Strength of Soil-Cement as a Function of Degree of Mixing

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This paper describes a laboratory investigation of the following variables involved in mixing portland cement into a clayey silt: (1) uniformity of soil and cement mixture, (2) compressive strength of the resultant soil-cement, (3) time of mixing, and (4) accumulative energy required for mixing.

Mixing was performed in a pugmill-type mixer and the energy required for mixing was automatically recorded. Specimens were compacted in the Harvard miniature compaction mold and, after curing seven days, were tested in unconfined compression. Cement concentration throughout the soil-cement mixture was determined by means of a radioactive tracer that was incorporated uniformly in the cement. This method of measuring cement content proved to be rapid and reasonably reliable. Degree of mixing was measured by the mixing uniformity coefficient. It was concluded that:

1. The relationship between uniformity of mix and strength of soil-cement is a logarithmic one; i. e. a straight line is obtained on a plot of strength versus $\log_{10}$ of I. Thus, when the cement and soil are poorly mixed a small increase in mixing uniformity results in an even smaller increase in strength; whereas for a well mixed sample, a small increase in mixing uniformity results in a large increase in strength.

2. The strength of soil-cement varies directly with the $\log_{10}$ of the accumulative energy required for mixing. This relationship holds within the limits tested, but it is apparent that there is a point beyond which further increases in mixing energy would have little effect on the strength of the soil-cement.

3. The relationship between mixing energy and uniformity of mix (I) appears as a curve on a plot of $\log_{10}$ I versus mixing energy, so that a small decrease in I (increase in mixing uniformity) requires a very large increase in the amount of mixing energy.

4. Other things being equal, accumulative mixing energy is approximately proportional to mixing time.

STABILIZING soils with portland cement has progressed from a modest beginning in the 1930's to an eminent position today as one of our most-common methods of soil stabilization. In the early days of soil-cement mixtures, farm equipment was used to mix the cement with the soil as there was no equipment designed specifically for that purpose. As soil-cement mixtures became more popular, the need for specially designed mixing equipment became increasingly apparent. This was particularly true with the clayey soils where it was necessary to pulverize the soil before mixing. It is to the credit of the mixing manufacturers that they met the need rapidly and effectively. Today we have powerful, highly mechanized mixing equipment that mix cement with soil far more speedily and efficiently than was once thought possible.

The Mixing Problem

Many people firmly believe that, thanks to our modern equipment, the days of mixing problems are a thing of the past. There is truth in this belief, since under ideal conditions cement can be mixed to some extent with almost any soil, including the fat clays. There is still the question, however, of how well the cement and soil are mixed. Numerous tests have shown that field strengths of soil-cement seldom match laboratory strengths (1a, 2). There is growing evidence that this is due to insufficient mixing.

The British, in their investigations of field mixing, use as a measure of field mixing efficiency, the ratio of field strength to laboratory strength. They have found varying values for mixing efficiency depending on the mixer type and soil type, but a value of 60 percent is typical. They note that if the mixing efficiency could be increased to 80 percent, 30 percent less cement might be used for the same strength (1a).

Further evidence that a mixing problem does exist comes from the Engineer Research and Development Laboratories, Fort Belvoir, Virginia, where cement stabilization was attempted on a well-graded gravel, a silty sand, and a fat plastic clay. Results were termed satisfactory on the gravel and silty sand but a failure on the clay. In addition, the strengths of samples taken from the silty sand mixture varied as much as 400 percent, indicating insufficient mixing (1b).

TABLE 1

COMPOSITION AND PROPERTIES OF SOIL

	Natural Soil	Soil-#40	Soil-#10
Percent by wt finer than #4	72		--
" " " " " #10	58		100
" " " " " #40	43		74
" " " " " #200	27		46
Percent finer than 0 002 m m	5		8 6
Percent clay mineral	12 (Illite)		20 (Illite)
Predominant non-clay mineral	Quartz		Quartz
Organic matter	trace		trace
Liquid limit in % dry wt of soil		24	
Plasticity Index		8	
Optimum water content for compaction in percent of soil dry wt			12.5
Unconfined compressive strength in psi at optimum water content			19

Reasons for a Mixing Study

The foregoing was pointed out to show that, with many soils (especially those that are fine grained), a high degree of mixing is difficult to obtain. Logic tells us, and indeed there is ample proof, that the attainment of a high degree of mixing is advantageous, because the more uniform the soil and cement mixture, the higher the strength of the compacted soil-cement; that is, thorough mixing, by using the cement more effectively, produces higher strength at a lower cost than does incomplete mixing. Thus interest in the strength of soil-cement necessitates interest in the degree of mixing.

The following questions are therefore raised: (1) Is the relationship between strength and degree of mixing linear? (2) How does the strength of soil-cement vary with the energy expended in mixing? (3) At what water content (with respect to optimum for density) can the most efficient use of the cement be obtained for the least work? (4) How can the degree of mixing be quickly determined in the field? The answers to these and other questions lie in increasing our knowledge of the principles of mixing and of the relationships and interactions of the many variables involved in mixing soil and cement. The laboratory investigation described in this paper was aimed at contributing toward this goal.

FACTORS INVOLVED IN THE SOIL-CEMENT MIXING STUDY

Variables

The process of mixing cement with soil involves numerous variables, many of them interdependent. In this investigation, an attempt was made to isolate and study several of these variables.

The variables studied were: (1) degree of mixing; (2) compressive strength of resultant soil-cement; (3) time of mixing; (4) accumulative energy required for mixing; and (5) water content.

The variables held constant were: (1) Type of soil (the soil used was a glacial till, obtained from the Stockbridge Bypass area in Western Massachusetts, in which all material coarser than a No. 10 sieve had been removed; the soil properties and composition are listed in Table 1). (2) Portland-cement concentration (a 10 percent concentration was used since it is a typical one for soils of slight to moderate plasticity). (3) Type of mixer (the pugmill type mixer used is described in Section II-D). (4) Speed of mixing (the main shaft of the mixer was set to rotate at 60 r.p.m., see Section II-D). (5) Time from the start of mixing to compaction (if the times were not held constant the strength would differ due to varying amounts of cement hydration taking place before compaction). (6) Compactive effort used in molding strength samples. (7) Density of strength samples for a given water content.

Determination of Cement Concentration

In any investigation of mixing soil and cement the most-difficult problem is that of determining the variation in cement concentration throughout the mixture. This may be done statistically by taking many small samples of uniform size from the mixture and finding the cement concentration in each. The normal ASTM T 144-49 titration procedure for determining cement content, while accurate and acceptable in most cases, takes an excessive amount of time. Since many hundreds of determinations had to be made, a more-rapid method was desired. Two other methods were investigated:

The Dye-Benzene Technique. In this procedure an oil-soluble, non-water-soluble dye is mixed uniformly with the cement. After the soil and dye-treated cement are mixed, many small samples of the mixture are taken, weighed, and a specified amount of benzene added to each. A colorimeter is used to determine the dye concentration and thus the cement concentration of each sample.

This procedure is satisfactory for certain soil-additive mixtures but proved unsatisfactory with cement. All of the dye could not be recovered, probably because the hydration of the cement trapped some of the dye.

The Radioactive-Tracer Technique. The determination of cement concentration by the radioactive-tracer technique is dependent on the generally accepted assumption that the rays emitted by radioactive material can be counted, and thus the quantity of radioactive material determined with a scintillation counter. If care is taken to insure that the geometry of each test is the same, i.e., position and size of the samples are the same, then the test is reasonably reliable. The accuracy with which the quantity of radioactive material present is determined, depends on the activity of the radiation, i.e., counts per second, and length of time of counting.

If the scintillation counter is in proper working order, the accuracy of counts per second can be figured statistically as follows: 67 percent of the time the counts per second for a given sample will be within one standard deviation of the mean, and 95 percent of the time within two standard deviations of the mean, where standard deviation in counts per second is equal to the square root of the total number of counts divided by the counting time in seconds (3). For example, if a sample were counted for 100 seconds and the total count was 10,000, the standard deviation in counts per second would $= \sqrt{\frac{10,000}{100}} = 1$ and 67 percent of the time the counts per second would fall within 1 percent of the mean.

The foregoing principles were employed to determine the cement content throughout a soil and cement mixture as follows: Cobalt 60 (Co^{60}) (a radioactive material) in powder form was mixed with cement in a ball mill until a uniform mixture was obtained. The uniformity of the mix was thoroughly checked by counting many small samples of the radioactive cement in the scintillation counter.

By the use of radioactive cement, determination of the cement concentration was a simple one. The small uniform size samples of soil-cement mix taken from each test were weighed, counted, and the cement content of each sample computed by comparison with a standard sample of radioactive cement.

