7. G. Y. Sebastyan. Discussion of Airfield Evaluation Procedures by Phillip P. Brown. Journal of the Aerospace Transport Division, Proc., ASCE, April 1965.
8. R. V. LeClerc and T. R. Marshall. Washington Pavement Rating System: Procedures and Applications. HRB, Special Rept. 116, 1971, pp. 112-121.
9. B. J. Dempsey and M. R. Thompson. Durability Properties of Lime-Soil Mixtures. HRB, Highway Research Record 235, 1968, pp. 61-75.
10. M. R. Thompson and B. J. Dempsey. Final Report on Durability Testing of Stabilized Materials. Civil Engineering Studies, Transportation Engineering, Univ. of Illinois, Urbana, Series No. 11, June 1974.
11. L. P. Suddath and M. R. Thompson. Load-Deflection Behavior of Lime-Stabilized Layers. U.S. Army Construction Engineering Research Laboratory, Champaign, Ill., Technical Rept. M-118, 1975.
12. J. L. Eades and R. E. Grim. Quick Test to Determine Lime Requirements for Lime Stabilization. HRB, Highway Research Record 139, 1966, pp. 61-72.
13. J. P. Nielsen and G. T. Baird. Nondestructive Pavement Load Rating. Proc., Symposium on Nondestructive Test and Evaluation of Airport Pavements. U.S. Army Waterway Experiment Station, Corps of Engineers, Vicksburg, Miss., May 1976.

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# Frost Action in Cement-Stabilized Colliery Shale

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**This paper describes a laboratory investigation of frost action in cement-stabilized colliery shales in which their performance is evaluated in terms of the heave developed during prolonged freezing. Tests of nine unburnt and four burnt shales showed that the addition of cement reduced heave, except in the case of some fine-grained unburnt shales. These results are discussed in relation to the effect of cement on pore size, on permeability, and on strength. Of the strength tests undertaken, only the direct tensile test provided data that could be related to the behavior observed during a freezing test. Significant heave occurred only when the heaving pressure generated at the freezing front was greater than the tensile strength. It is concluded that freezing behavior is consistent with an energy balance between the work done in heaving and the energy liberated by supercooled freezing.**

In recent years, there has been increasing interest in the use in road construction of nontraditional materials, such as industrial waste. A major source of such material in Great Britain is in the colliery tips that are probably the greatest single cause of dereliction of industrial land, so that their removal is also desirable in environmental terms. The material in these tips is the residue after coal has been removed in the washery and is generally referred to as colliery shale. It is customary to further describe the material as either unburnt or burnt because burning occurs in some tips under certain conditions. Broadly, burning converts the clay-like shale into a brick-like material having greatly changed properties.

Selected burnt shale has been used extensively in highway construction in Great Britain for many years as fill and as subbase material, but unburnt shale has been used significantly only during the past 8 years, following the issue of technical memoranda (1, 2) by the Department of the Environment that allow its use as common fill. However, because of its clay-like nature, it is unlikely that unburnt shale in its natural state will be suitable for use in pavement structures; the work reported in this paper is part of an investigation that examined its value when stabilized with cement. A preliminary study (3) showed that some unburnt shales could produce an acceptable soil-cement in terms of the strength criteria imposed in practice (4), and this prompted an extension of the work to the effect of frost action on materials of this type (5).

## OVERALL APPROACH

The aim of the investigation was to test colliery shales in their natural state and when stabilized with cement to identify the characteristics that influence their behavior when subjected to prolonged freezing. Because the principal interest was in the effect of cement treatment, the emphasis was on the measurement of tensile strength as specimen fracture appears to be an essential prerequisite for the growth of substantial ice lenses. Samples of nine unburnt and four burnt shales were studied to compare the behavior of the two types of shale and to evaluate their response to cement treatment.

The behavior of test specimens subjected to frost action was evaluated by the heave that occurred and by the pressure generated when the heave was restrained. Permeability tests were made to obtain data on the water-transport potential of the various materials.

### Preparation of Test Specimens

Cylindrical specimens, 152.4 mm high by 101.6 mm in diameter, were produced in constant-volume molds by using static compaction (6). To permit comparison among the results, the cement-stabilized specimens were made at the same moisture content as the unbound specimens [the optimum value determined on the unbound shale by using the 2.5-kg hammer in the British standard compaction test (7)]. The dry densities were adjusted so that the total air voids were the same for both the unbound and the cement-stabilized specimens of each shale.

The stabilized specimens were wax-coated immediately after extrusion from the mold and cured at 20 ± 2°C for the period between preparation and the test procedures.

## Tests Undertaken

### Frost-Heave Test

The Transport and Road Research Laboratory test (6) was used to measure the frost susceptibility and was performed either in a cold room or in a modified deep-freeze cabinet, as reported in detail elsewhere (8). The procedure involved positioning the specimens with their lower surfaces just in contact with water at room temperature and their upper surfaces unsealed. In this position, they were allowed to take up water by capillary flow for 24 h. They were then subjected to an air temperature of -17°C above their upper face with lateral insulation provided by a hardboard disc, so that the freezing front penetrated from the top to simulate field conditions. A heating system maintained the water-bath temperature at 4°C, so that water is available to support ice growth for the 250-h test period. The change in length of the specimens was monitored daily; the total increase in length during freezing is known as the frost heave. Standards based on experience in the severe winters of 1940 and 1947 in Great Britain classify materials heaving less than 13 mm as satisfactory, materials heaving 13 to 18 mm as marginally frost susceptible, and those heaving more than 18 mm as very frost susceptible.

