

Improvement of Strength of Soil-Cement With Additives

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The paper describes a search at the M.I.T. Soil Stabilization Laboratory for additives to improve the strength of soil treated with portland cement. Investigated were 29 additives, including dispersants, synthetic resins, waterproofing agents, and several salts and alkalis. The three soils studied were: a silt from New Hampshire, a clayey silt from Massachusetts, and a loess from Vicksburg, Miss. The soil samples were treated with 5 percent Type I normal portland cement plus 0.5 or 1.0 percent of the additives being studied; compacted; cured for 7 or 28 days; totally immersed in water for one day; and then tested for compressive strength.

The most effective additives were sodium carbonate, sodium hydroxide, sodium sulfate, and potassium permanganate. The trace quantities of these additives improved the strength of the soil-cement in excess of 150 percent for the two silts. Many of the other additives improved the strength of the silt significantly. The additives had a modest or no effect on the strength of the loess-cement.

Since a number of the additives that were effective are relatively cheap chemicals, they can permit economical improvement of soil-cement. The effectiveness may be limited, however, to certain soils.

● **PORTLAND CEMENT** is one of the most common and successful stabilizers for soil. Excellent results with soil-cement have been obtained in many parts of the world for a number of uses, especially for stabilizing pavement bases and subgrades. Nearly all soils which can be mixed with cement will respond to treatment. The difficulties of incorporating cement into plastic soils and the high cement requirements have, however, greatly limited its use with these soils. Acceptable clay-cement has been obtained with plant mixing and high cement concentration (> 15 percent).

Because of the present importance and considerable potential of soil-cement, the M.I.T. Soil Stabilization Laboratory has studied it for some years. Tests (Baker 1954) clearly showed a direct relation between the degree of mixing of soil and any stabilizer and the strength of the resulting product. Several studies at M.I.T. (Lambe 1954) showed that the mixing and compaction characteristics of soils could be markedly changed by the addition of trace chemicals, especially dispersants.

Based on these mixing and trace chemical studies, it was reasoned that the effectiveness of portland cement as a soil stabilizer could be enhanced with chemical additives. Denz and Steinborn (1953) investigated the effect of aggregants and dispersants on a sandy clay with 10 percent cement; they found that the chemicals could increase both the compacted density and strength a modest amount. For lower cement levels (1 percent) a higher percentage of strength increase (50 percent) was obtained. Continued study by Le Tellier and Wagner (1955) showed that considerable increase of strength could be effected on silt plus portland cement.

In 1955 a thorough review and investigation of the improvement of soil-cement with additives was undertaken. This paper, describing the most recent studies, indicates the very large improvements that are obtainable. A detailed explanation of the mechanisms employed by the various additives is not given, mainly because they are not yet well understood. Certainly, the dispersion mechanism which initiated this study is not the most important one. Some chemical reaction after compaction appears to occur in most of the systems. The authors are now studying the chemistry of the best systems, hoping to delineate the various reactions. Such an understanding should help in finding the most effective additives and in predicting the degree of response of different soils.

TABLE 1
PROPERTIES OF SOILS EMPLOYED IN STUDY

	Soil	Massachusetts	Visksburg	New Hampshire
		Clayey Silt	Loess	Silt
Textural composition ^a percent by weight	Gravel	0	0	0
	Sand	47	10	3
	Silt	42	86	90
	Clay	11	4	7
Engineering classification ^b		A-4(4)	A-7-6(10)	A-4(8)
Physical properties	L. L.	20	41	28
	P. L.	14	26	20
	P. I.	6	15	8
	Sp. Gr. ^c	2.77	2.80	2.72
	Max. dry density ^d in lb/ft ³	122.3	104.5	99.5
	Optimum moisture ^d in percent	13.3	18.5	19.9
Chemical properties	Cat. Ex. Cap., m. e./100 gm.	10	16	3
	pH	-	4.6	5.4
	Soluble salts, m. e. NaCl/100 gm.	-	0.2	-
	Organic matter, percent	-	1.8 ± 0.1	0.4 ± 0.1
Mineral composition ^e , percent by weight	Quartz	35	30	40
	Feldspar	20	30	40
	Mica	-	-	10
	Illite	30	15	10
	Montmorillonoid	-	20	-
	Fe ₂ O ₃	2.9	1.6	1.0

Based on M. I. T. classifications: Gravel-above 2.0 mm, sand-0.06 to 2 mm, silt-0.002 to 0.06 mm, clay-below 0.002 mm.