Determination of Degree of Mixing or Mixing Uniformity

Once the cement concentrations of many small-similar-size samples out of a large mixture are known, the uniformity of the mix can be computed. Before this is done, the scale to which mixing uniformity is related must be specified. In this paper, a perfect mixture exists when all the samples taken from the mixture have the same concentration of cement. This concentration should equal the concentration of cement in the entire mixture. However, both the definition of homogeneity and the values obtained for the mixing uniformity of the various mixes are dependent on the size of the samples taken from the mixture. Michaels and Puzinauskas have shown experimentally (8) that the mixing uniformity of a given mixture is inversely proportional to the square root of the volume of the samples taken from the mixture to determine the mixing uniformity.

There are several methods available for showing any variation from a homogeneous mixture of two materials. The simplest is to record the maximum range in variation of the samples taken; i.e., if ten small samples from a large mixture of soil and cement are analyzed, and the maximum and minimum cement concentrations determined are 15 percent and 5 percent respectively, then the range in variation is 10. This representation is unsatisfactory, however, since no indication of the variation within the maximum range is recorded.

A second method of representing variations in mixing uniformity consists of noting all variations from the mean concentration and taking the average as the mean deviation. In this method all the samples play a part in determining the final value used to represent the variation from homogeneity.

A third procedure that has more mathematical backing (4) than the above is the standard deviation or root-mean-square deviation; that is, the square root of the average of the sum of the squares of the deviations from the mean concentration. If C is the concentration of cement in the individual sample, C^m the mean concentration and n the number of samples taken, then:

$$\text{Standard deviation} = \sqrt{\frac{\Sigma_0^n (C - C^m)^2}{n}} \qquad (1)$$

and

$$\text{Percent standard deviation} = \frac{\sqrt{\frac{\Sigma_0^n (C - C^m)^2}{n}}}{C^m} \times 100$$

Either of these values could be used as a measure of uniformity of mix as they both vary from a finite value at no mixing to zero at perfect mixing. Michaels (6) has presented a modification of the above, called the "uniformity index," which is used in this paper.

The uniformity index (I) is the ratio of the standard deviation at mixing time t to the standard deviation at zero mixing. The advantage of this method is that the values vary from unity at no mixing to zero for a perfect mixture.

The standard deviation at zero mixing is derived as follows:

Let n_1 = number of samples taken from cement

n_2 = number of samples taken from soil

$n = n_1 + n_2$

$$\frac{n_1}{n} = C^m \quad ; \quad \frac{n_2}{n} = 1 - C^m$$

then standard Deviation$_0$ =

$$\sqrt{\frac{\Sigma_0^{n} (1 - C^m)^2 + \Sigma_0^{n_2} (C^m - 0)^2}{n}}$$

$$= \sqrt{\frac{n_1 (1 - 2C^m + C^{m^2}) + n_2 C^{m^2}}{n}}$$

$$= \sqrt{C^m \left[1 - 2C^m + C^{m^2}\right] + C^{m^2} (1 - C^m)}$$

$$= \sqrt{C^m (1 - C^m)}$$

Dividing (1) by (2) gives,

$$\text{The uniformity index (I)} = \sqrt{\frac{\Sigma_0^n (C - C^m)^2}{n (1 - C^m) C^m}}$$

The uniformity index (I), then, is a definite measure of the degree of mixing uniformity; the lower the value of I, the higher the degree of mixing, i.e., the more uniform is the mixture.

Equipment

Mixing Apparatus. All mixing was performed in the "plastograph" pugmill-type mixer shown in Figures 1 and 2. The pugmill consists of two counter-rotating shafts 1.59 cm. in diameter one rotating at 1.5 times the speed of the other; each shaft has 10 perpendicular prongs with each prong 2.22 cm. long and 0.635 cm. in diameter. The inside dimensions of the mixing box are 7.2 cm. by 10 cm. by 10 cm. The torque required for mixing is recorded automatically.

Strength-Test Apparatus. The equipment for determining the strength of soil-cement samples consists of a Harvard miniature compaction apparatus (7) for compacting and molding the sample, and a motor driven, worm screw, strain controlled unconfined-compression apparatus (5) for testing the strength of the sample, in which the load is measured with a proving ring and the deflection of the sample with a strain gage.

Scintillation Counter (3). The apparatus used to determine presence of radioactive material is the electronically operated scintillation counter. It consists of a crystal of sodium iodide for interaction with the gamma rays emitted by the sample, a photoelectric surface for catching the light flashes caused by the gamma rays striking the crystal, a photomultiplier tube for catching the shower of electrons caused by the light flashes on the photoelectric surface, an amplifier to amplify the pulse from the photomultiplier tube, and a scaling circuit (pulse counter) to count the pulses.

LABORATORY PROCEDURE

General

1. Twenty-two grams of radioactive cement was weighed into each of forty-eight 2-ounce jars (enough jars for test series at two water contents). From each jar, one gram was removed and put in 1-dram vials. Each jar then contained the amount of cement that was used in each test. The 1-gram samples of cement, taken from each jar, served as standards for later determination of cement variation throughout the soil-cement mixture. These samples served the further purpose of checking the radioactive cement for uniformity of activity.

2. For each test, 210 grams of soil was weighed into a large dish. The required water was added to the soil and mixed by hand with a standard kitchen tablespoon to insure uniform water distribution throughout the soil. Only two water contents (based on the dry weight of soil and cement) were studied; 14 percent, which is slightly above the optimum water content for compaction, and 11 percent, which is slightly below the optimum.

3. The moist soil was put in the mixing box of the "plastograph" and mixed for 30 seconds to insure randomness of the location of the soil in the box. Cement was placed in the center of the box between the two counter-rotating shafts. The mixer was started and run for a specified length of time determined by a stopwatch. The mixing times studied varied from 2 seconds to 2 minutes.

4. The work required for mixing was recorded automatically on a graph and the accumulative energy per gram of soil mixed was computed by graphical integration.

5. Eleven small samples were taken from various sections of the mixer and compacted with a small rod in 1-dram vials. The dry weights of the samples were 1.8 grams $\pm$ 0.1 gram and the compacted heights were 0.9 cm. $\pm$ 0.1 cm. The samples were kept within these limits to insure statistical accuracy and similar geometry for later counting in the scintillation counter.

6. A strength sample was compacted in the Harvard minature mold from the soil-cement remaining in the mixing box. A constant compactive effort was employed by compacting in three layers, 25 tamps per layer, with 40 lb. of spring tension per tamp.

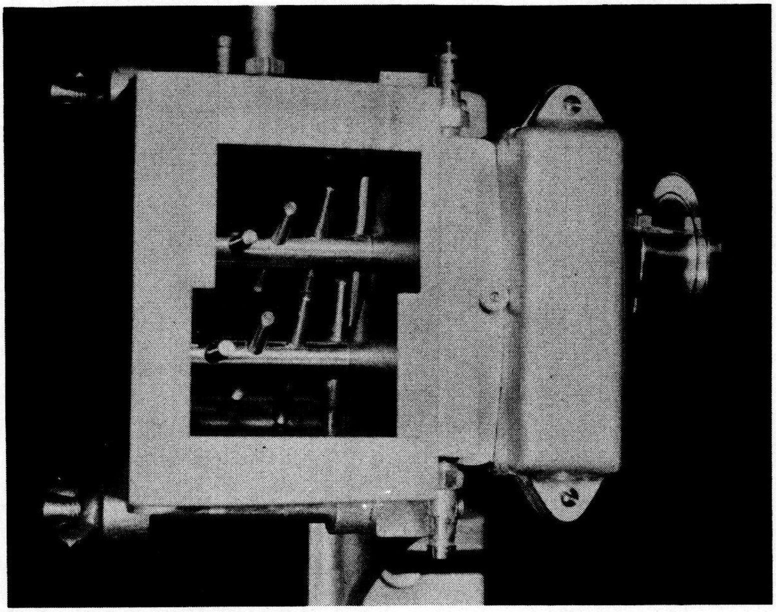

Figure 1. Detail of finger-prong mixer. Note staggered positions of prongs on each shaft.

7. The strength sample was cured for 7 days at greater than 90 percent relative humidity and then tested in unconfined compression.

8. The 11 small samples taken from the mix and placed in vials were weighed and counted in the scintillation counter. The weighing was done as soon after each test as possible to insure no water loss. The counting was done when convenient.

9. Cement concentration of each sample was computed by comparing the counts per second with that of the standard 1-gram cement sample. A measure of the variation of cement concentration through the soil-cement mixture was computed using the uniformity index. Ten percent was taken as the mean concentration from which the variation was measured. This was felt to be more realistic than using the mean of only 11 samples. In most cases the mean of the 11 samples was 10 ± 0.3 percent. The exceptions were for the very poorly mixed (short mixing time) tests.