The results given in Table 1 are of particular interest in relation to the suggestion (9) that the addition of 5 percent cement overcomes the frost susceptibility of burnt shale. Two of the four burnt shales remained marginally frost susceptible when stabilized with 5 percent cement and, of the nine unburnt shales tested, the addition of 5 percent cement increased rather than decreased the heave in two instances and had a negligible effect in another. Typical relationships for materials that respond satisfactorily to cement treatment and for materi als that do not so respond are shown in Figure 1. The critical factor, especially for the unburnt shales, appears to be the amount of material finer than 75 µm in the raw shale: This is consistent with the known effect (10) of fine particles on the freezing behavior of engineering soils. This is especially evident in Figure 2, which shows that adding 5 percent cement will reduce heave if the amount of fine material is less than about 30 percent. This provides a tentative basis for predicting the effect of cement on the heaving characteristics of shales.

### Restrained-Heave Test

The experimental method adopted (11) was similar to

**Table 1. Frost heave, restrained heave, and permeability tests.**

| Sample: Location | Sample: Amount Finer Than 75 µm (%) | Cement Content (%) | Average Heave (mm) | Heaving Pressure ($MN/m^2$) | Coefficient of Permeability (nm/s) |
|---|---|---|---|---|---|
| Unburnt shale | | | | | |
| Snowdown | 3 | 0 | 4.1 | 0.09 | 1 100 |
| | | 5 | 0.0 | — | — |
| | | 10 | -0.7 | — | — |
| Chislet sample A | 5 | 0 | 9.5 | — | 43 |
| | | 5 | 3.0 | — | — |
| | | 10 | 2.0 | — | — |
| | | 15 | -1.0 | — | — |
| Betteshanger | 6 | 0 | 5.0 | 0.20 | 49 |
| | | 5 | 1.0 | 0.21 | — |
| | | 10 | -1.0 | 0.20 | — |
| | | 15 | -1.1 | — | — |
| Chislet sample B | 10 | 0 | 10.7 | 0.21 | 22 |
| | | 5 | 1.0 | 0.19 | 16 |
| | | 10 | 0.0 | — | 29 |
| | | 15 | -1.0 | — | 60 |
| Tilmanstone | 19 | 0 | 50.8 | 0.59 | 5.6 |
| | | 5 | 16.5 | 0.48 | 24 |
| | | 10 | 6.2 | 0.43 | — |
| Bedlay | 21 | 0 | 7.9 | 0.36 | 8.1 |
| | | 5 | 2.5 | — | 1.2 |
| | | 10 | 0.9 | — | 3.6 |
| Rothwell | 31 | 0 | 12.7 | 0.50 | 1.6 |
| | | 5 | 12.4 | — | — |
| | | 10 | 4.3 | — | — |
| Peckfield | 38 | 0 | 6.4 | 0.60 | 0.34 |
| | | 2.5 | 14.1 | — | 3.9 |
| | | 5 | 11.5 | 0.48 | 35 |
| | | 7.5 | 9.6 | — | 31 |
| | | 10 | 7.2 | 0.44 | 39 |
| | | 15 | 4.4 | — | 15 |
| | | 20 | 3.6 | — | 4.1 |
| Bullcroft | 43 | 0 | 7.3 | 0.79 | 0.74 |
| | | 5 | 21.8 | — | 45 |
| | | 10 | 8.1 | — | 88 |
| Burnt shale | | | | | |
| Newdigate | 6 | 0 | 16.0 | — | 70 |
| | | 5 | 5.5 | — | — |
| | | 10 | 2.4 | — | — |
| Thornley | 9 | 0 | 30.9 | 0.26 | 380 |
| | | 5 | 8.0 | — | — |
| | | 10 | -1.0 | — | — |
| Tilmanstone | 11 | 0 | 42.5 | 0.36 | 19 000 |
| | | 5 | 16.4 | 0.36 | — |
| | | 10 | 2.5 | 0.40 | — |
| Wheatley Hill | 13 | 0 | 27.5 | — | 170 |
| | | 5 | 14.1 | — | 210 |
| | | 10 | 5.1 | — | 150 |

that used by Hoekstra, Chamberlain, and Frate (12). In this method, the specimen remains within the compaction mold for the 24-h water-uptake period and also during the subsequent freezing procedure. Unidirectional freezing is achieved by placing a thermoelectric device on the top of the specimen and is restrained by the heaving tendency of a steel reaction frame. The restraining force is monitored electrically. The heaving pressure is defined as the value at which the rate of increase is less than 0.001 $MN/m^2/h$ (Table 1).

Permeability

The movement of water to the freezing front generally takes place under conditions of unsaturated flow (13), although the soil immediately below the ice will become saturated if water is available (14). Thus, while the results of saturated permeability tests may not be directly applicable to frost action, they offer a convenient basis for examining the effects of cement stabilization and were therefore undertaken by using an experimental technique based on that of Bjerrum and Hoder (15).

