THE UNCONFINED COMPRESSIVE STRENGTH OF SOIL-CEMENT MIXTURES

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SYNOPSIS

To a sandy loam, a sandy clay loam, and a clay loam was added 5, 7, 9, and 11 per cent cement by dry weight. The optimum moisture content of each mixture was determined From each mixture cylinders, 4 in high and 2 in diameter, were compacted with moisture contents below, at and above optimum After curing for 28 days in a moist closet these cylinders were loaded to failure in unconfined compression in a constant-strain type of testing machine One additional series of tests was performed on cylinders compacted at optimum moisture from each soil type with 15 per cent cement.

Subsequently, other cylinders prepared from the three soils with 5, 7, 9, and 11 per cents cement at optimum moisture were, at the end of 28 days curing in a moist closet, subjected to cycles of wetting and drying, or to cycles of freezing and thawing At the end of 4, 8, and 12 cycles, respectively, two cylinders from the wet-dry cycle and two cylinders from the freeze-thaw cycle were loaded to failure in unconfined compression

From the results of these tests the following conclusions were drawn 1. The initial characteristics of a soil have more effect upon the compressive strength of a given soil-cement mixture than any other factor 2. Increasing the percentage of cement in a given soil from 5 to 11 produces a greater increase in compressive strength than do the factors of varying density and varying moisture content 3 The densest mixture of soil and cement will generally develop the highest compressive strength for a given soil and percentage of cement. 4 Because of the wide difference in the amount of water which is necessary to bring about maximum density, the water-cement ratio is not a suitable control for soil-cement mixtures. 5. As the cement content is increased from 5 to 15 per cent, some soils gain in compressive strength at a more rapid rate than the rate of cement increase Within this same range other soils do not gain in strength as rapidly as the cement is increased 6 Cycles of wetting and drying produced an increase in the compressive strength of mixtures of sandy loam and of some clay loam mixtures. 7. Cycles of freezing and thawing generally produced some decrease in the compressive strength of all cylinders, a marked decrease in the compressive strength being noted in those cylinders which contained the lower percentages (5 and 7) of cement

These tests were carried out under the writer's immediate supervision and under the direction of Captain K E Fields, Director, United States Waterways Experiment Station, Vicksburg, Mississippi.

The Office of the Chief of Engineers, United States Army, raised the question last spring as to whether or not compressive strength was a more desirable criterion for gauging soil-cement mixture performance than the standard tests of cycles of wetting and drying and of freezing and thawing. For an answer to this question a series of tests was carried out last summer under my immediate supervision at the United States Waterways Experiment Station in Vicksburg, Mississippi. The results of this investigation are herein reported.

Three types of soil, a sandy loam, a sandy clay loam, and a clay loam, were used in the investigation. These soils fell into the PRA A-1 or A-2 subgrade soil classification. The mechanical analysis of these soils is shown on Figure 1.

The test program was planned to answer the following questions. (1) what is the maximum compressive strength when the percentage of cement by dry weight of soil is 5, 7, 9, 11, (2) what is the effect of the water-cement ratio on the compressive strength of a soil-cement mixture, and (3) what are the effects of wetting and drying, and freezing and thawing on compressive strength?

The standard Proctor mold was not used for compacting the test cylinders in this investigation because it does not have a height-diameter ratio of two Nearly a half century of concrete testing has shown that in the compression test the cylinders must have a height of twice their diameter. These dimensions reduce the binding effect of friction on the ends of the cylinder, and they permit the full development of the shearing planes of rupture within the body of the cylinder, rather than to allow breaks through the ends of the cylinder These rupture planes, in accordance with the maximum shear stress theory of failure, commonly develop at an angle of about 60 deg. with the plane of major principal stress. Hence, a mold having a diameter of 2 in., and a height of 4 in. was chosen (Fig. 2). The compaction hammer was a modification of the type used by the Kansas State Highway Commission[1] The foot was $1\frac{1}{8}$ in. in diameter and a sliding weight of 2 2 lb was raised and dropped 12 in It was found by trial that 20 blows with this hammer in the small mold would give the same density as would 25 blows with the standard hammer in a Proctor mold