Exceptions

In order to have some tests in which a homogeneous mix was approached, several samples were made at each water content in which the cement was added to the dry

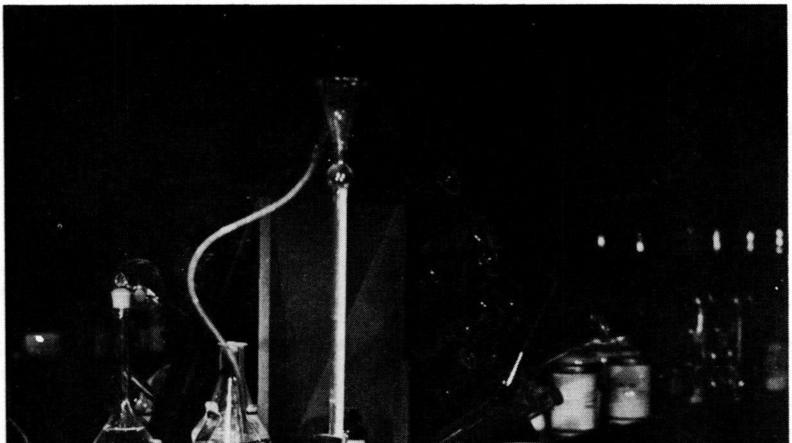

Figure 2. Mixing apparatus, the Brabender "plastograph."

TABLE 2

DATA SUMMARY
Water content w = 14 percent

Test	I	Mean Conc.*	Mixing Time	Accumulative Mixing Energy	Compressive Strength	Dry Density
		%	sec.	meter grams per gram	psi.	pcf.
1	18.5	10.26	2	0.5	75	120
2	12.8	8.58	2	0.5	84	120
3	10.7	10.10	2	0.5	128	121
4	13.8	7.43	2	0.5	80	120
5	6.1	10.31	5	1.1	99	120
6	9.8	8.85	5	1.0	96.5	120
7	6.3	9.90	7.5	1.7	95	121
8	10.1	9.68	7.5	1.8	101	120
9	11.8	10.69	7.5	2.7	-	
10	13.1	9.55	7.5	2.5	88.5	120
11	8.9	8.78	7.5	2.0	109	120
12	3.0	10.06	15	3.3	131	121
13	7.3	10.39	15	3.3	120	122
14	7.5	8.95	15	4.8	88	121
15	2.7	9.85	30	7.9	139	121
16	3.7	9.25	30	7.9	140	121
17	2.5	10.03	30	8.1	136	121
18	3.2	9.96	30	8.1	125	121
19	1.7	9.63	120	30.3	205	121
20	3.4	9.67	120	36.6	145	121
21	2.1	10.10	120	38.0	173	121
22	2.6	9.91	120	31.4	152	121
23	.34	10.04	hand mix	-	254	120
24	.16	9.82	hand mix	-	303	120
25	.60	9.94	hand mix	-	229	120
26	.46	10.06	hand mix	-	243	120
			Water Content w = 11 percent			
1	6.1	9.91	5	.95	157	121
2	8.6	0.01	5	1.0	160	121
3	4.3	10.10	15	3.3	232	122
4	2.6	9.63	15	3.6	231	122
5	2.8	10.25	30	8.1	224	122
6	4.4	9.35	30	6.8	186	120
7	3.4	10.31	120	38.0	237	121
8	3.6	9.87	120	31.6	246	122
9	0.37	9.85	hand mix	-	357	120
10	0.37	9.90	hand mix	-	368	120

* Average of samples taken out of mix.
** Measured to nearest pound per cubic foot.

soil and mixed by hand. Water was added to the soil and cement and again mixed by hand. No attempt was made to obtain a value for the work required for mixing. Because of the high homogeneity of these samples, a correction was applied to the computed mixing uniformity index. The correction consisted of subtracting from the computed I the value that would be obtained (due to the counting error) from a completely homogeneous mixture. With the scintillation counter, radioactivity of cement, and time of counting that were used, this I amounts to 0.0044; i.e., if the same sample were counted many times, the I obtained would equal 0.0044. tations, they were omitted. The above number of tests is sufficient to establish trends and to draw tentative conclusions. While many of the results found here will not apply quantitatively for other soils, the trends should be applicable. However,

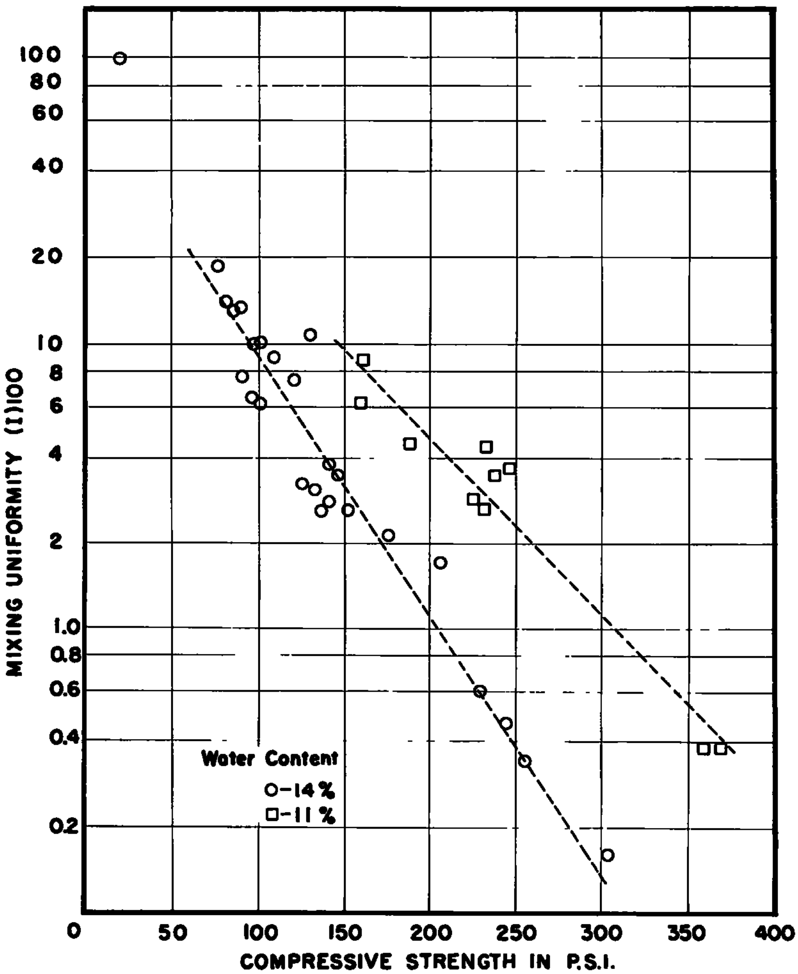

Figure 3. Unconfined compressive strength of soil-cement mixture versus the log of the mixing-uniformity index (I) of the mixture.

RESULTS

A total of 80 tests were run. Of these, the first 44 were principally concerned with evolving a satisfactory procedure, and in checking the reliability of the radioactive tracer method for determining cement concentration. Of the remaining 36 tests, 26 were run at 14-percent water content and 10 at 11-percent water content. More tests were planned at the second water content, but due to time limitations, the number of tests at 11-percent water content is admittedly small and any conclusions drawn from them will need considerable additional verification. Results of all tests are shown in Table 2 and Figures 3 through 8.

With the degree of mixing measured by the mixing uniformity index, in which zero mixing is unity and a completely homogeneous mixture is zero, the following trends are observed:

1. The strength of soil-cement varies

as the log of the mixing uniformity. An increase in uniformity of the mix (measured by a decrease in I) results in an increase in strength. This effect becomes more pronounced as a homogeneous mixture is approached (see Figures 3 and 4).

2. The rate at which the strength of the soil-cement increases with increase in uniformity of the mixture (decrease in I), is greater for the soil mixed at slightly below the optimum water content, than for the soil mixed at slightly above optimum. In addition, the strength at any given I is higher for the samples mixed and compacted on the dry side of optimum than on the wet side (see Figures 3 and 4).

point is quickly reached beyond which I does not decrease with mixing time (see Figures 7 and 8).

4. Accumulative mixing energy is approximately proportional to mixing time; i.e., the torque required for mixing does not change significantly with time, after the first few seconds of mixing. Plots of strength versus mixing time are similar to those of strength versus accumulative mixing energy (see Figures 5 and 6).

5. The strength of soil-cement varies as the log of the accumulative mixing energy required and as the log of the mixing time (see Figures 5 and 6).