The results given in Table 1 showed that cement treatment increased the coefficient of permeability so that for tests begun after 7-d curing, reduced heave after cement stabilization cannot be attributed to the anticipated reduction in permeability as the pores become filled with the hydration products.

Strength

Values of compressive strength have been reported in many papers dealing with cement-stabilized materials and provide a basis for comparison with the work of others and with the current performance requirements for soil cement. Care should be exercised, however, in interpreting the results obtained in this investigation because the test specimens had a height to diameter ratio of 1.5:1 rather than the more usual value of 2:1 and because the specimens were produced at moisture content and dry density values based on the British standard compaction test, which probably led to a compactive state inferior to that associated with current practice.

The tensile strength was considered to be especially important: Uniaxial tests were made because they allow the properties to be determined without the assumption of elastic behavior under load. However, the test specimens must be held in such a way that the failure load is not significantly influenced by local stress concentrations or by eccentricity. Ultimately, a glued end-plate system based on the work of Hughes and Chapman (16) was used in which the glue could be applied to a damp surface. The system worked well, with the failure locations being well distributed throughout the length of the specimens and with very few end failures (5). The success is attributed partly to the inherent tendency of the end zones of specimens produced in constant-volume molds to be marginally more dense and partly to the fact that the modulus of elasticity and Poisson's ratio for the glue and the stabilized shale were sufficiently close so that the differential lateral strains were not excessive.

The cylinder-splitting test was included in the work, despite of its known limitations (17) as a measure of tensile strength, because the program formulated included measuring the strength after the pretest soaking period, and this was not possible with glued end plates. The splitting test, through its simplicity, allowed this to be done and at least provided a broad indication of the relative behaviors of the materials examined.

Table 2 includes the results of estimating the 8-d direct tensile strength by evaluating the effect of the 24-h pretest soaking on the indirect tensile strength and multiplying the ratio so determined by the 7-d direct tensile-strength values. This defines the strength at the beginning of the freezing treatment and effectively throughout the test because additional hydration during the 250-h freezing period will probably be limited by the low temperature.

Table 2 shows that the cylinder-splitting strength is always greater than the direct tensile strength, the ratio varying between fairly wide limits but being typically 1.7:1. The direct tensile strength for a given cement content also varies with the source of the shale, and there is a trend for the shales having larger amounts of material finer than 75 µm to have lower strengths. Table 2 also shows that the 24-h soaking leads to an increase in strength in some materials but produces a severe loss in strength with others, with the largest reductions occurring with the shales containing a large proportion of material finer than 75 µm.

## INTERPRETATION OF TEST RESULTS

### Correlation of Tensile Strength and Frost Heave

Typical relationships (5) among heave, estimated 8-d direct tensile strength, and heaving pressure are shown in Figure 3 for two shales. These show that no positive heave occurs when the direct tensile strength of the stabilized material exceeds the heaving pressure and support the hypothesis that significant heave occurs only when the specimen has fractured, which confirms the results based on cylinder-splitting tests of Sutherland and Gaskin (18).

### Effect of Frost Heave on Residual Strength

If the frost susceptibility of cement-stabilized materials is evaluated by using heave criteria established for soils (6, 19), it is necessary to consider the changes that accompany only a small amount of heave. The initial cooling of the specimen produces a thermal contraction of approximately 1 mm and, because heave is measured from a datum defined by the height of the specimen before exposure to freezing, the total heave is this movement plus that to overcome the thermal contraction. Measurements taken throughout the test period are plotted in Figure 4 for a selection of cement-stabilized materials that display significantly different behavior patterns.

To measure the disruptive effects of heave, strength tests were performed on the specimens after completion of the heave test. On removal from the heave equipment, the specimens were placed in polythene bags and stored at 20°C for 3 d, and end caps were glued to those intended for the direct tension test. The results of testing at an age of 22 d are given in Table 3.

The results of the direct tension test show that many specimens suffered a substantial (often total) loss of strength in one direction as a result of the freezing test. The amounts of positive movement, which indicate the severity of damage, are plotted in Figure 5. In contrast, neither the compression test nor the cylinder-splitting test discriminate in this decisive way because the direction of fracture during frost heaving is unlikely to greatly influence the failure load either in compression or in cylinder splitting unless there is a general breakdown of the material.

### Effect of Existing Damage

Cement-stabilized materials may contain discontinuities arising from the presence of a plane of weakness caused during compaction or by an earlier exposure to frost. The effects of prefracture were therefore examined by freezing cement-stabilized shale specimens that had a plane of zero tensile strength formed by sawing at the expected equilibrium location of the zero isotherm. The results given in the following table show that the sawed specimens heaved more than the full specimens, but less than the unbound material: Unrestricted ice growth occurs at the discontinuity in the sawed specimens while lensing above this point is still restricted by the cementing action [Sutherland and Gaskin (18) found similar results with cement-stabilized pulverized fuel ash].

| Sample | Cement Content (%) | Average Heave (mm) Full | Sawed | Unbound |
|---|---|---|---|---|
| Unburnt shale | | | | |
| Chislet sample B | 5 | 1.0 | 5.6 | 10.7 |
| Snowdown | 5 | 0.0 | 2.3 | 4.1 |
| Tilmanstone | 10 | 6.2 | 13.6 | 50.8 |

The effect of successive severe winters was simulated by subjecting some of the cement-stabilized specimens to two frost-heave tests with thawing for 7 d at room temperature between the two tests. The values given in the following table show that once the material has fractured, subsequent freezing leads to increased heave, which confirms the results obtained with the sawed specimens.