Based on Highway Research Board system.

Determined on the fraction passing No. 10 sieve.

Determined by Harvard Miniature compaction apparatus, compacted in three layers with a 40-lb tamper, 25 blows per layer.

Determined on the fraction smaller than 0.074 mm.

The testing program described in the following pages was a screening one. For these screening tests only compressive strength has been used for evaluation; no freeze-thaw, wet-dry or abrasion tests have been run.

MATERIALS AND TESTING PROCEDURE

Materials

The research considered the effects of 29 chemicals on the strength of 3 soils of different composition stabilized with 5 percent portland cement. The 3 soils tested were a clayey silt from Massachusetts, a uniform silt from Manchester, N.H., and a uniform loess from Vicksburg, Miss. Properties of these soils are shown in Table 1.

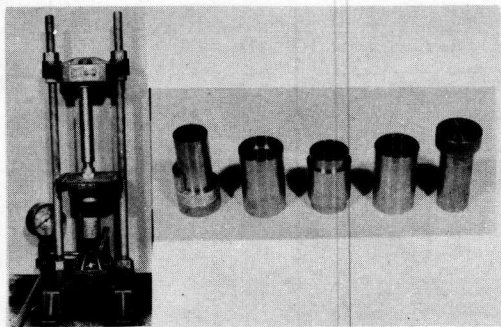


Figure 1. Assembly of static compaction apparatus.

Table 2 lists the 29 chemicals — dispersants, synthetic resins, bonding and water-proofing agents, alkalies, and salts.

Testing Procedure

Preparation of Soil, Cement, and Additive Mixtures. Five percent Type I normal portland cement was used in all cases with additives at concentrations of either $\frac{1}{2}$ or 1 percent, both cement and additive concentrations based on the dry weight of soil.

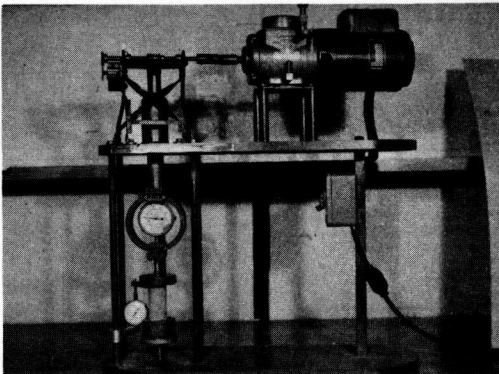


Figure 2. Testing machine for unconfined compression.

