British Practice in the Design and Specification of Cement-Stabilized Bases and Subbases for Roads

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Current British practice in the design and specification of soil-cement for use in the base or subbase for roads is described. The composition of the material, the structural design of roads incorporating soil-cement, and the methods used to control the quality of the material in practice are covered. A current specification for soil-cement is appended.

The suitability of a soil for stabilization is based on requirements similar to those in the United States: good grading, low plasticity of the fines, and freedom from deleterious chemical constituents. The pedological classification of a soil profile is used to estimate the depth of soil unsuitable for stabilization because of organic content; measurements of the pH of a soil-cement paste 1 hour after mixing are used as a check on the presence of deleterious organic matter.

Soil-cement is usually required to have a strength and state of compaction higher than certain specified values. The contractor selects the necessary cement content. Procedure involves carrying out tests to determine unconfined 7-day compressive strength of cylindrical or cubical specimens of soil-cement mixtures containing different cement contents. The specimens are usually prepared at a moisture content and dry density as close as possible to what is obtained in practice. If the specimens have a significantly different dry density, a correction is applied to the strength.

Tests to assess the effects of water and frost on a cement-stabilized soil are made only when the soil has certain characteristics: expansive clay minerals in cohesive soils and porous particles in granular soils.

Soil-cement has been widely used since 1945 for the construction of housing estate roads and low-traffic rural roads. These roads usually comprised a 6-in. thickness of stabilized soil with a minimum 7-day compressive strength of 250 psi, with a double surface dressing or thin pre-mixed bituminous carpet.

Cement-stabilized materials have also been used for the construction of main roads, in particular as the subbase of concrete and bituminous-surfaced roads. The most recent specification requires that the stabilized soil should have a minimum unconfined 7-day compressive strength of either 400 psi for cylindrical specimens or 500 psi for cubical specimens.

Paper sponsored by Committee on Soil-Portland Cement Stabilization.

The quality control of soil-cement during construction is based largely on tests to check the strength and state of compaction of the laid material. If the compaction state of the laid material differs significantly from that of the test specimens, corrections are made to obtain a more reliable strength indication.

•THE SYSTEMATIC use of soil-cement as a road base material in Great Britain dates from 1939, when the Road Research Laboratory followed up a study of American experience by carrying out a program of laboratory tests and small-scale field trials on soil-cement mixtures.

From the outset, it was decided to depart from American practice by using the unconfined compressive strength instead of the results of two American durability tests for evaluating the composition of soil-cement mixtures. This probably arose partly from doubts of the relevance of the results of the American tests to the performance of soil-cement as a road base material in the less severe climate of Great Britain and partly from a desire to adapt the equipment and test procedure used for the testing of concrete.

Strength as a criterion for the quality of soil-cement has provided a valuable basis for obtaining a better understanding of the properties and factors that can affect soil-cement performance in practice, and has helped to insure production at more uniform standards with consequent improvement in performance.

With increasing knowledge of factors affecting soil-cement strength, it became apparent that small differences in moisture content and state of compaction from the specified requirements could have as great an effect on the properties of the soil-cement as a significant error in cement content. This led to the view that specifications for soil-cement should require that strength and state of compaction exceed specified values and that the contractor should select a cement content which would consistently meet the strength requirement. This may represent a significant difference from the usual American practice.

Soil stabilization work in Great Britain is usually carried out either by direct labor under the control of the road authority or by a contractor working to the road authority's specification. In both approaches, however, decisions have to be made as to the suitability of a particular soil for stabilization, the moisture content and the state of compaction, and the required cement content for minimum strength.

COMPOSITION OF CEMENT-STABILIZED SOILS

The basic procedure followed in design of the composition of cement-stabilized soils broadly comprises four stages:

1. Laboratory tests of the physical and chemical properties of the soils are made to select soils suitable for stabilization with portland cement.
2. Laboratory tests, and sometimes full-scale trials, are made to determine the moisture content and state of compaction that can be consistently achieved with the cement-stabilized soil under average practical conditions.
3. Laboratory tests are made to determine the cement content which, for the selected moisture content and state of compaction, will enable the cement-stabilized soil to achieve a specified compressive strength.
4. The durability of the compacted cement-stabilized soil is tested by determining its resistance to the action of frost and of soaking in water.

It is not always essential to carry out all four stages and, with the necessary experience, stages 1 and 4 are often omitted.

SELECTION OF SOILS SUITABLE FOR STABILIZATION

The selection of soils suitable for stabilization is based on the following:

1. The particle-size distribution and plasticity properties must be such that the soil can be stabilized with an economical amount of cement and successfully processed with available mixing and compaction plant.

2. The soils have to be sufficiently free from undesirable chemical constituents that can either prevent the hardening of the cement-stabilized soil or cause a loss of durability through the subsequent disruption of the cement bonds.

Soil Type

Laboratory research and practical experience show that the amount of cement required for stabilization may become excessive with two groups of soil: (a) with certain granular soils, the material may be so single-sized that a considerable amount of cement is required to fill the relatively large volume of voids before any significant gain in strength is obtained (Fig. 1), and (b) with certain cohesive soils the inherent strength of the soil crumbs may be so low as to require a high cement content to provide a sufficiently strong matrix to achieve adequate stabilization (Fig. 2).

To eliminate single-sized granular soils it has been suggested that for British conditions the material should have a uniformity coefficient of not less than 10 (the coefficient of uniformity is the ratio of the particle size for which 60 percent of the material is finer to the particle size for which 10 percent is finer). This limitation will of course depend on the availability of other road-making materials, and in areas where single-sized sands predominate it may be possible economically to justify the use of high proportions of portland cement for stabilization.

Cohesive soils are unsuitable for stabilization if their liquid limit exceeds 45 percent and their plastic limit exceeds 20 percent. The difficulty of successfully stabilizing cohesive soils arises from the inability of many types of mixing plant to break down the soil into sufficiently small aggregations so that a satisfactory micro-distribution of cement can be achieved. Experiments have been made at the Road Research Laboratory (1) to determine the effect of the degree of pulverization on the unconfined compressive strength of a cement-stabilized clay soil. Some results of these experiments (Fig. 3) show that to obtain an adequate strength with a reasonable cement content the degree of pulverization has to be such that the majority of the aggregations are finer than $^3/_{16}$ in. There is a British Standard test (2) for determining the degree of pulverization, defined as the ratio of the weight of aggregations finer than $^3/_{16}$ in. to the total weight of the soil, expressed as a percentage. A degree of pulverization of at least 80 percent is often required for successful cohesive soil stabilization. Investigations of mixer performance shows that this degree of pulverization can be obtained with cohesive soils only by using single-pass mix-in-place plant. Stationary

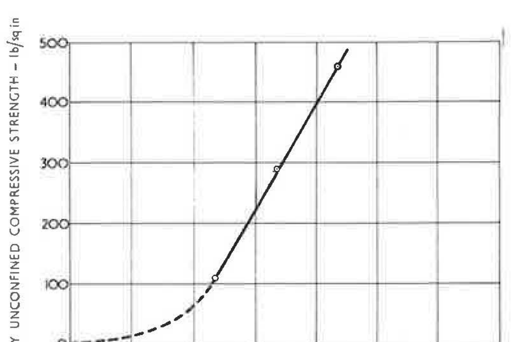


Figure 1. Relation between unconfined compressive strength and cement content for a stabilized uniformly-graded sand.

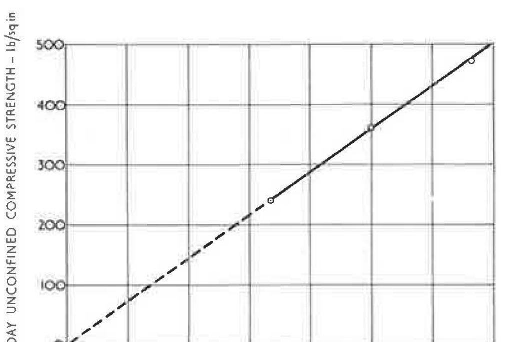


Figure 2. Relation between unconfined compressive strength and cement content for a stabilized heavy clay.