Figure 1. Relationship between heave and cement content for two unburnt shales showing notably different responses to cement stabilization.

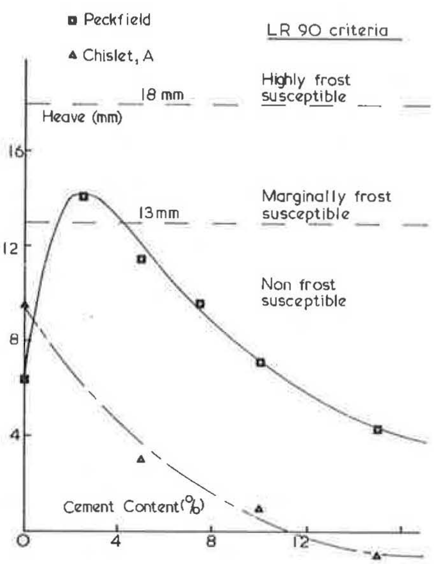



Figure 2. Relationship between heave ratio and amount of fine material in unbound shale.

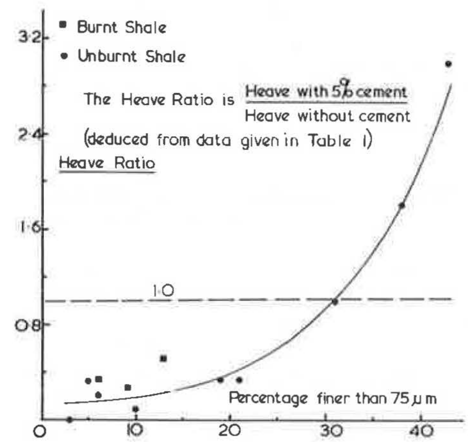



Table 2. Strength tests.

| Sample | Cement Content (%) | 7-d Compressive Strength ($MN/m^2$) | Tensile Strength ($MN/m^2$) Indirect 7-d (A) | Indirect 8-d (B) | Indirect Ratio [C = (B/A)] | Direct 7-d (D) | Estimated Direct 8-d (C × D) |
|---|---|---|---|---|---|---|---|
| Unburnt shale | | | | | | | |
| Snowdown | 5 | 1.61 | 0.19 | 0.15 | 0.79 | 0.13 | 0.10 |
| | 10 | 2.91 | 0.38 | 0.36 | 0.95 | 0.20 | 0.19 |
| Betteshanger | 5 | 1.71 | 0.22 | 0.22 | 1.00 | 0.16 | 0.16 |
| | 10 | 3.38 | 0.44 | 0.45 | 1.02 | 0.30 | 0.31 |
| | 15 | 4.93 | 0.62 | 0.66 | 1.06 | 0.39 | 0.39 |
| Chislet sample B | 5 | 2.29 | 0.33 | 0.30 | 0.91 | 0.17 | 0.15 |
| | 10 | 4.11 | 0.58 | 0.56 | 0.97 | 0.27 | 0.26 |
| | 15 | 5.65 | 0.83 | 0.86 | 1.04 | 0.33 | 0.34 |
| Tilmanstone | 5 | 1.74 | 0.21 | 0.17 | 0.81 | 0.13 | 0.10 |
| | 10 | 3.02 | 0.38 | 0.36 | 0.95 | 0.21 | 0.20 |
| Bedlay | 5 | 2.50 | 0.30 | 0.30 | 1.00 | 0.13 | 0.13 |
| | 10 | 3.77 | 0.53 | 0.57 | 1.07 | 0.22 | 0.24 |
| Rothwell | 5 | 1.50 | 0.22 | 0.02 | 0.09 | 0.13 | 0.01 |
| | 10 | 2.63 | 0.40 | 0.12 | 0.30 | 0.16 | 0.05 |
| Peckfield | 2.5 | 1.18 | 0.13 | 0.00 | 0.00 | 0.08 | 0.00 |
| | 5 | 1.41 | 0.18 | 0.01 | 0.06 | 0.11 | 0.01 |
| | 7.5 | 1.92 | 0.23 | 0.05 | 0.22 | 0.15 | 0.03 |
| | 10 | 2.10 | 0.27 | 0.08 | 0.30 | 0.17 | 0.05 |
| | 15 | 2.64 | 0.35 | 0.13 | 0.37 | 0.19 | 0.07 |
| | 20 | 3.15 | 0.44 | 0.22 | 0.50 | 0.20 | 0.10 |
| Bullcroft | 5 | 1.30 | 0.15 | 0.06 | 0.40 | 0.09 | 0.04 |
| | 10 | 2.19 | 0.27 | 0.17 | 0.63 | 0.14 | 0.09 |
| Burnt shale | | | | | | | |
| Thornley | 5 | 1.88 | 0.26 | 0.28 | 1.08 | 0.17 | 0.18 |
| | 10 | 3.65 | 0.51 | 0.55 | 1.08 | 0.33 | 0.37 |
| Tilmanstone | 5 | 1.39 | 0.14 | 0.13 | 0.93 | 0.13 | 0.12 |
| | 10 | 3.14 | 0.56 | 0.55 | 0.98 | 0.39 | 0.38 |

| Sample | Cement Content (%) | Average Heave (mm) 250 h | 500 h | Unbound 250 h |
|---|---|---|---|---|
| Unburnt shale | | | | |
| Chislet sample B | 5 | 1.0 | 4.1 | 10.7 |
| Chislet sample B | 15 | -1.0 | -1.0 | 10.7 |
| Snowdown | 5 | 0.0 | 2.1 | 4.1 |
| Tilmanstone | 10 | 6.2 | 14.9 | 50.8 |

