FINAL REPORT

# USE OF RETARDERS WITH CEMENT TREATED SOILS

by

M. C. Anday
Highway Research Engineer

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Highway Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

October 1970

VHRC 70-R17

## SUMMARY

The purpose of this study was to investigate various set retarding admixtures for possible use as an economical method of allowing long delay periods between the mixing of cement, soil and water and remixing. Three types of retarders were used in preliminary tests, from which one, a sugar and lime combination, was chosen for all further work.

The study comprised four phases. Phase I concentrated on the selection of a suitable test for determining retardation and the selection of the most suitable and economical retarder. As a result of this phase, a procedure based on a penetration test was developed; and sugar-lime combination was selected as the retarder to be used in the rest of the study.

Phase II was conducted to supply some basic information about the effect of the sugar-lime mixture on the hydration of cement paste. Using an X-ray diffraction technique an attempt was made to determine if any key compounds of hydration formed that could be used as indicators of the effective end of retardation. The results showed that the sugar-lime retarded cement paste did not develop $Ca(OH)_2$ reflections until set occurred, which was at a much later time than it occurred in the retarded soil-cement specimens. In addition, the variability of the test results was very high, apparently because of the extreme sensitivity of cement to sugar. Study of the retarded soil-cement system is further complicated by the possibility that the clay in the soil will adsorb some of the retardant.

Phase III investigated the effects of the sugar-lime retarder on the durability of soil-cement mixtures as measured by freezing and thawing tests. It was concluded that there was no harmful effect.

The last phase was a field project to determine the feasibility of using the sugar-lime retarder in the field. In this phase two experimental sections were constructed incorporating several variables. As a result of this phase it was concluded that the properties of cement treated soils will not be impaired if the compaction is delayed for 6 hours, or if the mixture is remixed and compacted at 6 hours and if the mixture is compacted immediately and not remixed. It was also concluded that strength development might be decreased about 50% if compaction of the mixture is delayed for 18 hours or if the mixture is remixed and recompacted after a delay of 18 hours.

FINAL REPORT

# USE OF RETARDERS WITH CEMENT TREATED SOILS

by

M. C. Anday
Highway Research Engineer

## INTRODUCTION

One of the important problems associated with cement stabilization of soils is that after mixing of the cement and soil there is only a limited amount of time available for manipulation, testing, and possible further manipulation. More specifically, there are only three to four hours of working time between mixing and the initial set of the cement. Any manipulation after the initial set must be done at the expense of ultimate product quality; or additional cement must be added to preserve quality. The project reported here was initiated in 1964[1] by M. C. Anday and W. C. Sherwood to investigate the possibility of using set-retarding admixtures to extend the time available for working with soil-cement mixtures.

The project involved four phases:

1. Selection of a suitable test method for measuring retardation, selecting an economical retarder for future testing, and initial laboratory pilot tests;

2. X-ray diffraction studies of retarded and non-retarded cement pastes to see if any precise identification of the end of retardation could be made;

3. Extensive laboratory studies to investigate the effects of the retarder on the strength and durability properties of cement treated soils; and

4. A field study to see if field mixing processes could adequately mix the retarder into the cement-soil mixture, and to check the results of the laboratory tests.

Interim reports on the first three phases and working plans for all phases have been written and are included in the list of references[2,3,4]. The work on the field study[5,6] will be detailed in this report along with a summary of the work on Phases I, II and III.

## PURPOSE AND SCOPE

The purpose of this project was to investigate various set-retarding admixtures for possible use as an economical method of allowing long delay periods between the mixing of cement, soil, and water, and compaction of the mixtures. (For a retarder to be effective it would need to be inexpensive, with controllable reactions, and have no deleterious effects on the strength or durability properties of the compacted soil cement.) Also, a relatively simple laboratory test was needed for determining the amounts of cement and retarder required for any desired degree of set retardation.

Three types of retarders were used in preliminary tests, from which one was chosen for all further work. Only one soil, a silty sand, was used in the Phase I tests, but the Phase III tests were run on a slightly clayey silt as well as the silty sand. Sufficient specimens were made in all phases so that the test results could be treated statistically.

## SUMMARY OF LABORATORY WORK

### Phase I

Considerations of economy eliminated all commercial concrete retarders from the study. Based on conversations and correspondence with members of the Portland Cement Association and various researchers, three admixtures were selected for preliminary study: hydroxylated carboxylic acid, a silicone admixture, and a sugar-lime mixture.

During the preliminary studies, a test procedure was devised to measure the effectiveness of each retarder. Briefly, the procedure was to first determine the amount of cement needed to produce an unconfined compressive strength of 500 psi after 7 days' moist curing of the Harvard miniature size specimens. Various percentages of retarder (by weight of cement) were next mixed with the soil cement and the mixtures compacted in a CBR mold. The rate of set curves for non-retarded and retarded specimens were established by measurements of resistance to penetration by a 1/20 square inch needle.

The amount of retarder selected for further work was that which satisfied the equation

$$\frac{R_{18}}{NR_{18}} = 0.4^{*}$$

* Based on previous laboratory tests this ratio was chosen for practicality.

where:

$R_{18}$ = resistance to penetration of retarded specimen after 18 hours, and

$NR_{18}$ = resistance to penetration of non-retarded specimens after 18 hours.

Appendix I of Interim Report No. 3 details the exact procedure for performing the above described operations. Based on the results of these initial tests (Figure 1), sugar and lime in the ratio 1:16 was chosen as the most likely retarding admixture for use in further testing. Table I lists the physical properties of the soil and the amounts of cement and retarder used.

Also included in this phase was a study of the effect of the retarder on the long-term unconfined compressive strength development of compacted Harvard miniature specimens. Mixtures of soil, cement, and retarder were compacted at optimum moisture with delay periods up to 18 hours and then moist cured for up

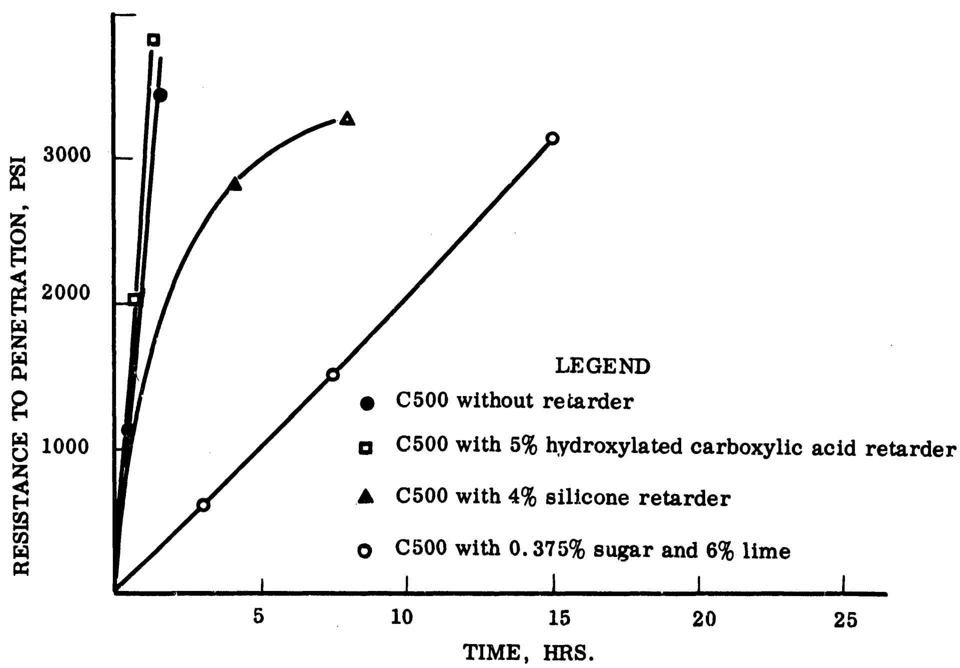



Figure 1. Relative retardation with different retarders.

TABLE I

PHYSICAL PROPERTIES OF SOILS USED

| Property | Soil A+ (Silty Sand) | Soil B (Clayey Silt) |
|---|---|---|
| % Passing No. 10 Sieve | 100.0 | 100.0 |
| % Passing No. 20 Sieve | 95.10 | 97.98 |
| % Passing No. 40 Sieve | 73.31 | 95.36 |
| % Passing No. 80 Sieve | 34.81 | 84.39 |
| % Passing No. 100 Sieve | 23.90 | 77.43 |
| % Passing No. 200 Sieve | 15.60 | 52.75 |
| Liquid Limit, % | 19 | 42 |
| Plasticity Index, % | N. P. | N. P. |
| Specific Gravity | 2.62 | 2.87 |
| *Maximum dry density, pcf | 117.6 | 94.3 |
| *Optimum moisture content, % | 11.6 | 25.7 |
| **% cement req'd. to stabilize, $P_{500}$ | 7.0 | 17.5 |
| *Maximum dry density, soil & cement | 123.8 | 95.9 |
| *Optimum moisture content, soil & cement | 10.4 | 24.5 |
| Amount of Retarder*** needed for 40% retardation**** | 0.375% Sugar + 6% Lime (Phase I) 0.375% Sugar + 10% Lime (Phase III) | 0.625% Sugar + 10% Lime |
| H. R. B. Classification | A-2-4 | A-5 (4) |

+ Sample taken from the same pit as was soil A used in the initial phase of this study (see Interim Report No. 1).

* AASHO T-99-57.

** See Appendix A for method of obtaining $P_{500}$.

*** By weight of cement.

**** See Appendix A for method of determining amount of retarder.

to 6 months. The delayed compaction specimens were compacted immediately after mixing then remixed and recompacted after the delay period. The possible effect of this procedure will be discussed later.

As can be seen in Figure 2, the retarder did not seriously decrease the long-term strength of the specimens with the possible exception of the 18 hour delayed specimens.

Interim Report No. 1[2] concluded that, for the particular soil used, a sugar-lime retarder was effective in retarding the rate of set and had no serious effects on the long-term strength development if the amount of retarder was properly selected.