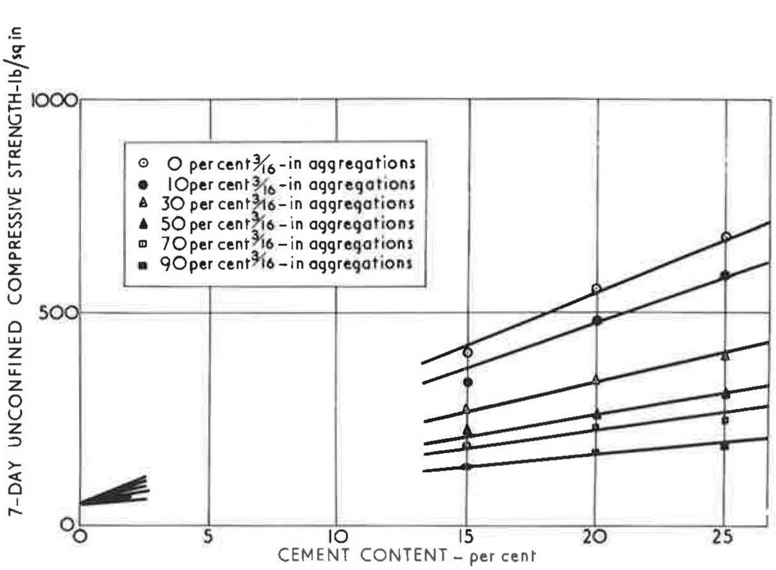


Figure 3. Relation between unconfined compressive strength of stabilized clay and cement content for various percentages of $^3/_{16}$-in. aggregations.

plant is suitable for mixing only granular soils with low cohesivity (3). Figure 4 shows results obtained with a pan-type mixer. With a sandy gravel and sand, both of low cohesivity, it was possible using a 1- to 2-min mixing time to produce a soil-cement mixture having strengths approaching those produced by an efficient laboratory-type mixer. With the cohesive clayey gravel and silty clay soils, only about 50 percent of the strength of the laboratory-mixed material was obtained in 1 to 2 min. When stationary plant is to be used for mixing, therefore, a further limitation has to be imposed on the permitted types of soil to be stabilized; that is, this type plant can only be used satisfactorily with non-plastic materials or granular materials containing less than about 10 percent plastic fines. The suggested limits of grading for single-pass mix-in-place and stationary plant work are shown in Figure 5.

Organic Matter

The presence of organic matter in the surface layers of soil often renders them unsuitable for stabilization with cement. In Great Britain organic matter can extend down to a depth of as much as 5 ft. The presence of a deep surface layer of organic soil may make it impracticable to use the mix-in-place method or to use the site as a borrow pit for materials, and a simple means of recognizing this situation is required. It has been found that the pedological classification of soil profiles used in agriculture meets this particular requirement (4). Over most of the country only five types of profile have to be considered: (a) the calcareous and (b) the high base status brown earth, for which no difficulty arises from the presence of organic matter right up to the

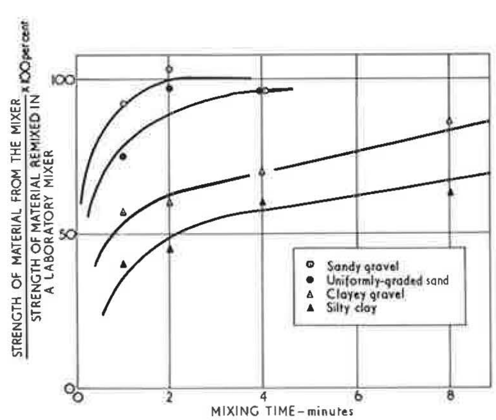


Figure 4. Results of mixing tests on stabilized soils produced by a pan-type concrete mixer.

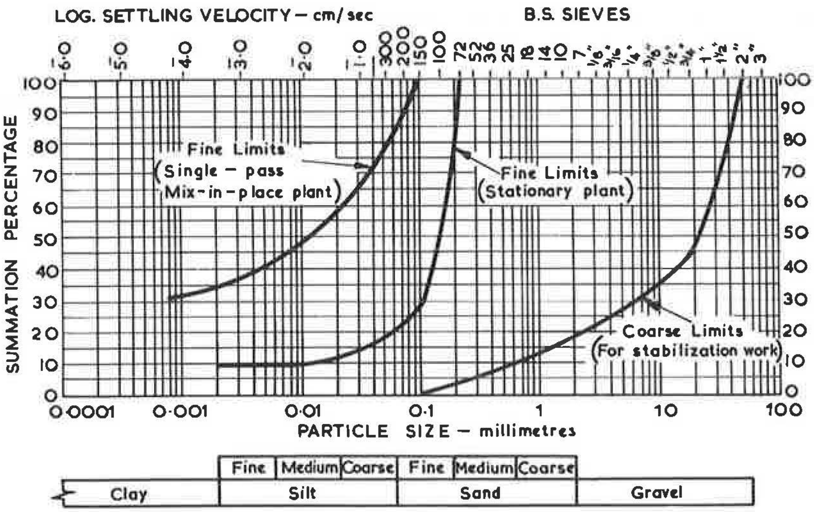


Figure 5. Limits of recommended grading for single-pass mix-in-place and stationary plant soil stabilization.

surface of the ground; (c) gley profiles, for which soils are suitable for soil stabilization usually below a depth of 15 in.; and (d) the low base status brown earth and (e) the podzol profiles, for which the soils are suitable for stabilization only at depths exceeding 2 to 5 ft. The whole of Great Britain is in the process of being mapped on a pedological basis, so that it is sometimes possible to identify the type of pedological profile directly from maps. Where this is not possible it is relatively simple to recognize the type of profile by visual examination in trial pits, and the two types of brown earth profile can be distinguished by a pH test on the soil.

Furthermore, a simple diagnostic test can be used to detect the presence in soils of organic matter that can prevent the normal hardening of portland cement (4). This test consists of making up a soil-cement paste using 10 percent portland cement and determining the pH value of the paste 1 hour after the addition of the water. A pH value below 12.1 indicates the presence in the soil of organic matter capable of preventing or hindering the proper hardening of the cement (Fig. 6). A higher value than 12.1 does not necessarily insure satisfactory hardening of stabilized soil; therefore, the test is used as a rejection test for unsuitable soils.

The determination of the calcium absorption capacity of soils has also been investigated as a diagnostic test for the presence of organic matter. This test has been of value in detecting organic matter in clean sands, a minimum calcium absorption value of 75 mg per 100 g of dry soil being the appropriate criterion. However, the test was found to be unsuitable for use with clay soils because of the ability of the clay fraction to absorb calcium in addition to the organic matter.

Sulfates

It is not uncommon for calcium sulfate, and more occasionally magnesium sulfate, to occur naturally in British soils. Research carried out at the Road Research Laboratory has shown that when such soils are stabilized with portland cement the resulting material may lack durability, particularly if subjected to an increase in moisture content after the material has hardened (5). It appears that disintegration of the stabilized soil may be brought about by a reaction between clay and sulfate ions in the presence of lime and excess water. There is some evidence to suggest that this reaction can result in the formation of ettringite (calcium sulfo-aluminate); this mineral occupies a greater volume than the reactants from which it is formed; an expansion which destroys

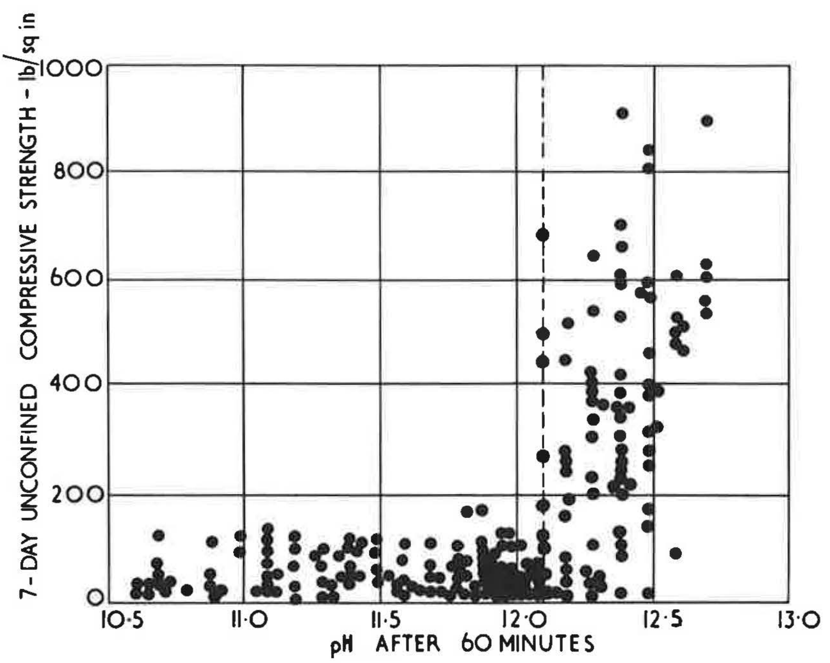


Figure 6. Relation between unconfined compressive strength and pH value for 10:1 soil-cement mixtures.