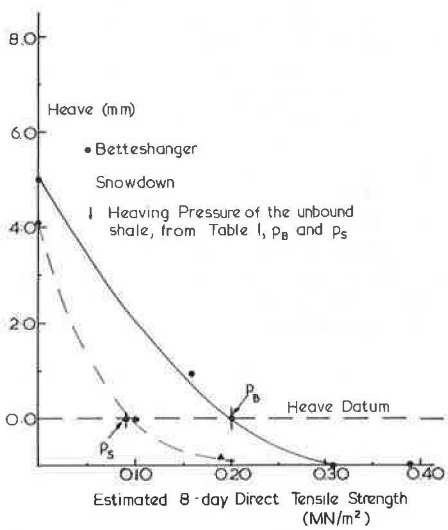
### Effect of Prolonged Hydration on Subsequent Frost Heave

Continuous hydration produces changes in the properties of cement-stabilized materials so that the heave of specimens tested at 7 d may not accurately predict the frost resistance of material subjected to freezing at a greater age. The effect of curing for 3 months before the frost-heave test is shown below.

| Sample | Cement Content (%) | Average Heave (mm) Cured for 7 d | Cured for 3 Months |
|---|---|---|---|
| Unburnt shale | | | |
| Snowdown | 5 | 0.0 | -0.5 |
| Tilmanstone | 10 | 6.2 | 5.6 |
| Burnt shale | | | |
| Tilmanstone | 5 | 16.4 | 12.9 |

This indicates that testing after 7 d provides a factor of safety because field performance is also affected by the time lapse between construction and the onset of severe freezing conditions.

Figure 3. Interrelationships among heave, heaving pressure, and direct tensile strength for cement-stabilized shale.




## MECHANISM OF FROST ACTION IN CEMENT-STABILIZED MATERIALS

To understand the freezing behavior of cement-stabilized shales, it is essential to consider not only the cementing action, but also the changes in pore structure produced by the addition of cement. These changes arise from the aggregation (20) of the cement particles and the soil grains by a mechanism similar to the action of lime on clay soils. As hydration proceeds, secondary cementation (21) causes further agglomeration and leads to the formation of clusters. The amount of aggregation depends on the cement content and the nature of the clay minerals. The aggregation reduces the pore space between the clay colloids and increases the size of the pores between the aggregate. It also increases the permeability as determined from saturated flow tests (although other factors, including reduced surface activity, should also be considered).

However, account must also be taken of the relationship between pore size and the free energy available (13). It has been suggested that the forces associated with frost heave arise from supercooled freezing of the thin films of water present within the smaller pores (10) and that the degree of supercooling and the magnitude of the associated forces are inversely proportional to the pore size (10, 22). Thus, if aggregation occurs, the forces developed during ice lensing will be less, which will reduce the heaving activity. This is supported by the observation that the heaving pressure of the finer graded unburnt shales is less for stabilized samples than for unbound samples (11). It is therefore clear that the increase in pore size accounts for some of the change in heave associated with the addition of cement.

Another factor to be considered when dealing with cement-stabilized materials is the tensile strength because this must be overcome by the expansive heaving pressure before appreciable heave can occur. Energy will be consumed in fracturing the material, which means that less will be available for water transport and for vertical uplift. This is consistent with the increased heave of cut specimens and of refrozen specimens.

The addition of 5 percent cement did not affect the heave of Rothwell unburnt shale and caused a marked increase in the heave of Peckfield and Bullcroft unburnt shales. Of all the shales tested, these had the finest gradings and the lowest permeability in the unbound state so that cement-induced aggregation should be most marked. The evidence for their increased permeability and decreased heaving pressure after stabilization is given in Table 1. It follows that the effect of aggregation on fine-graded shales is to reduce the free energy liber-

Figure 4. Movement versus time under test for selected, unburnt cement-stabilized shales.

