EFFECTS OF COMPACTION DELAYS AND MULTIPLE TREATMENTS ON THE STRENGTH OF CEMENT STABILIZED SOIL

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The effects of delayed compaction on the strength and durability of cement stabilized soils for base courses and subbases has been investigated. It was concluded that time delay does not adversely affect either strength or durability. However, prolonged time delay does increase the required level of compaction necessary to achieve a specified density so that it may be beyond the capability of ordinary highway compaction equipment. An example is given in the report showing how the results of this work can lead to more rational field compaction specifications for cement stabilized materials, in recognition of the fact that time delays are inherent in the construction process.

Aggregate supplies for road building purposes are becoming increasingly more costly and more scarce in many parts of the United States (10). Alternative road base materials such as cement treated aggregate or cement stabilized subgrade soil, which previously were relatively expensive, are now viable economic alternatives. However, use of such materials in lieu of a conventional aggregate base requires additional considerations to assure that a strong and durable material will result.

It is not uncommon to have a time delay between initial mixing and final compaction in excess of two hours for road-mixed cement stabilized construction. Previous research (1, 2, 3, 4, 5, 6, 7) has shown that time delays of this magnitude will result in the reduction of density, strength and durability of laboratory specimens compacted at constant compactive effort, such as that imparted by the standard AASHTO procedure. The reduction of these properties in a cement stabilized soil is a result of the time-dependent reaction that is occurring between the soil, cement, and water. As these constituents are mixed together the cement hydrates, and over time the products of hydration will effectively aggregate the soil particles. The increased frictional resistance to compaction that this creates requires an increase in the compactive effort necessary to achieve the required density.

A review of the literature (1, 2, 4, 6) indicates that if a high state of density can be achieved in cement stabilized mixtures subject to time delays, a strong and durable product will usually result. Most of the studies to date that have considered the effects of time delays on cement stablized soils have been limited to the use of standard AASHTO compaction effort. Since both dry density (related to void ratio) and moisture content (related to water/cement ratio) will ultimately affect strength gain, these factors should be considered jointly when cement stabilized soils are used.

In terms of field applications, it has generally been found (1, 3, 4, 6, 8, 17, 18) that increased compactive effort is beneficial to the dry density and therefore to the strength of cement stabilized soils. Previous research, however, does not indicate how much compactive effort is necessary to obtain 100 percent of the standard AASHTO dry density over varying time delays. In addition, if a level of compactive effort cannot be applied in the field to achieve 100 percent of the standard AASHTO dry density, it would be desirable to know what a reasonable specification would be for dry density, moisture content, and time delay, such that satisfactory strength and durability could be obtained.

Purpose and Scope of the Investigation

The purpose of this investigation was to study the effects of varying amounts of time delay before compaction on the strength of cement stabilized soils, in order that recommendations for field construction procedures could be made.

The investigation was carried out in three phases. Phase I consisted of determining the influence of moisture content on the strength and dry density of three conventional cement stabilized soil mixtures. Previous research (4, 5, 7) has shown that the optimum moisture content for maximum strength and for maximum dry density may not always be the same. In Phase I the optimum moisture content and dry density associated with the maximum strength of each cement stabilized soil mixture were determined using the standard AASHTO compaction method. These values were used in the two subsequent phases of the research.

Phase II involved an investigation of the influence of time delays on the dry density, strength, and durability of one of the three cement stabilized soil mixtures, compacted at the optimum moisture content for maximum strength. A kneading compactor was used to compact the specimens, using a compactive effort that permitted achieving the standard AASHTO density at zero time delay. These specimens were termed the "constant compactive effort" series, since the same compactive effort was used for all specimens, regardless of the amount of time that compaction was delayed. The data obtained were used to determine whether a direct relationship existed between strength and dry density, or durability and dry density.

Phase III involved compacting cement stabilized soil specimens to approximately 100 percent of the standard AASHTO dry density after the mixtures were subject to time delays of up to 6 hours. These specimens were termed the "constant density" series since the same density was attained, regardless of the amount of time that compaction was delayed. The amount of compactive effort required to obtain the desired dry density was recorded so that it could be compared to the capability of typical field compaction equipment.