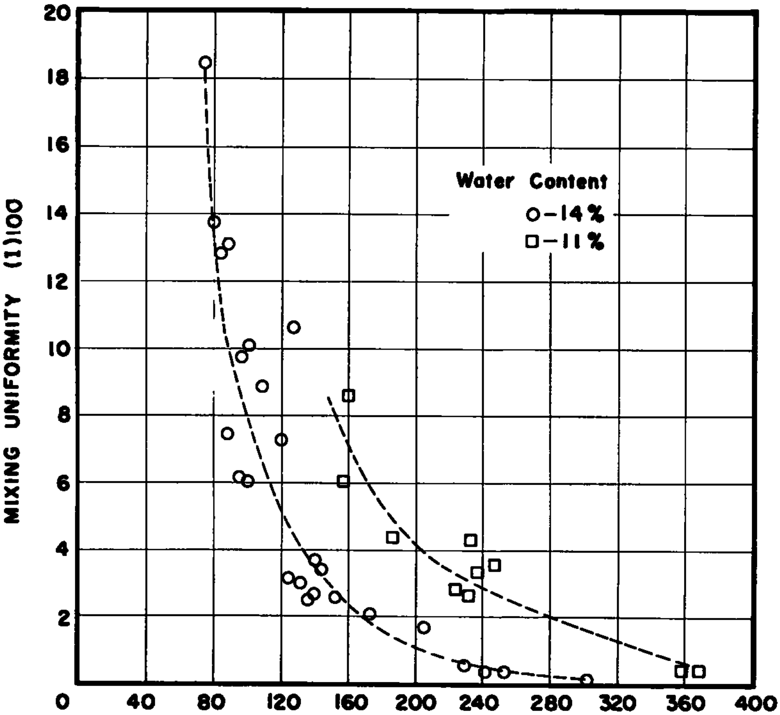

Figure 4. Unconfined compressive strength versus the mixing-uniformity index.

3. Mixing Uniformity (I) varies as some exponential function of mixing time; i.e. a plot of log I versus log mixing time approximates a straight line which can be expressed by the equation $I = kt^n$ where n is a negative number. This relationship holds, within the limits tested, for mixing at 14-percent water content. The data, while inconclusive, indicate that this relationship holds only for a relatively short time when mixing at 11-percent water content. Apparently the

This relationship appears to hold within the limits tested for the 14-percent water content but not for the 11-percent water content. As previously indicated, Figure 7 shows that when the cement and soil are mixed at 11-percent water content maximum uniformity occurs very rapidly, after which there is no decrease in I with mixing time. Since strength is dependent on I, curves such as those drawn in Figures 5 and 6, for 11-percent water content, appear logical.

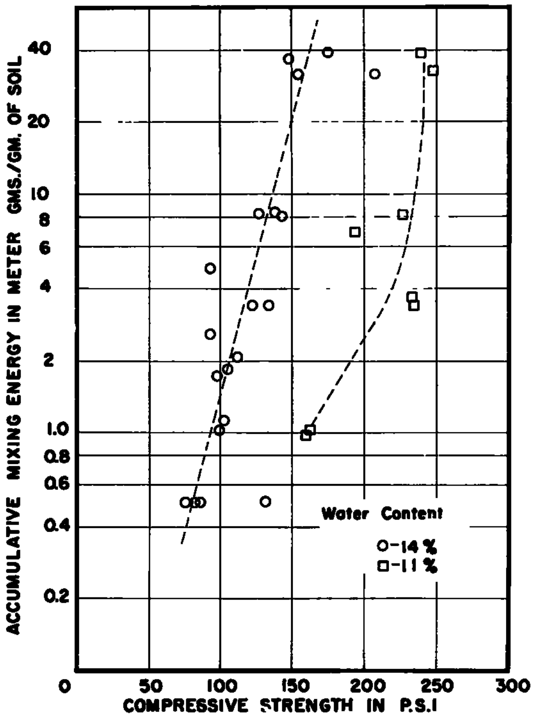

Figure 5. Unconfined compressive strength versus the accumulative energy required for mixing the cement with the soil.

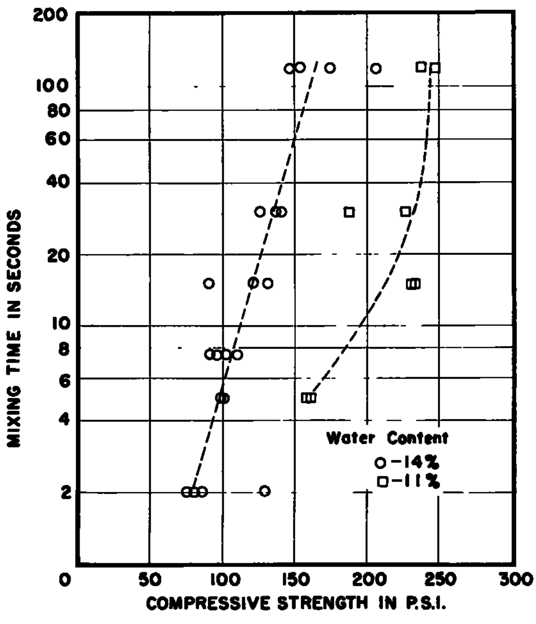

Figure 6. Unconfined compressive strength versus mixing time.

In addition, the one point that is considerably off the 11-percent water-content curves represents a sample whose density was about 2 pcf. less than most of the other samples. Since a small increase in density can result in a large increase in strength, the point would be much closer to the curves if a correction were made to account for the difference in density.

6. At any given mixing time or any given accumulative mixing energy, the strength of the soil-cement mixed and compacted slightly dry of optimum is greater than when mixed and compacted slightly wet of optimum. There is also some indication that the rate, at which strength increases with mixing time and with increasing accumulative mixing energy, is greater for the dry side than for the wet side (see Figures 5 and 6).

PRACTICAL SIGNIFICANCE OF RESULTS

Strength as a Function of Degree of Mixing and Mixing Time

One of the prime objectives of this investigation was to determine the relationship between the strength of soil-cement mix and the uniformity of the cement and soil mixture. The results, as previously stated, show that this relationship is not linear but logarithmic.

Since for a moderately well-mixed sample a small increase in the uniformity of the mixture results in a large increase in the strength, it is advantageous to obtain a uniform soil-cement mixture. Unfortunately, in order to get a small increase in uniformity, a large amount of energy is necessary, or, comparing strength and energy directly, Figure 5 shows that the increase in energy required is larger than the increase in strength obtained. The question of how long to mix with a given mixer is a matter of economics. Does the money saved from the reduced amount of cement required, due to improved mixing, more than offset the cost of the additional time and work needed to get the improved mixing?

There is obviously an optimum amount of field mixing for a specific mixer under a given set of mixing conditions. At present the optimum amount in number of passes or in forward speed of the mixing equipment cannot be predicted. This fact only serves to emphasize the need for a better understanding of the principles involved in mixing soil and cement.

The Effect of Water Content

The water content at which the soil and cement are mixed greatly affects the results obtained. (Before examining these effects a short digression on water contents may avoid later confusion. All water contents are based on the dry weight of the soil plus cement. Thus, the 11-percent water content, which is somewhat dry of the optimum for compaction (12. 5) of the soil and cement, is very near the optimum for compaction of the soil alone. In addition, the term "optimum water content," as used in this paper, always refers to the water content for maximum compaction of the soil and cement mixture.) A study of Figures 3 through 7 shows that greater efficiency is obtained by mixing slightly dry of optimum rather than slightly wet of optimum. For example:

1. Maximum mixing uniformity is approached more rapidly when mixed slightly dry of optimum than when mixed slightly wet of optimum.
2. The energy required for a given mixing time is about the same in both cases, but the energy required to approach ultimate mixing uniformity with the mixer is less when mixed on the dry side than when mixed on the wet side. In all likelihood the more-granular nature of the mixture on the dry side of optimum enables the maximum mixing uniformity to be approached more rapidly than on the wet side, where the additional water adds to the stickiness of the mix and slows down the attainment of maximum mixing uniformity.
3. The ultimate uniformity of mix is higher (lower I) when mixed on the wet side but not enough to compensate for the greater amount of time and energy required to obtain it.
4. The strength of the soil cement mixed and compacted on the dry side of optimum is higher than for the wet side. In addition, the rate at which the strength increases as the uniformity of the mix increases, is greater for the dry side mixtures. This observation is somewhat contrary to the recommendations of the Portland Cement Association (1) which specify that the soil-cement mixture should be compacted at optimum or slightly wet of optimum. Their reason for so specifying results from many years of field observations. They note that if the soil and cement are compacted dry of optimum, satisfactory curing of the surface of the soil-cement mixture is difficult to obtain. The results clearly show the great effect a small amount of water can make, as the difference in water contents between the two series of tests was only 3 percent. While the importance of close field control of mixing and compaction is recognized today, it should be reemphasized.