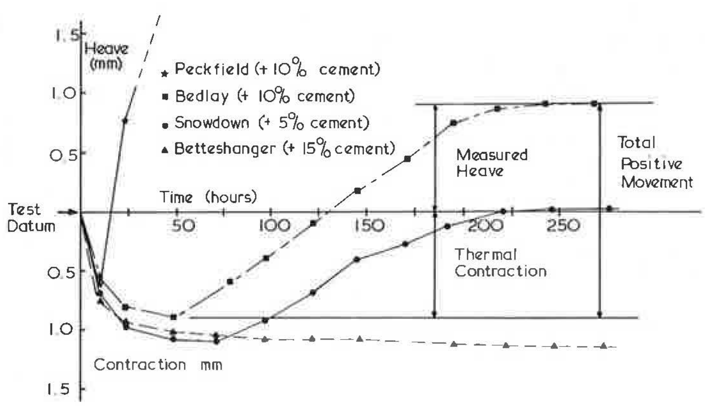
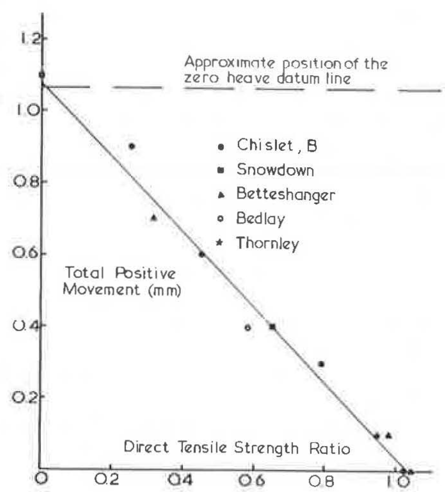


Table 3. Strength tests on cement-stabilized specimens after frost-heave test.

| Sample | Cement Content (%) | Measured Heave (mm) | Total Movement (mm) | Strength After Freezing/Strength Before Freezing: Compressive | Indirect Tensile | Direct Tensile |
|---|---|---|---|---|---|---|
| Unburnt shale | | | | | | |
| Snowdown | 5 | 0.0 | 1.1 | 0.83 | 0.87 | 0.00 |
| | 10 | -0.7 | 0.4 | 1.05 | 1.00 | 0.65 |
| Betteshanger | 5 | 1.0 | 2.1 | 0.85 | 0.73 | 0.00 |
| | 5[a] | -0.3 | 0.7 | — | — | 0.31 |
| | 10 | -1.0 | 0.1 | 0.95 | — | 0.98 |
| | 15 | -1.1 | 0.0 | 1.18 | 1.02 | 1.05 |
| Chislet sample B | 5 | 1.0 | 2.1 | 0.97 | 1.03 | 0.00 |
| | 5[a] | -0.4 | 0.6 | — | — | 0.45 |
| | 10 | 0.0 | 0.9 | 1.06 | 1.00 | 0.25 |
| | 10[a] | -0.7 | 0.3 | 1.08 | 1.01 | 0.79 |
| | 15 | -1.0 | 0.0 | 1.20 | 1.08 | 1.04 |
| Tilmanstone | 10 | 6.2 | 7.1 | 0.75 | — | 0.00 |
| Bedlay | 10 | 0.9 | 1.8 | 1.00 | 0.68 | 0.00 |
| | 10[a] | -0.5 | 0.4 | — | — | 0.58 |
| Peckfield | 5 | 11.5 | 12.4 | 0.08 | — | 0.00 |
| | 10 | 7.2 | 8.1 | 0.30 | 0.13 | 0.00 |
| | 20 | 3.6 | 4.6 | 0.65 | 0.30 | 0.00 |
| Bullcroft | 10 | 8.1 | 9.0 | 0.95 | — | 0.00 |
| Burnt shale | | | | | | |
| Thornley | 5 | 8.0 | 9.0 | — | — | 0.00 |
| | 10 | -1.0 | 0.1 | 1.15 | 1.07 | 0.95 |
| Tilmanstone | 5 | 21.4 | 22.5 | 0.45 | — | 0.00 |
| | 10 | 2.5 | 3.5 | 0.75 | — | 0.00 |

[a]Specimens tested for 100 h.

Figure 5. Movement during frost-heave test versus direct tensile-strength ratio for cement-stabilized shales.




ated during freezing. Consider the manner in which the free energy liberated is consumed: The initial strength of these shales is low, and there is a subsequent loss in strength during soaking (Table 2), so that relatively little energy is required to fracture the material. There is also an increase in permeability of at least two orders of magnitude and therefore less energy is required to lift water to the growing lens. Thus, more of the available energy can be used for heaving, and the behavior will be governed by the balance between the reductions in the free energy liberated and in the energy required for water transport and for fracture.

As the cement content was further increased, all three fine-graded shales showed reduced heave, in common with the other materials tested. This is attributed partly to the increase in strength and partly to the possibility that the more open pore structure caused by aggregation is offset by the pore-filling action of the hydration products. In some cases, there may be an overall increase in free energy, but the strength of the material may then be sufficient to either prevent or limit heave. Such cement contents would also reduce permeability and thus further limit heaving activity. The reduced heave of specimens cured for 3 months can be explained in the same manner.

## CRITERIA FOR JUDGING FROST SUSCEPTIBILITY OF CEMENT-STABILIZED MATERIALS

The reduction in the direct strength after a frost-heave test is indicative of the disruption that can result from even a relatively limited heave and supports the view (23) that the direct tension test detects minute cracks and localized weaknesses that are not detected by other strength parameters. Cement-stabilized shales that developed positive heave lost all tensile strength across the fracture, although the material above and below the crack appeared to be comparatively sound. It is therefore necessary to reconsider the heave criteria for cement-stabilized materials: Positive movement during the test is evidence of a nonreversible breakdown within the specimen, which emphasizes the need to evaluate the behavior of cement-stabilized materials in terms of their tensile strength.