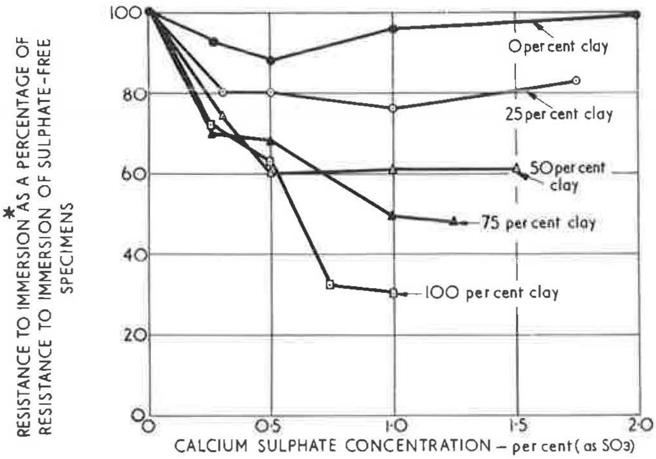
the bonds in the cement-stabilized soil can result. The extent of the reaction depends on the amount of clay in the soil, and it has been shown that the rate of disintegration increases with increase in proportion of clay in the stabilized soil (Fig. 7). It appears that a soil is unsuitable for stabilization with cement if it contains a very small proportion of sulfate ions, although it is not possible to put a value on this proportion from available knowledge. Determination of the sulfate content of soil is carried out according to test No. 8 of British Standard 1377:1961 (6). The sulfate is extracted from the soil with hydrochloric acid, and the sulfate is then precipitated from the solute as barium sulfate by the addition of barium chloride solution.

MOISTURE CONTENT AND COMPACTION STATE OF STABILIZED SOIL

After establishing the soil as suitable for stabilization, investigations are then made to determine the proportion of cement that will achieve a given compressive strength in practice. This involves making up specimens of soil-cement using different proportions of cement and determining their strength usually at 7 days but sometimes at 28 days. The test specimens have to be prepared at a moisture content and state of compaction as close as possible to those obtained in average practice. The next stage is to decide on the particular values of moisture content and state of compaction to use in these tests.

Moisture Content

The primary consideration affecting moisture content selection is that it should permit high states of compaction to be achieved in practice. Extensive investigations have been made at the Road Research Laboratory into the performance of plant for compacting soils (7, 8, 9, 10). These investigations have shown that with many types of granular soil a reliable guide to the moisture content to be used in practice is the optimum moisture content obtained with the British Standard compaction test using



*(Resistance to immersion = Strength of specimens cured for 7 days, soaked for 7 days x 100 per cent / Strength of specimens cured for 14 days)

Figure 7. Effect of calcium sulfate on strength of cement-stabilized clay-sand mixtures.

heavy compaction (equivalent to the modified AASHO test). There are, however, some types of sandy soil for which laboratory compaction tests do not accurately reflect the compaction characteristics in practice; in such cases full-scale trials are required to determine the appropriate moisture content for the stabilized soil.

In the case of cohesive soils the test specimens are often made up at a moisture content 2 percent below the plastic limit of the freshly-mixed soil-cement; this moisture content not only permits high states of compaction to be obtained in practice, but also insures a low water absorption capacity in the hardened soil-cement. This latter point is regarded as being important, since failures in cemented bases have occurred in cases where the material was compacted at too low a moisture content.

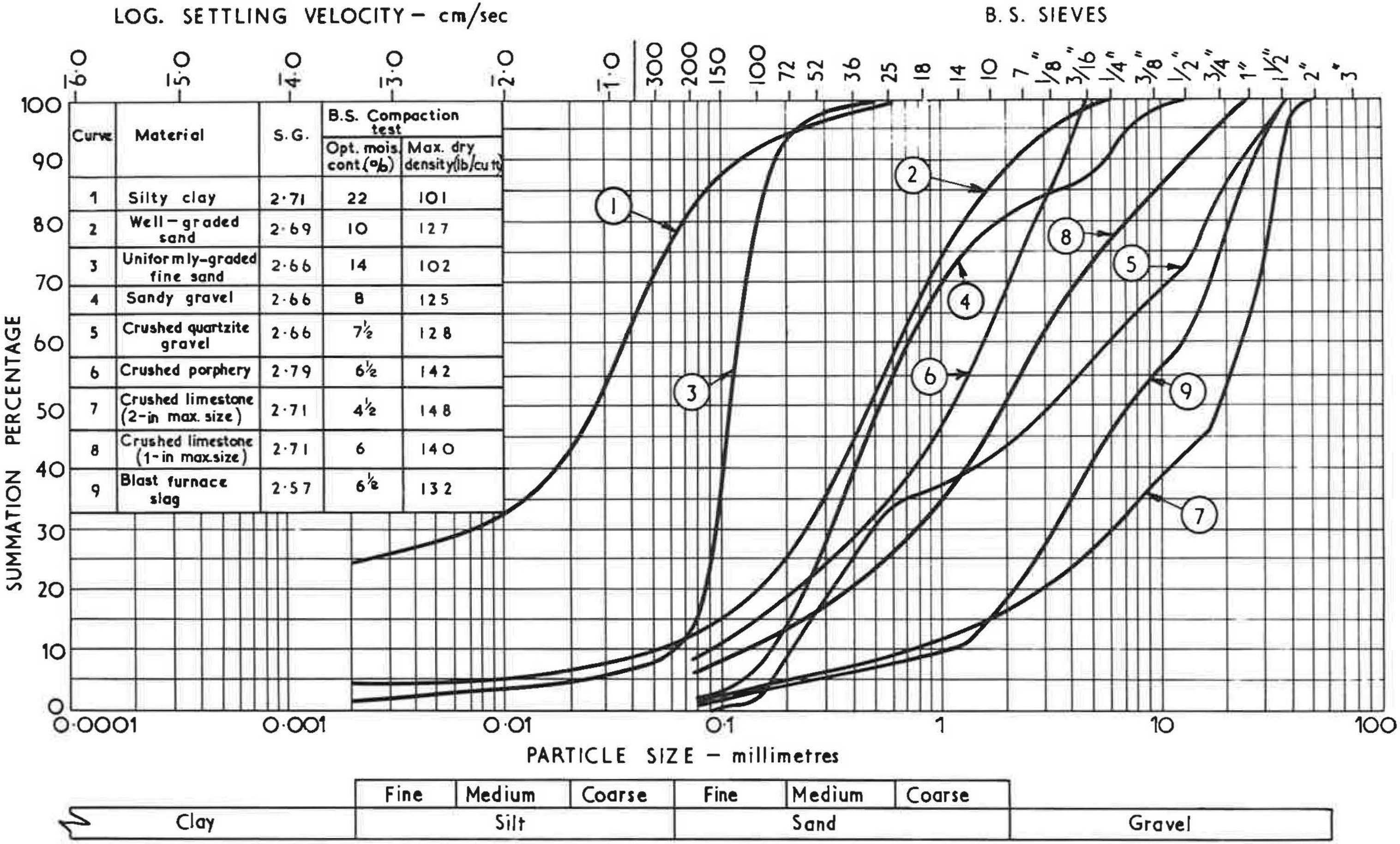
State of Compaction

Specimens are prepared at a dry density as close as possible to that likely to be obtained in practice. It is assumed that a well-compacted stabilized soil will have a dry density equivalent to an air content of 5 percent. The appropriate dry density can then be determined from the specific gravity of the soil particles and the cement and the moisture content of the soil-cement. The required weight of the soil-cement mixture is compacted in a constant volume mold.

An alternative method of preparing test specimens of stabilized soil is to compact the material to refusal using an electric vibrating hammer in a manner similar to that used for making concrete test specimens. Dry density is usually slightly higher than can be consistently produced by the compaction plant normally used for soil stabilization work.