For all three phases of the investigation both one-part and two-part cement stabilized soil mixtures were investigated. One-part mixtures are defined as those where all of the soil, cement and water are mixed together at one time. Two-part mixes involve mixing one-half of the cement and one-half of the water initially, followed by a twenty-four hour hermetic curing period prior to the addition of the remaining cement and water. This technique of multiple treatment (two-part mixing) represents the extreme antithesis to the conventional wisdom of minimizing the time for construction of soil-cement mixtures. It occurs occasionally in mixed-in-place construction where mixing is interrupted for a prolonged period or overnight. Earlier research (6) has suggested that some strength benefits were obtained using two-part mixing, however this research did not confirm those findings.

Materials and Methods

Soils

Three soils sampled from sites within Tompkins County, New York were used for testing. Soil A was a silty clay and Soil C was a clayey silt, each typical of the fine-grained subgrade soils found over a major portion of the United States. Soil B, a highly angular gravelly sand, was typical of the coarse-grained dense-graded materials used in the construction of cement treated aggregate bases. The physical properties of these three soils are shown in Table 1.

Portland Cement

The cement used throughout this investigation was Type IA portland cement, having an initial setting time of 100 minutes, a final setting time of 204 minutes. and a 28-day mortar cube strength of 730 kPa (5012 psi).

Mix Designs

Standard procedures for the determination of optimum cement content published by the American Society for Testing and Materials (11) and the Portland Cement Association (14) were used to obtain the mix designs. Freeze-thaw criteria controlled the mix design for Soil A, resulting in a design cement content of 13.5 percent by weight of dry soil. The short-cut procedure for sandy soils (14) was used for Soil B and Soil C, resulting in design cement contents of 5.0 and 12.0 percent, respectively.

Table 1. Properties of unstabilized soils.

	Soil A	Soil B	Soil C
Sieve Analysis			
Percent Passing			
19.1 mm (3/4 in)	100	100	100
13.2 mm (1/2 in)	100	90	100
4.75 mm (#4)	100	58	99
2.00 mm (#10)	100	42	98
0.425 mm (#40)	97	18	95
0.075 mm (#200)	90	2	87
0.050 mm	89	--	78
0.005 mm	57	--	25
0.002 mm	39	--	17
Physical Properties			
Liquid Limit	36		24
Plastic Limit	17		17
Plasticity Index	19	NP	7
Standard AASHTO Maximum Dry Density (kg/m^3)	1805	2195	1842
Optimum Moisture Content (pct.)	16.4	7.1	14.5
Modified AASHTO Maximum Dry Density (kg/m^3)	1919	2288	1942
Optimum Moisture Content (pct.)	13.3	5.9	12.2
Specific Gravity	2.76	2.68	2.71
Soil pH	7.8	--	7.7
Percent Loss on Ignition at 900°C	14.6	--	4.8
Classification			
AASHTO	A-6 (12)	A-1a	A-4 (8)
Unified	CL	SW	CL-ML

(1 kg/m^3 = 0.0624 lb/ft^3)

Mixing

A 12-liter, restaurant-type Blakeslee Model CC20 mixer, was used to mix the soil-cement mixtures. A speed of 250 revolutions per minute was used, and a total wet mixing time of 3 minutes was allowed for all soil-cement mixtures. The cement and dry soil were first hand-mixed to a uniform texture and upon the addition of water the measurement of time delay was begun and wet mixing was initiated. For the two-part mixtures a 1.5 minute mixing time was used for each part. The measurement of time delays for two-part mixes was initiated upon the addition of the second portion of the mixing water.

Moisture Contents

All moisture contents were based on the weight of dry solids, when dried in an oven at 110°C. The moisture contents used in calculating dry densities and plotted on the moisture-density curves were based on the molding moisture content, that is, the amount of water added to the soil-cement mixture plus any hygroscopic moisture in the soil that could be evaporated at 110°C.

Compaction

All specimens used in this investigation were 102 mm (4.0 inches) in diameter by 116 mm (4.58 inches) in height. Each specimen was compacted in three equal layers and was scarified between each layer. The specimens for Phase I, the moisture-density-strength study, were compacted in accordance with ASTM D558-57 (11), using a drop-hammer compaction corresponding to the standard AASHTO effort. In no instance were the compacted specimens broken up to be recompacted.