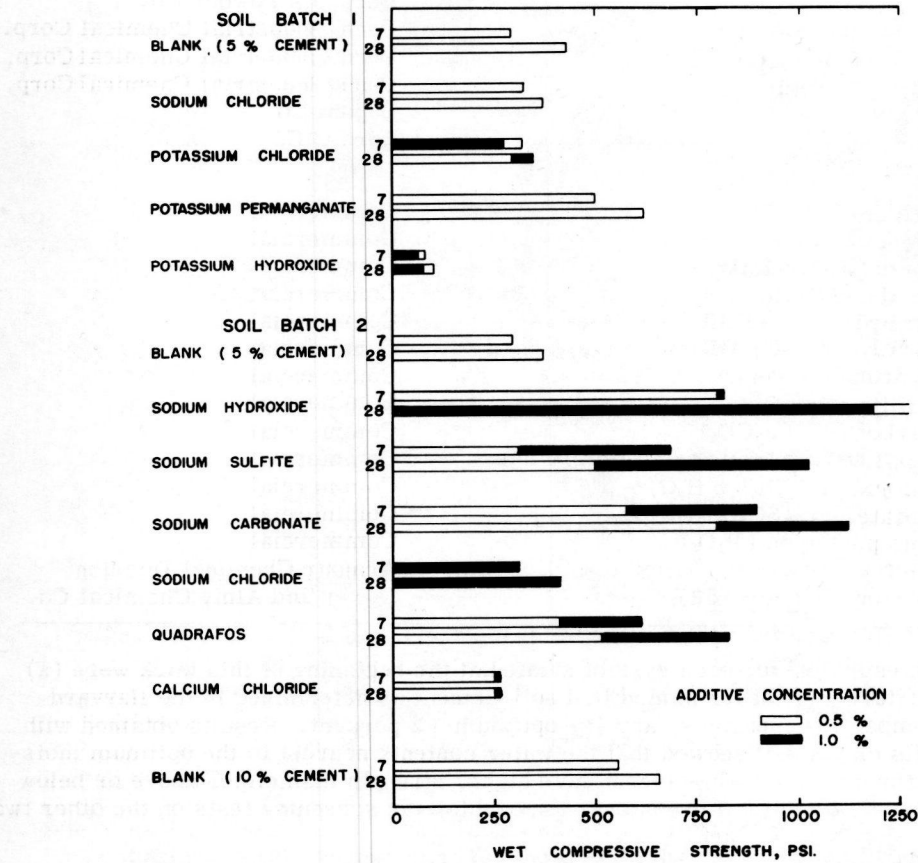


Figure 3. Effect of additives on 7 and 28 day wet compressive strength of cement stabilized Massachusetts clayey silt.

Air-dried soil passing No. 10 sieve was handmixed with a predetermined amount of cement. The chemical was dissolved in the mixing water in proper proportion and the solution added to the dry soil-cement; this procedure was followed with all chemicals with the exception of the following four synthetic resinous agents: Aroclor 4465, Vinsol, Piccolyte S-125, and Picco XX-100B. Because these resins were not water-soluble under ordinary conditions, they were pulverized and mixed dry with the soil-cement before the addition of water. In all cases mixing was done in a sigma-blade mechanical mixer for 5 min.

TABLE 2
CHEMICAL ADDITIVES EMPLOYED IN STUDY

Material	Source
Dispersants:	
Sodium tetraphosphate (quadrafos)	Rumford Chemical Co.
Pozzolith 2AA	Master Builders Co.
Daxad 21	Dewey and Almy Chemical Co.
Lignosol X2D	Lignosol Chemical, Ltd.
Synthetic resin bonding and waterproofing agents:	
Aroclor No. 4465	Monsanto Chemical Co.
Piccolyte S-125	Penn. Industrial Chemical Corp.
Picco SS-100B	Penn. Industrial Chemical Corp.
Vinsol (powdered resin)	Hercules Powder Co.
Piccopale emulsion A-1	Penn. Industrial Chemical Corp.
Piccopale emulsion A-35	Penn. Industrial Chemical Corp.
Losorb	Penn. Industrial Chemical Corp.
Polyvinyl alcohol (Grade 50-42)	Dupont Co.
Polyvinyl alcohol (Grade 5-88, 65-98)	Borden Co.
Others:	
Calcium chloride (CaCl_2)	Commercial
Sodium chloride (NaCl)	Commercial
Potassium chloride (KCl)	Commercial
Potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$)	Commercial
Potassium hydroxide (KOH)	Commercial
Calcium hydroxide ($\text{Ca}(\text{OH})_2$)	Commercial
Sodium hydroxide (NaOH)	Commercial
Sodium sulfite (Na_2SO_3)	Commercial
Sodium carbonate (Na_2CO_3)	Commercial
Borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10 \text{H}_2\text{O}$)	Commercial
Ferric chloride ($\text{FeCl}_3 \cdot 6 \text{H}_2\text{O}$)	Commercial
Ferric sulfate ($\text{Fe}_2(\text{SO}_4)_3 \cdot 6 \text{H}_2\text{O}$)	Commercial
Phosphorus pentoxide (P_2O_5)	Commercial
Arquad 2HT	Armour Chemical Division
Darax polyvinyl acetate X52L	Dewey and Almy Chemical Co.