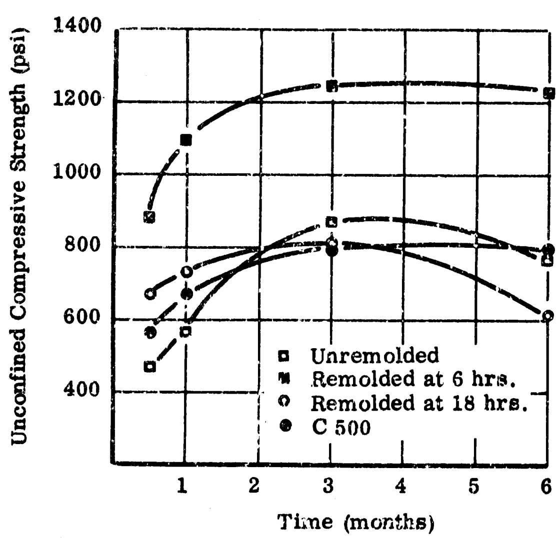



Figure 2. Effect of remolding on long-term strength, 0.375% sugar + 6% lime.

## Phase II

The reaction between sugar and cement is known to be very unstable; small changes in the quantity of sugar can produce very large retarding effects. Since there seemed to be little known about the reaction between sugar and cement, this phase attempted to supply some basic information. In particular it was desirable to know how long various quantities of sugar and lime would retard the initial set; what quantity would indefinitely delay set; and if there were any key compounds of hydration formed that could be used as indicators of the effective end of retardation.

An X-ray diffraction unit was used to examine specimens of cement, sugar, lime and water mixed at varying percentages with the water/cement ratio held const at 0.4. The specimens were stored in and X-rayed in a nitrogen atmosphere at approximately 100 percent relative humidity to prevent carbonation.

Results of the X-ray diffraction showed that retarded specimens do not develop $Ca(OH)_2$ peaks until set has occurred. However, in test specimens incorpo- rating the same proportions of retarder to cement as were used in Phase I, set occurred after 81.8 and 137.5 hours for the two specimens tested. These results would appear to indicate that the clay portion of the test soil was adsorbing the polai sucrose molecules, and that the effective amount of sugar available for set retardation would depend on the amount of clay in a given soil. Thus a high variability could be expected in laboratory tests using short curing times. The relation betwee the amount of sugar needed for retardation and the amount of clay present in a soil was not investigated, mainly because of the great difficulty in quantitatively analyzii a sucrose solution.

## Phase III

The final laboratory studies were performed to see if the addition of the sugar-lime retarder had any effect on the ability of the soil cement to withstand freezing and thawing. Two soils, the original silty sand and a clayey silt, were usec in this phase to permit generalization of the results.

The initial durability tests on the silty sand were carried out using a 7-day moist cure period. These tests produced very erratic strength results, so a combination of increased lime and increased curing time was tried. Tests showed that a minimum of 30 days curing in combination with the increased percentage of lime reduced the variability to reasonable values. The amount of lime used was not increased above the 1:16 ratio for the second soil, but the 30-day cure adequately controlled variability.

The following procedure was used to test the durability of the Harvard miniature size specimens. After mixing, the delayed compaction mixtures were stored in jars during the delay period. No initial compaction was used for the delay specimens as was done in Phase I. Compacted specimens were moist cured for 30 days, then subjected to freezing and thawing cycles of 16 hours freezing in air at -10°F and 8 hours thawing in the moist room. Seven specimens were tested for unconfined compressive strength after each of the following numbers of cycles: 0, 3, 6, 10, 15, 20, and 25.

The physical properties of the soils used for testing were shown in Table I. Delay times of 0, 6, and 18 hours were used for the retarded specimens. A complete set of specimens with no retarder was molded as a control.

Typical results are presented in Figure 3. The ordinate values were obtained by dividing, for each set of specimens, the strength after 0 freeze thaw cycles (initial strength) into the strength after "n" freeze thaw cycles. In this way a number is obtained that represents the percent of initial strength remaining after freezing and thawing. The effects of varying initial strengths are thus eliminated, and a durability comparison can be made based on only the loss of strength during freezing and thawing.

It can be seen from Figure 3 that addition of the retarder actually increased the durability of this soil. The results from the other soil were not quite as impressive, but there were no indications in any case that the durability was significantly decreased by the addition of retarder.

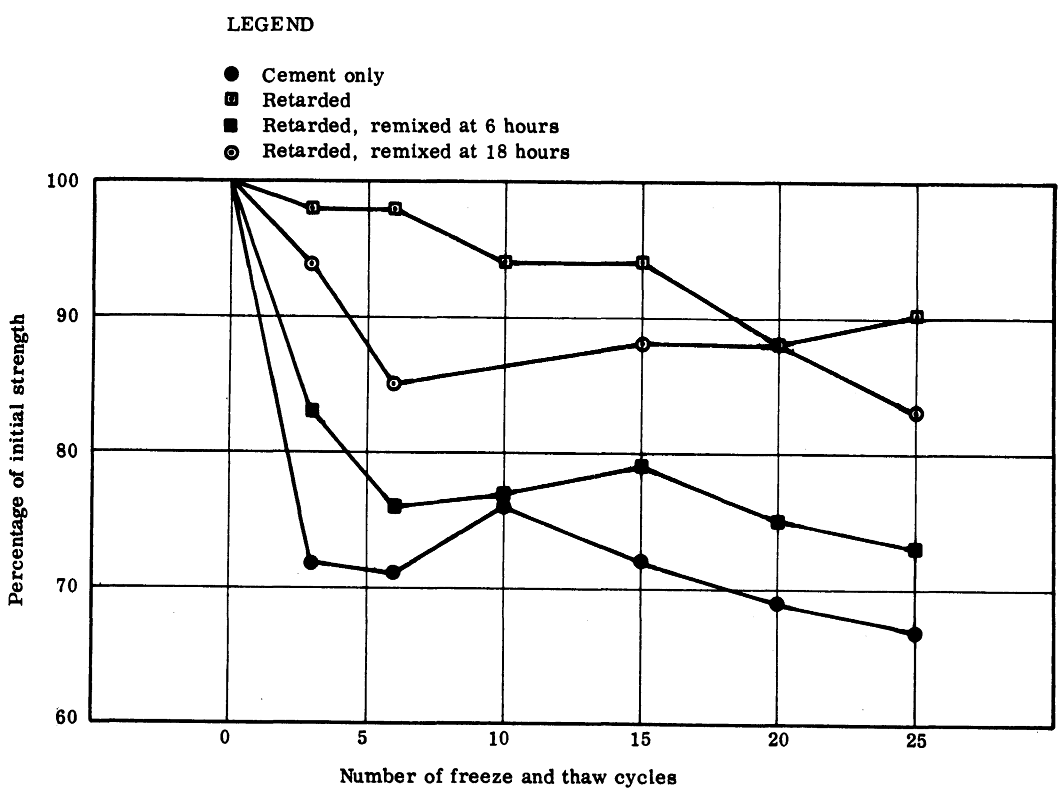



Figure 3. Percentage of initial strength after freezing and thawing.

A comparison of the initial strength data from this phase with the strengths obtained for the same soil and curing times in Phase I revealed that the sample preparation procedure would affect the strengths greatly. Whereas Phase I data (Figure 2) showed that retarded, 6-hour delayed compaction specimens (compacted initially, remixed and recompacted) had higher strengths than non-retarded soil cement specimens, Phase III data showed no increase, and possibly a slight decrease for these specimens, which were compacted only after the delay period. The initial strength behavior of the 18-hour delayed compaction specimens was also observed to show a slight decrease rather than an increase. These observations indicate that compacting and later remixing the soil would be beneficial in the field.

The results of the Phase III study showed that the addition of a sugar-lime retarder to soil-cement mixtures does not decrease the ability of these mixtures to resist freezing and thawing.

Interim Report No. 3[4] concluded that, based on the laboratory test program, a sugar-lime set retarding admixture could safely be used in soil cement work provided the amount of retarder was chosen properly. Before full-scale field usage, however, a field project would be necessary to answer two questions:

1. How uniformly can the retarder and soil be mixed in the field, particularly if the soil is near optimum water content?

2. How will small variations in soil type or amount of retarder over a construction zone affect the action of the retarder?

The field project plan and performance will be discussed as the next section of this report.

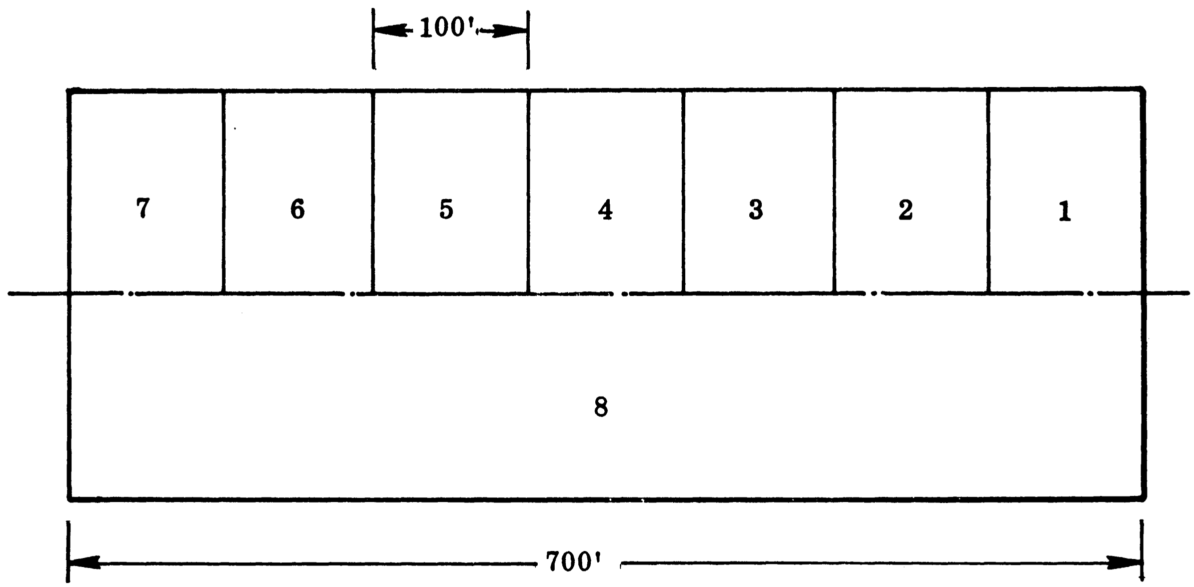
## FIELD WORK

To determine the feasibility of using sugar and lime as a retarder in the field, experimental sections were installed on a regular state force construction project on Route 623 near Manakin in Goochland County. Two sites, stations 68+00 to 75+00 and 88+50 to 94+50, were chosen for projects 1 and 2 respectively. Two sites were chosen to permit a determination of the repeatability of the results, and these two projects are discussed separately.