The soil-cement specimens for the remainder of the investigation were compacted using a kneading compactor. The kneading foot and the load-duration relationship conformed substantially to the test methods of the California Department of Transportation. The compactor was capable of applying contact pressures up to 5000 MPa (700 psi).

Curing

All specimens were cured for 7 days at 23 plus or minus 1°C (73 ± 2°F) in a moist atmosphere near 100 percent relative humidity. Each specimen was sealed in a plastic bag during curing to maintain a constant moisture content.

Strength

The unconfined compressive strength of each specimen was measured. After curing, the ends of each specimen were capped using a sulfur-type capping compound. The tests were run on a universal testing machine having a spherically seated loading head using a loading rate of 1.25 mm (0.050 inches) per minute.

Durability

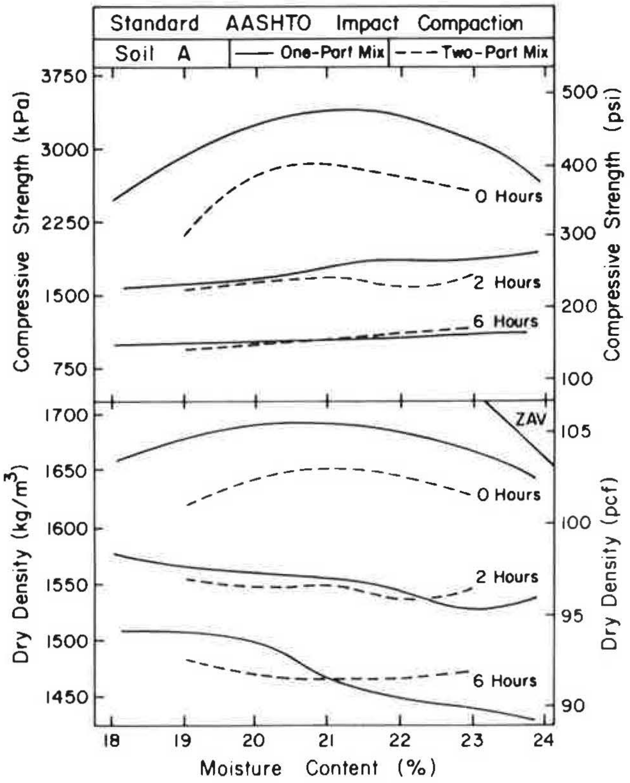
The strength of specimens subject to vacuum saturation has been found to have a high correlation with the strength of samples subject to freeze-thaw cycling (16). After 7 days of curing, the specimens were subjected to vacuum saturation, capped, and tested for unconfined compressive strength.

Discussion of Results

Moisture-Density-Strength Relationships

Figures 1, 2, and 3 illustrate the influence of moisture content on the dry density and strength of the three cement stabilized soils. A minimum of fifteen compacted specimens were fabricated in establishing each of the curves shown in the three figures. The results for the two fine-grained soils (Soils A and C) show that the moisture content for maximum strength of a one-part mix subject to a minimum time delay (0 hours) was the same or slightly greater than that for maximum dry density. However, for the coarse-grained Soil B the moisture content associated with maximum strength was lower than that for maximum dry density. It can be seen in Figure 2 that deviations in moisture content from the optimum for maximum strength of the coarse-grained material will cause large decreases in strength.

Figure 1. Moisture-density-strength relationship for cement-stabilized Soil A.



The dependence of strength on moisture content is a result of the manner in which the type of soil obtains strength when stabilized with cement. Strength gain in coarse-grained soils is similar to that of concrete. The function of the cement paste in concrete is to fill the voids within the aggregate matrix and bond the particles together. In cement stabilized soils however, the voids are not completely filled with paste (18). Strength in a cement stabilized coarse-grained soil can therefore be seen as a function of both water-cement ratio (a specific moisture content associated with a given cement content) and degree of compaction (dry density).

For fine-grained soils, strength gain is obtained through cementation as well as through the chemical combination of the individual soil particles with the products of cement hydration. While the dry density and moisture content are primary factors influencing strength gain, so are the mode of compaction (19), cement content, soil chemistry, temperature, and mixing technique, along with many other variables that affect the soil-cement reaction (23, 24, 25).

