INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Investigation of some Problems in Soil Stabilization
Recherches touchant certains problèmes de stabilisation des sols

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Summary

This paper describes briefly investigations made, at the Road Research Laboratory, into four problems arising in soil stabilization. These are:—
(1) The stabilization of heavy clay soils with cement.
(2) The stabilization of organic soils with cement.
(3) The method by which surface-active agents waterproof soils.
(4) The stabilization of soils with synthetic resins.

Sommaire

Cet exposé décrit brièvement des recherches, entreprises au Laboratoire de Recherches Routières (Road Research Laboratory), portant sur quatre problèmes qui se posent dans la stabilisation des sols. Ils sont:
1° La stabilisation au ciment des sols argileux lourds.
2° La stabilisation au ciment des sols organiques.
3° La méthode par laquelle l'imperméabilisation des sols est effectuée par l'emploi de matériaux polaires.
4° La stabilisation des sols aux résines synthétiques.

Introduction

Since the last International Conference on Soil Mechanics and Foundation Engineering there has been a considerable increase, both in the United Kingdom and in the British colonies, in the use of stabilized soil for constructing road foundations. In the United Kingdom the emphasis has been on the use of soil-cement for housing estate roads, while in the colonies interest has centred on soil-waterproofing agents for earth roads.

The Road Research Laboratory in the United Kingdom has carried out investigations on problems arising in these applications of stabilized soil, and four such investigations are briefly described in this paper. Two were concerned with extending the range of soils which can be successfully stabilized with cement, and the other two with the treatment of soils with organic chemicals.

The Stabilization of Heavy Clay Soils with Cement

Cement-stabilization is being successfully applied in the United Kingdom to most granular soils and to cohesive soils with liquid limits less than 40 per cent (*Road Research Laboratory*, 1952). A cement content of 10 per cent by weight is usually employed, and construction is normally undertaken by the "mix-in-place" method. It would be advantageous if the use of the process could be extended to cohesive soils with liquid limits greater than 40 per cent. While this could be achieved by adding sand as well as cement to the cohesive soil, such a procedure increases the cost of construction and makes the process less attractive economically.

To determine whether a heavy clay soil (liquid limit 70 per cent) could be stabilized with cement, laboratory experiments were made to determine the unconfined compressive strength at an age of 7 days of the clay-cement mixtures containing from 10 to 40 per cent of cement. The test specimens were compacted to maximum density and optimum moisture content (B.S. compaction test). Some specimens were maintained at a constant moisture content in a damp atmosphere during the curing period, while others were immersed in water for 5 days. The results (Fig. 1) showed that, while 10 per cent of cement was sufficient to produce a material with adequate strength at constant moisture content, 20 per cent was required to prevent the material breaking down in the presence of free water. Further tests showed that stability in the presence of free water could be achieved with 15 per cent of cement if supplemented by 2 per cent of hydrated lime.

Similar experiments made with another type of clay (liquid limit 75 per cent) showed that 20 per cent of cement with 2 per cent of hydrated lime was required to prevent break-down of the stabilized soil on immersion in water.

These experiments will have to be extended to other types of cohesive soils, but they show that if adequate mixing can be obtained in the field, the soil-cement process can be successfully extended to deal with some cohesive soils with higher liquid limits than those that are at present used. Where such soil-cement mixtures are to be used under humid climatic conditions, the strength of the stabilized soil after immersion in water appears to offer the best means of evaluation.
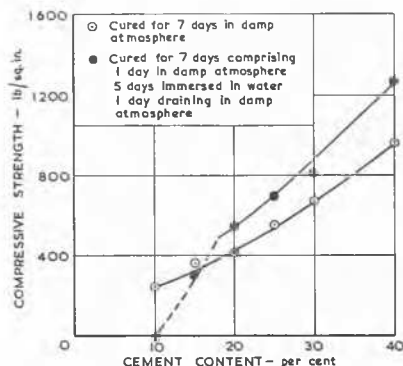

Fig. 1   The Effect of Cement Content on the Compressive Strength of Clay-Cement Specimens
Effet de la teneur en ciment sur la résistance à la compression d'échantillons d'argile-ciment

In the course of other laboratory work, an interesting linear relationship (Fig. 2) was obtained between the California bearing ratio (C.B.R.) of clay-cement specimens and the corresponding unconfined compressive strength. The normal British requirement for cement-stabilized soil of 250 lbs./sq.in. at an age of 7 days was found to correspond to a C.B.R. of 90 per cent. Allowing for the lower efficiency of mixing usually obtained under field conditions, a C.B.R. of 90 per cent for laboratory-mixed material at an age of 7 days is regarded as a satisfactory criterion for assessing the stability of stabilized soil base materials, and it is also compatible with the compressive strength criterion.