### Project 1

#### Construction

The layout of the first project was as planned in the testing plan for the field phase[6] and is shown in Figure 4.




Key:
1. 6-hr. delay prior to initial compaction
2. Compacted, 6-hr. delay, remixed and recompacted
3. No delay, compacted immediately
4. Compacted, 9-hr. delay, remixed and recompacted
5. 9-hr. delay, remixed and recompacted
6. Compacted, 18-hr. delay, remixed and recompacted
7. 18-hr. delay prior to initial compaction
8. Control Section, no retarder, standard soil cement; entire section mixed and compacted at one time

Figure 4. Layout of project 1.

As can be seen from this layout, two specific questions were investigated:

1. The effect of sugar and lime as a retarder in both uncompacted (sections 1, 5 and 7) and compacted (sections 2, 4 and 6) mixtures prior to remixing, and

2. the effect of sugar and lime as a retarder in unremixed material (section 3).

A control section (section 8), of course, was provided for overall comparison.

The specific properites of the soils involved in project 1 are given in Appendix A, and the mix design is given in Table II.

The amounts of cement, sugar and lime needed, as shown in Table II, were predetermined in the laboratory for a representative soil taken from the project.

The construction sequence followed is shown in Table III. It was anticipated that the construction would begin at 7:00 a. m. but because of delays it was commenced two to three hours late. As a result, construction of sections 4 and 5 was abandoned since the manipulation on these sections would have had to be accomplished at unreasonably late hours.

The scarification of the roadway was accomplished with a grader. The cement and lime were distributed by a box spreader attached to the back of a truck. Sugar was added by pouring a known amount into the water in a water truck.

TABLE II

MIX DESIGN FOR PROJECT 1

| | | |
|---|---|---|
| Maximum Density, pcf (average) | — | 102 |
| Optimum Moisture, % (average) | — | 18.6 |
| Percent Cement | — | 14 |
| Percent Sugar (by weight of cement) | — | 0.5 |
| Percent Lime (by weight of cement) | — | 10 |

TABLE III

CONSTRUCTION SEQUENCE

| | |
|---|---|
| Start 0 hr. | Mix sections 1-5 |
| $\frac{1}{2}$ hr. | Compact sections 2, 3, and 4 |
| 1 hr. | Begin tests on section 3 |
| 2 hrs. | Mix and compact control section |
| $2\frac{1}{2}$ - $6\frac{1}{2}$ hrs. | Begin tests on control section |
| 6 hrs. | Remix section 2, compact sections 1 and 2 |
| $6\frac{1}{2}$ hrs. | Begin tests on sections 1 and 2 |
| 9 hrs. | Remix section 4, mix sections 6 and 7 |
| $9\frac{1}{2}$ hrs. | Compact sections 4, 5, and 6 |
| 10 hrs. | Begin tests on sections 4 and 5 |
| 27 hrs. | Remix section 6, compact sections 6 and 7 |
| $27\frac{1}{2}$ hrs. | Begin tests on sections 6 and 7 |

It should be realized that the control one exercises over the addition of the cement, lime, and sugar is much more limited in the field than it is in the labortory. For example, the amount of cement (or lime) added was controlled by placing a steel plate one square yard in area in front of the spreader and weighing the amount deposited upon the plate. The amount of sugar added was controlled by making sure that the sprinkler truck made even passes and that all of the solution was used up. Thus, though they were somewhat successful, the field methods were much cruder than the laboratory methods.

All mixing was accomplished by a Seamen type mixer. Though this machine produces a homogenous mixture, its depth control is somewhat limited since anywhere from 3 to 6 inches of material are mixed.

Prior to adding cement, sugar, and lime the moisture content of the soil was checked and brought somewhat below optimum since more water was going to be added during the application of the sugar.

All compaction was accomplished by a sheeps-foot roller until it "walked-out", and then with a rubber-tired roller. No effort was made to control density and it was left to the state forces to decide when to stop rolling.

Testing

After final compaction the density and moisture of each section were determined with nuclear devices using the air-gap technique and a random testing plan.

The hardening of the soil cement was determined with a homemade penetrometer type apparatus that consisted of the following components:

1. CBR jack mounted on a heavy beam
2. Supports for the beam
3. Proving ring, capacity 2,000 lb.
4. Penetration needle, area = 1/40 sq. in.

The assembly is shown in Figure 5. With a stop watch and a hand crank, the penetrometer was used at a rate of 2 inches per minute and the reading at 1 inch was recorded. This apparatus, although limited in its capacity (since the needle was jacked against the weight of the beam and the CBR jack), was easy and quick to use. Speed was of primary importance since much testing was needed in a short time.

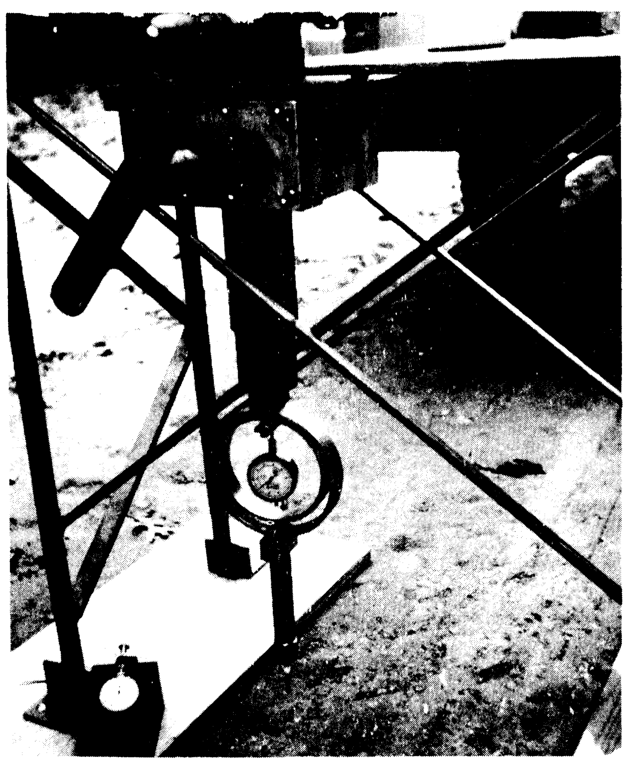


Figure 5. Penetration apparatus used in field testing.

Three penetration readings were taken at three random spots in each section. The tests were started at the termination of final compaction in each section, and were in most cases continued until the capacity of the apparatus was reached.

Project 1 was started on November 5, 1969 and was completed on November 7.

## Project 2

This project was constructed with the same personnel and equipment as were used on project 1. Based on the experience gained from project 1, however, several modifications were made.

### Construction

The specific properties of the soils used in project 2 are given in Appendix B.

As was discussed earlier, sections 4 and 5 of project 1 were found to be impractical to construct. They were, therefore, also eliminated for project 2. Two new sections were added, however, to investigate the effect of remixing without adding retarders. The layout of project 2 is shown in Figure 6.

In addition to the change made in the layout of project 2, the cement requirement was reduced to around 5%. The mixture, therefore, was no longer considered soil cement but a cement treatment.

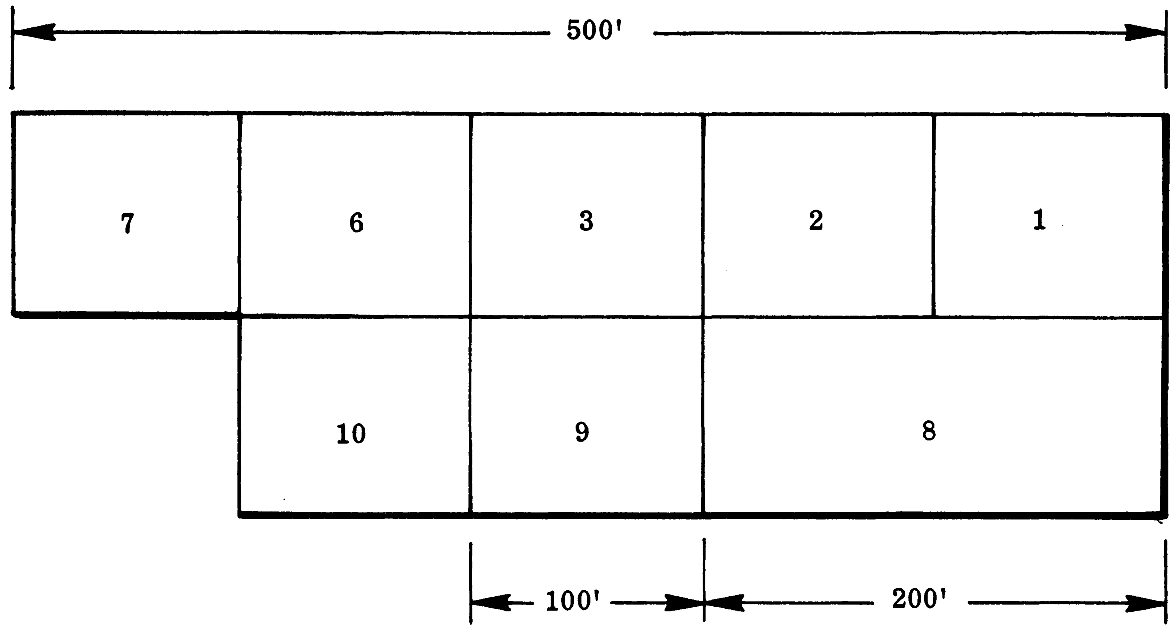
### Testing

Testing on project 2 was conducted similar to that on project 1, using the nuclear devices for moisture and density determinations and the penetrometer for the determination of the hardening of the cement treated soil.

## RESULTS — PROJECTS 1 AND 2

### Cement Coverage

As explained earlier in this report the distribution of cement was determined by placing a steel plate in front of the spreader on the ground to be covered with cement, then weighing the amount deposited on this plate and calculating the cement, coverage. Using this procedure the cement coverage was determined at the center and at the right and left of the center. The results are given in Table IV.




Key:
1. 6-hr. delay prior to initial compaction
2. Compacted, 6-hr. delay, remixed and recompacted
3. No delay, compacted immediately
6. Compacted, 18-hr. delay, remixed and recompacted
7. 18-hr. delay prior to initial compaction
8. Control section, no retarder
9. Cement only, no retarder, compacted, 6-hr. delay, remixed and recompacted.
10. Cement only, no retarder, 6-hr. delay prior to initial compaction.