If the specimens have a dry density significantly different from the design value, a correction can be applied to the result of the strength test to allow for the effect of dry density on the strength of the stabilized soil. The importance of making this correction cannot be overstressed as failure to achieve the design state of compaction in practice can have a profound effect on the strength and durability of the material.

Evidence (3) of the importance of obtaining a high state of compaction in cement-stabilized material was obtained in an investigation carried out with a range of soils and crushed stone (Fig. 8). A linear relation was obtained between the unconfined compressive strength of the cement-stabilized material and its dry density when the test results were plotted on logarithmic scales (Fig. 9). The relation between



Curve	Material	S.G.	B.S. Compaction test	
			Opt. mois. cont.(%)	Max. dry density(lb/cu ft)
1	Silty clay	2·71	22	101
2	Well-graded sand	2·69	10	127
3	Uniformly-graded fine sand	2·66	14	102
4	Sandy gravel	2·66	8	125
5	Crushed quartzite gravel	2·66	7½	128
6	Crushed porphery	2·79	6½	142
7	Crushed limestone (2-in max. size)	2·71	4½	148
8	Crushed limestone (1-in max.size)	2·71	6	140
9	Blast furnace slag	2·57	6½	132

Figure 8. Materials used in study of effect of dry density on unconfined compressive strength.

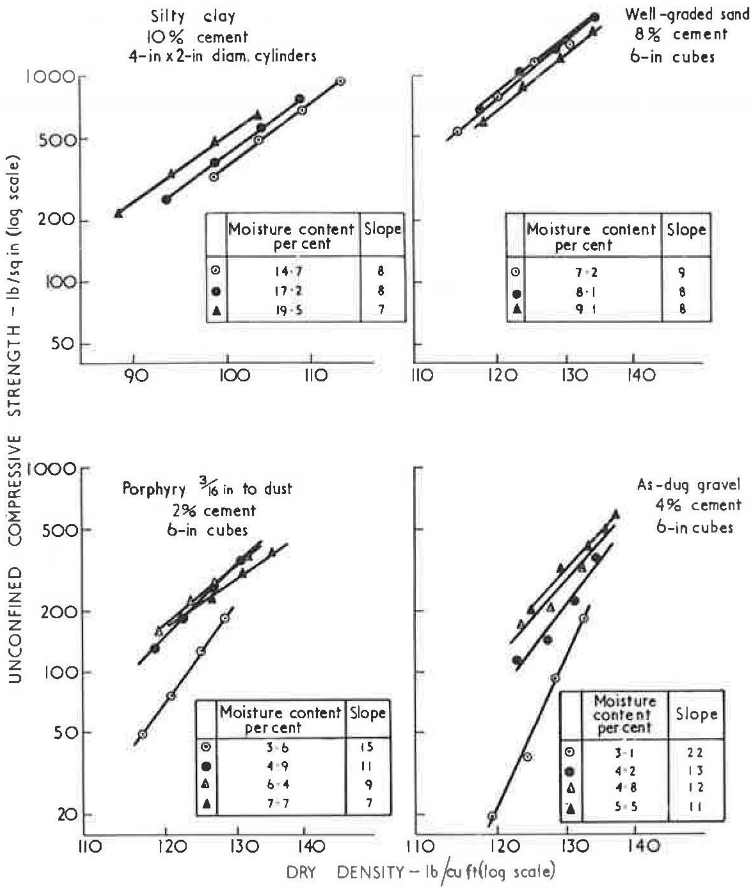


Figure 9. Relations on logarithmic scales between 7-day unconfined compressive strength and dry density for stabilized materials at various moisture contents.

strength and density was

$$S = KD^n$$

in which

S = compressive strength;
D = dry density; and
n and K = constants

The slope of the relation n was found to depend on the type of material and its moisture content, the effect of the cement content being very small. Table 1 shows that the value of n ranged between 5 and 22 with an average of about 10. Considering the average value of n = 10, this means in effect that a change in dry density of only 1 percent will produce a change in the strength of the stabilized materials of 10 percent. This effect is now widely recognized in Great Britain and it has had a considerable influence on both the design and control of cement-stabilized bases.

DETERMINATION OF CEMENT CONTENT TO MEET A SPECIFIED STRENGTH

The tests for determining the strength of stabilized soils are those described in British Standard 1924:1957 (2). These tests require the use of cylindrical specimens having a height-diameter ratio of 2:1. Soils are divided into three groups: fine-grained, medium-grained and coarse-grained. The lengths of specimens for these three soil groups are 4, 8 and 12 in., respectively. Experience has shown that the 12-in. specimens are too cumbersome and heavy to handle; it seems probable that the next revision of the standard specification will require 6-in. cubical specimens instead of 12-in. long cylindrical specimens for coarse-grained soils.

The specimens are cured at constant moisture content; this is usually achieved by coating the surface with paraffin.

Strength determination is usually made at 7 days; the relation is then determined between the 7-day strength of the stabilized soil and the cement content, from which the design cement content is determined. Allowance is made, in the specification for the stabilized soil, for the higher strength achieved with cubical specimens as compared with cylindrical specimens with a height/diameter ratio of 2:1.

Check tests are made in accordance with British Standard specification No. 12 (11), and particular attention is paid to the results of mortar cube tests. In this way allowance can be made for any difference in the properties of the cement used in the laboratory tests and the actual stabilization work.

TABLE 1

VALUES OF CONSTANT n IN THE RELATION $S = KD^n$ FOR MATERIALS STABILIZED WITH PORTLAND CEMENT

Material	Cement Content (%)	Moisture Content (%)	n
Silty clay	10	14.7	8
		17.2	8
		19.5	7
Well-graded sand	8	7.2	9
		8.1	8
		9.1	8
Uniformly-graded fine sand	4	14	8
	7	14	8
	10	14	8
Sandy gravel	4	3.1	22
		4.2	13
		4.8	12
		5.5	11
Crushed quartzite gravel (1½-in. max.)	4	3.7	13
		5.4	12
		7.2	11
		8.7	10
Crushed porphyry (3/16-in. max.)	2	3.6	15
		4.9	11
		6.4	9
		7.7	7
Crushed limestone (2-in. max.)	2	3.3	12
		4.0	9
		4.9	6
		5.5	5
Crushed limestone (1-in. max.)	2	3.0	17
		4.3	11
		5.8	7
		7.0	5
Blastfurnace slag (1½-in. max.)	2	4.1	16
		5.3	12
		5.7	11
		6.4	8

DURABILITY OF CEMENT-STABILIZED SOILS

Experience suggests that cement-stabilized soil made strictly in accordance with specifications is a durable road base material with considerable water and frost resistance. In cases where the material has lacked durability, there has usually been evidence either that the material was inadequately compacted during construction or that it was mixed at too low a moisture content. Laboratory tests made to examine the effects of water and frost on cement-stabilized soils confirm that materials made to specification are highly durable; the addition of even small amounts of cement to a frost-susceptible material reduces the heave to negligible proportions (Fig. 10). Therefore, durability tests are made only when it is suspected that the stabilized soil may be affected by either water or frost as a result of some special soil characteristics. There are two characteristics which have to be considered with British soils: the presence of expansive clay minerals in cohesive soils and weak porous particles in granular soils. With stabilized cohesive soils, the swelling of small aggregations of clay on an increase in moisture content may disrupt the bonds holding the aggregations together and result in considerable softening of the material (Fig. 11). With stabilized granular soils having porous particles, disruption of the material can result by the action of frost forming ice lenses from water drawn through the relatively permeable porous material (Fig. 12). In such cases, tests are useful for determining whether a stabilized material having adequate durability can possibly be produced by increasing cement content.

In B.S. 1924:1957 there is a test for determining the effect of soaking stabilized soils in water. The unconfined compressive strength of a number of cylindrical specimens of stabilized soil is determined at 14 days. Half the specimens are cured at a constant moisture content for this period. The remaining specimens are cured at a constant moisture content for 7 days and then immersed in water for 7 days. The average strength of the immersed specimens is expressed as a percentage of that of the specimens maintained at a constant moisture content. Stabilized soils which are known to be durable rarely suffer a loss in strength of more than 10 percent when subjected to this immersion test.