Full-scale experiments have shown that mix-in-place equipment of the rotary tiller type is not capable of mixing cement adequately with heavy clay soils, but satisfactory results have been obtained with twin-shaft pottery pug-mills. In order to study the efficiency of such a mixer the compressive strength of soaked specimens of stabilized soil processed in the mixer

and tested at an age of 7 days was expressed as a percentage of the corresponding strength of similar specimens made by mixing the soil and cement in a laboratory double-paddle mixer. With a clay (liquid limit 70 per cent) an efficiency of 45 per cent was obtained with a pottery mixer when cement and lime were mixed with the clay at a moisture content of 27 per cent. The efficiency rose to 67 per cent when the moisture content was increased to 37 per cent. This mixer was used in the construction of an experimental road of clay stabilized with 15 per cent of cement and 2 per cent of lime. The material produced had a granular texture, quite unlike the original clay. No difficulty was experienced in placing it between forms and compacting it with power rammers, to give a material which, after curing, had considerable strength and resistance to softening by water.

These experiments indicate that the stabilization of a fairly wide range of clay soils with cement and lime should be possible in practice. Suitable mixing equipment incorporating the pug-mill principle, but with adequate output, needs to be developed to make the processing of such soils economically competitive with other methods of constructing road bases.

The Effect of Organic Matter in Soil-Cement Stabilization

When cement is added to soil that is free from organic matter, the cement hydrates with the water present in the soil, and forms a hard matrix of set cement round the soil particles. When organic matter is present in the soil, however, this setting can be delayed or prevented. Samples of soil of this type have recently been examined: most of them were sandy soils taken from immediately below the surface layers of agricultural soil. The proportions of organic matter found in the samples ranged from 0.25 to 5.0 per cent by weight of the mineral matter.

The retarding effect is not related to the total quantity of organic matter present in the soil, but apparently to some fraction of it which constitutes an "active" part. Fig. 3 shows the strengths of cylindrical soil-cement specimens made from a sandy soil taken from a proposed road site. The soil was
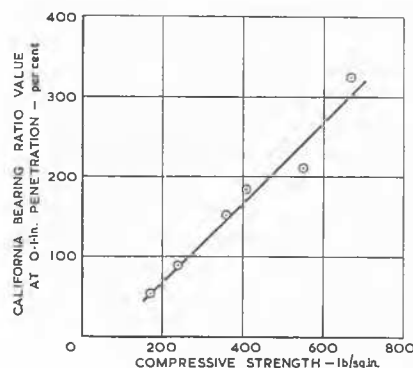

Fig. 2   Relationship Between California Bearing Ratio and Compressive Strength of Clay-Cement Specimens at Age of 7 Days
Relation entre l'indice portant Californien et la résistance à la compression d'échantillons d'argile-ciment
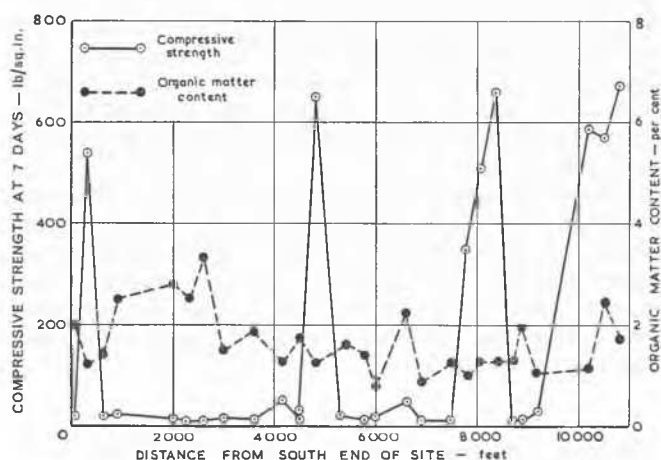

Fig. 3   Organic Matter Contents of Samples of Organic Sandy Soils Taken from the Site of a Proposed Soil-Cement Road, Together with the Unconfined Compressive Strengths of Mixtures of the Soils with Normal Portland Cement
Teneur en matière organique d'échantillons de sol sableux organique prélevés d'un chantier d'une route en sol-ciment et résistances à la compression de mélanges de ces sols avec du ciment Portland ordinaire

stabilized with 10 per cent of normal Portland cement and tested at an age of 7 days. The figure also indicates the proportions of organic matter present in each of the samples of the untreated soil, determined by ignition at 1,000° C. No correlation was found between the organic content of the soil and the corresponding strength of the soil-cement.