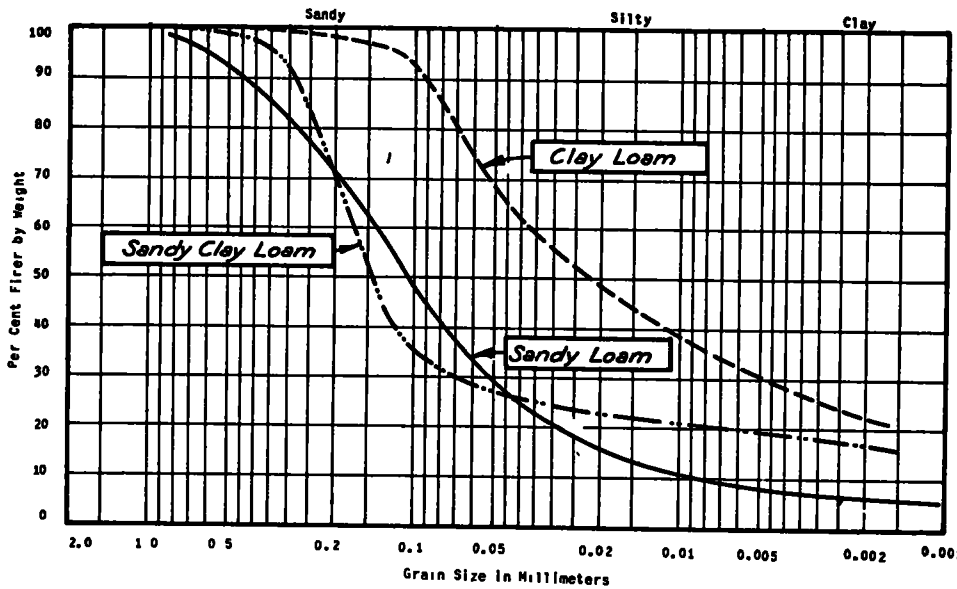

Figure 1. Grain Size Curves

The compression machine for loading the cylinders to failure is shown on Figure 3 A screw jack is driven at a constant rate of speed by a small electric motor. The strain is measured by an extensometer dial held in the upper yoke. The stress is indicated by the deformation of the steel ring which has been previously calibrated. Observations for load and deformation were taken at 30-sec intervals until rupture occurred. The speed of loading was such that failure occurred in approximately 5 to 10 min.

[1] Hamilton, L W, "Compaction of Embankments," *Proceedings*, Highway Research Board, Vol 18, Part II, p. 162 (1938).

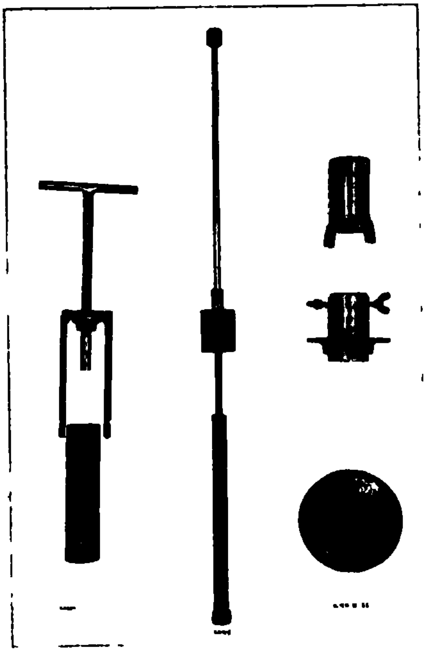

Figure 2

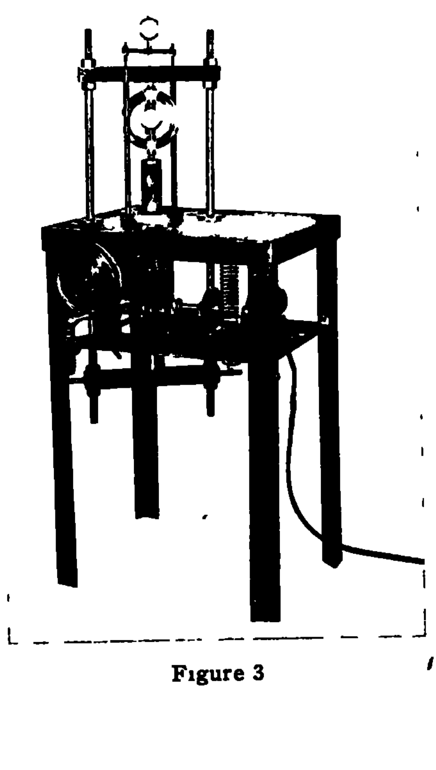

Figure 3

The first part of the investigation was concerned with the maximum compressive strength of each soil type containing various percentages of cement, and the effect of water-cement ratio on these compressive strengths For this purpose the optimum moisture content of the sandy loam was determined for the raw soil, for a mixture with 5 per cent cement, and for a mixture with 11 per cent cement. The results of these determinations are shown on Figure 4 Values of optimum