Figure 6. Layout of project 2.

TABLE IV

CEMENT COVERAGE

| Project / Location | % Cement by Weight of Dry Soil | |
|---|---|---|
| | Project 1 | Project 2 |
| Left of center | 18.3 | — |
| Center | 12.0 | 4.9 |
| Right of center | 16.3 | — |
| Average | 15.6 (14.0)* | 4.9 (5.0)* |

* Design cement content

It is apparent from this table that the cement coverage is not uniform, but on the average it is close to the designed amount.

## Lime Coverage

The lime coverage was determined in the same manner as the cement but only for project 1. Table V shows the results.

## Compaction

The results of the density tests with the nuclear devices are shown in Table VI.

From Table VI it is seen that the densities and the moistures are fairly uniform but somewhat more variable for project 2. The standard deviations are mostly within acceptable limits.

## Retardation

As explained earlier, the strength development of each section was determined by the modified CBR penetrometer. Three timed readings were taken at three randomly selected sites in each section of each project. The data are shown in Appendices C and

TABLE V

LIME COVERAGE FOR PROJECT 1

| Location | % Lime by Weight of Cement |
|---|---|
| Left of Center | 10.1 |
| Center | 10.4 |
| Right of Center | 9.6 |
| Average | 10.1 (10.0)* |

* Design lime content.

TABLE VI

RESULTS OF DENSITY AND MOISTURE TESTS

| Section | PROJECT 1 | | PROJECT 2 | |
|---|---|---|---|---|
| | Dry Density, pcf | Moisture, % | Dry Density, pcf | Moisture, % |
| 1 | 95.1 (1.2) | 21.1 (1.0) | 94.5 (2.8) | 24.0 (1.7) |
| 2 | 95.8 (1.6) | 21.4 (1.6) | 96.6 (1.4) | 20.8 (0.9) |
| 3 | 95.6 (1.0) | 20.0 (1.3) | 97.2 (1.5) | 21.1 (0.7) |
| 6 | 95.8 (2.3) | 19.8 (2.0) | 98.5 (2.0) | 17.5 (1.6) |
| 7 | 94.7 (1.4) | 19.7 (1.2) | 101.6 (2.2) | 15.0 (1.2) |
| 8 | 95.6 (3.0) | 18.7 (2.7) | 98.3 (2.1) | 21.4 (2.7) |
| 9 | — | — | 92.1 (1.2) | 22.3 (0.9) |
| 10 | — | — | 96.6 (4.2) | 20.0 (2.5) |

Numbers in parentheses indicate standard deviation.

D for projects 1 and 2 respectively. (As can be seen from the results the data in most cases show good repeatability. In some cases, however, one of the three test results varies significantly from the other two. During the testing the cause of this variation was investigated to determine if a hard substance such as a piece of stone could cause the variation. In some cases this was found to be true and the test values were discarded. In other cases, however, no cause was found and the test values were included in the data.)

To indicate the trends in the strength development of each section, plots of the data shown in Appendices C and D were prepared. Figures 7 and 8 show the overall data for project 1, between zero and 30 hours and 30 hours and the end of testing respectively. Similarly for project 2, Figures 9 and 10 were prepared.

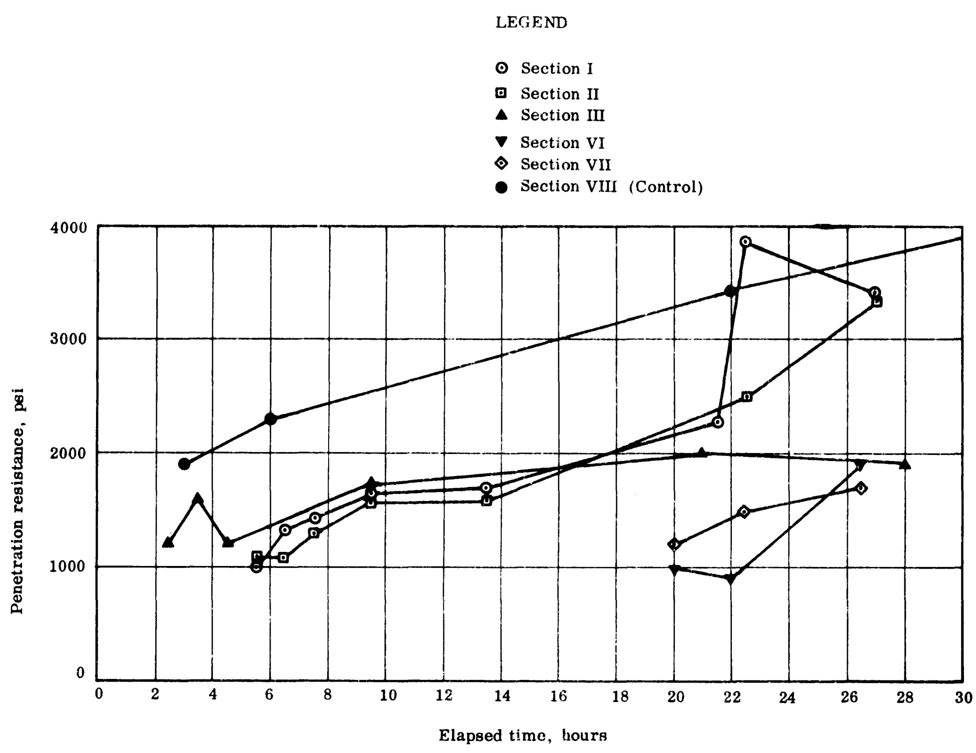



Figure 7. Strength development of each section of project 1 at early stages.

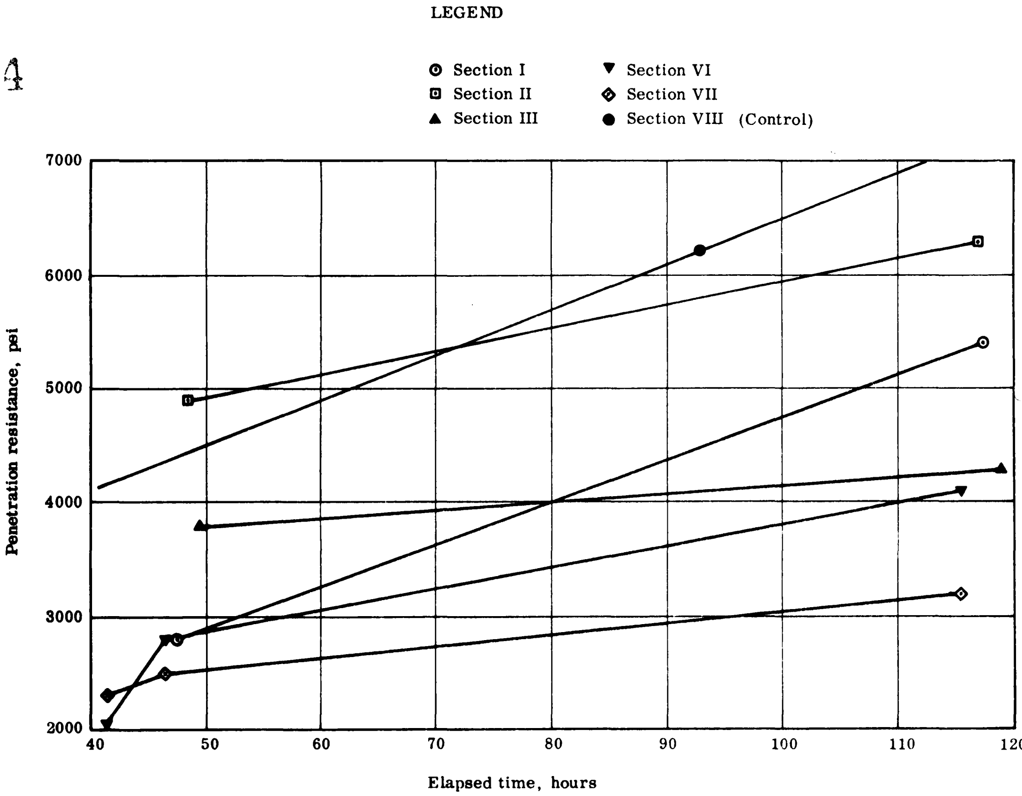



Figure 8. Strength development of each section of project 1 at later stages.

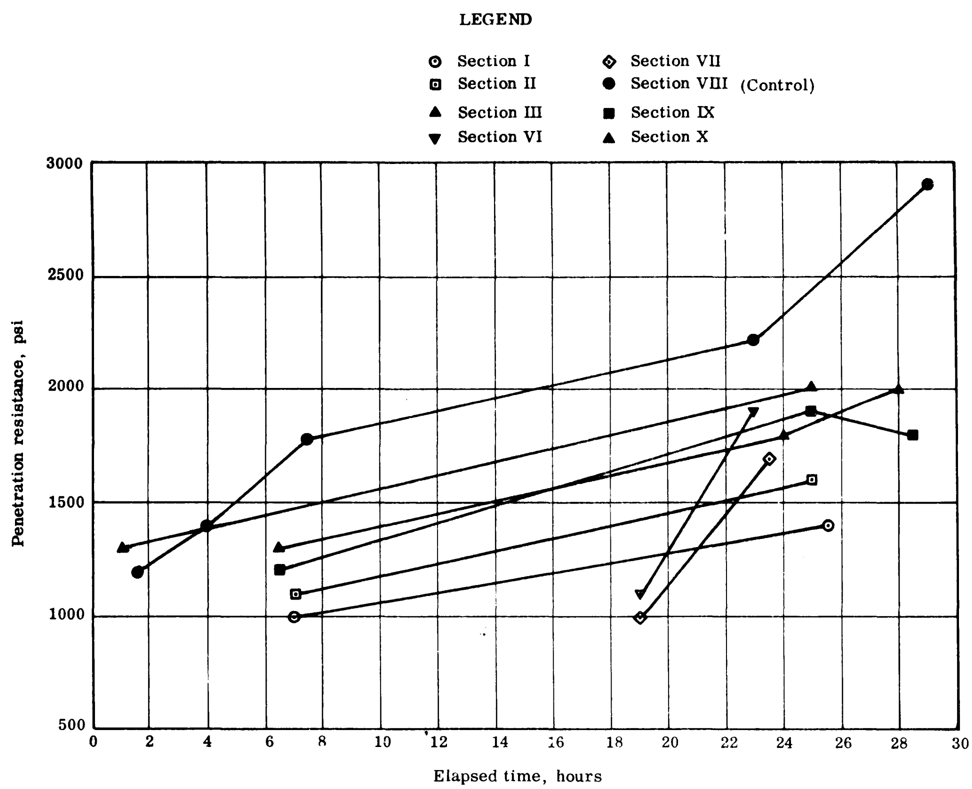



Figure 9. Strength development of each section of project 2 at early stages.