When Portland cement hydrates, the cement grains are believed to liberate calcium, silicate and aluminate ions into the water. These subsequently combine to form the hydrated calcium silicate and aluminate compounds which constitute the matrix of the hardened cement paste. The retarding effect of "active" organic matter is believed to be due to its ability to combine with the calcium ions, which are thereby not available for the reactions in which the matrix compounds are formed.

This view is supported by the results of experiments in which the amounts of calcium absorbed by the soils described above were determined. 100 g of the air-dried soil were shaken with 250 ml of a saturated solution of calcium hydroxide, the suspension was filtered and the amounts of calcium remaining in the filtrates were determined. In Fig. 4 the absorption of calcium is plotted against the 7-day strengths obtained with 10 per cent of normal Portland cement; this shows that setting was prevented when the amounts of calcium absorbed exceeded 70 mg per 100 g of dry soil.

The retarding effect of organic matter of this type can be reduced or eliminated if a water-soluble calcium salt is added to the soil simultaneously with the cement. The salt is believed to satisfy the absorptive capacity of the organic matter for calcium ions, thus permitting the calcium from the cement to complete its reaction with the other components in a normal manner. The nitrate, chloride, hypochlorite, acetate and hydroxide of calcium have all been found to be suitable for this purpose. Only the chloride and hydroxide are available economically in the quantities required for road making,
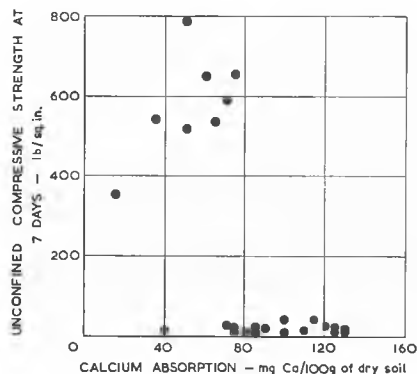

Fig. 4 Effect of the Absorption of Calcium by Organic Sandy Soils on the Unconfined Compressive Strengths of Mixtures of the Soils with 10 per cent of Normal Portland Cement
Effet de l'absorption de calcium par des sols sableux organiques sur les résistances à la compression de mélanges de ces sols avec 10 pour cent de ciment Portland ordinaire

however, and of these the chloride has been found to be the most effective. A convenient method of incorporation is by the use of a form of rapid-hardening Portland cement to which 2 per cent by weight of calcium chloride is added during manufacture.

The 7-day unconfined compressive strengths of specimens prepared with a series of samples of organic sand, taken from different points on a proposed road site and stabilized with

Table 1 Unconfined Compressive Strengths after 7 Days of Specimens of Organic Sand from East Suffolk, Stabilized with 10 per cent of Normal Portland and 10 per cent of Rapid-Hardening Cement

Sample No.	Unconfined compressive strength (lb./sq.in.)	
	Normal Portland cement	Rapid-hardening cement
1	11	30
2	650	915
3	21	415
4	17	327
5	15	181
6	22	379
7	42	80
8	10	747
9	8	167

10 per cent of normal Portland and 10 per cent of rapid-hardening cement (Table 1), show that in all but two cases satisfactory hardening was obtained with the rapid-hardening cement.

Tests with other samples have confirmed the above finding that the amount of calcium chloride present in the rapid-hardening cement is sometimes insufficient to provide the necessary concentration of calcium ions. Satisfactory strengths have been obtained in such cases by adding calcium chloride separately in proportions up to 3 per cent by weight of the soil, together with 10 per cent of normal Portland cement.

The Effects of Surface-Active Waterproofing Agents

A method that has been proposed for stabilizing cohesive soils is to incorporate in them small proportions (1 to 3 per cent by weight of the soil) of surface-active chemicals. The object of using these materials is to prevent a serious loss of bearing strength under wetting conditions by reducing the rate at which water is absorbed by the soil. The water-proofing effect is believed to be due to the formation of water-insoluble films of the chemicals of molecular thickness on the air/water interfaces in the soil, thereby reducing the surface tension of the soil water (Clare, 1949).