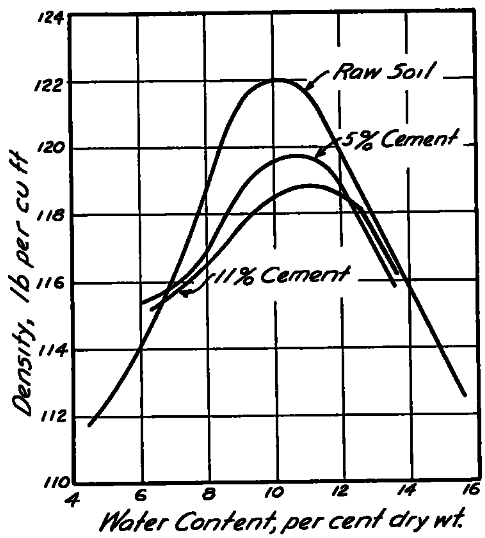

Figure 4. Moisture Density Control for Sandy Loam

moisture for other percentages of cement were interpolated. Similar determinations were made for the sandy clay loam, and for the clay loam Then cylinders of sandy loam, having cement contents of 5, 7, 9, and 11 per cent by dry weight of soil were molded at moisture contents which were above and below this predetermined optimum. After curing for 28 days in a moist closet, these cylinders were tested to failure in unconfined compression The results are shown on Figure 5. It will be noticed that the maximum compressive strength in these tests was developed by those cylinders which had been molded with moisture contents at, or very close to, the optimum Figure 6 shows the cylinders in this test group after being loaded to failure The compressive strength of the raw soil was insignificant. The maximum compressive strength of the cylinders with 11 per cent cement was nearly 900 p s.i.

A similar series of tests was made on cylinders of the sandy clay loam (Fig. 7). With this soil the maximum compressive strength apparently developed when the moisture content was below the optimum

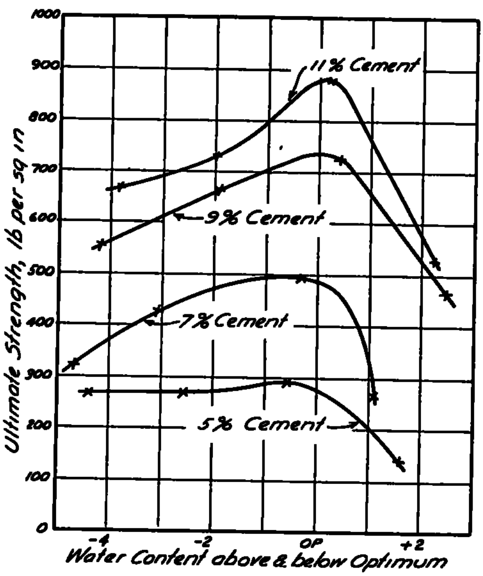

Figure 5. Strength Versus Water Content Sandy Loam

However, for the mixtures with 9 and 11 per cent cement the densest cylinders were made at moisture contents somewhat less than the predetermined optimum. In these instances then, the cylinders of maximum density were still the ones of maximum strength The cylinders molded with 5 and 7 per cent cement at moisture contents approximately two percentile points less than the optimum were stronger and about one pound per cubic foot lighter than those molded at optimum moisture content.

The maximum compressive strength was developed in every mixture of clay loam by the densest cylinder. This result is not apparent on Figure 8, but came from the dry weights of the cylinders. With this clay loam soil it was possible to vary the moisture content a little above or below the optimum without producing as much as a 1-lb difference in the density of the cylinder.

Comparison of the compressive strengths which these cylinders developed with the water-cement ratios by weight shows a scattering of results which follows only a vague pattern (Fig. 9). This indicates that the water cement ratio is not a suitable method of control for soil-cement mixtures. The reason for this is that every soil, and every mixture of soil and cement, requires a different amount of water in order to secure maximum density from the same compaction. And in every case but two the densest cylinders were the strongest ones.

For a comparison of the maximum compressive strengths developed by each soil type, the stress-strain curve of the strongest cylinder of each soil (all contained 11 per cent cement) is shown in Figure 10. This graph shows clearly the much higher strengths of the sandy loam and sandy clay loam soils over the clay loam The conclusion to be drawn therefrom is that the cleaner soil, the one most nearly resembling a concrete aggregate, is the soil which will develop the highest compressive strength when mixed with cement and molded at optimum moisture.

