A quick test to evaluate the pozzolanic quality of a fly ash. SRL Contr. No. 62-19.

22. Mateos, M. Heat curing of sand-lime-fly ash mixtures. SRL Contr. No. 63-15.