The method used hitherto at the Road Research Laboratory for evaluating soil-waterproofing agents has been the capillary water absorption test (Road Research Laboratory, 1952). In this test cylindrical specimens of the stabilized soil are prepared at a predetermined dry density and moisture content such that the air content of the compacted soil is 10 per cent by volume. The specimens are then placed in water 2 mm deep, and the weight absorbed is determined by measuring the increase in weight of the specimens after various intervals of time. While useful for the comparative evaluation of different waterproofing agents, this method does not indicate the highest moisture content likely to be reached by the stabilized soil in the road, and it is therefore impossible to predict what the minimum bearing strength will be in relation to that of the untreated soil.

Croney, 1952, has shown that in humid climates the moisture content reached by compressible cohesive soils in the foundations of roads is likely to be a function of the weight of the pavement or any soil overburden, the depth of the water-table and the suction of the water in the soil. This suction has a continuous relationship with the moisture content of the soil, and the laboratory techniques by which this relationship is
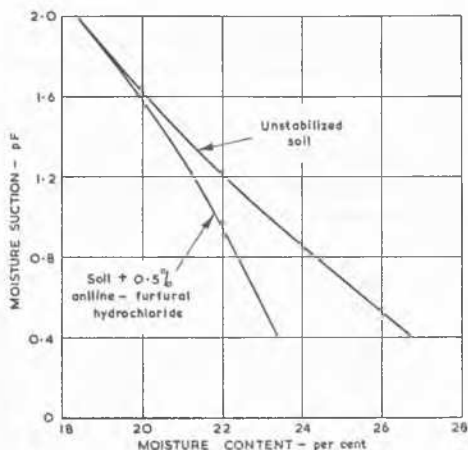
Fig. 5 Suction Moisture Content Relationships (wetting) for a Clayey Sand, With and Without the Addition of a Small Proportion of Aniline-Furfural Hydrochloride

Relations humidité/succion (mouillage) d'un sable argileux, sans et avec l'addition d'une petite quantité d'hydrochlorate d'aniline-furfurol

established have been described by *Croney, Coleman* and *Bridge*, 1952.

For given conditions of overlying weight and depth of water-table, the moisture content of the stabilized soil layer in a road structure will be controlled by the moisture suction of the stabilized soil. Consequently, one requirement of a waterproofing agent is that it should have the effect of reducing the moisture content of a soil for a given suction. Experiments have been made to determine the suction/moisture content relationships for the wetting condition of a clayey sand (20 per cent of particles $< 2\mu$) with and without the addition of a surface-active waterproofing agent, aniline-furfural hydrochloride, which has a satisfactory performance when examined by the capillary water absorption test. Determinations were made of the moisture contents obtained at suctions in the range 0.4 to 2.0 using the pF notation, by means of the suction plate apparatus.

The results (Fig. 5) show that with suctions at the lower end of the range employed, the addition of the aniline-furfural hydrochloride reduced the moisture content attained from about 27 per cent to about 23 per cent, while at the higher suctions (pF 1.5 to pF 2.0) practically no reduction in moisture content was obtained. Under a surfacing of very light weight the suction of a stabilized soil base would not be less than pF 2.0 when the water-table was at a depth greater than 100 cm below the surface. The results indicate, therefore, that the use of the aniline-furfural hydrochloride in such a case would serve a useful purpose only if the water-table occurred at levels less than 100 cm from the surface.

The forces operative in the lower ranges of moisture suction are derived chiefly from the surface tension at the air/water interfaces in the soil, while at higher suctions they are derived from the absorptive forces present at the soil/water interfaces. The results suggest that in the present tests the waterproofing agent acted principally by reducing the surface tension at the air/water interfaces. Unlike the organic compounds normally employed in chemical operations to lower the surface tension of water, the surface-active materials principally under consideration in this work are insoluble in water and, once formed, the films of chemical are coherent and do not disperse from the points at which they are formed.
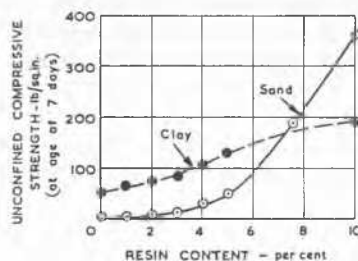
The Stabilization of Soils with Resorcinol/Formaldehyde Resin

