PROPOSAL FOR IMPROVED TENSILE STRENGTH OF CEMENT-TREATED MATERIALS

Robert F. Cauley, Center for Highway Research, University of Texas at Austin; and
Thomas W. Kennedy, Department of Civil Engineering, University of Texas at Austin

Tensile stresses created in cement-treated bases and subbases by shrinkage and wheel loads have been shown theoretically and from field observations to be very important to the design of pavement systems. However, there is little information that relates the mix design of cement-treated materials to the tensile characteristics of the individual pavement layers. This paper discusses the various mixture and construction factors involved in the design of cement-treated bases and subbases and relates these factors to the tensile and shrinkage characteristics of cement-treated materials. A rationale is developed for including tensile strength considerations in the design method utilized by the Texas Highway Department for cement-treated mixtures not only to improve tensile strength but to minimize shrinkage cracking. Finally, recommendations for the mix design and construction of cement-treated bases and subbases are presented.

•THE tensile properties of cement-treated subbase and base courses are of primary importance in the improvement of the performance characteristics of pavements and should be considered in the design of the cement-treated mixture. Tensile stresses are created at the interface of the layers of a pavement structure when it deflects under the weight of a vehicle as it moves along the highway. Tensile stresses are also produced when drying causes a cement-treated base or subbase to contract or shrink and subgrade friction keeps the base from contracting. Shrinkage cracking occurs when the tensile stresses exceed the tensile strength of the cement-treated pavement layer.

At present very little information is available that can be used to design a mixture entirely on the basis of tensile strength criteria. Theoretical analyses can predict the magnitude of the tensile stress in a pavement subjected to loads; however, even if these estimates are accurate, there is no way of relating tensile properties to the ability of the pavement material to resist environmental influences and repeated applications of load. This can be accomplished only through additional study or indirectly from field observation and evaluation of the performance of pavements composed of materials with known tensile properties.

Thus, mix design and construction procedures should be used to improve the tensile strength of cement-treated bases and subbases, which in turn should improve the load-carrying capacity of the pavement and minimize shrinkage cracking. This paper attempts to relate the tensile strength characteristics of cement-treated materials to findings concerning shrinkage cracking and presents a mix design procedure that considers these characteristics.

FACTORS INFLUENCING TENSILE STRENGTH AND SHRINKAGE CRACKING OF CEMENT-TREATED MATERIALS

Figures 1 and 2 show the relationships between tensile strength and various mixture and construction factors for cement-treated materials. These relationships were developed using a regression equation obtained from a previous analysis (2). The tensile

Publication of this paper sponsored by Committee on Soil-Portland Cement Stabilization.

Figure 1. Relationship between tensile strength and cement content for rounded gravel and crushed limestone.