After the foregoing tests were completed it was decided to carry the tests on a little further to determine approximately the relationship between the increase in compressive strength of soil-cement mixtures and increasing percentages of cement. So, cylinders of all soils were molded at the optimum moisture content with 15 per cent cement, cured for 28 days and tested to failure. Using the results on cylinders with 5 per cent


Raw Soil
5 Per Cent Cement
7 Per Cent Cement
9 Per Cent Cement
11 Per Cent Cement
Optimum
+2
-2
-4
SANDY LOAM

Figure 6

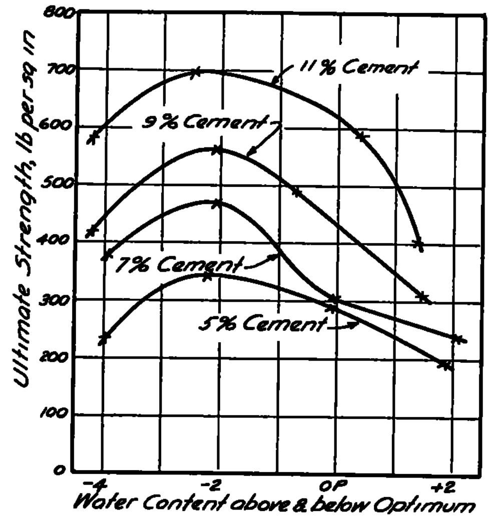

Figure 7. Strength Versus Water Content for Sandy Clay Loam

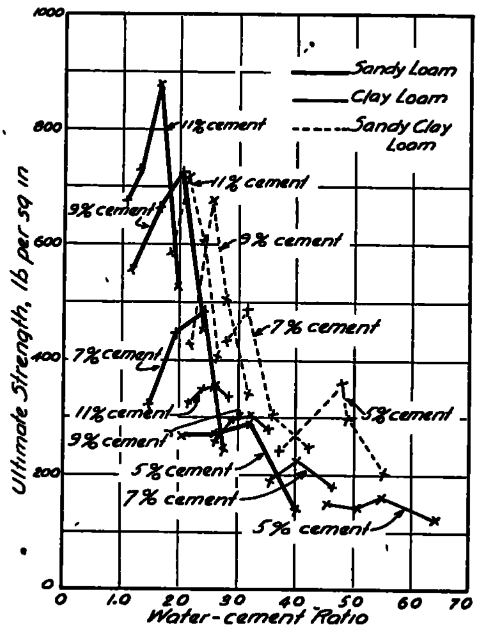

Figure 9. Water-Cement Ratio, Versus Ultimate Strength

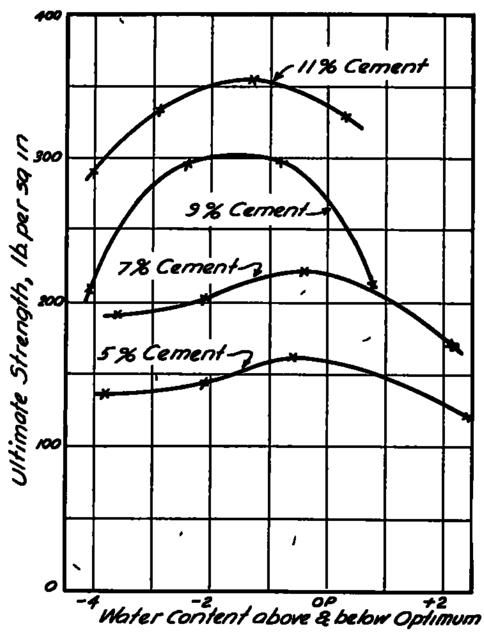

Figure 8. Strength Versus Water Content Clay Loam

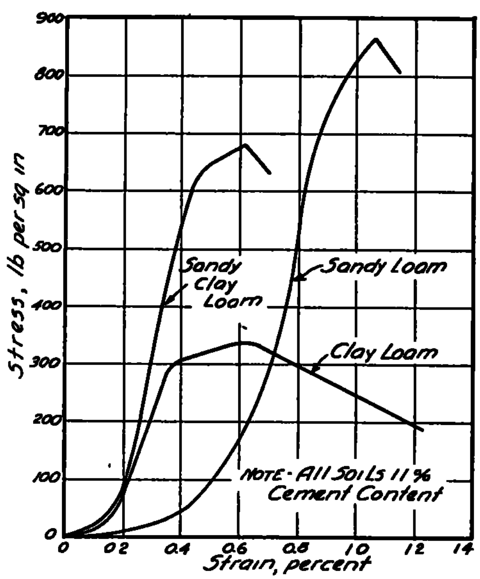

Figure 10. Stress-Strain Curves for Comparison of Maximum Strengths

cement content as a base for comparison (Fig. 11), the rate of increase in the strength of the sandy loam was found to be more rapid than the rate of increase in the cement content. Contrarily, with the sandy clay loam and the clay loam the increase in strength after the cement content reached 10 per cent was very small. This result is a further indication of the inadequacy of cement stabilization for clay soils