Table 2 summarizes the results of the moisture density-strength tests for zero time delay. The moisture content for maximum strength and the associated dry density, for each of the three cement stabilized soils, were used as the controlling parameters for Phase II and Phase III of the research: the constant compactive effort study and

Figure 2. Moisture-density-strength relationship for cement-stabilized Soil B.

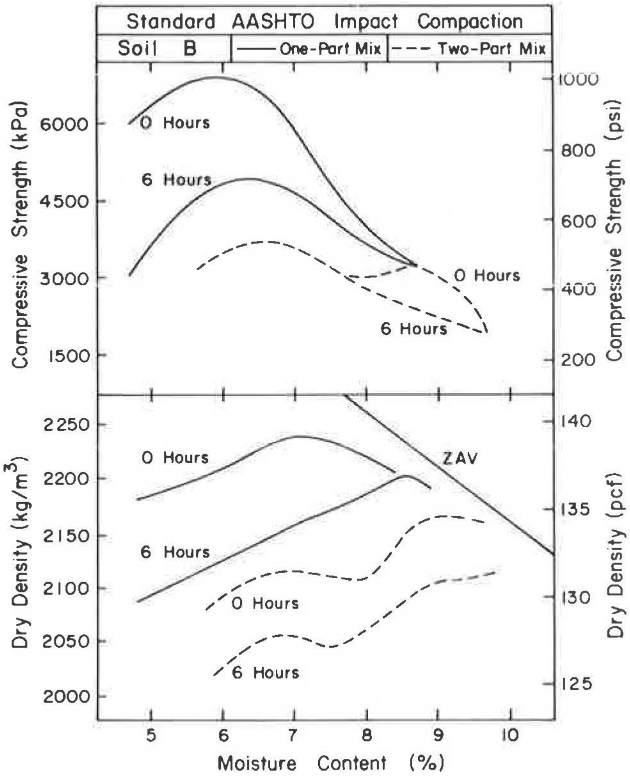
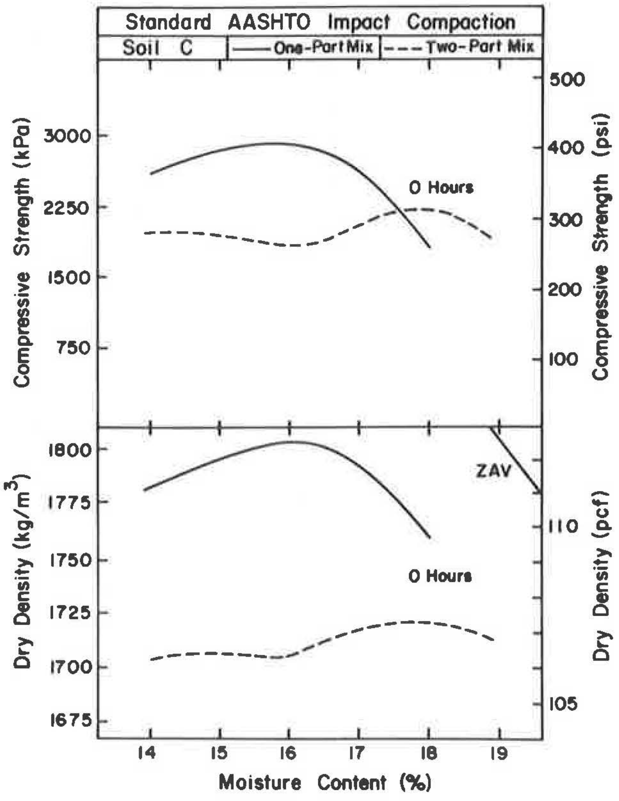


Figure 3. Moisture-density-strength relationship for cement-stabilized Soil C.



the constant density study. Since kneading compaction rather than drop-hammer compaction was used in the subsequent phases of the research, the compactive effort (i.e., the hydraulic pressure setting) necessary to achieve the desired density at the given moisture content for zero time delay was determined for each of the stabilized mixtures. Because the standard AASHTO density was attained at this pressure setting, it is termed the standard AASHTO compaction pressure. In a similar manner the pressure setting necessary to achieve modified AASHTO density was determined. These pressures are reported in Table 3 for each soil-cement mixture.