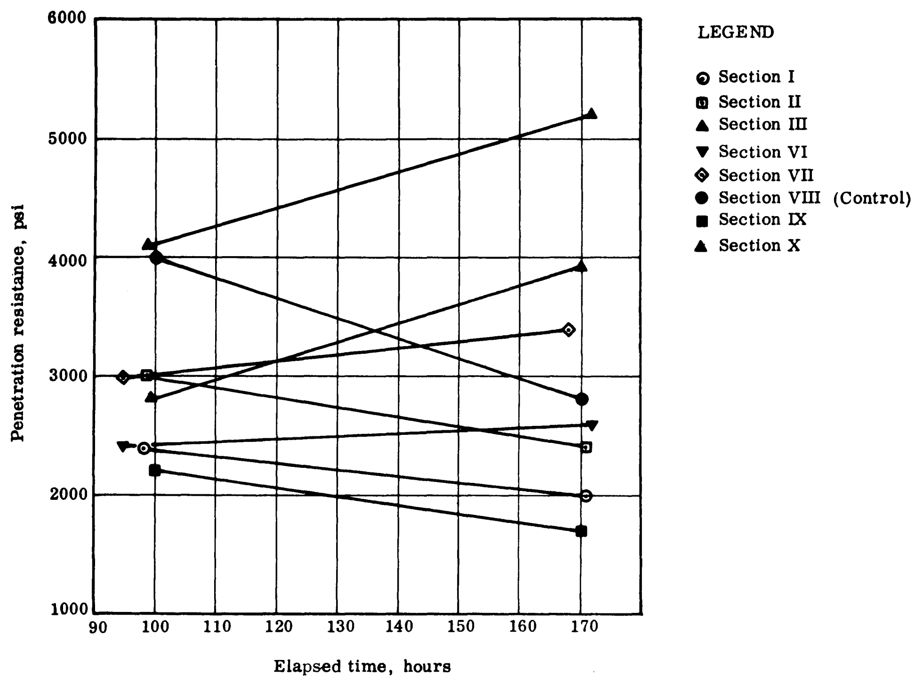



Figure 10. Strength developments of each section of project 2 at later stages.

## DISCUSSION OF RESULTS

From the data presented it can be seen that the cement and lime coverages were as good as could be expected. It is realized that the design is based on laboratory testing where more control can be exercised. This closer control undoubtedly results in more uniform data and one could not expect that the same accuracy could be obtained in the field.

The densities and moisture contents of both projects were fairly uniform as was shown in Table VI. In project 1 all sections had about 95% of the maximum dry density and a moisture content very close to the optimum (20.8%).

Project 2 had somewhat more variable densities and moisture contents. Although most densities were above 95% of the maximum dry density, section 9 had 92.1% and can be considered low. Section 7 had 101.6% and can be considered high. The moisture contents of project 2, though close to optimum (21.5%) in most cases, included some high and low values, such as those for section 1 (24.0%) and section 7 (15.0%). None of these variations, however, are believed to have had any effect on the strength development of the mixtures in question.

The strength development of each section in each project was analyzed by comparing all sections to their respective control section (section 8). In this manner the effect of adding retarder and mixing could be detected since section 8 was a regular cement section. Tables VII and VIII show the results of this analysis.

TABLE VII

STRENGTH DEVELOPMENT OF ALL SECTIONS OF PROJECT 1

| Section | Strength as Percent of that of Control Section | | | |
|---|---|---|---|---|
| | 6 hours | 20 hours | 24 hours | 115 hours |
| 1 | 50 | 65 | 104 | 75 |
| 2 | 48 | 68 | 78 | 88 |
| 3 | 58 | 61 | 55 | 61 |
| 6 | — | 30 | 38 | 58 |
| 7 | — | 37 | 44 | 46 |

TABLE VIII

STRENGTH DEVELOPMENT OF ALL SECTIONS OF PROJECT 2

| Section | Strength as Percent of that of Control Section | | | |
|---|---|---|---|---|
| | 7 hours | 19 hours | 23 hours | 170 hours |
| 1 | 58 | 60 | 62 | 72 |
| 2 | 64 | 68 | 71 | 86 |
| 3 | 86 | 87 | 89 | 185 |
| 6 | — | 53 | 87 | 93 |
| 7 | — | 48 | 73 | 122 |
| 9 | 71 | 80 | 83 | 61 |
| 10 | 77 | 79 | 81 | 140 |

Before Tables VII and VIII are discussed, the terms "retardation" and "strength development" should be defined. This is best done by reference to Figure 11. In this figure, curve (b) shows the theoretical strength development of a soil-cement mixture; that is, no strength is developed until the initial set, say 6 hours after mixing, and then the strength rises sharply. Curve (a) shows what actually happens. It shows that there is a strength increase even before initial set. Curve (c) shows what one might expect from a soil-cement mixture with a retarder. That is, there is a slower pickup of strength as compared to curve (a), with the anticipation that as time passes the value of curve (c) will reach that of curve (a).

In the working plan[1] and Interim Reports 1 and 3[2,4] of this study, "retardation" was defined according to the system shown in Figure 12.

In the design of the amount of retarder to be used it was desired that at 18 hours the strength of the soil cement with retarder be 40% of that of the plain soil cement. Actually this is "strength development" rather than "retardation". In this case retardation is 60%, the complement of strength development. This important distinction is emphasized here.

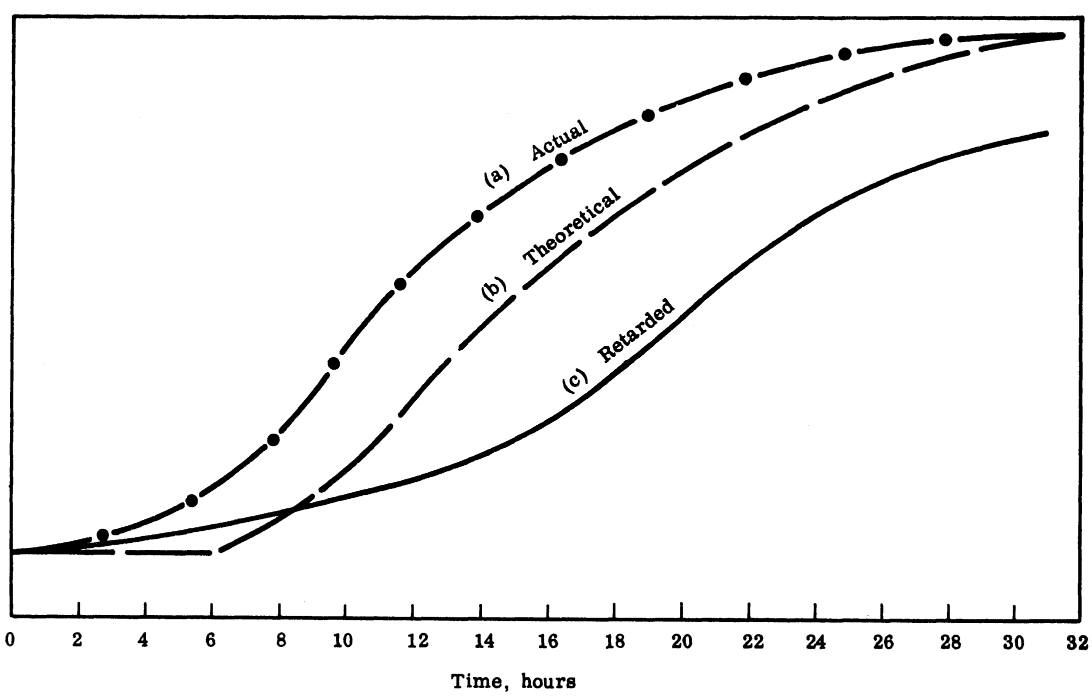



Figure 11. Strength development of plain and retarded soil cement mixtures.

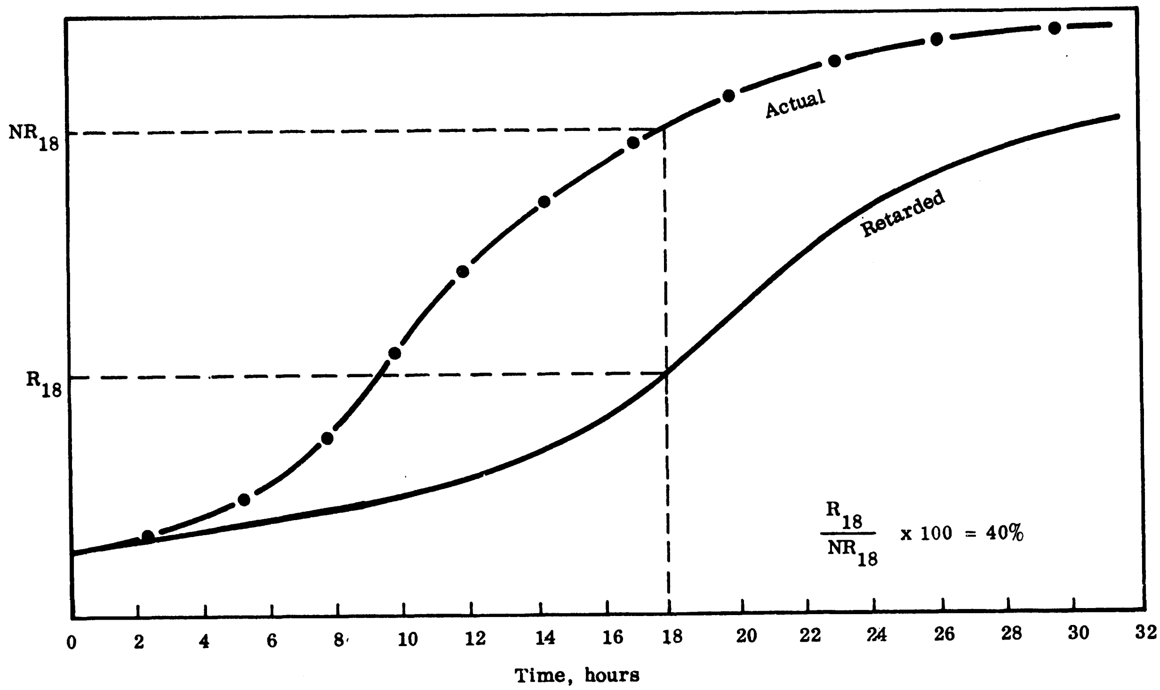



Figure 12. Retardation.