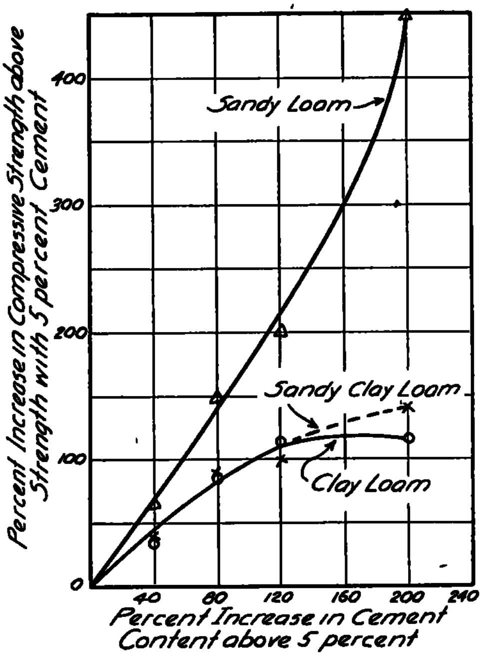

Figure 11. Percent Increase in Strength Versus Percent Increase in Cement

The next phase of the investigation concerned the effect of cycles of wetting and drying, and of freezing and thawing upon the compressive strengths of these soil cement mixtures Cylinders of each soil type with 5, 7, 9, and 11 per cent cement were compacted at the optimum moisture content and cured for 28 days in a moist closet. Then two cylinders from each group were tested to failure. These results agreed closely with the previously determined 28-day compressive strengths At the end of 4, 8, and 12 cycles, respectively, of wetting and drying and of freezing and thawing, two other cylinders from each group were tested to failure. The results of these tests are shown in Table 1

When the sandy loam contained 5 per cent cement, its 28-day compressive strength was 425 p.s.i. With each cycle of freezing and thawing this compressive strength decreased. Surprisingly enough the compressive strength increased with cycles of wetting and drying. Some further tests were made to determine whether or not this increase in strength was due to the additional age which the cylinders had. However, a satisfactory answer to this question was not found.

When the sandy loam contained 7 per cent cement, its 28-day compressive strength was 540 p s i , and 12 cycles of freezing and thawing produced less than 10 per cent reduction in this strength The compressive strength of the cylinders after cycles of wetting and drying was approximately twice the 28-day compressive strength With additional percentages of cement the compressive strengths continue to increase with no change in the trends noted above.

The cylinders of sandy clay loam containing 5 per cent cement also developed a 28-day compressive strength of 425 p s i. With this mixture, though, the cycles of wetting and drying and of freezing and thawing were very detrimental to the compressive strength. This soil mixture could maintain its 28-day compressive strength through cycles of freezing and thawing only when the percentage of cement was 9, and through cycles of wetting and drying only when the percentage of cement was 11.

The clay loam cylinders containing 5 per cent cement developed a 28-day compressive strength of 240 p s i but none of these cylinders was durable enough to stand even four cycles of wetting and drying or of freezing and thawing. Even after the cement content of the clay was raised to 11 per cent, its 28-day compressive strength was scarcely more than 10 per cent higher than the strength with 5 per cent cement, and the cylinders were still not durable enough to withstand 12 cycles of freezing and thawing. However, the wetting and drying cycles did begin to make these clay loam cylinders stronger when the cement content was 9 per cent

Recent studies [2] showing that a concrete highly resistant to freezing and thawing is produced when minute quantities of mineral oils, animal or vegetable fats, or natural resins are added to the cement prompted the Laboratory to consider the possibility of using such cements successfully with soil cement mixtures. These tests have thus far not been made. Further tests, however, were made with cement which had been treated with a dispersing agent, sold under the tradename "TDA." These results were disappointing in that although this dispersing agent has been shown [3] to produce a stronger and more durable concrete, it apparently had no beneficial effects when used with cement for soil stabilization.