Table 2. Moisture-density-strength relationships for cement stabilized soils using standard AASHTO impact compaction, zero time delay, and one-part mixing.

		Soil A	Soil B	Soil C
Maximum 7-day Unconfined Compressive Strength	(kPa) (psi)	3310 480	6960 1010	2790 405
Maximum Dry Density	(kg/m³) (pcf)	1689 105.4	2220 138.6	1804 112.6
Moisture Content for Maximum Density	(percent)	20.5	7.0	16.0
Moisture Content for Maximum Strength	(percent)	21.0	6.3	16.0
Cement Content	(percent)	13.5	5.0	12.0

Table 3. Kneading compaction pressure required to achieve standard and modified AASHTO densities for cement-stabilized soils at zero time delay with one-part mixing.

		Soil A	Soil B	Soil C
Standard AASHTO Compaction Pressure	(kPa) (psi)	1170 170	1520 220	1100 160
Modified AASHTO Compaction Pressure	(kPa) (psi)	2620 380	2410 350	2620 380

Constant Compactive Effort Study

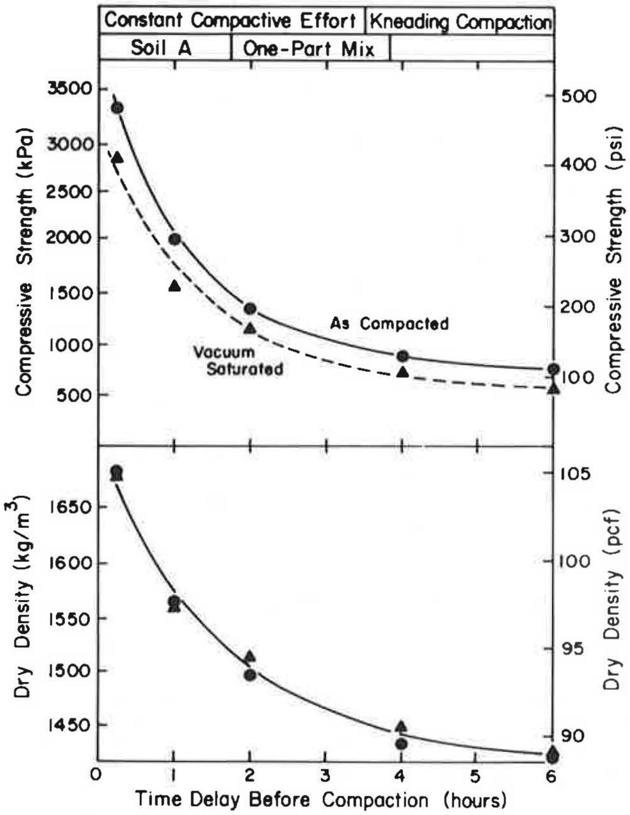
The influence of time delay upon the dry density, strength, and durability of cement stabilized Soil A was investigated in Phase II of the research. Specimens compacted with the kneading compactor were given a compactive effort equivalent to that of standard AASHTO compactive effort, as determined by varying the hydraulic pressure setting on the compactor until at zero time delay the density at the optimum moisture content for maximum strength was equal to the standard AASHTO density.

The effect of delaying compaction up to six hours is shown in Figure 4. Each data point represents the average of three test specimens. Where a constant compactive effort is used, time delay before compaction results in a significant loss of density, which in turn results in strength reduction. The direct interrelationship between density and strength is also shown in Figure 5.

This behavior has also been noted by MacLean and Lewis (8).

The durability of the material, as measured by the strength retained after saturation, is also shown in Figure 4. It can be seen that regardless of the amount of time delay, approximately 80 percent of the as-compacted strength was retained after saturation. Thus time delay before compaction does not appears to have a major influence on durability losses for cement stabilized soils.

Figure 4. Effect of time delay on strength and density of cement stabilized Soil A at constant compactive effort.



Constant Dry Density Study

Time Delay Influence on Strength. The preceding results imply that time delay causes reduced density, and thus reduced strength, where compactive effort is held constant. It should be noted, however, that most construction specifications require that a minimum density be achieved. The question of whether there would be a loss in strength due to time delays where a constant density is achieved was the subject of the third phase of the research.