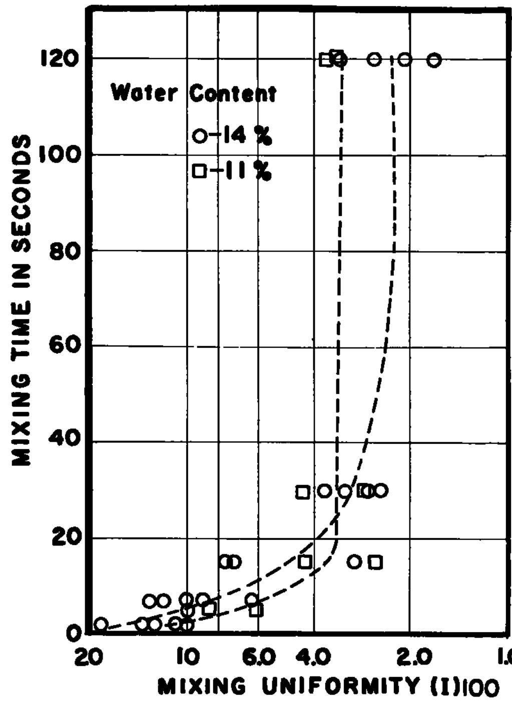

Figure 7. The log of mixing uniformity versus mixing time.

Differences Between Field Strengths and Maximum Possible Strengths

The British in their investigation of mixing have found that, with many soils, field strengths fail to match laboratory strengths (1a, 2), where laboratory strengths are represented by the strengths of samples taken from the field and given additional mixing in a laboratory mixer before compaction. This is all the more significant when one considers that the strengths of samples mixed by hand are appreciably stronger than those mixed in a laboratory mixer (see Table 2 and Figure 3). Thus, field strengths may be only a small fraction of the ultimate that theoretically can be developed.

The reason for this difference in strengths is partially due to the lower degree of field control over the variables involved (water content, cement concentration, etc.) in comparison to the control over the variables when mixing in the laboratory. Usually, however, a more-important reason is the lower degree of mixing that is obtained in the field. As no method has been developed for determining field degree of mixing, most engineers, on soil-cement construction today, are quite satisfied that they are getting good mixing as long as the soil is readily pulverized and the soil and cement are visually mixed well. The term "good mixing," however, is strictly relative.

By the standards of 20 years ago, the term "good mixing" can justifiably be used to describe the quality of field mixing today, but on consideration of the improvement in mixing that is still available, there is less justification for the use of the term. Table 2 and Figure 3 show that the minimum I attained with the laboratory pugmill mixer (which must be considered as efficient or more efficient than any field mixer today) is about 0.025. The strength at this I, for example, is half of that at I = 0.001 so from a strength viewpoint, the importance of degree of mixing, and the room for improvement in the quality of mixing, are apparent.

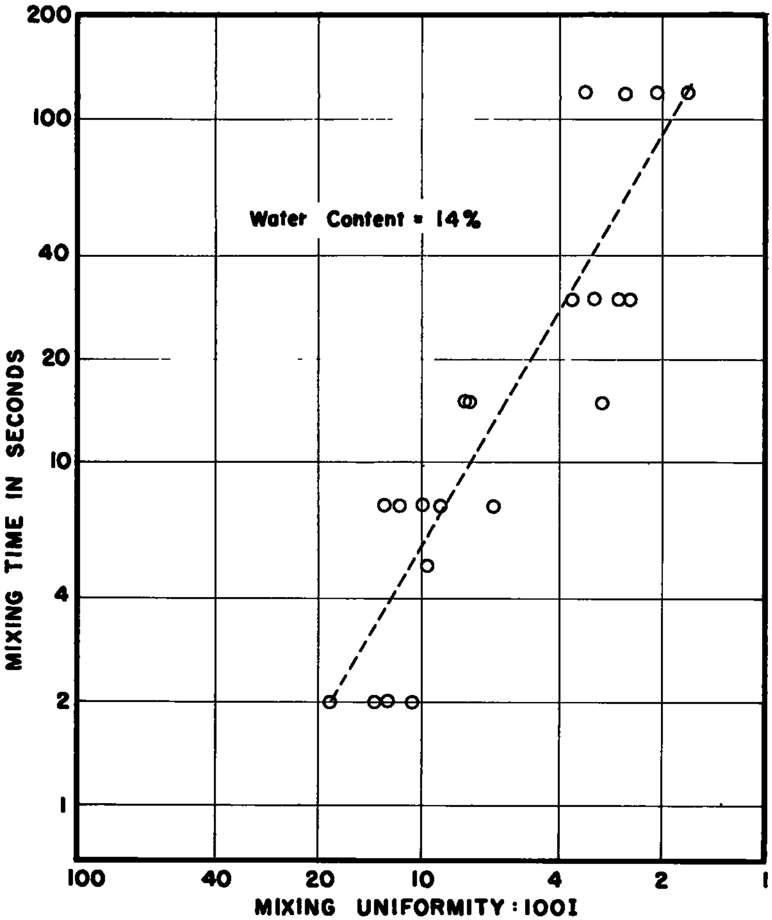

Figure 8. The log of mixing uniformity versus log of mixing time.

Comparison of Results with Those of Other Experimentors

While comparatively little work has been done on the principles of mixing additives with soil, Michaels and Puzinauskas (6) have investigated the variables involved in mixing dextrose, kaolinite and water. Although such a system is quite different from a system of cement, silty soil, and water, there is significant similarity in some of the results.

For example, they observe that:

1. Except for the very short and very long mixing times, log I versus log mixing time plots as a straight line which can be expressed by $I = kt^n$ where t = mixing time and n is a negative number.
2. Mixing uniformity is approached more rapidly on the dry side of the plastic limit than on the wet side. Considering the plastic limit similar to optimum water content, the results are in qualitative agreement.

The work of the British has already been mentioned. Their work indicates, in agreement with this study, that there is still considerable room for improvement in the degree of mixing that is obtained in the field.

Accuracy of Data and Sources of Error

To get statistical accuracy in a soil-cement study, many hundreds of tests are necessary, due to the large scatter of results obtained in various aspects of the test procedure. For example: The standard deviation of strengths of 10 soil-cement samples mixed by hand, prepared, cured and tested in the same way was 8 percent. Thus, the strength points on the various graphs are plotted with a probable accuracy of plus or minus 8 percent. In addition, the values obtained for accumulative mixing energy are accurate only to about plus or minus 5 percent. Since a slight change in water content, caused by evaporation or by a mistake in addition, can appreciably affect the energy requirements, the value of 5 percent is probably conservative.

The accuracy of the value obtained for mixing uniformity is greatly dependent on the uniformity of the mixture. Since only 11 samples are used to determine mixing uniformity in each test, the values obtained for the nonuniform mixtures are less accurate than those obtained for the uniform mixtures. However, an accuracy of plus or minus 3 percent may be taken as typical.

With the foregoing in mind, any interpretation of the results from relatively few tests must be made with appropriate reservations.

RECOMMENDATIONS

The results obtained in the investigation prompt the following recommendations:

1. Soils similar in nature to the one used in this study should be mixed slightly on the dry side of optimum to obtain maximum uniformity for the least work. Whether the soil and cement mixture should then be compacted slightly dry of optimum, at optimum, or slightly wet of optimum appears to be dependent on such variables as: (1) amount of water required for complete cement hydration; (2) curing process to be used; (3) time from start of mixing to compaction; (4) strength desired; (5) flexibility desired; and (6) resistance to weathering desired. If a satisfactory curing procedure is available, the strongest soil-cement results from compacting slightly dry of optimum. On the other hand, higher compressibility, greater flexibility and greater resistance to weathering are obtained by compacting slightly wet of optimum. The procedure followed today is to compact at optimum, and perhaps this is the best compromise.
2. On large soil-cement jobs an investigation should be conducted to determine the amount of mixing required to obtain maximum strength and mixing uniformity for the least cost with the existing equipment. This would not slow up the construction process as the soil to be stabilized would be available for investigation enough ahead of time to allow for normal highway-construction procedures to be followed. The investigation would consist of mixing, at various speeds and number of passes, with the mixer, cement with some of the soil in question and making strength samples from the different mixes. The strengths at 24 hours (if time is short) or at some other time, could then be compared and the optimum amount of mixing, in terms of cost and desired strengths, determined. In this way, the actual probable field strength of the soil-cement mix could be predicted ahead of time, and in many cases, savings in cement quantities could then be obtained. Until an on-the-spot method of determining degree of mixing in the field is available, the above investigation would prove helpful on major soil-cement jobs.
3. More effort should be spent on increasing our knowledge of the principles of mixing, and specifically, on the principles involved in mixing additives to soil.
4. The mixing-equipment manufacturers should continue their efforts to develop better and more-efficient mixing equipment.