In the frost test (B.S. 1924:1957), the reduction in the unconfined compressive strength of cylindrical specimens subjected to repeated cycles of freezing and thawing is expressed as a percentage of the strength of specimens of the same age but which have been maintained to constant temperature and moisture content. All specimens are cured at constant temperature for 7 days. Then half the specimens are subjected to 14 cycles of freezing for 16 hours at -5 C and of thawing for 8 hours at 25 C. Freezing conditions are applied only to the top face of the specimen and the bottom face is immersed to a depth of ¼ in. in water at a temperature of 8 C. The test has been criticized on the grounds that there is insufficient control of the temperature conditions during the freezing period and the test needs further development.

Another frost test makes use of compacted samples 6 in. high and 4 in. in diameter. Nine such specimens can be

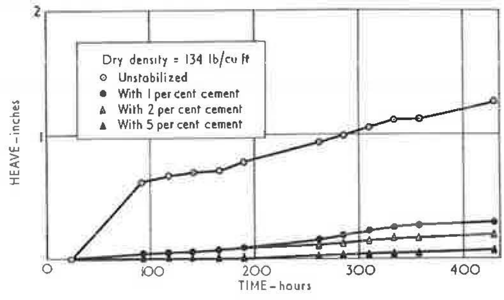


Figure 10. Effect of cement content on frost heave for natural gravel samples stabilized with ordinary portland cement.

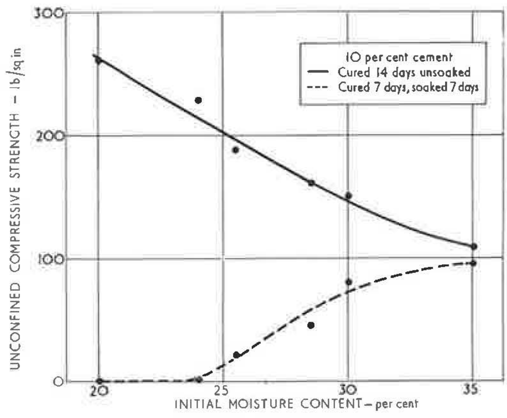


Figure 11. Effect of initial moisture content on loss in strength of cement-stabilized cohesive soil due to immersion in water.

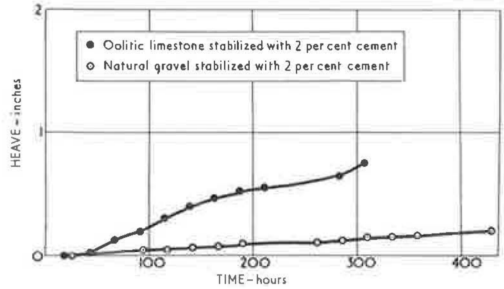


Figure 12. Comparison of frost heave of a porous limestone and a non-porous gravel, both stabilized with ordinary portland cement.

accommodated in the apparatus shown in Figure 13. The specimens stand together on porous ceramic trays in contact with water maintained at a temperature of 4 C. The space between the samples is packed with a coarse dry sand leaving only the upper surfaces exposed to a refrigeration temperature of -17 C. The top of each specimen reaches an equilibrium temperature of -6 C to -10 C, and the zero isotherm remains at a point approximately halfway down the sample. The temperature conditions specified remain constant for about 14 days. Any heave that occurs in the materials is measured daily by push rods in contact with waxed-hardboard caps which cover the top faces of the samples. The frost susceptibility of the stabilized materials is assessed in terms of the amount of heave that occurs after 250 hours of freezing. A heave of more than ½ in. is regarded as an indication of inadequate resistance to severe frost conditions. This criterion is only tentative, and laboratory research is being carried out to investigate its validity.

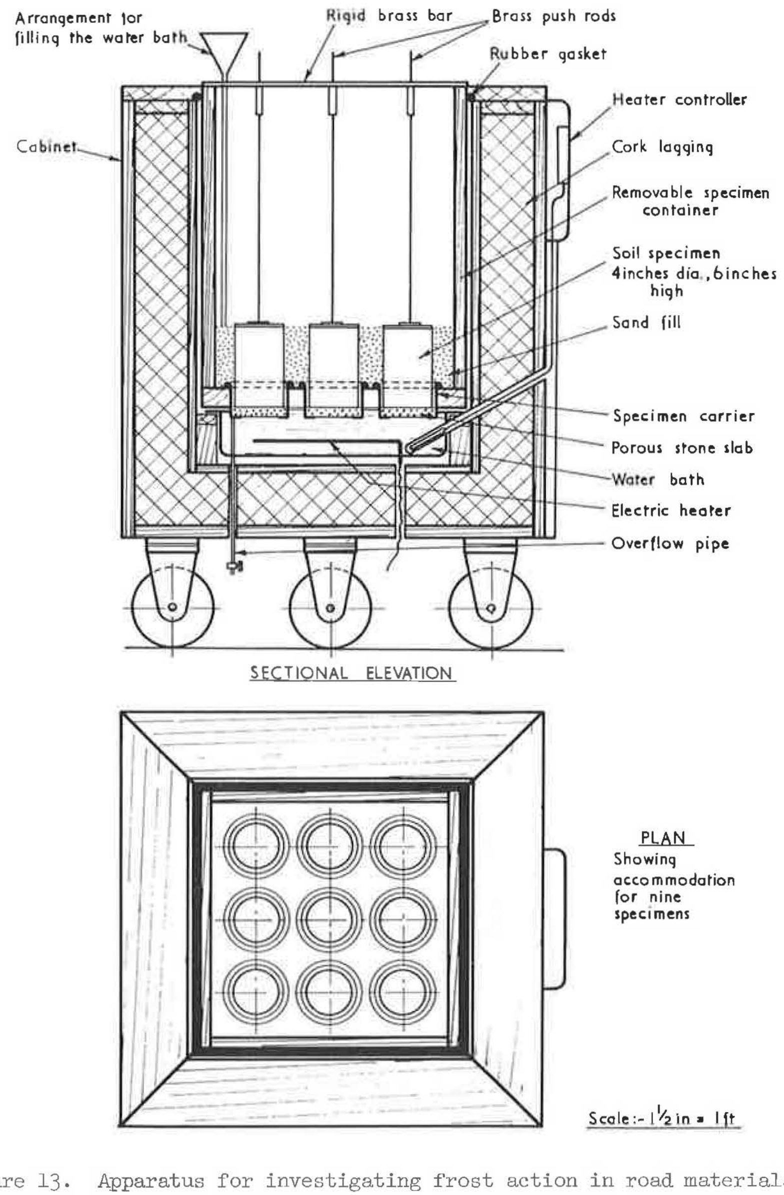


Figure 13. Apparatus for investigating frost action in road materials.

PAVEMENT DESIGN

Although cement-stabilized soil was used during World War II for the construction of military airfields, it has only been used on a considerable scale in Great Britain as a constructional material for roads since 1945. The following briefly summarizes the use of stabilized soil in road pavements.

Minor Roads

Minor roads are principally housing estate roads, lightly-trafficked rural roads, and car parks carrying less than 150 commercial vehicles per day. Soil-cement bases approximately 6 in. thick and usually surfaced with a double surface dressing or thin pre-mixed bituminous surfacing have been used in a considerable mileage of such roads.

The bases were constructed mostly by the mix-in-place method on subgrades having a California bearing ratio (CBR) value generally more than 6 percent. Preliminary design work on the composition of the stabilized soil was usually not as rigorous as that described previously in this paper. After determining the soil suitable for stabilization, laboratory tests determined the cement content necessary for an unconfined compressive strength of 250 psi with cylindrical specimens at 7 days. The origin of this criterion was research carried out at the British Road Research Laboratory in 1939, which showed that a minimum compressive strength of 250 psi at 7 days was required to insure that cement-stabilized soils satisfied the requirements of the American wet-dry and freeze-thaw tests.

Main Roads

The structural design of main roads is governed by the requirements of Road Research Note No. 29 (12). This document, prepared by the British Ministry of Transport and the Road Research Laboratory, contains recommendations for the design of bituminous-surfaced and concrete pavements for various categories of roads defined by the amount of commercial traffic they will carry 20 years after construction. Cement-stabilized soil is permitted as the base material for flexible roads carrying light and medium traffic (i.e., roads estimated to carry less than 1,500 commercial vehicles per day in 20 years). In addition cement-stabilized soil is permitted as the subbase material for both bituminous-surfaced and concrete roads. The material is not permitted as the base of bituminous-surfaced roads carrying heavy traffic, since excessive deformation has occurred on some stretches of heavily-trafficked bituminous roads having cemented bases.