Water contents used for each system studied at the beginning of this work were (a) optimum moisture content for unmodified soil-cement as determined in the Harvard miniature compaction apparatus, and (b) optimum ± 2 percent. Results obtained with Massachusetts clayey silt showed that the water contents nearest to the optimum moisture content for untreated soil-cement gave higher strength than either above or below optimum. Only optimum water content was used for the screening tests on the other two soils.

Molding of Specimens. Needed for the screening work was a simple method of preparing soil samples to determine the relative effect of different additives on the stability

TABLE 3
SUMMARY OF RESULTS OF BENEFICIAL ADDITIVES ON THREE SOIL-CEMENT SYSTEMS
BASED ON 7-DAY CURING STRENGTH^a

Improvement (percent)		New Hampshire Silt (percent)		Massachusetts Clayey Silt (percent)		Vicksburg Loess (percent)
20 to 50	1.0	Aroclor 4465	1.0	Vinsol	0.5	Quadrofos
	1.0	Vinsol	1.0	Aroclor 4465	0.5	Lignosol X 2D
	0.5	Quadrofos	0.5	Quadrofos	1.0	PVA (50-42)
	1.0	Piccopale emulsion A-1			0.5	Picco XX-100B
	1.0	Quadrofos			1.0	Picco XX-100B
	1.0	Calcium chloride			0.5	Sodium carbonate
					1.0	Lignosol X 2D
50 to 100	0.5	Piccopale emulsion A-35	1.0	Potassium permanganate	1.0	Sodium sulfite
	1.0	Potassium chloride	0.5	Sodium carbonate	1.0	Sodium carbonate
	0.5	Calcium chloride			0.5	Sodium sulfite
	0.5	Potassium permanganate			1.0	Sodium hydroxide
	0.5	Sodium chloride			0.5	Sodium hydroxide
	0.5	Sodium hydroxide				
	0.5	Potassium dichromate				
	1.0	Sodium chloride				
	1.0	Potassium dichromate				
100 to 150	1.0	Potassium permanganate	1.0	Quadrofos		
	1.0	Sodium sulfite	1.0	Sodium sulfite		
150 to 200	1.0	Potassium hydroxide	0.5	Sodium hydroxide		
	1.0	Sodium hydroxide	1.0	Sodium hydroxide		
	0.5	Sodium sulfite	1.0	Sodium carbonate		
Over 200	0.5	Sodium carbonate				
	1.0	Sodium carbonate				

^aBlank is soil plus 5 percent cement; all other systems are soil plus 5 percent cement plus additive.