CONCLUSIONS

The work described in this paper is only part of a continuing investigation on mixing that is being conducted at the M. I. T. Soil Stabilization Laboratory. Results to date indicate: (1) strength of soil-cement varies as the log of mixing uniformity (I); (2) strength varies as the log of mixing time, or as the log of accumulative mixing energy, up to the ultimate mixing uniformity of the mixer; (3) ultimate mixing uniformity and maximum resultant strengths are obtained more rapidly when mixing slightly on the dry side of optimum than on the wet side of optimum; (4) at any given mixing time or at any given I the strength of soil-cement mixed and compacted slightly dry of optimum is greater than when mixed and compacted slightly wet of optimum; and (5) there is appreciable room for improvement in mixing, especially for the clayey soils.

ACKNOWLEDGMENTS

The writer is indebted to his thesis supervisor T. W. Lambe for his encouragement and constructive criticisms and to R. T. Martin, A. S. Michaels, and V. Puzinauskas for their helpful ideas. The writer is grateful to J. Irvine and J. Winchester of the Chemistry Department at the Massachusetts Institute of Technology for their assistance in the development of the radioactive-tracer technique for determining cement concentrations in soil-cement.

The research described in this paper was conducted for a thesis to be submitted in partial fulfillment of the requirements for the S. M. Degree at the Massachusetts Institute of Technology and was sponsored jointly by the Massachusetts Institute of Technology and the Department of Public Works of the Commonwealth of Massachusetts.

References

1. Proceedings of the Conference on Soil Stabilization, M. I. T., 1952. (a) Robinson, P. J. M. "British Studies on the Incorporation of Admixtures with Soil." (b) Rodes, V. H. "Incorporation of Admixture with Soil." (c) Jones, R. P. "Commercial Stabilization Equipment: Development of the P and H Single Pass Processing Method." (d) Hurst, J. "Wetherington-Berner Stabilization Equipment." (e) Seaman, H. J. "Mechanical Stabilization and the Processing of Stabilized Soils: The Seaman Pulvi-Mixer." (f) Wood, C. W. "Soil Stabilization with Wood Roadmixers and Allied Equipment." (g) Heacock, R. C. "Barber-Greene Company's Experience and Observations on Soil Stabilization." (h) Harrington, M. P. "Discussion on Preceding 5 Papers." (i) Catton, M. D. "Soil Cement: A Construction Material."

2. A series of unpublished reports on mixing by the Ministry of Supply, Great Britain, 1950-1952.

3. Friedlander, G., and Kennedy, J. W., Introduction to Radiochemistry, John Wiley and Sons, Inc., New York, 1949.

4. Herdan, G., Small Particle Statistics, Elseivier Publishing Co., New York, 1953.

5. Lambe, T. W., Soil Testing for Engineers, John Wiley and Sons, Inc., New York, 1952.

6. Michaels, A. and Puzinauskas, V., "Evaluating Performance Characteristics of Mechanical Mixing Processes: The Dextrose-Kaolinite-Water System," M. I. T., 1953.

7. Wilson, S. D., "Small Soil Compaction Apparatus Duplicates Field Results Closely," Eng. News-Record, November 2, 1950.

8. "Soil Solidification by Chemical Methods;" Final Report, Phase V., M. I. T. for Engineer Research and Development Laboratories; Fort Belvoir, Virginia.

Discussion

JAMES H. REYNOLDS, Jr., ERDL, Roads and Airfields Branch, Fort Belvoir, Virginia—Congratulations are in order for this vigorous attack on a significant problem which only recently has received adequate attention. The ingenious techniques are particularly interesting, and emphasize as no other approach has done the remarkable benefits that could be derived from proper design of equipment and of field processing. Results obtained are conclusive in their trends and startling in some of their implications.

Although the increase of strength with decreasing I_V is conclusive as shown in Figure 3, it is felt that other possible contributors to this effect should be discussed. (Here it might be noted that I_V, being analogous to the coefficient of variation, is, in fact, a direct index of non-uniformity.) Data for densities of the strength samples perhaps should be included if only for the peace of mind of the reviewer, since great strength increases are possible with relatively little density increase. Again, it might have been noted that there is a well defined (although small) increase of mean cement content with mixing time, strength, and (inversely) with the I_V. It is perhaps unrealistic to assign the very large strength increase to the small increase in cement content, but the undeniable relationship should be examined. It is of interest that Cornell, under contract to ERDL, has developed relationships for tensile strength on CL and CH soils which apparently verify Baker's conclusions.

As dramatic as Figure 3 is (strength versus I_V), enthusiasm must unfortunately be tempered by the practical consideration of Figure 5 which shows that to double the strength, the accumulative energy must increase over 200 fold—a consideration which offers considerable challenge to equipment manufacturers and field engineers who expect to extrapolate or exploit these or similar studies in their designs. (A plot of accumulative energy versus I_V should perhaps be included in the paper to underline this point.) It might be noted that J. C. Smith of Cornell, under contract to ERDL, has adapted the Michaels-Puzinauskas technique to the evaluation of full scale commercial mixers with some encouraging results. For the first time, it is felt, the way has been opened to definitive comparisons of mixing equipment.

Some expanded discussion of the Cobalt 60 technique might be in order; particularly desirable would be the relationship between radioactivity of the mix versus cement content. This approach may receive wide application in laboratory studies and deserves separate treatment, particularly in view of the clumsy (although accurate) ASTM titration procedure. In this connection it may be pointed out that ERDL has analyzed a large number of field samples of soil-cement by means of an automatic titrator. Control samples show that with this expedient method an accuracy of 0.1 percent in cement content may be expected on a sample with 14 percent cement.

It might be noted that "tighter" strength results may perhaps have been possible had strengths been taken after 14 or even 28 days curing since with NPC the strength-time slope is quite steep at 7 days.

A plot of the mean coefficient of variation of cement content (taken from Baker's data) and of the I_V versus time shows that no more accuracy is to be expected of the C. V., although the slightly flatter slope of the C. V.—time relationship (on a log-log plot) illustrates lower sensitivity of the C. V. to the time factor, and thus may allow easier analysis. Other than its convenience in plotting, little immediate advantage can be seen in the use of I_V, since it is, essentially, the standard deviation divided by a constant.

Again, to present some academic opposition to an academic concept, even the most "perfectly mixed" soil will, when sample size equals particle size ($<1\mu$) be poorly mixed.

One possible explanation for the wet-versus-dry side of optimum discrepancy (MIT versus PCA) may be, that in the field, the soil water is already present and thoroughly diffused and absorbed in the soil system, thus not being as readily available for the hydration of the additive. In Baker's experiments the water was added to air-dried soil and not being thoroughly diffused (despite the hand mixing) may be easily available to the cement. It should further be noted that Baker's conclusions are derived from initial strength, whereas the case for "optimum plus" mixing is largely based on the durability of cement under weathering conditions.

The next step is obviously to extend these and similar analyses to evaluation of other types of laboratory equipment, full-scale equipment, and to surfacing design principles, and then to saturate equipment manufacturers and design engineers with their significance.

P. J. M. ROBINSON and J. F. CAPPS—Baker's paper is a valuable contribution to the work initiated at M. I. T. on the problem of mixing, and in its grasp of the significance of the factors affecting the problem and the practical value of the applications suggested for its conclusions is worthy of study both from the academic and the engineering point of view.

As far as the contents of the paper itself are concerned, perhaps the salient point which occurs is that pointed out by the

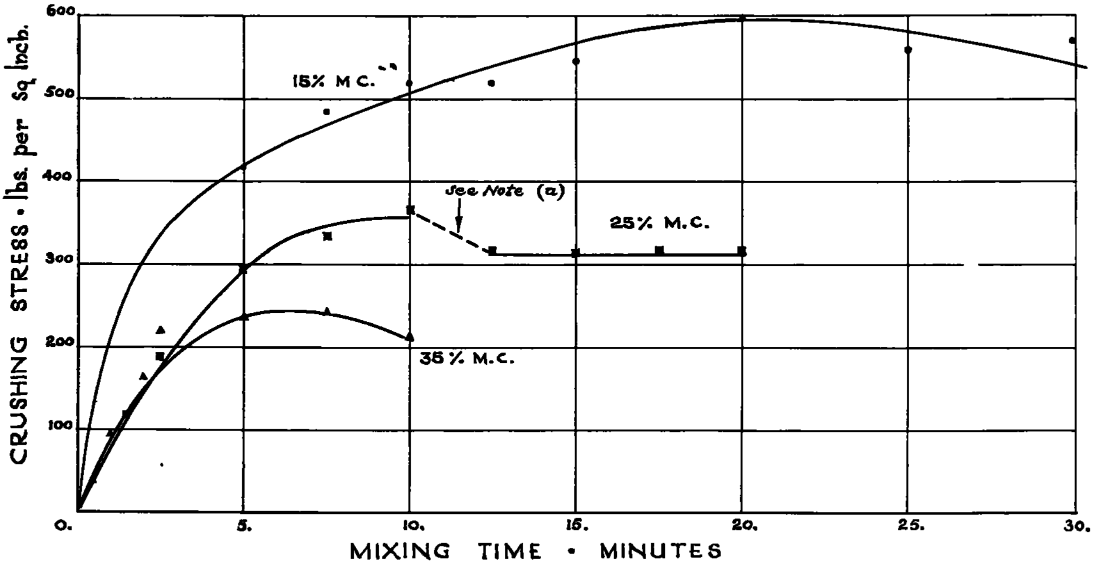

Figure A. Relationship between mixing time and compressive strength for Ferndown clay + 20 percent of 417 cement in Winkworth mixer.

author—the large variation in strength of soil-cement specimens. It appears that the author makes the assumption that as the standard deviation of 10 specimens is 8 percent of the mean, then each of his results, the compressive strength of one specimen, can be out by plus or minus 8 percent. In fact, if 10 results do have a standard deviation of 8 as Grubb (Reference A) has shown, the range over which the individual results can be assumed to lie is $\frac{8}{0.3249}$ percent or $\pm$ 12 percent.