For any given category of road, the pavement design of bituminous-surfaced roads consists of a constant thickness of surfacing and base with a variable thickness of subbase depending on the CBR value of the subgrade. A 6-in. minimum thickness of stabilized soil base is recommended for roads estimated to carry from 150 to 450 commercial vehicles per day; for roads estimated to carry between 450 and 1,500 commercial vehicles per day an 8-in. base is required. With the heaviest category of traffic (more than 4,500 commercial vehicles per day) the thickness of the recommended subbase can be as much as 20 in. (for CBR of 2 percent), but in such cases it is usual to employ a suitable granular subbase material and to stabilize if necessary the top 6 in. of the subbase, generally by mix-in-place method. This stabilized layer, in addition to complying with the strength requirements of the subbase (a CBR value of at least 20 percent for the heaviest category of traffic), also provides an excellent working platform for the construction of the base. By constructing a stabilized soil subbase during good weather, it has often been possible to carry on with the construction of the base during the wet winter months, whereas work has sometimes had to be suspended when unstabilized gravel subbases have been used in similar circumstances.

Two large full-scale road experiments will be carried out by the Road Research Laboratory to determine the conditions under which cemented bases can be successfully used in heavily-trafficked bituminous roads (13). Various compositions of the cemented base will be obtained by using different gradings of aggregate and different strengths of the cemented material. Bases will be constructed to a constant thickness beneath a constant thickness of bituminous surfacing at one site, and certain compositions will be laid to form bases having a range of thicknesses under different types and thicknesses of surfacing at a second site.

SPECIFICATIONS FOR CEMENT-STABILIZED SOIL BASES AND SUBBASES

In the early stages of the development of soil stabilization in Great Britain, the specifications were usually of the "methods" type; that is, the mix proportions (cement content and moisture content) were specified together with the details of the plant to be employed and the method of carrying out the work. The control of the process was thus limited very largely to supervision of the constructional procedure.

With the increased use of stabilized soil and the greater knowledge of the properties of the material which have become available in recent years, the form of the specification has changed. The properties of the final product are specified, and the contractor is given considerable freedom in the way the process is carried out. Although in this "end product" form of specification a considerable amount of control testing is required, it results in a stabilized layer having more consistent properties which is likely to perform more satisfactorily under heavy traffic conditions. It also results in some saving in the amount of cement required for a given strength for the layer and encourages the development and use of improved processing plant.

The main factors now specified are the minimum state of compaction of the layer and the minimum unconfined compressive strength of specimens of the stabilized material made to the same state of compaction. The most suitable moisture content for the stabilized material is determined from preliminary full-scale trials carried out under the supervision of the engineer responsible for the work.

Compaction Requirement

It is usual to define the minimum state of compaction required in stabilized soil in terms of a maximum permissible air content for the material. The maximum air voids usually permitted is 5 percent; that is, the stabilized material has to be compacted to a dry density of at least 95 percent of the saturation dry density. This corresponds approximately to a relative compaction of at least 100 percent of the maximum dry density of the British Standard compaction test which is almost identical to AASHO T99-57.

Specification of the state of compaction in terms of air voids is considered to have the advantage of simplifying the control work where variations in the type of material occur. Thus, in the relative compaction procedure such variations would require frequent laboratory compaction tests to be made before the results of the dry density measurements could be interpreted, whereas the value of the air void requirement can be applied without change to a wide range of materials provided they are reasonably well graded. It must be stressed that in the air void method the actual control of the state of compaction is carried out by dry density measurements and it is only in the interpretation of such results that the air void criterion is employed.

Strength Requirements

It is now usual in Great Britain to specify the strength of stabilized materials in terms of a minimum unconfined compressive strength of the completed layer. No consistent value of the minimum strength has been employed in the past but generally it has been of the order of 250 to 500 psi for specimens cured at constant moisture content for 7 days. The most recent Ministry of Transport specifications for stabilized soil require a minimum value of 400 psi for cylindrical specimens having a height/diameter ratio of 2:1 and 500 psi for cubical specimens. These values refer to the mean of five test specimens made on samples of the stabilized material taken at random over each 1,000 sq yd of completed layer. The specimens have to be compacted to a dry density within 2 pcf of the average value being achieved in the stabilized layer.

Although a lower strength has often been required for subbases in comparison with that for bases, the present tendency is to require the same strength for both as it is now recognized that subbases must withstand high stresses from construction traffic.

A recently revised version of the Ministry of Transport Specification (14) is given in the Appendix.

CONTROL TESTS FOR CEMENT-STABILIZED SOILS

Tests for Compaction and Moisture Content

The sand-replacement test is usually employed for determining the dry density of compacted stabilized layers. Generally, five test determinations are made at random over each 1,000 sq yd of completed layer to provide a mean value for control purposes. Where the results are required very quickly, rapid methods of moisture content determination (15) may be employed but these are not considered to be as reliable as the oven-drying procedure.

Comparisons have been recently made of the results of dry density measurements of cement-stabilized bases determined by the sand-replacement test and on cores cut from the hardened material. This work has indicated that the sand-replacement test can sometimes be seriously in error, the results being up to 10 pcf higher than those for the cores. The probable cause of this error is the slight inwards collapse of the sides of the hole made for the sand-replacement test during excavation. The largest errors have occurred when wet unstable granular material has been employed. As a result of these findings, dry density measurements by the sand-replacement test are now delayed for at least 4 hours after the completion of the compaction work to allow the material to acquire an initial set. This procedure has been shown to result in reasonable agreement between the core measurements and the sand-replacement test.

Studies have been made at the British Road Research Laboratory of the use of gamma and neutron radiation methods of determining the density and moisture content of compacted layers, but this work has indicated that serious errors in the measurement of dry density can result from existing methods. Both the type of material and the density gradients in the compacted soil layer have been found to have a serious effect on the calibration of the apparatus.

Strength Tests

The control of the strength of stabilized soil in practice is carried out by determining the unconfined compressive strength of the material using the previously described test procedures.

For control purposes the strength of stabilized material is normally determined at 7 days. However, research (16) carried out by the Road Research Laboratory has indicated that it is possible to test specimens at an age of only 1 or 2 days and to use the results to predict the strength likely to develop at 7 or 28 days. The accuracy of such predictions (about 10 percent) is thought to be sufficiently close for field control work and any disadvantage in the error of prediction would be offset by the advantage of obtaining the strength at an early stage. However, this early testing procedure has not yet been applied on any large-scale work.

Cement Content Tests

Current British specifications for soil stabilization do not normally specify the cement content of the material. The contractor is responsible for complying with the minimum strength requirements. However, instances may sometimes arise where it is desirable to determine the cement content (such as in connection with trials to determine the performance of the processing plant). Either the E.D.T.A. method or the flame photometer method can be employed. Full details of these two methods are given in Road Research Road Note No. 28 (17). Both methods are based on a comparison of the calcium content of the soil-cement mixtures with that of the soil and cement. For this reason neither method is applicable to soils with high or variable calcium contents and in such cases a less accurate method based on determination of the sulfate content has to be employed.

ACKNOWLEDGMENT

This work was carried out as part of the program of the Road Research Board of the Department of Scientific and Industrial Research, United Kingdom. The paper is published by permission of the Director of Road Research.