In North America, where freeze-thaw tests are used, the change in compressive strength is used for assessing the frost susceptibility of cement-stabilized and lime-stabilized materials. The formulation of dual criteria based on a limiting change in length and a limiting loss of compressive strength has been considered (23, 24), but the main emphasis is usually on changes in compressive strength (25). Other work (26) has included studies of frost susceptibility in terms of the effect on the cylinder splitting strength.

Heave criteria are also used in North America for evaluating the frost susceptibility of cement-stabilized and lime-stabilized materials. A dimensional criterion that limits the change in length within the frozen zone to 1 percent is considered appropriate for subbase materials because the wheel-load stresses are low. For the specimens tested in this investigation, this requirement would correspond to a movement of 1 mm, which agrees with the finding that a total heave of more than about 1 mm resulted in complete loss of tensile strength in the stabilized specimens. Other workers (23) have suggested that the expansion should be limited to 0.1 percent, but this may be unduly exacting for a subbase material (although it may be applicable to road-base materials where the tensile stresses induced by wheel loads and by restrained movement are higher). Separate criteria may be required for subbase and road-base materials, and separate test procedures may also be necessary. A continuous freezing test with a heave criterion is probably appropriate for subbase materials because the prolonged periods of low temperature may induce failure by water transport to the stable freezing front. For road-base materials, a testing regime that subjects specimens to cycles of freezing and thawing, so as to simulate short duration but repeated damage, may be more relevent. This approach to durability evaluation requires careful consideration of the field environment, both with respect to the thermal regime and to the assessment of damage (27).

CONCLUSIONS

The freezing behavior of cement-stabilized colliery shale is a complex phenomenon that can be tentatively explained in terms of an energy balance. In both unbound and cement-stabilized shales, the forces associated with frost action arise from the supercooled freezing that occurs in the soil pores. These forces are then responsible for transporting water to the freezing front and for lifting the frozen soil plus any imposed load. In cement-stabilized shales, the tensile strength of the materials is analogous to an imposed load that must be overcome before heaving can occur, so that considerable energy may be consumed before appreciable lensing occurs. Stabilization also causes changes in pore structure that affect both the permeability of the material and the degree of supercooling that occurs (so that stabilization influences freezing behavior both directly and indirectly).

Significant heave develops only in materials in which the heaving pressure is greater than the direct tensile strength, so that massive ice lensing is preceded by fracture of the material at the freezing front. With certain exceptions, the addition of cement reduces the heave of colliery shale, which is attributed to the tensile strength imparted and to the changes in pore structure that result from cement stabilization. The exceptions to this are the fine-graded, unburnt shales in which the addition of cement leads to aggregation of the clay colloids. These materials developed only very limited tensile strength, and the changes in pore size produced large increases in permeability, so that the energy liberated is largely available for heaving.

Both the compressive strength test and the cylinder-splitting test have limitations as means of quantifying the damage suffered during a freezing test, but this is not so for the direct tension test. In particular, the increase in length during freezing that is evidence of a nonreversible breakdown is clearly reflected only in the direct tension test results.

The current heave criteria for the frost susceptibility of cement-stabilized materials should be reconsidered. A tensile strength criterion may be especially relevant for road-base materials, although a heave criterion may be acceptable for subbase materials.

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REFERENCES

1. Use of Unburnt Colliery Shale as Filling Material in Embankments. U.K. Ministry of Transport, Technical Memo T4/68, 1968.
2. Use of Unburnt Colliery Shale as Filling Material in Embankments. U.K. Department of the Environment, Technical Memo H4/74, 1974.
3. R. J. Kettle and R. I. T. Williams. Cement-Stabilized Unburnt Colliery Shale. Roads and Road Construction, Vol. 47, No. 559, 1969, pp. 200-206.
4. Specification for Road and Bridge Works. U.K. Department of the Environment, Her Majesty's Stationery Office, 1969.
5. R. J. Kettle. Freezing Behavior of Colliery Shale. Univ. of Surrey, PhD thesis, 1973.
6. D. Croney and J. C. Jacobs. The Frost Susceptibility of Soils and Road Materials. U.K. Transport and Road Research Laboratory, Crowthorne, England, Rept. LR90, 1967.
7. Methods of Testing Soils for Civil Engineering Purposes. British Standards Institution, London, BS 1377, 1967.
8. R. J. Kettle and R. I. T. Williams. The Development of Frost-Heave Testing Equipment. Materiaux et Constructions, Vol. 6, No. 34, 1973, pp. 299-306.
9. J. R. Lake and C. K. Fraser. A Laboratory Investigation of the Physical and Chemical Properties of Burnt Colliery Shale. U.K. Transport and Road Research Laboratory, Crowthorne, England, Rept. LR 125, 1967.
10. E. Penner. Heaving Pressure in Soils During Unidirectional Freezing. Canadian Geotechnical Journal, Vol. 4, No. 4, 1967, pp. 398-408.
11. R. J. Kettle and R. I. T. Williams. Frost Heave and Heaving-Pressure Measurements in Colliery Shales. Canadian Geotechnical Journal, Vol. 13, No. 2, 1976, pp. 127-138.
12. P. Hoekstra, E. Chamberlain, and T. Frate. Frost-Heaving Pressures. HRB, Highway Research Record 101, 1965, pp. 28-38.
13. B. Chalmers and K. A. Jackson. Experimental and Theoretical Studies of the Mechanism of Frost Heaving. Res. Rept. 199, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H., 1970.
14. A. E. Z. Wissa and R. T. Martin. Behavior of Soils Under Flexible Pavements: Development of Rapid Frost-Susceptibility Tests. Department of Civil Engineering, MIT, Cambridge, Res. Rept. R68-77, 1968.
15. L. Bjerrum and J. Hoder. Measurement of the Permeability of Compacted Clays. Proc., 4th International Conference on Soil Mechanics and Foundation Engineering, London, Vol. 1, 1957, pp. 6-8.
16. B. P. Hughes and G. P. Chapman. Direct Tensile Test for Concrete Using Modern Adhesives. Rilem, Bulletin 26, 1965, pp. 77-80.
17. M. Walker. Is Anyone for Cylinder Splitting? New Civil Engineer, May 2, 1974, pp. 28-31.
18. H. B. Sutherland and P. N. Gaskin. Factors Affecting the Frost-Susceptibility Characteristics of Pulverized Fuel Ash. Canadian Geotechnical Journal, Vol. 7, No. 1, 1970, pp. 69-78.
19. P. T. Sherwood. The Properties of Cement-Stabilized Materials. U.K. Transport and Road Research Laboratory, Crowthorne, England,