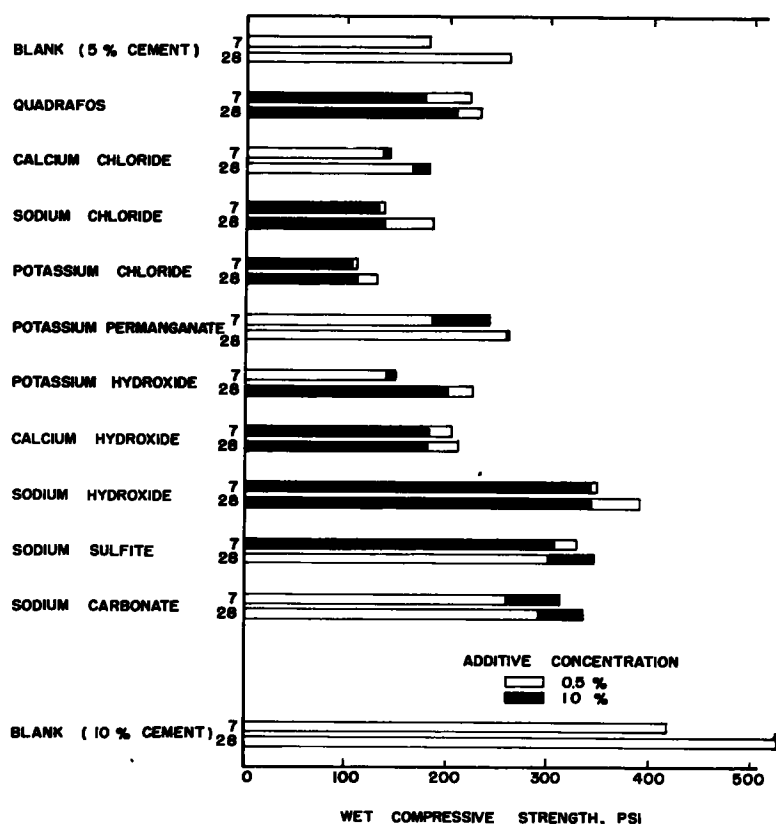


Figure 4. Effect of additives on 7 and 28 day wet compressive strength of cement stabilized Vicksburg loess.

of soil-cement. This method should be fast and simple, and yet display the full benefits of the additive.

Dynamic compaction methods were discarded since they entailed too much molding effort; static compaction from one end was also found to be unsatisfactory since it yielded a specimen denser at one end than the other. The method adopted was static compaction from both ends; a Harvard miniature-size mold (1.313 in. in diameter, and 2.816 in. high) was fitted with an extension collar and piston at each end. Compaction was then carried out simultaneously at both ends under a specified pressure by means of a hydraulic jack. This specified pressure was that required to mold soil-cement to the maximum dry density as determined by dynamic procedure, that is, compacted in three layers by a 40-lb spring tamper with 25 blows per layer. Figure 1 shows the assembly of the molding apparatus.

Static compaction admittedly is generally less representative of field compaction; however, it appeared to give satisfactory and reproducible results for this screening test program.

Curing of Specimens. Molded specimens were cured for periods of both 7 and 28 days in a desiccator maintained at 100 percent relative humidity and room temperature (about 20 to 25 C).

Testing of Specimens. All specimens were subjected to a 24-hr complete immersion in distilled water at room temperature prior to testing in unconfined compression. Complete water immersion is a most severe treatment for stabilized soils.

The apparatus used for determining compressive strength was a proving-ring type machine (Fig. 2). The maximum pressure causing failure of the specimen was taken as the compressive strength.

TABLE 4

**SUMMARY OF RESULTS OF BENEFICIAL ADDITIVES ON THREE SOIL-CEMENT SYSTEMS
BASED ON 28-DAY CURING STRENGTH^a**

Improvement (percent)		New Hampshire Silt (percent)		Massachusetts Clayey Silt (percent)		Vicksburg Loess (percent)
20 to 50	0.5	Pozzolity 2AA	0.5	Aroclor 4465	1.0	Sodium carbonate
	0.5	Lignosol X 2D	1.0	Aroclor 4465	1.0	Sodium sulfite
	1.0	Calcium hydroxide	0.5	Sodium sulfite	0.5	Sodium hydroxide
	1.0	Aroclor 4465	0.5	Quadrofos		
	0.5	Potassium chloride	1.0	Potassium permanganate		
	0.5	Aroclor 4465				
	0.5	Vinsol				
	1.0	Vinsol				
	1.0	Piccopale emulsion A-35				
50 to 100	1.0	Calcium chloride			1.0	Sodium hydroxide
	1.0	Borax				
	0.5	Calcium chloride				
	0.5	Piccopale emulsion A-35				
	0.5	Sodium chloride				
	0.5	Quadrofos				
	1.0	Potassium hydroxide				
	0.5	Potassium permanganate				
100 to 150	0.5	Sodium hydroxide				
	1.0	Sodium carbonate	0.5	Sodium carbonate		
	0.5	Potassium dichromate	1.0	Quadrofos		
	1.0	Potassium chloride				
	0.5	Sodium sulfite				
	1.0	Quadrofos				
	1.0	Sodium chloride				
	1.0	Potassium dichromate				
150 to 200	1.0	Sodium sulfite				
	0.5	Sodium carbonate	1.0	Sodium sulfite		
Over 200	1.0	Sodium hydroxide	1.0	Sodium carbonate		
	1.0	Potassium permanganate	1.0	Sodium hydroxide		
			0.5	Sodium hydroxide		

^aBlank is soil plus 5 percent cement; all other systems are soil plus 5 percent cement plus additive.