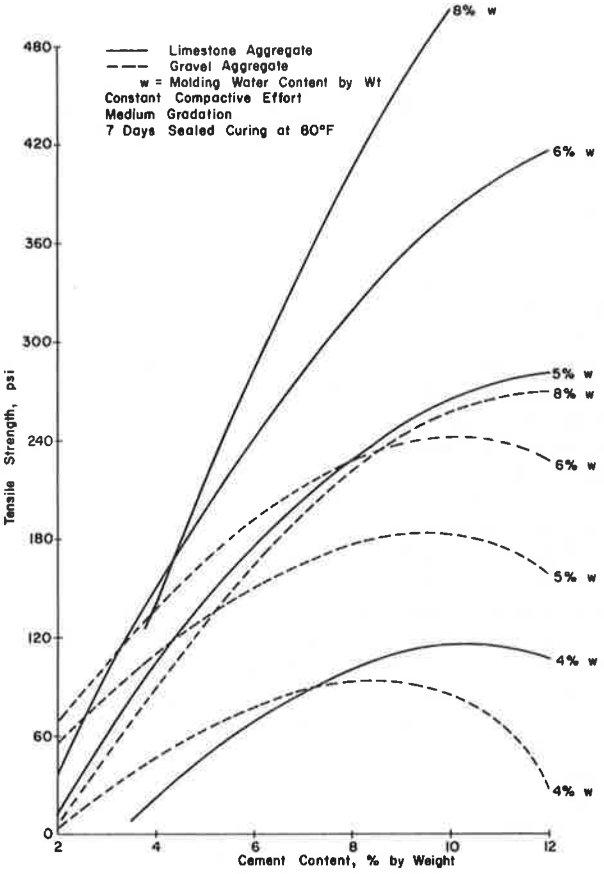
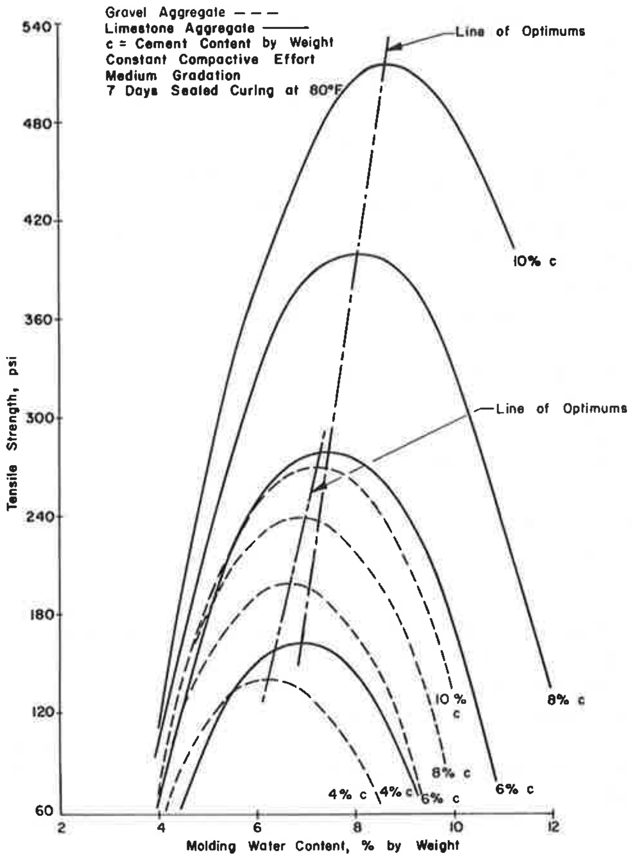


Figure 2. Relationship between tensile strength and molding water content for rounded gravel and crushed limestone.



behavior trends illustrated in these relationships are discussed and interpreted in terms of previously reported observations concerning shrinkage cracking of cement-treated soils.

Type of Soil

The tensile properties of cement-treated materials were studied for two types of soil: a basically smooth, nonporous gravel and an angular, rough-textured, comparatively porous crushed limestone. It was found that the mixtures containing limestone aggregate were stronger than mixtures containing gravel for tensile strengths greater than approximately 125 psi and that the strength differential increased as molding water content and cement content increased. This could indicate that the surface texture and angularity of the aggregate are more important than its inherent strength, since limestone was the weaker aggregate. Aggregates with a rough surface texture and angularity provide a stronger bond with the cement matrix and better packing of the cement-treated mixture. Also, it was found (16) that in specimens prepared with limestone the aggregate failed before the cement matrix did, whereas with gravel the initial failure was at the aggregate-cement interface.

Tensile strength was found to increase as gradation became coarser. The increase in strength was probably due to the decreased surface area of the coarse-graded material, as compared with the fine-graded material, because the amount of cement required to produce a structural material decreases as the surface area of the soil decreases (3). It has also been found (18, 22) that a well-graded soil is preferable to one that has a uniform or open gradation, since higher densities are attainable, the void content is minimized, and these soil types require the least amount of cement for adequate stabilization.