In view of the above definitions the strength development data as shown in Tables VII and VIII are analyzed as follows:

Project 1 - Sections 1 and 2 showed good strength development (75% and 88% respectively) at around 115 hours, at which time the testing was ended. (See Figure 4 for characteristics of each section.) These results indicate that one may delay compaction or mixing for 6 hours and not impair the strength of the pavement if retarder is used in the mix. Section 3 developed only 61% of the strength of the regular soil cement section. This might indicate that if a soil cement pavement is constructed with retarder and mixing is not delayed or the material remixed, it then might not develop sufficient strength as would the soil cement without retarder. It should be noted however, that the testing, due to necessity, was stopped at around 115 hours and that the strength development might continue for periods much longer than this. More will be said about this subject later in this report.

For sections 1, 2 and 3 it can also be said that the designed strength development of 40% was approximately achieved.

At early periods, sections 6 and 7 showed somewhat more retardation than that for which they were designed. They also had about half the strength of the regular soil cement section at the end of 115 hours, which might indicate that delaying compaction and/or remixing at 18 hours weakens the mixture though a retarder is added. Again, more will be said about this possibility later is this report.

Project 2 - Sections 1 and 2 showed trends similar to those noted for project 1; that is, they showed good strength development at early periods (72% and 86% respectively).

Unlike section 3 of project 1, section 3 of project 2 showed an unexpected amount of strength development. It should be realized, however, that in project 2 the control section showed some strength decrease between 100 and 170 hours (see Figure 10). Since the strength development of each section is compared to the strength development of the control section, some percentages became more than 100.

Sections 6 and 7 of project 2, again unlike matching sections of project 1, showed good strength development. One might conclude that in project 2 delaying compaction and/or remixing at 18 hours did not impair the pavement strength.

Sections 9 and 10 (no retarder) did not indicate any trends other than maybe indicating that remolding close to initial set is not as critical as one may think.

## Field Samples

On the advice of the Soils Research Advisory Committee, an attempt was made to obtain core samples from the two projects about 7 months after construction. Since project 1 had about 14% cement in it, cores were successfully taken. The attempt to take cores from project 2 was unsuccessful. Details of the data on the cores taken from project 1 are given in Appendix E. A summary of the strength development data on the cores as measured by the unconfined compression test together with the last penetration readings taken during field testing are shown in Table IX.

It is interesting to note from Table IX that the strength development of sections 1, 2 and 3 was as expected; that is, their strengths either came close to that of the control section or exceeded it. Unfortunately, however, on sections 6 and 7, the results of tests at 115 hours and at 7 months agree, which indicates that mixing and/or compacting at 18 hours even with a retarder might result in a strength loss of about 50%. The reason for the above strength loss is hard to pin down but it could be one of the following:

1. Insufficient amount of retarder because of inadequacy of field controls

2. Too much retarder due to inadequacy of field control

3. Field condition (poor control over mixing, distribution of additives, etc.)

TABLE IX

SUMMARY OF STRENGTH DEVELOPMENT DATA FOR PROJECT 1

| Section | Strength as Percent of that of Control Section | |
|---|---|---|
| | From Penetration Tests at 115 hrs. | From Cores After 7 Months |
| 1 | 75 | 151 |
| 2 | 88 | 82 |
| 3 | 61 | 136 |
| 6 | 58 | 57 |
| 7 | 48 | 48 |

It is unfortunate that an intermediate compacting and/or mixing period such as 9 hours, though planned, was not actually included in the experiment. This omission, as explained earlier, was due to difficulty in scheduling.

Interpolations can be made between the results of the 6-hour and 18-hour compacting and/or mixing. Because of the variability of the data, however, the author thought such an attempt to be unjustified.

## SUMMARY AND CONCLUSIONS

Based on the data presented in this report the following conclusions are believed to be warranted.

1. If a designed amount of sugar and lime is added to a soil cement or cement treated soil mixture as a retarder then the strength development of the mixture will not be impaired if:

    (a) The compaction is delayed for 6 hours;

    (b) the mixture is remixed and compacted at 6 hours; or

    (c) the mixture is compacted immediately and not remixed.

2. The strength development of the same mixture might be decreased about 50% if:

   (a) The compaction of the mixture is delayed for 18 hours; or

   (b) the mixture is remixed and recompacted after a delay of 18 hours.

3. Interpolations can be made between the 6-hour and 18-hour results. Such interpolations might result in extending the remixing and compacting periods to more than 6 hours. Since this extension of remixing time can not be supported by actual data, the author did not attempt such interpolations.

## RECOMMENDATIONS FOR IMPLEMENTING STUDY FINDINGS

It is noted that the study concluded that cement treated soils incorporating sugar and lime as retarder can be remanipulated at six hours. They, however, can not be remanipulated at eighteen hours without a loss in strength.

Since the remanipulation at six hours is an extension of only two hours from the time allowed in the present Virginia specifications, the expense of adding a retarder is not economically advantageous in regular construction work. It is therefore recommended that sugar and lime not be used as a retarder in the construction of cement treated soils on a routine basis.

Since if they are used in the proper amounts, sugar and lime are effective in retarding the set of cement treated soils up to six hours, it is recommended that in special instances when a remanipulation period of up to six hours is needed, the sugar and lime combination be used as a retarder.

These recommendations have been made to the Materials Division of the Virginia Department of Highways.

## ACKNOWLEDGEMENTS

The author expresses sincere thanks to the personnel of the Ashland Residency of the Virginia Department of Highways, without whose help the field investigation could not have been carried out. Specifically, thanks are extended to R. B. Goodloe, Resident Engineer; B. C. Neblett, Assistant Resident Engineer; E. R. Gray, Maintenance Supervisor; B. B. Harris, Area Superintendent; and John J. Williams, Inspector.

Thanks are also extended to A. D. Newman, District Materials Engineer in the Richmond District, and his personnel for taking the cores for the strength tests.

The assistance of H. T. Craft, Information Officer; S. N. Runkle, Research Analyst; D. C. Wyant, Summer Trainee; M. O. Harris and L. E. Wood, Materials Technicians; and Samir Habal, graduate assistant; is also gratefully acknowledged.

# REFERENCES

1. Anday, M. C., and W. C. Sherwood, "Use of Retarders with Cement Treated Soils, Working Plan," Virginia Highway Research Council, August 1964.

2. Anday, M. C., and W. C. Sherwood, "Use of Retarders with Cement Treated Soils, Interim Report No. 1," Virginia Highway Research Council, November 1965.

3. Noble, D. F., and M. A. Ozol, "Use of Retarders with Cement Treated Soils, Interim Report No. 2," Virginia Highway Research Council, October 1968.

4. Tice, J. A., "Use of Retarders with Cement Treated Soils, Interim Report No. 3," Virginia Highway Research Council, November 1968.

5. Tice, J. A., "Use of Retarders with Cement Treated Soils, Working Plan for Field Study," Virginia Highway Research Council, January 1969.

6. Tice, J. A., "Testing Plan for Field Study of Retarders in Cement Treated Soils," Virginia Highway Research Council, June 1969.

# APPENDICES

# APPENDIX A

## PROPERTIES OF SOILS USED IN PROJECT 1

| Property | SECTION 1 | 2 | 3 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|
| % Passing 1½" screen | | | 100 | | | |
| % Passing 1" screen | | | 97.3 | | | 100 |
| % Passing 3/4" screen | 100 | 100 | 93.6 | 100 | 100 | 90.9 |
| % Passing 3/8" screen | 88.1 | 93.5 | 80.3 | 94.4 | 80.6 | 70.4 |
| % Passing No. 4 screen | 75.1 | 72.5 | 62.6 | 75.3 | 59.6 | 54.9 |
| % Passing No. 10 screen | 59.8 | 32.1 | 41.2 | 49.3 | 29.2 | 36.8 |
| % Passing No. 20 screen | 52.9 | 28.1 | 36.0 | 41.6 | 25.8 | 32.9 |
| % Passing No. 40 screen | 47.3 | 25.0 | 32.2 | 35.8 | 23.3 | 29.7 |
| % Passing No. 80 screen | 41.0 | 21.9 | 28.1 | 30.3 | 20.5 | 25.6 |
| % Passing No. 100 screen | 39.4 | 21.1 | 27.1 | 29.0 | 19.8 | 24.6 |
| % Passing No. 200 screen | 35.2 | 19.0 | 24.3 | 25.1 | 18.0 | 22.1 |
| % Clay | 20 | 12 | 15 | 14 | 11 | 15 |
| % Silt | 11 | 5 | 7 | 10 | 6 | 6 |
| % Sand | 69 | 83 | 78 | 76 | 83 | 79 |
| Liquid Limit, % | 27 | 46 | 49 | 44 | 39 | 37 |
| Plasticity Index, % | 9 | 20 | 23 | 16 | 16 | 15 |
| HRB Classification | A-2-4(0) | A-2-7(1) | A-2-7(1) | A-2-7(1) | A-2-6(0) | A-2-6(0) |
| Specific Gravity | 2.65 | 2.65 | 2.75 | 2.67 | 2.67 | 2.64 |