CONCLUSIONS

1. The initial characteristics of a soil have more effect upon the compressive strength of a soil-cement mixture than any other factor. The sandy loam with 5 per cent cement had a much higher 28-day compressive strength than the clay loam had with 15 per cent cement

2. Increasing the percentage of cement in a given soil from 5 to 11 produces a greater increase in compressive strength than do changes in other factors, such as, variations in density or limited variations in moisture content.

3. The densest mixture of soil and cement will develop the highest compres-

TABLE 1

EFFECTS OF WETTING AND DRYING, AND FREEZING AND THAWING ON COMPRESSIVE STRENGTH

(Load at failure in pounds per square inch)

Material and mixture		28 days curing	Cured, then wetted and dried			Cured, then frozen and thawed		
			4 cycles	8 cycles	12 cycles	4 cycles	8 cycles	12 cycles
Sandy loam—	5%	424	643	462	809	331	289	223
	7%	541	1100	1050	1069	554	477	490
	9%	804	1446	1438	1975	751	696	581
	11%	970	1644	1870	2020	975	863	866
Sandy clay loam—	5%	426	127	148	153	180	147	143
	7%	596	420	363	334	414	395	351
	9%	567	388	420	538	516	558	510
	11%	657	574	593	717	563	648	669
Clay loam—	5%	242	iii	iv	iii	i	iii	iv
	7%	286	iii	iv	vi	127	162	x
	9%	188	254	306	344	161	151	xii
	11%	272	308	459	xii	207	235	xii

(Roman numerals indicate cycle at which specimens disintegrated)

[2] Swaze, M A, "More Durable Concrete with Treated Cement," *Engineering News-Record*, June 19, 1941, p 74.

[3] Kennedy, H L, "Practical Application of Catalysis and Dispersion to Cement and Concrete," Journal of the Boston Society of Civil Engineers, January 1937, Vol. XXIV, No 1, page 28.

sive strength for a given soil and percentage of cement

4. Because of the wide difference in the amount of water which is necessary to bring about maximum density, the water-cement ratio is not a suitable control for soil-cement mixtures.

5. As the cement content is increased from 5 to 15 per cent, sandy soils gain in compressive strength at a more rapid rate than the rate of cement increase. Within this same range clay soils do not gain in strength as rapidly as the cement is increased.

6. Cycles of wetting and drying produced an increase in the compressive strengths of all sandy loam cylinders, and of some clay loam cylinders.

7. Cycles of freezing and thawing generally produced some decrease in the compressive strength of all cylinders, a marked decrease in strength being noted in those cylinders which contained the lower percentage of cement.

ACKNOWLEDGMENT

Finally, I wish to give full acknowledgment of indebtedness to the Corps of Engineers of the United States Army, who sponsored this investigation and in whose laboratory the tests were performed The request for the investigation originated with Messrs T. A. Middlebrooks and G. E Bertram, principal engineer and engineer respectively in the Office of the Chief of Engineers, Washington, D C. The tests were carried out in the Soils Laboratory of the United States Waterways Experiment Station, Vicksburg, Mississippi, where Captain K E Fields is the director

DISCUSSION ON COMPRESSIVE STRENGTH OF SOIL-CEMENT MIXTURES

Mr. Harold Allen, *Public Roads Administration* The paper demonstrates the possibility of the use of compressive strength tests as a basis for the design of soil-cement mixtures for use in base course construction.

However, the conclusions offered are quite general when consideration is given to the fact that the tests were made on soils having characteristics within a narrow range and obtained from a limited number of sources.

The conclusion that the water-cement ratio is not a suitable control for soil-cement mixtures is too broad. It is entirely possible that the water-cement ratio law may be valid for mixtures having consistencies and curing conditions other than those used by Professor Watson in making his tests. This comment is supported by the fact that the sandy-loam samples subjected to alternate wetting and drying showed marked increases in strength. It is quite likely that the immersion during the wetting portion of the cycle provided the additional water required for the further hydration of the cement and thus produced the increase in strength. If the water necessary to hydrate the cement had been added in making the samples and if curing conditions were provided to insure no loss of moisture, the strengths at 28 days might have followed the water-cement ratio law.