With regard to the cement stabilization of soils containing cohesive material, current specifications of the Texas Highway Department (21) require that the soil be pulverized so that a minimum of 80 percent passes a No. 4 sieve, and it has been shown (6) that this requirement is satisfactory from the standpoint of the durability characteristics of a soil-cement mixture. A more appropriate criterion for the establishment of a maximum acceptable percentage of cohesive material in a cement-stabilized mixture, however, may be the shrinkage characteristics of the mixture.

George (9) found that the shrinkage crack intensity increases with the type and amount of clay-size particles in the soil. Cement-treated mixtures containing kaolinite were found to shrink faster, whereas total shrinkage was higher for those containing montmorillonite. It was recommended that the clay content be limited to 8 percent if the clay mineral is montmorillonite, 15 percent if it is kaolinite, and appropriately interpolated amounts of each if the soil contains both clay types. Also, the soil should not contain large aggregates (greater than 1-in. nominal size) because these aggregates intensify the stress in the shrinking matrix and enhance crack intensity.

Thus it appears that a well-graded soil with a minimum of cohesive material should be specified for a cement-treated mixture and that possibly an angular coarse aggregate with a rough surface texture should be used rather than a rounded, smooth gravel.

Cement Content

Cement content is the most significant factor affecting unconfined compressive strength, shrinkage cracking, and tensile strength of cement-treated soils (6, 12, 15, 16). It has been shown (6, 16) that compressive and tensile strengths increase with an increase in cement content, provided there is adequate moisture for hydration of the cement. In addition, shrinkage crack intensity decreases, even though overall shrinkage is higher, because the greater tensile strengths offset the increase in shrinkage (9).

The relationship between tensile strength and cement content for various molding water contents and two aggregate types is shown in Figure 1. From this it appears that there may be an optimum cement content that produces maximum tensile strength for each aggregate type, molding water content, and curing time. This optimum is obvious for the rounded gravel, and the curves for crushed limestone suggest that there would have also been an optimum cement content for it if specimens containing more than 12 percent cement at water contents of 5 percent and above had been included. The optimum cement content probably represents the maximum amount of cement that can be hydrated at the given water content in a given curing time. Davidson et al. (5) suggest that the same type of relationship exists between cement content and the unconfined compressive strength of cement-treated soils.

For the granular materials studied, shrinkage would be expected to vary directly with the amount of hydrated paste. George (9) found that there was an optimum cement content for minimum shrinkage and that for granular soils this cement content was somewhat below that needed to satisfy freeze-thaw durability criteria (ASTM D560-57). The time rate of shrinkage and crack intensity, however, decreased as the cement content increased, presumably because of the increased tensile strength and ability to resist cracking. George (9) recommended that the cement content be equal to or greater than that specified by the freeze-thaw test criteria and that type II cement be used rather than type I.

Thus it appears that the cement content specified should be one that will result in maximum tensile strength for the specified water content and type of material, with the maximum cement content being limited by economic considerations and the minimum being established by the strength and durability requirements.

Molding Water Content

As implied in the previous section, molding water content is closely related to the tensile strength of cement-treated materials. The relationship between molding water content and indirect tensile strength is shown in Figure 2. This relationship definitely indicates that there is an optimum molding water content that provides maximum tensile strength. However, the actual optimum is dependent on aggregate type, cement content, and probably curing time. Nevertheless, for a given type of material, type and amount of compaction, and curing condition, there appears to be a line of optimums.

The molding water content for a cement-treated soil has traditionally been determined from the results of moisture-density tests (ASTM 558-57 and AASHO T134-70). It has been shown, however (5, 6), that the optimum water content for maximum density does not necessarily coincide with the optimum for maximum strength.