Experiments have been made to study the effects of incorporating in soil, proportions ranging from 1 to 10 per cent by weight of a synthetic resin, resorcinol/formaldehyde. The use of this material for stabilizing soil has been proposed by *Blott*. Resorcinol and formaldehyde are believed to polymerize when mixed with damp soil to form a matrix of hardened resin in which the soil particles are embedded, thereby increasing the strength of the soil mass. It is also probable that films of polymerized material are also formed on the air/water interfaces in the soil, thus reducing the rate at which water can be absorbed.

Measurements were made of the strength of cylindrical specimens prepared from a sandy soil (less than 5 per cent of particles $< 2\mu$) and from a clay (50 per cent of particles $< 2\mu$) to which proportions of resin up to 10 per cent by weight were added. These specimens were maintained at a constant moisture content and tested after 7 days.

The results (Fig. 6) show that the addition of 10 per cent of the resin increased the compressive strength of the sand from zero to 360 lbs./sq.in. and that of the clay from 50 to 190 lbs./sq.in. Comparative tests, in which the same soils were stabilized with 10 per cent of normal Portland cement, gave strengths of 187 lbs./sq.in. with the sandy soil and 340 lbs./ sq.in. with the clay.

Capillary water absorption tests (*Road Research Laboratory*, 1952) with an acidic clayey sand ($pH = 4.0$) and an alkaline clay ($pH = 8.0$) showed that a significant waterproofing effect was obtained with both soils (Fig. 7). This contrasts with the results of previous tests with natural resins, which have been

Fig. 6 Effect of Resin Content on Unconfined Compressive Strength of Sand and Clay Specimens Stabilized with Recorcinol/Formaldehyde Resin

Effet de la teneur en résine sur la résistance à la compression d'échantillons de sable et d'argile stabilisés à la résine résorcine/formaldéhyde
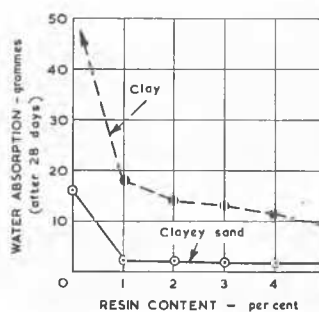

Fig. 7 Effect of Resin Content on Water Absorption of Clayey Sand and Clay Specimens Stabilized with Resorcinol/Formaldehyde Resin

Effet de la teneur en résine sur l'absorption d'eau d'échantillons de sable argileux et d'argile stabilisés à la résine résorcine/formaldéhyde

found to be effective only with acidic soils. The addition of 1 per cent of the resorcinol/formaldehyde resin to the clayey sand gave a waterproofing effect that was only slightly improved by increasing the resin content. With the clay the addition of 1 per cent of the resin prevented the test specimens from disintegrating after 28 days' absorption, and the amounts of water taken up were halved by increasing the resin content to 5 per cent.

Pure pyrogallol was found to be a satisfactory substitute for the resorcinol component of the resin for increasing the strength of the sand, but pyrogallol/formaldehyde resin did not reduce the rate of absorption of water by the clayey sand to the same extent as resorcinol/formaldehyde resin. A crude industrial extract, with a high content of di-hydric phenols, obtained in the low-temperature carbonization of coal, was also examined. It was not found to be a satisfactory substitute for resorcinol for increasing the strength of the sand, but some waterproofing of the clayey sand was obtained when 0.6 per cent of the extract and 0.4 per cent of formaldehyde were added. No improvement in strength or waterproofing was observed in comparable experiments with a crude phenolic oil obtained during the distillation of coal tar.

Measurements have also been made with an Ostwald viscometer of the setting times of solutions of resorcinol in aqueous formaldehyde by studying the kinematic viscosities of the solutions under different conditions. Setting was found to occur after approximately 8 hours at a temperature of 25 °C when 3 per cent of hydrated lime was added to the solution. The time of setting was found to increase if small proportions of lime were used or if the concentration of resorcinol and formaldehyde was below 20 per cent. When more lime was added, or when the concentration of chemicals was increased, however, no reduction in the time of setting was obtained. Increasing the temperature of the resin from 20 °C to 40 °C was found to reduce the time of setting from 8 hours to 1 hour.

Acknowledgments

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