REFERENCES

1. Grimer, F. J., and Ross, N. F., "The Effect of Pulverization on the Quality of Clay-Cement." Proc. 4th Internat. Soil Mech. Conf., 2: 109-13 (1957).
2. British Standard No. 1924:1957, "Methods of Test for Stabilized Soils." British Standards Institution, London (1957).
3. Grimer, F. J., "Studies of Factors Affecting the Strength of Cement-Stabilized Materials." Dept. of Scientific and Industrial Research, Road Research Tech. Paper No. 65 (in press).
4. Sherwood, P. T., "Effect of Soil Organic Matter on the Setting of Soil-Cement Mixtures." Dept. of Scientific and Industrial Research, Road Research Tech. Paper No. 61 (1962).
5. Sherwood, P. T., "Effect of Sulfates on Cement- and Lime-Stabilized Soils." HRB Bull. 353, 98-107 (1962).
6. British Standard No. 1377:1961, "Methods of Test for Soil Classification and Compaction." British Standards Institution, London (1961).
7. Williams, F. H. P., and Maclean, D. J., "The Compaction of Soil: A Study of the Performance of Plant." Dept. of Scientific and Industrial Research, Road Research Tech. Paper No. 17 (1950).
8. Lewis, W. A., "Further Studies in the Compaction of Soil and the Performance of Compaction Plant." Dept. of Scientific and Industrial Research, Road Research Tech. Paper No. 33 (1954).
9. Lewis, W. A., "Investigation of the Performance of Pneumatic-Tyred Rollers in the Compaction of Soil." Dept. of Scientific and Industrial Research, Road Research Tech. Paper No. 45 (1959).
10. Lewis, W. A., "Recent Research into the Compaction of Soil by Vibratory Compaction Equipment." Proc. 5th. Internat. Soil Mech. Conf., 2: 261-8 (1961).
11. British Standard No. 12: 1958, "Portland Cement (Ordinary and Rapid Hardening)." British Standards Institution, London (1958).
12. "A Guide to the Structural Design of Flexible and Rigid Pavements for New Roads." Dept. of Scientific and Industrial Research, Road Note No. 29 (1960).
13. Lee, A. R., and Croney, D., "British Full-Scale Pavement Design Experiments." International Conf. on Structural Design of Asphalt Pavements, Univ. of Michigan (1962).
14. "Specification of Road and Bridge Works." Ministry of Transport and Civil Aviation (in press).
15. Croney, D., and Jacobs, J. C., "The Rapid Measurement of Soil Moisture Content in the Field." Roads and Road Construction, 29: 343, 191-4 (1951).
16. Grimer, F. J., and Krawczyk, J., "Strength/Age Relations for Soil-Cement with Particular Reference to the Prediction of Later Strengths from Earlier Ones." Magazine of Concrete Research (1963, in press).
17. "The Determination of the Cement or Lime Content of Cement- or Lime-Stabilized Soils." Dept. of Scientific and Industrial Research, Road Note No. 28 (1960).

Appendix

CURRENT SPECIFICATION IN USE IN GREAT BRITAIN FOR CEMENT STABILIZED MATERIALS

This specification, which forms part of the revised specifications for Road and Bridge Works (14), was prepared by the British Ministry of Transport with the assistance of the British Road Research Laboratory.

(804) Cement stabilized materials for bases and sub-bases

Materials to be stabilized

The material used for stabilization may be a naturally occurring soil, a washed or processed granular material, crushed rock or slag, an industrial waste product (such as pulverised fuel ash, burnt colliery shale) or any combination of these providing the material is free from organic contamination which would affect the setting of the cement and does not contain such a proportion of sulphates or other chemical that the long-term durability of the stabilized material will be affected (See notes for guidance of engineers).

The material shall be well-graded with a coefficient of uniformity of not less than 10 and have a grading finer than the following limits:-

B.S. sieve size	Percentage passing
2 in	100
1½ in	95
¾ in	45
⅜ in	35
3/16 in	30
No. 7	25
No. 25	12
No. 52	5
No. 200	0

If the material is plastic it shall have a liquid limit not greater than 45 per cent and a plastic limit not greater than 20 per cent as determined in accordance with B.S. 1377.

In the event of the contractor offering a material having a grading curve falling slightly outside the limits stated in the Table, or plasticity properties slightly outside the limits given above, the Engineer may approve its use subject to his being satisfied, as a result of such tests as he may require that it meets all other requirements specified in the Clause. The material may, however, prior to its use in the works be subject to disapproval by the Engineer if, although having acceptable grading or plasticity properties, it is shown during the preliminary trials to be incapable of producing a well closed final surface to the compacted layer, or if the compacted stabilized material is considered to be frost susceptible.

Cement and cement content

Ordinary Portland or other approved cement to B.S. 12: Portland cement or Portland blastfurnace cement to B.S. 146: Portland blastfurnace cement shall be used. The cement content shall be such as to provide a crushing strength to the requirements stated in this Clause.

Moisture content

The moisture content of the mixed cement stabilized material shall be determined from preliminary field compaction trials, using the mixed material, employing the type of plant and method of operation which has been approved by the Engineer for the main work and using the optimum moisture content as determined in the laboratory compaction test using heavy compaction (B.S. 1377 Test 11) as a basis.

If water has to be added during mixing it shall be free from organic contamination and the source of supply shall be approved by the Engineer.

Method of stabilization to be used

If the layer to be stabilized does not exceed 6 inches in compacted thickness it may be constructed in one layer within the range 3-6 in after compaction using either mix-in-place or stationary plant for the mixing process provided the plant meets the requirements specified in the Clause. If the course to be stabilized exceeds 6 inches in compacted thickness it shall be constructed in two or more layers each within the range 3 in to 6 in in thickness when compacted. When two or more layers are employed the mix-in-place process will only be permitted for the construction of the bottom layer.

Mixing

The plant to be used for pulverising and mixing the stabilized material shall be approved by the Engineer on the basis of preliminary trials to establish that the plant is capable of producing the degree of mixing and uniformity of the stabilized material specified in this Clause.

If stationary plant is used it shall be of the power driven paddle or pan type and may be of the batch or continuous type. When mix-in-place construction is employed with plastic soils, the mixer shall be of the single-pass type and the degree of pulverisation as determined in accordance with B.S. 1924 achieved in one pass shall not be less than 80 per cent. With non-plastic materials both single and multi-pass equipment will be permitted.

The proportioning of the cement in the stabilized mixture shall be by weight or, if approved by the Engineer, by volume.

If batch mixers are used the appropriate measured amounts of material and cement shall be delivered into the mixer. Water may be added during mixing to bring the moisture content of the resulting mixture to the optimum moisture content for compaction as determined by the preliminary trials. Special care shall be taken with batch type paddle mixers to ensure that the cement is spread uniformly in the loading skip so that it is fed uniformly along the mixing trough and that with both paddle and pan mixers the cement is proportioned accurately by a separate weighing or proportioning device from that used for the material being stabilized. Mixing shall be continued until the mixture has the uniformity required by this Clause and for not less than one minute unless a shorter minimum period is permitted by the Engineer, after satisfactory preliminary trials.

If continuous mixing is used the paddles, baffles and rate of feed of material shall be adjusted to give a uniformly mixed material. The spray bar distributing water into the mixer, if it is required, shall be adjusted to give uniformity in moisture content throughout the mix.

If the mix-in-place process is used the mixers shall be equipped with a device for controlling the depth of processing and the mixing blades shall be maintained or reset periodically so that the correct depth of mixing required is obtained. The cement shall be spread ahead of the mixer by means of a cement spreader of a type to be approved by the Engineer fitted with control gates or other device to ensure a uniform and controllable rate of spread of cement both transversely and longitudinally.

If multi-pass equipment is being employed, the soil shall first be pulverised to the required depth and degree with successive passes and the moisture content adjusted if it is more than 3 per cent below the value required for compaction. The cement shall then be spread and mixing continued with successive passes until the required depth and uniformity of processing has been obtained.

With single-pass equipment the forward speed of the machine shall be selected, in relation to the rotor speed, such that the required degree of mixing, pulverisation and depth of processing is obtained.

The machine shall also be set so that it cuts slightly into the edge of the lane processed previously so as to ensure that all the material forming the layer has been properly processed. If it is necessary to adjust the moisture content of the material to the optimum for compaction, water shall be added during the mixing operation using a water sprayer of such a design that the water is added in a uniform and controlled manner both transversely and longitudinally.

Where hard non-plastic soil is encountered in situ, the Engineer may approve the use of a scarifier or prepariser ahead of the mixer but with plastic soils no prior scarification will be permitted unless the soil is subsequently recompacted before processing with the single-pass mixer.

The output of the mixing plant shall be such that a minimum rate of 20 linear yards per hour measured longitudinally of completed stabilized layer can be maintained in order to permit satisfactory compaction of the material.

Transporting and spreading plant-mixed material

The plant used for transporting the mixed material shall have a capacity suited to the output of the mixing plant and the site conditions and shall be approved by the Engineer. All transporting plant shall be capable of discharging cleanly.