Strength and density tests for various types of cement-treated soils have shown that the water contents for maximum strength are on the dry side of standard AASHO optimum for sandy soils and on the wet side for clay soils. For mixtures containing both sand and clay, it has been found that the difference between optimum for maximum density and optimum for maximum strength is practically negligible for sand-clay mixtures containing more than 25 percent clay (5). With delays prior to compaction of up to 6 hours, Lightsey et al. (13) found that maximum compressive strength and durability did not occur at optimum for density. In granular soils, excess moisture improved the strength and durability characteristics of the mixture. However, with no delay, maximum compressive strengths were obtained at water contents on the dry side of the optimum for density. In cement-treated clay soils, which normally are stronger when compacted on the wet side of optimum, increasing the molding water content 2 to 3 percentage points above optimum had no appreciable effect on the compressive strength and durability of the mixture with delays in compaction of 4 to 6 hours (13).

Water content is also important from the standpoint of minimizing shrinkage and shrinkage cracking. Appreciably larger shrinkage strains have been observed for mixtures compacted on the wet side of the optimum moisture content for density, and it was recommended that cement-treated materials be compacted on the dry side to minimize total shrinkage (9, 11).

Therefore, cement-treated mixtures should be compacted on the dry side of optimum for density in order to maximize tensile strength and minimize total shrinkage, both of which minimize cracking. In addition, delays in compaction should be taken into consideration when the water content for compaction is being established.

Density and Compactive Effort

Cement-stabilized soils that have been compacted to adequate density generally have given satisfactory field performance, provided that minimum strength requirements were achieved. Adequate density usually has been defined in terms of moisture-density relationships for the cement-treated mixture, such as standard or modified AASHO moisture density tests. Since compaction at optimum moisture content does not necessarily produce maximum strength, it can be assumed that maximum density does not necessarily produce maximum strength.

It has been found (2) that there is no definite relationship between tensile strength and density. It should be noted, however, that the specimens studied were compacted using a gyratory shear compactor and that even a low compactive effort produced a high density. Thus the range of densities was comparatively small, 130 to 136 pcf. It is not surprising, therefore, that density did not have a significant effect on tensile strength, because it can be reasoned that, once a given level of compaction has been achieved, additional compaction has little if any beneficial effect and other factors are much more important.

Shrinkage, however, is also affected by density, with shrinkage cracking decreasing with an increase in compactive effort. To minimize shrinkage it has been suggested that cement-treated materials be compacted to the highest density possible, and George (9) recommended a minimum of 95 percent of modified AASHO density.

Because high density would presumably reduce total shrinkage and have little effect on tensile strength, high density would presumably minimize cracking. The only danger in this approach is the possibility that other factors might reduce tensile strength. For example, if a high compactive effort is used without a corresponding decrease in water content, the soil would be compacted substantially on the wet side of optimum, which might cause a loss of tensile strength, or, if the water content is reduced, there might be inadequate water for the hydration of the cement.

Curing

Curing Temperature—Extreme temperatures during the curing period can cause problems in the construction of cement-treated bases and subbases. At temperatures below about 40 F, hydration of the cement stops (4). Therefore, cement-treated materiaals should be protected from freezing for a period of at least 7 days after placement.

Extremely high temperatures also have a significant effect on cement-treated mixtures. Indirect tensile and compressive strengths increase with increased curing temperature (2, 16). These higher strengths are attributed to an increased hydration rate because of the higher temperature; therefore, higher strengths would be expected at earlier ages, although the effect on ultimate strength is probably negligible. However, because shrinkage is related to loss of moisture and because cracking is closely related to the rate of moisture loss, high temperatures and the accompanying loss of water could tend to promote cracking.

It has been recommended that cement-treated subbases and bases not be constructed in hot weather or under conditions of high wind and low humidity (10, 11). However, because these conditions prevail in many parts of the southwestern United States for a major portion of the year, in these areas special attention should be given to sealing the surface of cement-treated bases and subbases immediately after compaction and maintaining the seal for an adequate period of curing.

Type of Curing—The results of previous studies to determine the effect of type of curing generally have always indicated the desirability of sealing the mixture to prevent loss of moisture. Sealing maintains an adequate amount of moisture for the hydration of the cement and thus increases the tensile strength. Pendola et al. (16) found that the average indirect tensile strength for 4-in.-diameter specimens cured for 7 or 21 days in a sealed condition was approximately 200 and 150 percent respectively of the average strength for specimens that were subjected to air-dried curing. Others have shown similar results for compressive strength (14, 17). Thus it is recommended that cement-treated mixtures be sealed immediately after compaction and cured in a sealed condition for an adequate period of time.