This is based on samples mixed by hand. Machine mixing is anyway not as good from the point of view of consistency. In an experiment at M. E. X. E. 10 specimens of identical mixes, two sets mixed in different machines, the third set mixed by hand, gave coefficients of variation of 14. 5, 20. 1 and 10. 7 percent. While the value of 10. 7 percent agrees well with Baker's result on hand mixing, it does show that the strength errors from machine mixes are likely to be considerably higher than he estimates. The fact that in the early stages of machine mixing the consistency will be even less than the values quoted and one specimen will, therefore, have a greater possibility of not having a truly representative strength makes the likely error still greater. The point of this argument is that for indicating anything other than general trends in a series of results, one specimen is not sufficient, as Baker has pointed out, and British practice is to base results on ten specimens wherever possible. As Baker has further pointed out, this increases the magnitude of the work and makes the evaluation of a series of tests very laborious. Nevertheless, it is quite clear from his results that this large number of specimens is the only basis for accurate work. Incidentally the author uses on pages 9 and 19 the expression Standard Deviation, for a percentage. British practice is to use the term Coefficient of Variation for this figure.

A further point is the consideration of the performance of the cement itself. For example, in the above specimens where identical mixes were used, the cement being 417 a proprietary brand containing calcium chloride. While the coefficients of variation were as quoted, giving an indication that the hand mixing gave a marked improvement on the dispersion of the cement through the soil, yet the strengths achieved in the order quoted were 652, 594 and 484 lb. per square inch respectively. This may indicate that there is an optimum degree of mixing for the attaining of a high strength and that further dispersion of the cement may produce a lower strength. This is illustrated graphically in Figure A, which shows some results obtained in an experiment at M. E. X. E. It is notable that after reaching a peak there is a fall in crushing strength. This would lead to the conclusion that the two minutes in the machine in Baker's work is not the time required by that particular mixer to reach this optimum value. This is borne out by the curve in Figure B for a double paddle mixer with sand, where six minutes mixing has not achieved this point. The finger prong mixer used by Baker would not be regarded as likely to equal a double paddle mixer in performance, so that the optimum value would be reached even later.

(It is not clear whether this drop in strength is a disadvantage from the point of view of practical considerations of a constructional material, and investigations as to performance under freezing conditions and so on would be interesting.)

As regards the difference in strength due to the change in moisture content, this might be only due to the increase in the water-cement ratio rather than to any difference in the mixing itself. The similar power absorption figures for the two sets of results shown by Baker do not indicate that the properties of the soil have changed very much as far as the mixer is concerned. Tests at M. E. X. E. on sand, Figure C, over the range of moisture contents used by Baker, for which the power-moisture-content figures are given in Figure D show a difference of about 30 psi. This is a similar figure to Baker's results. Experiments with a clay where the power figures shown in Figure F do vary considerably with moisture content still show, as in Figure E that the increasing moisture content gives about this decrease in strength. From these, it might be inferred that even where moisture content is affecting the degree of mixing, increases give decreasing strength, which is what would be expected from experience in concrete practice.

There is a further factor which will cause a difference in Baker's results which may modify the above, and that is the difference in density which, since he has not

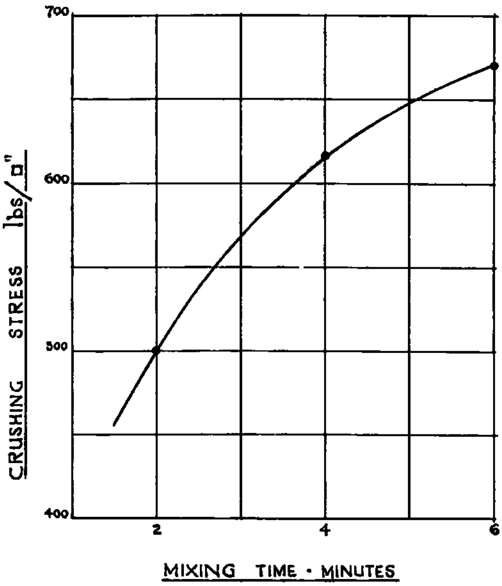

Figure B. Relationship between mixing time and crushing strength for Hurn sand + 14 percent of 417 cement at 13 percent moisture content and 106 pcf. dry density mixed in a double-paddle mixer.

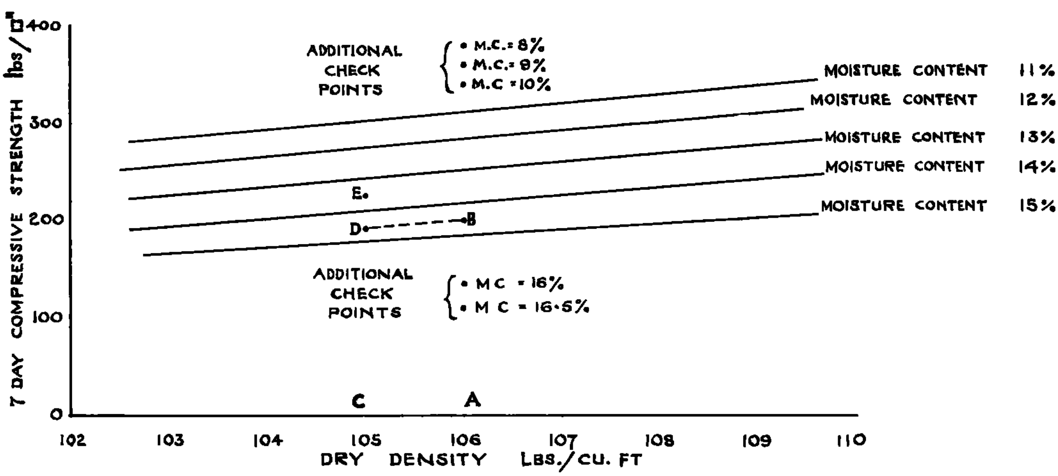

Figure C. Effect of moisture content and dry density on compressive strength of Hurn sand + 8 percent N.P.cement + 2 percent lime.

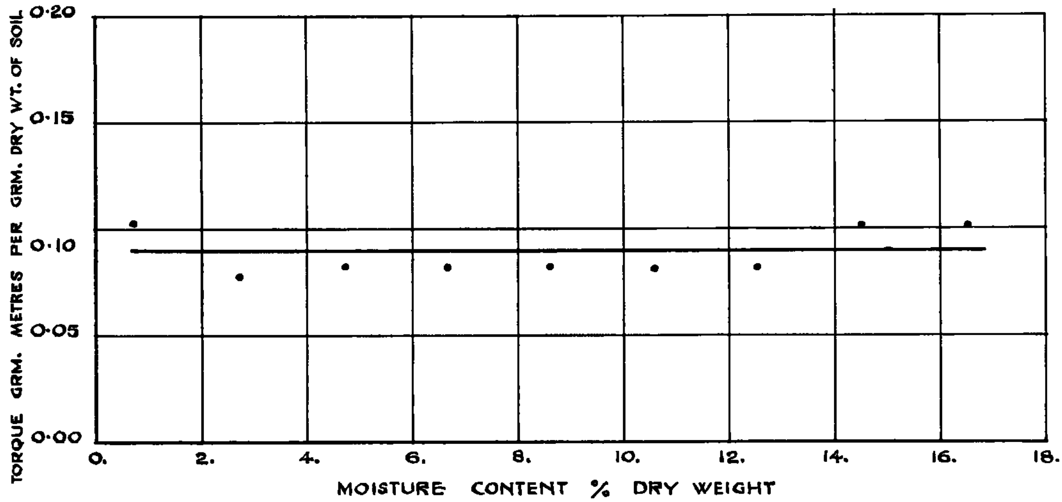

Figure D. Relationhhip between moisture content and mixing power for Hurn sand in Baker-Perkins double Z-paddle mixer.

given values, it has not been possible to compute.