The mixed material shall be removed directly from the mixer after mixing and transported directly to the point where it is to be laid. The mixed material shall be covered during transit and while awaiting spreading to prevent it from drying off from wetting by rain. Where the stabilized material is being used to form a base layer it shall be spread and tamped evenly without delay by an approved paver to the levels and shape to give, after compaction, the specified thickness of layer and surface regularity. Where the conditions or location preclude the operation of a paver or where the material is being used for a sub-base layer, the material may be spread by any other approved method which is shown to avoid segregation of the material and which will produce after compaction the specified levels, shape, thickness of layer and surface regularity.

Compaction

Compaction shall commence as soon as possible after the mixed material has been spread and shall be completed within a period of two hours of mixing or such shorter period as may be necessary in drying weather.

Compaction shall be carried out initially with a 2-3 ton smooth-wheeled roller followed by an 8-10 ton smooth-wheeled roller, and finished, if necessary with a 2-3 ton smooth-wheeled roller or the compaction can be carried out by such other means such as pneumatic-tyred or vibrating rollers, dropping weight or vibrating plate compactors as are approved as a result of compaction trials. The work of compacting shall be continued in such a manner as to produce throughout the full depth of layer an average dry density corresponding to not more than 5 per cent air content at the moisture content at which the stabilized material is compacted or such other air content as the Engineer shall permit as a result of the preliminary compaction trials.

Where it is necessary to employ more than one layer of stabilized material, the material for each successive layer shall, subject to the following proviso, be placed and compacted within two hours of the completion of the compaction of the layer beneath. Where it is not possible to achieve this and the two hour limit has to be exceeded, the surface of any layer remaining so exposed shall be subjected to the curing process required by this Clause.

Special care shall be taken to obtain full compaction in the vicinity of both transverse and longitudinal construction joints and the Contractor shall, if required, provide special small compactors to assist in this work. Any loose uncompacted material left in the vicinity of construction joints shall be removed prior to the placing of fresh stabilized material.

The approval of the Engineer shall be subject to each layer on completion of compaction being well closed, free from movement under the roller, from compaction planes, ridges, cracks or loose material and, within the tolerance for surface finish allowed in this Clause, true to the lines and levels shown on the Drawings. All loose, segregated or otherwise defective areas shall be broken out to the full depth of the layer and recompacted. If this cannot be carried out within the two hour limit specified, the material broken out shall be removed and replaced with freshly processed and properly compacted material without extra charge.

Protection and curing

The surface of any layer of stabilized material, unless it is to be covered within two hours by another layer of the material or other pavement course, and any exposed edges shall be cured as soon as compaction is completed for a period of at least 7 days. Curing shall be achieved by any of the following methods:

(1) Covering the surface of the stabilized layer with an approved impermeable plastic sheeting laid so that joints in the sheeting are overlapped by at least 3 feet and held down at intervals by suitable means so that the sheets will not be blown off the layer by wind.

(2) Spraying the surface of the stabilized layer with an approved quick breaking 55 per cent bitumen emulsion at a rate not lighter than 6 sq yd per gallon of emulsion. Where it is necessary to limit heat absorption of the base, the bitumen emulsion shall, where directed by the Engineer, be lightly blinded with coarse sand or fine gravel at a rate of 200 sq yd per ton.

(3) On very small schemes where the Engineer does not require methods (1) or (2) to be used, covering the stabilized layer with at least a 3-in thick layer of suitable soil which is kept in a damp condition by periodic spraying with water during the curing period and completely removed on completion of this period.

During frosty weather the stabilized layer shall be protected by means of a layer of straw or soil at least 3 inches thick covered by impermeable sheeting and maintained in position during the period of the frost. Work involving the use of cement shall not be continued when the descending air temperature in the shade falls below 38° F nor shall it be resumed until the ascending air temperature reaches 38° F. Frozen material shall not be used in the stabilized layer and all work shall be discontinued if, in the opinion of the Engineer the weather is in any way likely to be harmful to the process of construction.

Where side forms are used in the construction of the stabilized layer they shall be firmly secured in place and not removed until at least 6 hours after the completion of the compaction work. The edges exposed by such removal shall be protected from drying and be cured for a period of at least 7 days after construction by use of any of the methods listed above.

Construction traffic or other vehicles shall not use any stabilized layer until it has been cured for a period of at least 7 days. Thereafter, the use of the stabilized layer by traffic shall be subject to the requirements of Clause 27/20.

If shown on the Drawings or stated in the Bill of Quantities, the stabilized layer shall, after curing and approval be then sealed by surface dressing in accordance with Clause 914 but using instead variations (b), (e) and (f) in Clause 710.

Joints

The Contractor shall so organise his work that longitudinal joints against hardened stabilized material are avoided as far as possible. Wherever possible, in any day's work the area constructed shall extend the full width of the carriageway. At the end of each day's work on completion of compaction, the transverse edge of the layer shall if stabilized be feathered out and shall be cut back vertically to the full depth of construction of the layer before work starts again. Alternatively the work may be terminated against an approved stop end. When the joint has been cut back or formed it shall be adequately protected from drying out. On resumption of work the vertical face of the joint shall be brushed to remove loose material and freshly mixed stabilized material shall be butted tightly against the previous work. Joints in the layers, where more than one layer is required, shall be staggered a distance of 5-10 ft.

Accuracy of surface and the thickness of stabilized base or sub-base

The surface of the completed stabilized base or sub-base shall be within the limits of tolerance of surface irregularity permitted in the specification for surface levels of flexible and concrete bases (Clause 27/18).*

Preliminary trials

At least ten days before the main work of stabilization is started, the Contractor shall construct an area of stabilized material of 500-1,000 sq yd extent as stated in the Bill of Quantities as a preliminary trial at a site to be approved by the Engineer. For this trial the Contractor shall use the materials, mix proportions, mixing, laying, compaction plant and construction procedure that is proposed for the main work. The preliminary trial is to test the efficiency of mixing, spreading and compaction plant and the suitability of the methods and organisation proposed by the Contractor. The results of the dry density measurements made in the stabilized trial area will be used to confirm the moisture content and minimum state of compaction to be attained in the main stabilization work.

Crushing strength and uniformity of the mixed material

The average crushing strength at an age of 7 days for each batch of 5 test specimens made and tested in accordance with Clause 30/2 shall not be less than 400 lb/sq in for cylindrical samples having a height/diameter ratio of 2:1 or 500 lb/sq in for cubical specimens. If an area of stabilized layer represented by the 5 test specimens has an average strength less than the specified minimum values the area shall be replaced with acceptable stabilized material.

In addition to complying with the minimum specified strength, the stabilized material shall have such a uniformity that the root mean square value of the coefficient of variation of crushing strength of five successive batches of 5 test specimens shall not exceed 40 per cent.

30/2 Provision for testing cement-stabilized material

Samples of the mixed cement-stabilized material shall be taken from the site immediately prior to the compaction of the material. Five samples shall be taken at random times and spacings over each 1,000 sq yd of completed layer or such other area as the Engineer decides. From each sample a cylindrical or cubical test specimen as appropriate to the type of material shall be prepared, cured and tested using the procedure given in B. S. 1924. The specimen shall be compacted to a state of compaction within 2 lb/cu ft of the average density being achieved in the compacted stabilized layer. After preparation the specimens shall be cured at constant moisture content within the range of curing temperatures given in B. S. 1924 for a period of 7 days. The specimens shall then be weighed, the dimensions checked and tested in unconfined compression. A representative portion of the crushed material from each specimen shall be retained for a moisture content determination in accordance with B. S. 1924 and the dry density of each test specimen shall then be determined using the weight, dimensions and moisture content of the material.

The results of the 5 test specimens shall be averaged to give a representative figure for the area from which the samples were originally taken.

To obtain a comparable average value for the state of compaction of the stabilized layer, 5 determinations of dry density shall be made at random over each 1,000 sq yd of stabilized layer or such other area as the Engineer decides and the results averaged. The method to be used for determining the dry density shall be the sand-replacement method according to British Standard 1377; Methods of Testing Soils for Civil Engineering purposes. The measurements shall be made at least 4 hours after the completion of the compaction work and preferably within a period of 24 hours.

*This clause requires an accuracy of surface level of ± $\frac{3}{4}$ in for sub-bases and ± $\frac{1}{2}$ in for bases of flexible pavements.