Average Maximum Density = 102.0 pcf
Average Optimum Moisture Content = 18.6%

# APPENDIX B

## PROPERTIES OF SOILS USED IN PROJECT 2

| Property | SECTION | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 6 | 7 | 8 | 9 | 10 |
| % Passing $1\frac{1}{2}$" screen | | | | | | 100 | | |
| % Passing 1" screen | 100 | 100 | 100 | 100 | 100 | 94.1 | 100 | 100 |
| % Passing 3/4" screen | 97.2 | 91.3 | 94.0 | 94.6 | 87.1 | 80.7 | 95.9 | 93.0 |
| % Passing 3/8" screen | 78.9 | 84.8 | 75.8 | 76.9 | 62.5 | 51.3 | 75.7 | 76.3 |
| % Passing No. 4 screen | 54.6 | 67.3 | 59.0 | 59.4 | 48.3 | 32.7 | 59.2 | 62.8 |
| % Passing No. 10 screen | 27.6 | 44.2 | 37.2 | 38.7 | 32.5 | 19.1 | 43.0 | 44.4 |
| % Passing No. 20 screen | 25.5 | 39.7 | 34.3 | 36.1 | 27.4 | 17.4 | 39.0 | 40.0 |
| % Passing No. 40 screen | 22.7 | 34.0 | 29.1 | 31.9 | 21.9 | 15.3 | 34.0 | 34.9 |
| % Passing No. 80 screen | 20.6 | 30.9 | 24.9 | 28.2 | 18.8 | 13.9 | 30.0 | 30.4 |
| % Passing No. 100 screen | 20.0 | 30.2 | 24.0 | 27.3 | 18.1 | 13.5 | 29.0 | 29.3 |
| % Passing No. 200 screen | 18.7 | 28.3 | 21.6 | 25.0 | 16.4 | 12.5 | 26.5 | 26.6 |
| % Clay | 17 | 11 | 9 | 12 | 8 | 8 | 12 | 16 |
| % Silt | 10 | 6 | 7 | 8 | 7 | 3 | 6 | 8 |
| % Sand | 73 | 83 | 84 | 80 | 85 | 89 | 82 | 76 |
| Liquid Limit, % | 47 | 46 | 29 | 38 | 30 | 49 | 35 | 29 |
| Plasticity Index, % | 22 | 23 | 12 | 17 | 12 | 23 | 16 | 12 |
| HRB Classification | A-2-7(1) | A-2-7(2) | A-2-6(0) | A-2-6(1) | A-2-6(0) | A-2-7(0) | A-2-6(1) | A-2-6(0) |
| Specific Gravity | 2.63 | 2.62 | 2.61 | 2.65 | 2.61 | 2.65 | 2.63 | 2.64 |

Average Maximum Density = 100.5 pcf
Average Optimum Moisture Content = 21.5%

# APPENDIX C

## STRENGTH DEVELOPMENT DATA FOR

## PROJECT 1

(The data presented in Appendices C and D are given to demonstrate the variability in the result of penetration tests made. For the figures in the body of the report they were converted to pounds per square inch values through the formulas:

$$\text{range 0-100, psi} = \frac{0.9048\ D}{A}$$

$$\text{range 100-900, psi} = \frac{0.8778\ D + 2.5\ \text{pounds}}{A}$$

when D = Dial Reading
A = Area of penetration needle = 0.0258 sq. in.)

SECTION 1

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 1 | 5.25 | 21 | 14 | 30 |
| | 6.50 | 58 | 40 | 44 |
| | 7.50 | 36 | 27 | 28 |
| | 9.50 | 31 | 35 | 29 |
| | 13.00 | 53 | 63 | 58 |
| | 21.25 | 67 | 81 | 63 |
| | 28.00 | 73 | 90 | 42 |
| | 46.75 | 91 | 82 | 86 |
| | 50.25 | 81 | 80 | 65 |
| | 117.5 | 159 | 304 | 115 |
| 6 | 5.30 | 37 | 36 | 24 |
| | 6.30 | 33 | 30 | 36 |
| | 7.25 | 38 | 42 | 49 |
| | 9.30 | 58 | 65 | 63 |
| | 13.50 | 49 | 43 | 47 |

SECTION 1

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 6 | 21.30 | 64 | 56 | 52 |
| | 22.80 | 118 | 99 | 72 |
| | 26.10 | 112 | 101 | 98 |
| | 117.5 | 133 | 130 | 135 |
| 11 | 5.50 | 30 | 32 | 36 |
| | 6.25 | 32 | 37 | 35 |
| | 7.25 | 58 | 51 | 40 |
| | 9.50 | 49 | 46 | 41 |
| | 13.25 | 43 | 40 | 41 |
| | 21.50 | 56 | 64 | 76 |
| | 23.00 | 123 | 152 | 104 |
| | 26.25 | 120 | 114 | 135 |
| | 117.70 | 142 | 108 | 214 |

SECTION 2

| | | | | |
|---|---|---|---|---|
| 1 | 5.5 | 34 | 26 | 33 |
| | 6.0 | 37 | 32 | 26 |
| | 7.0 | 38 | 41 | 38 |
| | 9.3 | 37 | 35 | 31 |
| | 13.25 | 46 | 52 | 50 |
| | 21.50 | 81 | 54 | 81 |
| | 47.0 | 132 | 138 | 146 |
| | 50.25 | 124 | 137 | 140 |
| | 117.75 | 168 | 52 | 221 |
| 6 | 5.5 | 29 | 31 | 26 |
| | 6.75 | 33 | 35 | 35 |
| | 7.5 | 28 | 29 | 33 |
| | 9.3 | 42 | 40 | 41 |
| | 13.3 | 38 | 32 | 40 |
| | 21.5 | 52 | 49 | 135 |
| | 28.0 | 58 | 82 | 53 |

APPENDIX C (Continued)

SECTION 2

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 6 | 47.2 | 118 | 139 | 123 |
| | 50.4 | 142 | 155 | 151 |
| | 117.8 | 179 | 174 | 230 |
| 11 | 5.7 | 36 | 36 | 29 |
| | 6.0 | 32 | 20 | 28 |
| | 7.0 | 33 | 34 | 46 |
| | 9.25 | 60 | 62 | 66 |
| | 13.5 | 60 | 45 | 51 |
| | 21.7 | 68 | 62 | 71 |
| | 23.25 | 118 | 107 | 60 |
| | 26.3 | 117 | 138 | 126 |
| | 117.9 | 177 | 113 | 195 |

SECTION 3

| | | | | |
|---|---|---|---|---|
| 1 | 2.0 | 31 | 35 | 31 |
| | 3.7 | 52 | 44 | 44 |
| | 4.4 | 39 | 30 | 39 |
| | 9.0 | 70 | 68 | 65 |
| | 21.8 | 59 | 72 | 49 |
| | 47.3 | 117 | 108 | 104 |
| | 52.0 | 121 | 115 | 106 |
| | 118.2 | 163 | 126 | 174 |
| 6 | 2.25 | 36 | 48 | 35 |
| | 3.6 | 43 | 62 | 38 |
| | 4.5 | 39 | 36 | 36 |
| | 9.1 | 39 | 42 | 36 |
| | 21.9 | 47 | 42 | 78 |
| | 47.5 | 119 | 138 | 142 |
| | 118.25 | 98 | 114 | 129 |

APPENDIX C (Continued)

SECTION 3

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 11 | 2.3 | 27 | 30 | 35 |
| | 3.5 | 36 | 36 | 38 |
| | 4.6 | 26 | 35 | 46 |
| | 9.2 | 40 | 36 | 45 |
| | 22.0 | 50 | 52 | 74 |
| | 28.0 | 49 | 54 | 54 |
| | 47.5 | 106 | 52 | 72 |
| | 50.5 | 115 | 105 | 85 |
| | 118.3 | 71 | 73 | 135 |

SECTION 6

| | | | | |
|---|---|---|---|---|
| 1 | 19.6 | 34 | 32 | 28 |
| | 21.9 | 38 | 99 | 32 |
| | 26.3 | 44 | 63 | 48 |
| | 41.75 | 85 | 79 | 68 |
| | 46.0 | 75 | 71 | 82 |
| | 115.0 | 87 | 124 | 125 |
| 6 | 19.75 | 47 | 41 | 52 |
| | 22.0 | 41 | 36 | 44 |
| | 26.4 | 62 | 54 | 53 |
| | 41.7 | 54 | 93 | 95 |
| | 46.1 | 61 | 94 | 103 |
| | 115.1 | 133 | 115 | 134 |
| 11 | 20.8 | 26 | 24 | 33 |
| | 22.1 | 28 | 28 | 26 |
| | 26.5 | 54 | 57 | 57 |
| | 41.6 | 74 | 54 | 42 |
| | 46.2 | 99 | 67 | 76 |
| | 115.2 | 110 | 114 | 122 |

APPENDIX C (Continued)

SECTION 7

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 1 | 19.9 | 55 | 44 | 47 |
| | 22.25 | 51 | 68 | 42 |
| | 26.70 | 31 | 44 | 52 |
| | 41.4 | 92 | 113 | 83 |
| | 46.25 | 106 | 75 | 88 |
| | 115.6 | 118 | 145 | 163 |
| 6 | 20.25 | 39 | 34 | 26 |
| | 22.3 | 34 | 30 | 36 |
| | 26.75 | 82 | 49 | 60 |
| | 41.3 | 72 | 110 | 94 |
| | 46.3 | 65 | 115 | 67 |
| | 115.7 | 85 | 106 | 90 |
| 11 | 20.4 | 41 | 25 | 32 |
| | 22.4 | 51 | 38 | 36 |
| | 26.8 | 41 | 46 | 54 |
| | 41.25 | 72 | 64 | 56 |
| | 46.4 | 77 | 65 | 68 |
| | 115.75 | 112 | 75 | 93 |

SECTION 8 (Control Section)

| | | | | |
|---|---|---|---|---|
| 1 | 3.5 | 53 | 52 | 48 |
| | 6.2 | 53 | 56 | 42 |
| | 22.25 | 75 | 63 | 57 |
| | 93.7 | 204 | 227 | 185 |
| 2 | 3.4 | 41 | 61 | 47 |
| | 6.1 | 63 | 54 | 66 |
| | 22.2 | 72 | 148 | 126 |
| | 93.6 | 177 | 138 | 144 |

APPENDIX C (Continued)

SECTION 8 (Control Section)

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 3 | 3.3 | 46 | 70 | 44 |
| | 6.0 | 71 | 73 | 61 |
| | 22.1 | 112 | 78 | 99 |
| | 93.5 | 228 | 173 | 81 |
| 4 | 3.2 | 98 | 76 | 66 |
| | 5.9 | 105 | 63 | 65 |
| | 22.0 | 146 | 138 | 77 |
| | 93.4 | 208 | 226 | 154 |
| 5 | 3.0 | 50 | 49 | 31 |
| | 5.8 | 61 | 57 | 49 |
| | 21.9 | 103 | 98 | 122 |
| | 93.3 | 95 | 74 | 86 |
| 6 | 2.9 | 38 | 51 | 46 |
| | 5.75 | 90 | 72 | 84 |
| | 21.8 | 104 | 76 | 75 |
| | 93.25 | 202 | 188 | 286($\frac{1}{2}$) |