The question then arises as to how valid are the conclusions which Baker has drawn. Those which are considered to necessitate further discussion are enumerated below.

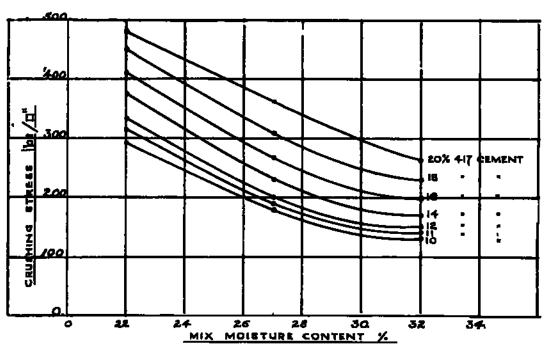

Figure E. Relationship between moisture content and crushing strength for Ferndown clay + 417 cement.

Conclusion 2

Strength varies as the log of mixing time, or as the log of accumulative mixing energy up to the ultimate mixing uniformity of the mixer.

It may be that Baker has not reached the ultimate mixing uniformity of this mixer. While the linear log relationship seems to hold before the highest compressive strength is being approached, as shown in Figure G, it appears that a peak is reached and the relationship changes. That this peak is not due to a loss of strength due to setting phenomena occurring with the quick action '417' cement is shown by the relationship for normal Portland which indicates the same thing at about the same time. This diagram confirms rather clearly that Baker's mixer is less efficient than the double paddle type, and it even seems as though the subsequent handling and forming of the specimen in the early stages of mixing may confer a higher strength than the mixing alone.

Conclusion 3

Ultimate mixing uniformity and maximum resultant strengths are obtained more rapidly when mixing slightly on the dry side of optimum than on the wet side of optimum.

It appears that Baker may have been experiencing what appears to be due to moisture along with sandy soils, though it is not clear what effect density may have had.

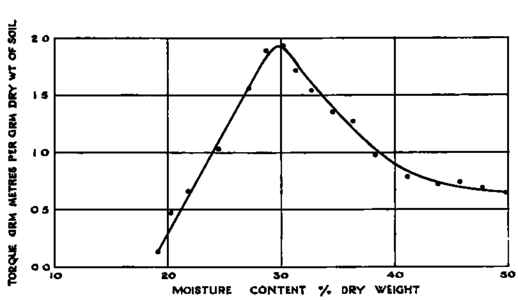

Figure F. Relationship between moisture content and mixing power for Ferndown clay in Baker-Perkins double Z-paddle mixer.

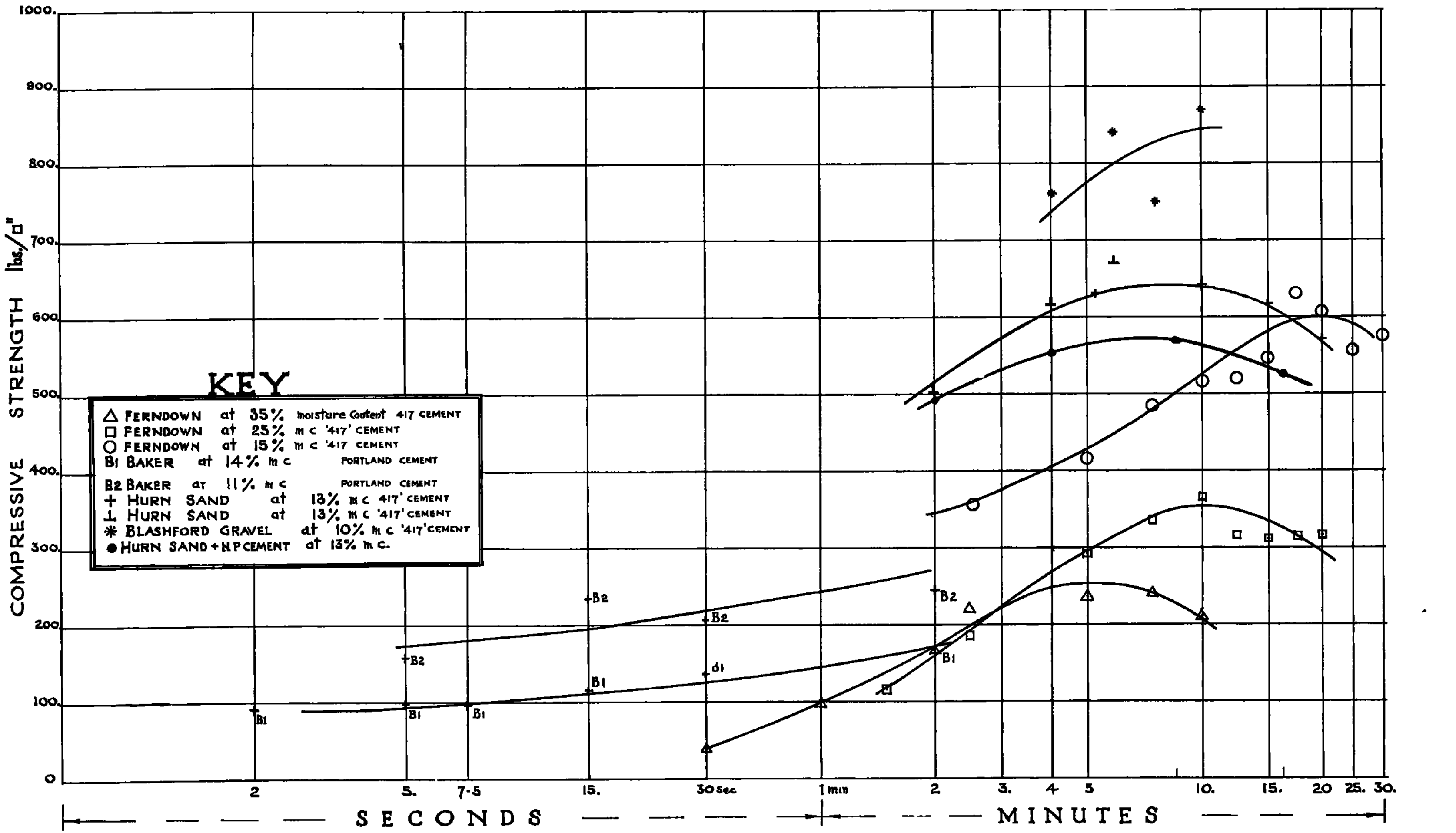

Figure G. Relationship between mixing time (logarithim scale) and compressive strength of various soil-cement mixes.

Certainly his conclusion does hold good for the clay soils but only as far as the magnitude of strength is concerned. Although the values of the maximum strengths are higher in the dry state, the wet soils achieve their maximum more quickly.

Finally some comment is necessary on the method of measuring the degree of mixing. Work is proceeding in Britain on methods based on the chemical determination of the cement content. So far, this has not proved a satisfactory system but nothing exhaustive has yet been planned with it. Baker's method certainly seems to offer a most satisfactory solution from the point of view of the ease with which it can be carried out. Certainly it is clear that compressive strength may be most misloading if used as a measure of the mix achieved. If this work continues, some consideration should shortly be given by those concerned with this problem in Britain and America to standardising both the methods used in carrying out this work and the presentation of the results obtained from it.

NOTE (a) In Figure A it will be noticed that there is a discontinuity in the graph of results for 25 percent moisture content. This is reproduced from the original where it was thought that this might be because the tests with 12½ - 20 minutes mixing time at this moisture content were carried out some time after the other tests were completed, and a different batch of cement was used for them. In fact, when these results are interpreted as on Figure G they do not seem to represent such a discontinuity.

Reference A.

"The Best Unbiassed Estimate of Population Standard Deviation Based on Group Ranges". Frank E. Grubbs, Chalmers L. Weaver, Ballistic Research Laboratory No. 596, Aberdeen Proving Ground, 1946.

CLYDE N. BAKER, Jr., Closure—The author is grateful for the critical discussion of his paper by Reynolds. His suggestion that density data should be included in the paper is a point well taken. The addition has been made, and it is interesting to note that the densities are approximately the same for the test series at both water contents. The suggestion was offered that the inclusion in the paper of a plot of radioactivity versus cement content would be desirable. This relationship is linear, since the cement used in all the tests contained Cobalt 60 in the form of cobalt oxide such that one gram of cement had an activity of 0.05 micro curies. This activity was chosen as being about the minimum with which satisfactory counting results could be obtained in the scintillation counter.

The author also appreciates the commentary by Robinson and Capps as it significantly adds to the value of the paper. Their comments evidently result from an extensive amount of laboratory research.

It should be pointed out that the data discussed in this paper were only the first part of a series of tests. The complete results and conclusions from these tests can be found in a thesis by the author under the title "Strength of Soil-Cement as a Function of Degree of Mixing," M.I.T., June 1954.

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