In Figure 6 are shown the results of strength tests on the three cement stabilized soils, where the compactive effort at each level of time delay was adjusted to enable attaining approximately 100 percent of standard AASHTO density. For Soils A and C each data point represents the average of three tests. For Soil B each data point represents a single test.

Soil B presented difficulty in achieving constant density. Slight variations in density resulted in large variations in strength. The influence of density on strength was quantitatively defined in a manner similar to Figure 5, and the individual test results were normalized to adjust for density variations before they were plotted in Figure 6.

Figure 5. Strength-density relationship for cement stabilized Soil A.

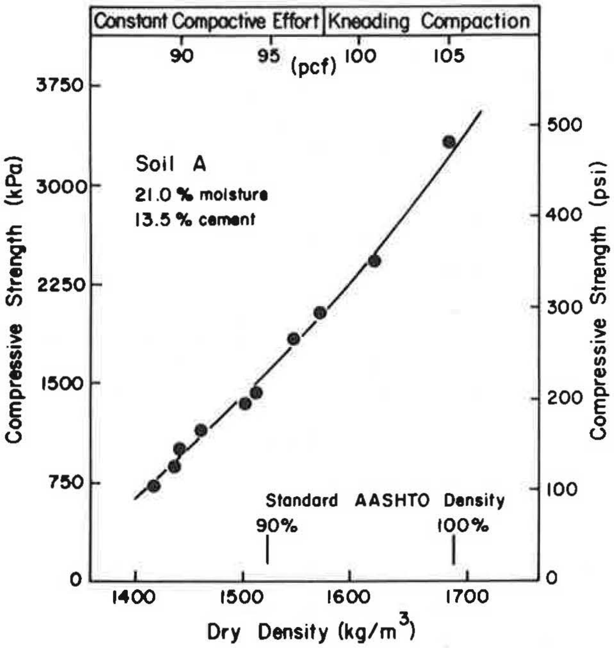
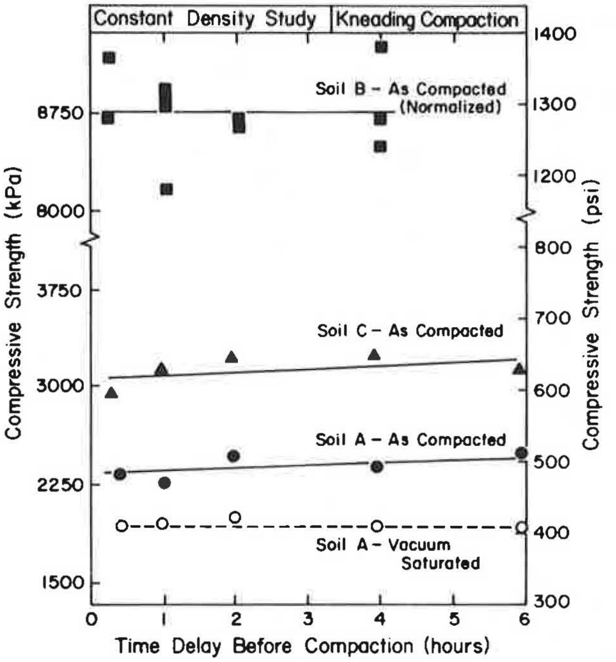


Figure 6. Effect of time delay on strength of cement stabilized soils at constant density.



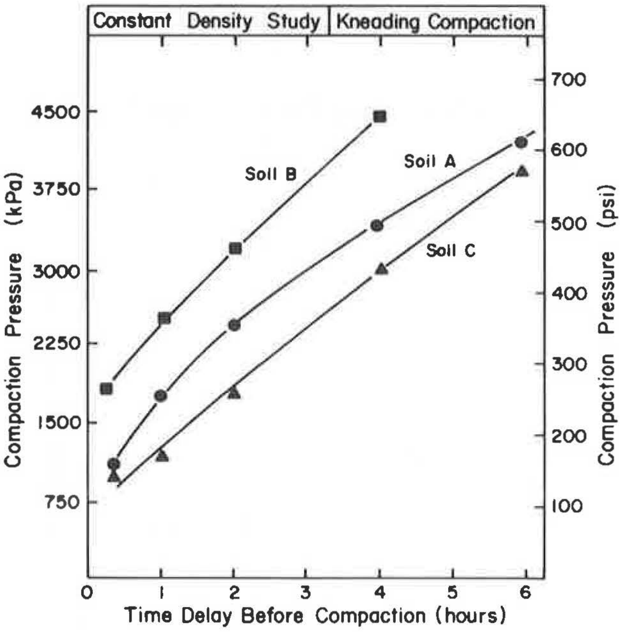
Statistical analyses have determined that none of the lines reported in Figure 6 have slopes which are different from zero at the 0.05 significance level (20). Thus it may be concluded that time delays have no influence on strength when a given density is achieved.