# APPENDIX D

## STRENGTH DEVELOPMENT DATA FOR PROJECT 2

### SECTION 1

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 1 | 7.1 | 25 | 45 | 36 |
| | 25.5 | 13 | 48 | 40 |
| | 98.0 | 62 | 69 | 96 |
| | 171.0 | 73 | 57 | 50 |
| 6 | 7.0 | 20 | 28 | 36 |
| | 25.4 | 44 | 50 | 62 |
| | 98.1 | 64 | 49 | 58 |
| | 171.0 | 22 | 31 | 23 |
| 11 | 6.9 | 23 | 19 | 25 |
| | 25.3 | 48 | 25 | 40 |
| | 98.2 | 76 | 85 | 43 |
| | 171.0 | 120 | 55 | 86 |

### SECTION 2

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 1 | 6.8 | 33 | 22 | 26 |
| | 25.2 | 35 | 50 | 45 |
| | 98.3 | 105 | 97 | 91 |
| | 171.0 | 70 | 74 | 69 |
| 6 | 6.75 | 34 | 35 | 27 |
| | 25.1 | 45 | 35 | 42 |
| | 98.4 | 91 | 71 | 73 |
| | 171.0 | 101 | 99 | 79 |
| 11 | 6.7 | 36 | 43 | 34 |
| | 25.0 | 45 | 49 | 50 |
| | 98.5 | 73 | 99 | 74 |
| | 171.0 | 46 | 55 | 30 |

APPENDIX D (Continued)

SECTION 3

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 1 | 0.75 | 51 | 33 | 25 |
| | 24.7 | 54 | 52 | 59 |
| | 98.6 | 121 | 82 | 106 |
| | 171.0 | 150 | 133 | 165 |
| 6 | 0.8 | 37 | 42 | 34 |
| | 24.75 | 51 | 79 | 63 |
| | 98.7 | 105 | 75 | 80 |
| | 172.0 | 71 | 155 | 65 |
| 11 | 1.0 | 27 | 33 | 39 |
| | 24.9 | 55 | 48 | 51 |
| | 98.75 | 170 | 160 | 150 |
| | 172.0 | 187 | 201 | 140 |

SECTION 6

| | | | | |
|---|---|---|---|---|
| 1 | 18.6 | 32 | 21 | 39 |
| | 22.9 | 68 | 125 | 30 |
| | 94.3 | 64 | 71 | 67 |
| | 172 | 59 | 101 | 62 |
| 6 | 18.7 | 36 | 40 | 25 |
| | 23.0 | 40 | 97 | 30 |
| | 94.4 | 61 | 91 | 95 |
| | 172.0 | 105 | 95 | 58 |
| 11 | 18.8 | 33 | 29 | 22 |
| | 23.1 | 30 | 29 | 35 |
| | 94.5 | 32 | 80 | 65 |
| | 172.0 | 37 | 56 | 81 |

SECTION 7

| | | | | |
|---|---|---|---|---|
| 1 | 19.0 | 15 | 25 | 34 |
| | 23.2 | 69 | 17 | 71 |
| | 94.5 | 122 | 89 | 70 |
| | 168.0 | 200 | 110 | 120 |

APPENDIX D (Continued)

SECTION 7

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 6 | 19.2 | 38 | 20 | 39 |
| | 23.25 | 35 | 100 | 50 |
| | 94.7 | 70 | 86 | 130 |
| | 168.0 | 68 | 121 | 112 |
| 11 | 19.25 | 34 | 20 | 25 |
| | 23.3 | 20 | 44 | 22 |
| | 94.75 | 95 | 50 | 64 |
| | 168.0 | 47 | 51 | 49 |

SECTION 8 Control Section

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 1 | 1.6 | 28 | 24 | 32 |
| | 3.8 | 26 | 44 | 42 |
| | 7.2 | 48 | 40 | 42 |
| | 22.9 | 71 | 73 | 55 |
| | 28.9 | 63 | 32 | 30 |
| | 100.3 | 78 | 113 | 63 |
| | 171.0 | 58 | 47 | 44 |
| 2 | 1.5 | 36 | 29 | 29 |
| | 3.75 | 37 | 25 | 19 |
| | 7.25 | 37 | 54 | 61 |
| | 22.8 | 49 | 56 | 67 |
| | 28.8 | 95 | 50 | 38 |
| | 100.25 | 74 | 73 | 85 |
| | 171.0 | 78 | 109 | 105 |
| 3 | 1.4 | 30 | 32 | 43 |
| | 3.6 | 36 | 52 | 44 |
| | 7.3 | 72 | 70 | 46 |
| | 22.75 | 22 | 28 | 60 |
| | 28.75 | 82 | 95 | 107 |
| | 100.2 | 100 | 148 | 140 |
| | 171.0 | 33 | 79 | 22 |

APPENDIX D (Continued)

SECTION 8 (Control Section)

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 4 | 1.3 | 38 | 28 | 32 |
| | 3.5 | 38 | 43 | 40 |
| | 7.4 | 50 | 58 | 34 |
| | 22.6 | 75 | 75 | 90 |
| | 28.8 | 99 | 115 | 110 |
| | 100.0 | 89 | 156 | 133 |
| | 171.0 | 113 | 30 | 115 |
| 5 | 1.25 | 41 | 44 | 48 |
| | 3.4 | 48 | 53 | 58 |
| | 7.5 | 63 | 54 | 52 |
| | 23.5 | 67 | 40 | 120 |
| | 28.6 | 86 | 102 | 115 |
| | 100.0 | 190 | 170 | 51 |
| | 171.0 | 30 | 129 | 92 |
| 6 | 1.2 | 31 | 34 | 30 |
| | 3.3 | 35 | 53 | 28 |
| | 7.6 | 47 | 51 | 66 |
| | 22.3 | 54 | 68 | 80 |
| | 28.5 | 85 | 103 | 72 |
| | 100.0 | 111 | 98 | 152 |
| | 170.0 | 148 | 103 | 105 |

SECTION 9

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 1 | 6.2 | 43 | 32 | 40 |
| | 24.6 | 66 | 51 | 71 |
| | 28.4 | 35 | 42 | 46 |
| | 99.8 | 59 | 55 | 60 |
| | 170.0 | 24 | 72 | 42 |
| 6 | 6.25 | 33 | 32 | 34 |
| | 24.5 | 47 | 64 | 62 |
| | 28.3 | 40 | 33 | 54 |
| | 99.75 | 62 | 67 | 46 |
| | 170.0 | 37 | 100 | 39 |

APPENDIX D (Continued)

SECTION 9

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 11 | 6.3 | 38 | 28 | 28 |
| | 24.4 | 44 | 30 | 49 |
| | 28.25 | 82 | 59 | 75 |
| | 99.7 | 40 | 62 | 105 |
| | 170.0 | 50 | 32 | 38 |

SECTION 10

| Location No. | Elapsed Time, Hours | 3 Individual Dial Readings | | |
|---|---|---|---|---|
| 1 | 6.4 | 26 | 22 | 38 |
| | 24.25 | 32 | 30 | 32 |
| | 28.2 | 59 | 39 | 20 |
| | 99.6 | 73 | 50 | 74 |
| | 170.0 | 31 | 35 | 34 |
| 6 | 6.5 | 37 | 57 | 41 |
| | 24.0 | 66 | 74 | 43 |
| | 28.1 | 60 | 79 | 40 |
| | 99.5 | 78 | 61 | 105 |
| | 170.0 | 100 | 82 | 90 |
| 11 | 6.6 | 36 | 34 | 43 |
| | 24.0 | 30 | 62 | 82 |
| | 28.0 | 60 | 65 | 80 |
| | 99.4 | 140 | 50 | 97 |
| | 170.0 | 250 | 240 | 130 |

# APPENDIX E

## DATA ON THE CORES TAKEN FROM PROJECT 1

| Section | Core No. | Diameter, in. | Height, in. | H/D* Ratio | Moisture Content, % | Strength, psi |
|---|---|---|---|---|---|---|
| 1 | 3 | 3.86 | 5.0 | 1.30 | 22.3 | 517 |
| | 4 | 3.86 | 4.70 | 1.21 | 17.4 | 684 |
| | 5 | 3.88 | 4.70 | 1.21 | 14.3 | 969 |
| 2 | 1 | 3.89 | 4.50 | 1.16 | 16.4 | 509 |
| | 2 | 3.90 | 4.60 | 1.18 | 16.8 | 536 |
| | 3 | 3.85 | 4.60 | 1.19 | 22.3 | 344 |
| | 4 | 3.88 | 4.20 | 1.08 | 20.1 | 266 |
| | 5 | 3.86 | 5.10 | 1.32 | 19.9 | 299 |
| 3 | 1 | 3.90 | 4.40 | 1.13 | 17.0 | 754 |
| | 2 | 3.84 | 4.50 | 1.17 | 14.9 | 725 |
| | 3 | 3.60 | 4.75 | 1.32 | 23.5 | 836 |
| | 4 | 3.70 | 5.00 | 1.35 | 23.0 | 540 |
| | 5 | 3.60 | 5.40 | 1.50 | 22.0 | 403 |
| 6 | 1 | 3.75 | 5.00 | 1.33 | 18.5 | 444 |
| | 2 | 3.70 | 4.40 | 1.19 | 19.9 | 233 |
| | 3 | 3.70 | 4.60 | 1.24 | 20.0 | 335 |
| | 4 | 3.93 | 5.10 | 1.30 | 18.9 | 198 |
| | 5 | 3.60 | 6.10 | 1.69 | 17.6 | 162 |
| 7 | 2 | 3 | 4.25 | 1.18 | 20.9 | 89 |
| | 4 | 3 | 3.50 | 0.97 | 17.8 | 498 |
| | 5 | 3 | 5.70 | 1.55 | 20.5 | 94 |
| 8 | 1 | 3.75 | 4.50 | 1.64 | 20.7 | 408 |
| | 2 | 3.60 | 4.50 | 1.73 | 21.5 | 280 |
| | 2A | 3.60 | 4.10 | 1.14 | 23.8 | 545 |
| | 3A | 3.75 | 4.10 | 1.09 | 23.8 | 746 |
| | 4 | 3.63 | 4.75 | 1.30 | 18.5 | 386 |
| | 5 | 3.75 | 4.55 | 1.21 | 21.7 | 507 |

*Only the cores with a H/D ratio equal to or greater than 1 were used.