RESULTS

Effect of Additives on Compacted Density

None of the trace additives studied had any large effect on the compaction characteristics of the soil and cement mixtures. Most of the dispersants, alkali reagents with sodium (ions and salts with sodium-ions, caused a modest increase in maximum compacted density (1 to 7 lb per cu ft) and a slight decrease in optimum moisture. Several additives increased strength but had no influence on the compaction characteristics. There was not any observable relation between strength increase and density increase. These facts indicate that the strength improvements are not primarily due to any effects on compacted density.

Although there are no numerical data on the degree of mixing, visual observations suggest that the use of trace additives is not a significant aid to mixing.

These and other considerations strongly point to some chemical reaction, or reactions, between various components in the system with a resulting increase of cementing action. Now in progress are a number of investigations aimed at ascertaining what reactions occur and what the effects are of the various reactions.

Effectiveness of Additives

Tables 3 and 4 show that over one-half of the chemicals tried increased the strength of the soil-cement. There were seven chemicals which, when used at concentrations of

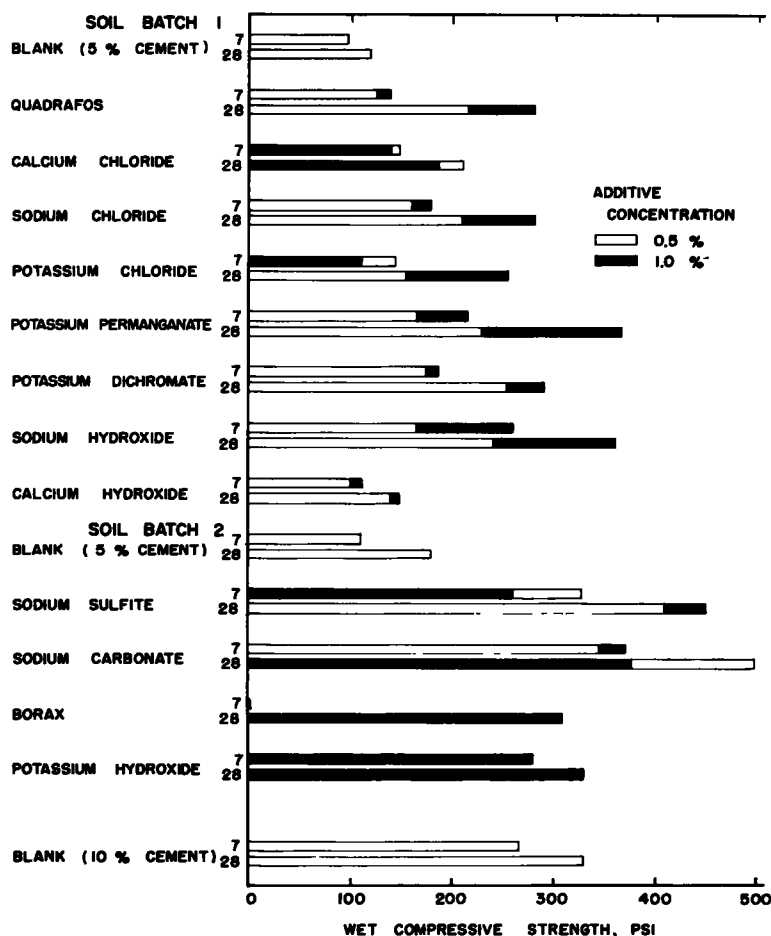


Figure 5. Effect of additives on 7 and 28 day wet compressive strength of cement stabilized New Hampshire silt.

TABLE 5

COST COMPARISON OF STABILIZED NEW HAMPSHIRE SILT WITH CEMENT ALONE AND WITH CEMENT PLUS ADDITIVE FOR A REQUIRED STRENGTH^a

	Soil-Cement		Soil-Cement Plus Additive	
Compressive strength required, psi	300	300	300	300
Concentration of admixtures required, percent	12 cement	5 cement plus 0.5 sodium carbonate	5 cement plus 1.0 sodium hydroxide	5 cement plus 1.0 sodium sulfite
Cost ^a per mile for stabilizer and additives, dollars	5,340	3,170	3,540	3,850

^aThe cost estimates are for a mile of base course 8-in. thick and 12 ft. wide, with a compacted dry density of 100 lb per cu ft. The prices of chemicals are obtained from Oil, Paint and Drug Reporter Weekly, December 10, 1956.