Length of Curing—Because cement continues to hydrate for extended periods of time, it can be assumed that longer periods of sealed curing produce higher strengths. Thus the curing period should be long enough to develop adequate strength to resist expected loads and shrinkage stresses. With regard to shrinkage, George (11) found that longer curing in general increases the total shrinkage of sandy soils but that the reverse was true for clayey soils. Nevertheless, he recommended (9) that shrinkage cracking be minimized by an adequate period of curing, because the rate of evaporation of water from the surface of the fresh cement-treated base was found to be the most important factor influencing shrinkage and shrinkage cracking.

Currently the Texas Highway Department determines its cement-treated mixture design on the basis of 7 days of moist curing so that, it is hoped, stresses induced by construction, traffic, or shrinkage will not exceed the strength of the base or subbase. In view of previous findings and current practice, it is recommended that sealed or moist curing be provided for a minimum of 7 days.

MIX DESIGN

The design of cement-treated materials is concerned with establishing the cement content and molding water content that will result in a material with sufficient strength and durability to resist load and environmental stresses. The procedure described in the following sections is a supplement to the mix design method currently used by the Texas Highway Department, but the concept may be utilized for other areas as well.

Texas Highway Department Mix Design Method

The basic criterion of the Texas Highway Department for the establishment of a satisfactory mixture is that the cement content chosen produce a cement-treated base with a minimum compressive strength of 650 psi after 7 days of moist during. The specifications (21) describe the types and gradations of materials for use in construction of the cement-treated base. These materials contain no cohesive material and belong to AASHO soil groups A-1-a or A-1-b, which may be adequately stabilized with cement contents of 3 to 8 percent (19). Three test cylinders are prepared and tested in unconfined compression for each of the following cement contents: 4, 6, and 8 percent. On the basis of these tests, the cement content required to produce a cement-stabilized base of the specified strength is selected.

Procedure for Supplementary Tests

In addition to specimens prepared as a part of the foregoing procedure, it is recommended that supplementary specimens be prepared to determine the cement content and molding water content that will produce maximum tensile strength. For coarse-grained materials these specimens should be compacted on the dry side of the estimated optimum water content for maximum density, since it has generally been shown that tensile strength is maximum and cracking is minimum for materials compacted dry of optimum.

The steps described in the following may be used to establish a cement content and compaction water content that improve tensile strength and reduce shrinkage cracking. Because this procedure is a supplement to that used by the Texas Highway Department, its use is intended for those soil types currently specified in Texas Highway Department specifications (21). In general, good-quality granular materials are economically available in Texas, and for a mix design involving these materials cement contents of 4, 6, and 8 percent should be used in preparing the supplementary specimens (step 1 below). However, if it should become necessary to use other materials, the cement contents contained in Table 1 are suggested as reasonable guidelines for the supplemental procedure. The figures referred to in the following procedures show hypothetical relationships that may serve to clarify the mix design procedure:

1. Determine the optimum water content for the material with a 6 percent cement content. Optimum water contents for 4 and 8 percent cement can be estimated from the relationship (20)

$$W = W_m + 0.25(C - C_m) \qquad (1)$$

where

W = estimated optimum molding water content, percent, for either the high or low level of cement content;

W_m = the optimum moisture content, percent, for the middle level of cement content, determined from the moisture-density curve;

C = the high or low level of cement content, percent; and

C_m = the middle level of cement content.