Mr. F. V. Reagel, *Missouri State Highway Department:* In the report no mention is made of any special moisture requirement or control of the specimens at the time of testing in compression. In discussing moisture content, a distinction should be made between moisture at time of compaction and moisture at time of testing. We found that specimens cured in our moist closet (90 per cent humid) for 28 days absorbed additional and different amounts of moisture, depending upon the character of soil materials. Values obtained from strength tests under these conditions impress us as reflecting more the moisture content than the cement content. In order to bring the specimens to a standard condition for testing, we are considering evacuating and immersion

Conclusion Number 5 suggests to us that the slight increase of strength with increase of cement in clay soils as compared to a large increase with sandy soils may be due to the relative avidity for water of the clay and the sand The specimens all being prepared at optimum moisture, the transfer of water from the clay to the cement for hydration, especially in the higher cement content specimens may be retarded beyond the time interval of the test. The relative perviousness of sand and clay might also influence hydration.

A further consideration of moisture at the time of testing leads us to question the validity of comparing strength tests on cycles of wetting and drying with tests after freezing and thawing. This comparison is inferred in conclusions Number 6 and Number 7.

Strength tests have a definite value and appeal The difficulty is finding a common denominator for evaluating such tests. At the same time, any effort in this direction should lead to a better understanding of the role of the cement admixture in soil stabilization.

MR. L. D. HICKS, *North Carolina State Highway and Public Works Commission*: Mr. Watson's paper was to report an investigation conducted for the purpose of determining whether or not compressive strength was a more desirable criterion for gauging soil-cement mixture performance than the standard tests of cycles of wetting and drying and of freezing and thawing. The following comments are not made to cast any reflection upon an excellent paper reporting the results on an interesting investigation, but to throw additional light upon the subject and to offer suggestions that might further prove or disprove the use of the compressive strength as a criterion for indicating performance

It is noted that no correlation is made between the compressive strengths obtained in this investigation and the standard tests for durability by freezing and thawing and wetting and drying, or performance under field conditions. Such a correlation was probably impossible in the short time used in the investigation, however, correlation with performance is essential. M. D Catton's paper "Research on the Physical Relations of Soil and Soil-Cement Mixtures" presented at the 1940 meeting of the Highway Research Board is a valuable contribution in that it attempts a correlation between all known factors and the durability tests. This is an indirect correlation with field performance if it is assumed that the durability tests are correlated with performance. Catton states that "such factors as grain size, gradation, silt and clay content, density, optimum moisture, water holding capacity, surface area, organic content, void-cement ratio, hydrogen ion concentration, compressive strength, etc , contributes to an analysis of soil and soil-cement relations but they are so diverse and interrelated in character and influence that none of them have a constant, major, predominating influence." This statement is supported by data consisting of results of soil and soil-cement tests on 329 soils from 37 states which were performed over a period of five years.

Mr. Watson's conclusions relative to the greater effect of the initial characteristics of a soil upon the compressive strength of a given soil-cement mixture are true with certain soils, but not necessarily true with all He did not give any characteristics of the soils other than the mechanical analyses, so I believe the statement is not supported with sufficient data. There are many factors not revealed by a mechanical analysis of a soil that may have a marked effect upon the compressive strength of a soil-cement mixture. Particle shape, mineralogical composition, and organic matter also, can affect the compressive strengths.

To establish a definite relation between compressive strength and performance of soil-cement mixtures would certainly eliminate much work and expenditure of much time and money in the design of soil-cement mixtures, however, much work and time will be required definitely to prove the relationship. At present it would seem that a definite relationship does not exist with all types of soils. It may be possible that a relationship does exist with the same soil type, which, if proved, would be a step toward the goal of substituting the compressive strength test for the standard durability tests. Some work along this line is being done by our laboratory, but sufficient data has not been collected to prove the relationship

Mr Miles D. Catton, *Portland Cement Association* The data and the conclusions by Professor Watson are in general agreement with those reported by other investigators.

The discussion does not include lengthy analysis of the material and also wisely confines itself to the three soils investigated. Two points will be enlarged upon with the hope that this additional discussion will be helpful and increase our knowledge and understanding of compacted soil-cement mixtures.

Conclusion No. 1 states that, "The initial characteristics of a soil have more effect upon the compressive strength of a soil-cement mixture than any other factor." This is in conformance with the data and the data presented by other investigators It should be pointed out, however, that even soils of the same general gradation may require considerable differences in cement content to achieve the same strength. Such phenomena are shown in Figures 11 and 20 in the paper on "Research on the Physical Relations of Soil and Soil-Cement Mixtures" presented at the December, 1940, meeting of the Highway Research Board.