Again it is seen in Figure 6 that saturation of Soil A specimens resulted in approximately 80 percent strength retention, regardless of the amount of time delay. These results further support the previous conclusion that time delays up to 6 hours do not adversely affect the durability of soil-cement.

Time Delay Influence on Compaction Effort. It has been shown that time delays of up to six hours do not result in strength losses where a given density can be achieved. However, time delay does make it increasingly difficult to achieve density, as shown in Figure 7. In the figure it can be seen that the level of compactive effort, as measured by the pressure setting on the kneading compactor, increases significantly with increasing time delay. The coarse-grained Soil B exhibited a higher frictional resistance for all levels of time delay than did either Soils A or C, which were fine-grained.

At zero time delay a kneading pressure of about 2600 kPa (380 psi) was sufficient to provide at least modified AASHTO density in all three cement stabilized soils (Table 3). As shown in Figure 7, however, after one to three hours of time delay, depending upon soil type, a kneading pressure of 2600 kPa would only provide standard AASHTO density.

Figure 7. Effect of time delay on compaction pressure required to achieve standard AASHTO density for cement stabilized soils.



Limiting Time Delays. It has been reported that the modified AASHTO compaction curve represents an upper bound on the density that can generally be produced by most types of field compaction equipment (21, 22). For the purposes of this study a limiting time delay was defined as the time delay at which modified AASHTO compactive effort was required to obtain standard AASHTO density. Based upon the results reported in Table 3 and Figure 7, for the cement stabilized soils A, B, and C the limiting time delays would be 2.3, 1.0, and 3.3 hours, respectively.

It can be concluded that it would be very difficult to attain a specified standard AASHTO density for a cement stabilized soil when a time delay between mixing and compaction in excess of three hours is incurred. The higher frictional resistance of coarse-grained soils, such as those used in base courses, may be expected to result in a limiting time delay more on the order of one hour.

Significance of Cement Time of Set

The cement used in these tests had an initial setting time of 1.7 hours, and a final setting time of 3.4 hours. Arman and Saifan (2) have noted the influence of cement setting time on the behavior of fine-grained soil-cement mixtures. In Figure 4 it can be seen that the greatest strength losses occur prior to initial set, and that after final set only a small amount of strength loss occurs. It should be noted however that the setting test for cement is somewhat arbitrary, and it depends on the mechanical response of the paste to applied load. Setting time is therefore defined by the frictional resistance of the hydrating paste. Similarly, cement stabilized soils exhibit increased frictional resistance to applied compaction, when compaction is delayed for a period of time (Figure 7). However, when sufficient compactive effort is applied to overcome the frictional resistance, such that a specified density is achieved, no loss of strength results. The data in Figure 7 do not suggest that either initial or final setting time had any major influence on the compactive effort required to achieve strength and density in the three soil-cement mixtures considered in this investigation.

Application to Compaction Specifications

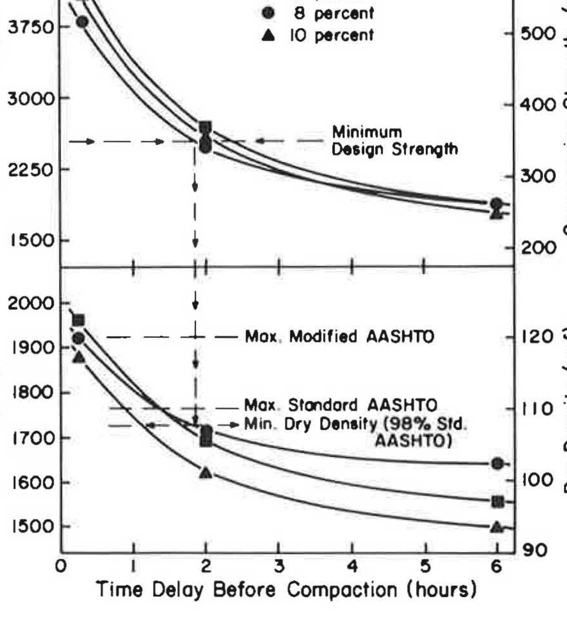
The intent of this research was to establish a method for determining a realistic field compaction specification for cement stabilized soils subject to time delays before compaction. The results of this research have shown that a limiting time delay of one to three hours, depending on soil frictional characteristics, can be tolerated if cement stabilized soils are to be compacted to 100 percent of standard AASHTO density with field compaction equipment. Alternatively, time delays greater than the limiting time delay can be expected to result in reduced dry density and therefore lower strength.