2. For each cement content, mold duplicate specimens at optimum water content and at water contents that are 1, 2, and 3 percent below the optimum value. Compaction and curing procedures are as outlined in the Texas Manual of Testing Procedures (20). One of the duplicate specimens should be tested in compression and one in indirect tension (1).
3. For each cement content, plot the relationships between unconfined compressive strength and molding water content (Fig. 3a) and between indirect tensile strength and molding water content (Fig. 3b).
4. From the relationships between compressive strength and molding water content, estimate the cement content that provides an unconfined compressive strength of 650 psi (Fig. 3a).
5. Using the relationships between tensile strength and molding water content, determine the water content that provides maximum tensile strength for the cement content determined in step 3 (Fig. 3b).
6. Ensure that the water content determined in step 4 still provides for a minimum compressive strength of 650 psi at the cement content established in step 3. If the minimum compressive strength requirement has been met, then a mix design has been obtained that should give maximum tensile strength for the given cement and water content while meeting current specifications for minimum compressive strength. If the molding water content that gives maximum tensile strength appears to cause compressive strength to drop below 650 psi, then the cement content should be increased by ½ percentage point and the steps repeated beginning with step 3. This iteration should be carried out until a mix design is obtained that gives maximum tensile strength and a minimum unconfined compressive strength of 650 psi.

Based on the reported findings of previously conducted studies of the strength and shrinkage characteristics of cement-treated materials and the findings concerning the indirect tensile strengths of cement-treated materials, it is felt that the foregoing procedure should improve the tensile strengths of cement-treated bases and subbases and minimize shrinkage cracking. At the present time, however, the procedure has not been laboratory- or field-tested and should be tried simply as a supplement to mix design procedures currently used.

Method of Test for Indirect Tension

Specimen Size—Because the Texas Highway Department uses 6- x 8-in. specimens for unconfined compressive testing of cement-treated materials, 6- x 8-in. specimens should be used for indirect tensile testing; 4-in.-diameter specimens can be used, but it is recommended that the same size of specimen be used for testing in both unconfined compression and indirect tension.

Loading Rate—The loading rate currently used for compressive tests on cement-treated materials is 0.14 in. per minute, and it is proposed that this loading rate be used for indirect tensile testing of these materials.

Equipment Required—For testing in unconfined compression, a compression testing machine meeting the requirements of ASTM Designation D1633-63 should be used. The indirect tensile test requires equipment capable of applying compressive loads at a controlled deformation rate, a means of measuring the applied load, and ½-in.-wide curved-face loading strips, which are used to apply and distribute the load uniformly along the entire length of the specimen (1). Thus the compression testing machine mentioned may also be used for testing in indirect tension, provided a guided loading head with loading strips attached to the upper and lower parallel platens is used. Such a device is described in detail by Anagnos and Kennedy (1).

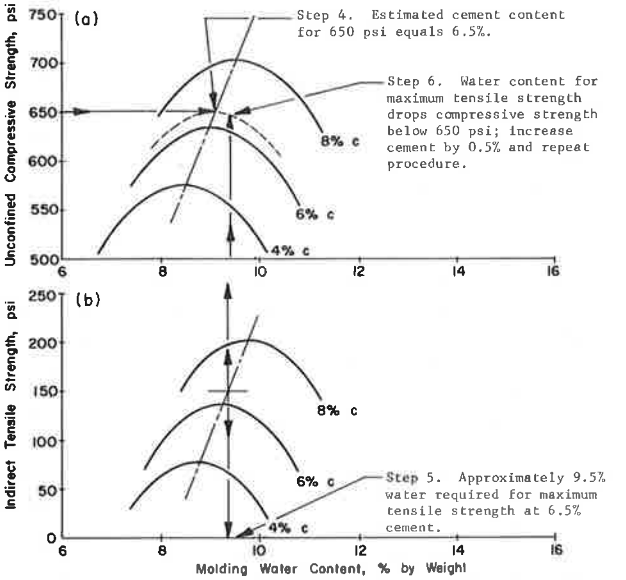
Table 1. Cement requirements of AASHO soil groups.