It is believed that other important factors to consider as causing differences in compressive strengths of various soils containing the same cement contents are the chemical and physico-chemical makeup of the soil. Data illustrating these points are shown in Figures 16 and 17 and discussed in the conclusions of the paper just mentioned. The structural strength of the soil grains themselves are also important and will produce differences in compressive strength

The other point of interest which may be enlarged upon deals with the influence of density on compressive strengths. Professor Watson points up the changes in compressive strength brought about by changes in densities The data submitted by Professor Watson show that these density changes are also accompanied with increases or decreases in moisture content from the optimum Therefore, it is obvious that the moisture change is also a determining factor. These data submitted by Professor Watson do not permit definite analysis of the relative influence of moisture and density. Some research on this point has been conducted in the soil-cement laboratory of the Portland Cement Association These data indicate that in general variations in moisture content from the optimum are of greater significance and have greater influence on decreases in compressive strengths than do decreases in density. This fact is brought out with particular emphasis by some clay soils whose density decreases with increases in moisture contents in the moisture-density test, yet compressive strengths increase

It would be expected that moisture contents of the mixtures at time of compaction would be of significant importance since moisture is needed to hydrate and crystallize the cement.

Mr. T. E. Stanton, *California Division of Highways:* First taking up Professor Watson's conclusions:

1. Conclusion one is a very general statement and is true within broad and

very uncertain limits. It certainly should not, however, be assumed to be generally true, as we have developed strengths above 2,000 lb per sq. in. in samples containing high clay contents.

2. While it is true that increasing percentages of cement will usually produce consistent increases in compressive strength, nevertheless variations in compaction will also produce equally great changes in certain cases

3. Correct according to our observations.

4. Correct.

5. Correct.

6. We have made no studies along this line but the same tendency has been noticed in a few cases.

7. Correct so far as our observations go It may also be noted that the less the compaction, the greater the effect of freezing and thawing

Taking up the details of Professor Watson's study, however, we are unable to see that the methods of test and the scope of the work shed any light at all on the question propounded by the U. S Army Engineers, "whether or not compressive strength was a more desirable criterion for gauging soil-cement mixture performance than the standard tests of cycles of wetting and drying and of freezing and thawing." So far as the published data are concerned, Professor Watson's report seems not to settle this question one way or another and several assumptions are made which might readily be challenged.

On page 494—"Nearly a half century of concrete testing has shown that in the compression test the cylinders must have a height of twice their diameter"—while it is true that this is the accepted standard dimension specimen for portland cement concrete, it does not necessarily follow that these dimensions are the most appropriate and a great many concrete tests are made on cubes and on cylinders which are cut from pavements in which the height-diameter ratio is usually less than two. Such tests are readily correlated with the results on the standard cylinders. At any event, even if the height-diameter ratio of two is correct for high strength concrete, it does not follow that such tall specimens are essential for the weaker types as the normal angle of shear is much less than 60° in the weaker specimens Furthermore, specimens with a height-diameter ratio greater than one develop a marked problem in compaction and it is much more important that the compaction of test specimens be properly carried out than it is to adhere to some theoretical height-diameter ratio for testing.

We have developed a method of compaction which gives greater density and corresponding weight per cubic foot than does the standard Proctor Method and find that frequent density measurements made on construction projects are in excellent agreement with the densities secured with our laboratory method It is our opinion that it is unjustifiable to draw conclusions from laboratory data unless some evidence of correlation with actual performance can be shown. For example, Professor Watson's paper seems to indicate that clay loam types of soil are unsuited because they did not show a marked increase in strength with increasing cement content. This statement can hardly be accepted until we have evidence concerning the strengths which are necessary for a cement treated base.

It has long been known that the crushing strength of naturally cemented gravel bases is rarely above 200 lb. per sq. in. even when dry and in the most favorable condition, and in a dry condition clay-bound gravel roads can sustain very heavy traffic if the surface is protected from abrasion. Therefore, while California has consistently specified that cement treated mixtures should develop crushing strengths in excess of 1,000 lb. for a specimen height-diameter ratio of one, we have one or two roads giving excellent performance where the crushing strength is not more than 600 lb.

Against Professor Watson's evidence that clay soils are unsuitable, we can cite test results in two cases which seem to indicate a different conclusion. A sample from Road II-Teh-3-D which contained 76 per cent of fines by wash analysis (passing 270 mesh) with 32 per cent of clay and colloids developed 1,400 lb. per sq. in. in 14 days with 10 per cent of cement and compacted to a density represented by 121 lb. per cu. ft. A second sample from Road II-Sha-3-A contained 42 per cent by wash, 17 per cent clay, developed 1,235 lb in 14 days with a density of 131 lb per cu. ft. Some experiments with abode soils brought more erratic results. It is our feeling that broad generalizations are to be distrusted until supported by really comprehensive and complete data.