1 percent or less, more than doubled the strength of the silts treated with cement.

Figures 3, 4, and 5 present the strength data as bar graphs. The white bars show the strengths of soil-cement with 0.5 percent additives and black bars show the strength with 1 percent additives. For example, Figure 5 shows that 0.5 percent sodium carbonate increased the 7-day strength of New Hampshire silt (with 5 percent cement) from 100 psi to 345 psi and the 28-day strength from 180 psi to 500 psi. The 1 percent sodium carbonate treatment gave a 7-day strength of 370 psi and a 28-day strength of 375 psi. Figure 5 also shows that the silt and 10 percent cement with no additive had a 7-day strength of 265 psi and a 28-day strength of 330 psi.

The preceding example illustrates several important general points, namely:

1. The beneficial effects were not merely due to acceleration of cement hydration since these effects are apparent at 28 days. Other tests show that the benefits fully persist after four months of curing, the maximum period so far investigated.
2. The influence of chemical concentration is not predictable. An increase from 0.5 to 1 percent sodium carbonate caused a beneficial effect on the 7-day strength but a detrimental effect on the 28-day strength increase. Until the nature of the chemical reaction can be better understood, optimum treatment levels for any system will have to be determined by trial.
3. The chemical additives can be more effective than a sharp increase in the amount of cement added. For example, the addition of 1 lb of sodium carbonate gave more strength increase than 10 lb of cement.

Response of Soils to Treatment

The test data show that both cement-silts responded to chemical treatment better than did the loess from Vicksburg. This fact can be seen in Tables 3 and 4 which indicate no additive as much as doubled the loess-cement strength. During the last decade, stabilization research at M.I.T. on many soils and many stabilizers has always shown that different soils respond to stabilization in greatly different extents.

Certain general correlations between soil composition and soil responses to various types of stabilization have been noted. There are too few data and too little understanding of the principles of chemical reactions in soil-cement to draw such correlations at this time. It is apparent, however, that different soils will respond differently to cement plus chemical treatment.

Economics of Chemical Treatment

Although the test program has not advanced far enough to warrant a detailed economic study on the use of additives to soil-cement, it does indicate that significant financial savings are possible. Table 5 presents a cost comparison of New Hampshire silt-cement with and without additives. The figures show that the cost of total admixture per pile, to obtain a strength of 300 psi, is considerably less for the cement plus additives than for the cement alone (\$3,200 vs \$5,300). The use of strength alone as a performance criterion may not be justified. There would also be a saving in material handling, and possibly a saving in soil processing, with the cement-chemical combination.

Certainly, at this stage of the research, the economics of chemical treatment of soil-cement looks very promising.

SUMMARY AND CONCLUSIONS

This paper describes an experimental investigation aimed at improving the effectiveness of portland cement as a soil stabilizer. The sole criterion of improvement is based on the compressive strengths of moist-cured and water-immersed specimens.

The results show that, on two of the three soils tested, low level chemical treatment gave strengths more than double those of soil-cement specimens with no chemical additive. More modest improvements were obtained on the third soil. Since a number of the beneficial additives are relatively cheap and since the effective treatment levels are percent or less, based on the dry soil weight, the use of additives to soil-cement is economically interesting.

Not enough is yet known to explain in detail the mechanism the additives employ to increase the strength. Chemical reactions which result in further cementation are obviously occurring.

ACKNOWLEDGMENTS

The test results presented in this paper were obtained by the second-named author working under the general supervision of the first-named. Suggestions from Dr. A. S. Michaels and Dr. R. T. Martin of the M.I.T. Soil Stabilization Laboratory have aided the research.

The studies on soil-cement at M.I.T. have been supported mainly by the Waterways Experiment Station, Corps of Engineers. The authors gratefully acknowledge the help and encouragement the Station has given to soil stabilization research at M.I.T.

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