AASHO Soil Group	Physical Description	Usual Range in Cement Requirement		Estimated Cement Content and That Used in Moisture-Density Test, Percent by Weight	Cement Contents for Wet-Dry and Freeze-Thaw Tests, Percent by Weight
		Percent by Volume	Percent by Weight		
A-1-a	Gravel and sand	5-7	3-5	5	3-5-7
A-1-b	Coarse sand	7-9	5-8	6	4-6-8[a]
A-2	Silty or clayey gravel and sand	7-10	5-9	7	5-7-9
A-3	Uniform sand, nonplastic	8-12	7-11	9	7-9-11
A-4	Sandy loam	8-12	7-12	10	8-10-12
A-5	Silt and clay loam	8-12	8-13	10	8-10-12
A-6	Lean clay	10-14	9-15	12	10-12-14
A-7	Fat clay	10-14	10-16	13	11-13-15

Source: Soil-Cement Laboratory Handbook (19).

[a] These cement contents conform with those recommended by the Texas Highway Department (21).

Figure 3. Hypothetical relationships between compressive and tensile strength and molding water content: (a) compressive strength versus molding water content; (b) tensile strength versus molding water content. C = cement content.



Step 4. Estimated cement content for 650 psi equals 6.5%.

Step 6. Water content for maximum tensile strength drops compressive strength below 650 psi; increase cement by 0.5% and repeat procedure.

Step 5. Approximately 9.5% water required for maximum tensile strength at 6.5% cement.

Note: Step 1. For illustrative purposes, assume that the optimum moisture content for maximum density was 10% for material with 6% cement. Equation 1 then gives estimated water contents of 9.5 and 10.5% for 4 and 8% cement, respectively.

For testing done by the Texas Highway Department a motorized gyratory press can be used for loading specimens; it requires only minor modifications to be utilized this way. These modifications are described in detail by Anagnos and Kennedy (1).

RECOMMENDATIONS

The purpose of this paper is to consolidate the findings and recommendations from two studies concerned with the tensile properties of cement-treated materials (2, 16) and to interpret these findings in terms of the results of studies concerning shrinkage (7, 8, 9, 10, 11). The recommendations that follow are the result of the foregoing evaluation and interpretation.

Materials

1. A well-graded soil with a minimum of cohesive material should be used for cement-treated subbases whenever possible.
2. If it is necessary to use a soil containing cohesive material, it is recommended that the clay content be limited to 8 percent for montmorillonite, 15 percent for kaolinite, and appropriately interpolated amounts of each if the soil contains both clay types.
3. The soil should not contain aggregate larger than 1-in. nominal size.
4. Possible consideration should be given to using type II cement rather than type I for the purpose of minimizing shrinkage cracking, since it has been suggested.
5. Depending on the clay content of the soil, it may be desirable to replace 1 or 2 percent of the cement with lime to minimize shrinkage.

Mix Design

It is recommended that the mix design procedure outlined in this report be used to establish the required water and cement contents for a cement-treated base or subbase. The procedure involves compaction on the dry side of optimum moisture for maximum density and results in a minimum compressive strength of 650 psi and a maximum tensile strength for the given water and cement content.

Construction and Curing

1. Expected delays in compaction of the subbase should be taken into consideration when the moisture content of a cement-treated mixture is specified. The recommendation is that 2 to 4 percent excess compaction moisture be added if the time between mixing and compaction is greater than 2 hours and the soil is granular and if the delay is less than 2 hours and the soil is fine-grained.
2. Cement-treated bases and subbases should be compacted to at least 95 percent of modified AASHO density.
3. The cement-treated subbase should be sealed immediately after compaction and cured under sealed conditions for at least 7 days in order to reduce the possibility of damage due to construction traffic and to reduce shrinkage cracking.
4. A cement-treated subbase should not be constructed under extremely cold weather conditions. Current guidelines, which specify that the subbase not be mixed or placed when air temperature is below 40 F and falling but may be mixed or placed when the air temperature is above 35 F and rising, appear to be satisfactory. The subbase should also be protected to prevent its freezing for a period of 7 days after placement or until it has hardened.