For satisfactory field performance of cement stabilized soils, achieving a given minimum level of strength may be expected to be of primary importance. Strength determines the load supporting capability of the pavement, and it has an important influence on the durability and fatigue resistance of the material. This research has shown that the strength of soil-cement is controlled by the density that is achieved during compaction. Since most construction specifications for cement stabilized soils include a requirement for minimum density, the strength and satisfactory performance of the material is determined by the degree to which the specification is reasonable.

The way in which the procedures described in this report may be used to develop reasonable compaction specifications will be illustrated in the following example.

1. It is first necessary to select a minimum acceptable 7-day compressive strength. Local experience can determine this value. A minimum strength of 2400 kPa (350 psi) is recommended where local experience is insufficient.
2. For the selected soil, the minimum required cement content is determined using conventional procedures (14). Careful attention must be paid to avoiding time delays before compaction in this work. The compacted laboratory specimens from the moisture-density investigation are cured for 7-days at 23°C (73°F) and 100 percent relative humidity. The specimens are capped and their compressive strengths determined. Test results are plotted in a manner similar to Figures 1-3. The moisture content and density for maximum strength are determined and will be used in the compaction specification.
3. Using the same compaction procedures as in step 2, additional specimens are prepared after time delays of two hours and six hours, using optimum moisture content, and optimum plus and minus two percentage points. The specimens are cured as before and the strength and density results are plotted as in Figure 8.
4. The results shown in Figure 8 are interpreted as follows. Entering with the minimum acceptable strength (from step 1), the minimum allowable percentage of standard AASHTO density that will permit this strength to be attained can be determined. This minimum density will be used in the compaction specification. The associated maximum allowable time delay can be read in Figure 8 (approximately two hours in this example). If the time appears to be unrealistically short for the expected construction procedures, then either the minimum acceptable compressive strength must be reduced, or the design cement content must be increased.

Figure 8. Example of application of methods to construction specifications for a cement stabilized soil.



For this example a typical compaction specification might read: "The cement stabilized soil shall have a minimum cement content of 5 percent by weight of dry soil. It shall be compacted at a moisture content of 8 plus or minus 2 percent. A minimum compacted dry density of 172.5 kg/m^3 (107.7 lb/ft^3) shall be achieved." Consideration should be given to utilizing quality control measures such as running average density or probability-based control measures. The use of these measures is widely reported in the literature. Consideration might also be given to specifying a limiting time delay, after which compaction should not be attempted. Care should be taken to avoid making this time period too short, so that it does not subordinate the minimum density requirement.

Conclusions

This investigation has studied the effects of delayed compaction on the strength and durability of three cement stabilized soils, representative of base course and subgrade materials. The results of this investigation have led to the following conclusions:

1. If a specified level of density is achieved, no adverse effects on the strength or durability of cement stabilized soils will be attributable to time delays between mixing and compaction of up to six hours.
2. Time delays greater than one to three hours will increase the required compactive effort for cement stabilized soils to a level which may be beyond the capabilities of ordinary highway compaction equipment.
3. For any particular cement stabilized soil, a limiting time delay can be identified, after which time the required density cannot be achieved.
4. Multiple-part treatment does not appear to offer any advantages over ordinary one-part treatment in terms of the compressive strength of cement stabilized soils.
5. Moisture content, compactive effort, time delay, and soil type jointly affect the strength and durability of cement stabilized soils. A rational means of considering these factors in preparing specifications for field construction control has been described in this report.

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