ACKNOWLEDGMENTS

The authors wish to thank the sponsors, the Texas Highway Department and the Federal Highway Administration of the U.S. Department of Transportation, for their support of the research reported herein. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

REFERENCES

1. Anagnos, J. N., and Kennedy, T. W. Practical Method of Conducting the Indirect Tensile Test. Research Rept. No. 98-10, Center for Highway Research, Univ. of Texas at Austin, Oct. 1971.
2. Anagnos, J. N., Kennedy, T. W., and Hudson, W. R. Evaluation and Prediction of Tensile Properties of Cement-Treated Materials. Research Rept. No. 98-8, Center for Highway Research, Univ. of Texas at Austin, Oct. 1970.
3. Catton, M. D. Research on the Physical Relations of Soil and Soil-Cement Mixtures. HRB Proc., Vol. 20, 1940, pp. 821-855.
4. Concrete Technology Instructor's Guide. Portland Cement Assn., 1965.
5. Davidson, D. T., Pitre, G. L., Mateos, M., and George, K. P. Moisture-Density, Moisture-Strength and Compaction Characteristics of Cement-Treated Soil Mixtures. HRB Bull. 353, 1962, pp. 42-63.
6. Felt, E. J. Factors Influencing Physical Properties of Soil-Cement Mixtures. HRB Bull. 108, 1955, pp. 138-162.
7. George, K. P. Cracking in Cement-Treated Bases and Means for Minimizing It. Highway Research Record 255, 1968, pp. 59-71.
8. George, K. P. Cracking in Pavements Influenced by Viscoelastic Properties of Soil-Cement. Highway Research Record 263, 1969, pp. 47-59.
9. George, K. P. Final Report on Crack Control in Cement-Treated Bases. Engineering Experiment Station, Univ. of Mississippi, 1970.
10. George, K. P. Final Report on the Study of Criteria for Strength and Shrinkage Control of Cement-Treated Bases. Engineering Experiment Station, Univ. of Mississippi, May 1968.
11. George, K. P. Shrinkage Characteristics of Soil-Cement Mixtures. Highway Research Record 255, 1968, pp. 42-58.
12. George, K. P., and Davidson, D. T. Development of a Freeze-Thaw Test for Design of Soil-Cement. Highway Research Record 36, 1963, pp. 77-96.
13. Lightsey, G. R., Arman, A., and Callihan, C. D. Changes in the Characteristics of Cement-Stabilized Soils by Addition of Excess Compaction Moisture. Highway Research Record 315, 1970, pp. 36-45.
14. Maner, A. W. Curing of Soil-Cement Bases. HRB Proc., Vol. 31, 1952, pp. 540-558.
15. Nakayama, H., and Handy, R. L. Factors Influencing Shrinkage of Soil-Cement. Highway Research Record 86, 1965, pp. 15-27.
16. Pendola, H. J., Kennedy, T. W., and Hudson, W. R. Evaluation of Factors Affecting the Tensile Properties of Cement-Treated Materials. Research Rept. No. 98-3, Center for Highway Research, Univ. of Texas at Austin, Jan. 1969.
17. Prevention of Moisture Loss in Soil-Cement With Bituminous Materials. HRB Research Report 8F, 1949.
18. Robnett, D. L., and Thompson, M. R. Soil Stabilization Literature Reviews. Illinois Cooperative Highway Research Program, June 1969.
19. Soil-Cement Laboratory Handbook. Portland Cement Assn., 1959.
20. Manual of Testing Procedures, Vol. 1. Texas Highway Dept., Materials and Test Div., Revised Edition, 1971.
21. Standard Specifications for Construction of Highways, Streets, and Bridges. Texas Highway Dept., 1972.
22. Winterbaum, H. F. State-of-the-Art Survey of Soil Stabilization, Vol. 1. Naval Air Engineering Center, Philadelphia, 1968.