Rept. LR 205, 1968.
20. L. R. Chadda. The Phenomenon of Aggregation in the Stabilization of Soils With Cement. Indian Concrete Journal, Vol. 44, No. 5, 1970, pp. 210-212.
21. A. Herzog. Evidence for Skeleton-Matrix Structure in Clays Stabilized With Portland Cement. Proc., 5th Australian-New Zealand Conference on Soil Foundation Engineering, Petone, 1967, pp. 55-61.
22. D. H. Everett and J. M. Haynes. Capillary Properties of Some Model Pore Systems With Reference to Frost Damage. Rilem, Bulletin 27, 1965, pp. 31-38.
23. R. G. Packard and G. A. Chapman. Developments in Durability Testing of Soil-Cement Mixtures. HRB, Bulletin 36, 1963, pp. 97-122.
24. L. T. Norling. Standard Laboratory Tests for Soil-Cement Development: Purpose and History of Use. HRB, Highway Research Record 36, 1963, pp. 1-10.
25. M. R. Thompson. Durability and Frost Resistance of Lime and Cement-Treated Soils. Proc., Symposium on Frost Action on Soils, Organization for Economic Cooperation and Development, Vol. 2, 1973, pp. 377-393.
26. D. L. Townsend and T. W. Klym. Durability of Lime-Stabilized Soils. HRB, Highway Research Record 139, 1966, pp. 25-39.
27. B. J. Dempsey and M. R. Thompson. Effects of Freeze-Thaw Parameters on the Durability of Stabilized Materials. HRB, Highway Research Record 379, 1972, pp. 10-18.

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# Tensile-Strength Determinations of Cement-Treated Materials

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**Differences in values of the tensile strength of cement-treated materials measured by using flexure, direct tension, and split tension tests are explained analytically by using Griffith failure theory; and predicted values are shown to agree well with the strength data available in the literature. The results indicate that the direct tension test provides the most reliable values of tensile strength of cement-treated materials, even when the failure surface is close to the interface between the cap and the specimen. Flexural strengths deduced from beam tests can be as much as twice the actual tensile strengths, depending on beam geometry, moduli in tension and compression, and degree of fixity at support and load-application points. The split tension test appears most suitable for practical use in evaluation of the tensile strength of cement-treated materials because it is simple to perform and yields measured values that do not deviate by more than 13 percent from the actual tensile strength.**

Cement-treated bases used in pavement structures are subjected to tensile stresses caused by applied wheel loads, shrinkage, and internal temperature gradients. When these stresses exceed the tensile strength of the material, cracking takes place (1, 2, 3), which results in increased deflections and stress transmissions to the subgrade (4). In addition, the presence of open cracks permits the entry of water into the subgrade, which leads to decreased subgrade support and thereby hastens pavement deterioration. Determination of the tensile strength of cement-treated materials is therefore a desirable part of the design process for pavement structures containing these materials.

Tensile strength has been measured by using flexure tests, direct tension tests, and split tension tests (e.g., 2, 5, 9). The estimation of tensile strength from flexural-beam tests and split tension tests is usually made by using simplifying assumptions about the stress-deformation characteristics of the material, i.e., linear-elastic behavior with the modulus in tension ($E_t$) equal to the modulus in compression ($E_c$). The values of tensile strength obtained on this basis vary and depend on the kind of test used. The split tension test gives lower values of tensile strength than do the flexure and direct tension tests (5, 6), and the flexure test gives higher values than does the direct tension test (2, 5).

Experimental work on the stress and strain behavior of cement-treated soils has shown that the modulus in compression is greater than the modulus in tension (2, 3, 5). Bofinger (5) has suggested that the flexural-beam and the split tension tests do not measure the actual tensile strength of the cement-treated soil because $E_c$ and $E_t$ are not equal and concluded that the direct tension test is the only method that can directly measure the tensile strength of the material. On the other hand, Pretorius (2) has shown that there are stress concentrations at the ends of the specimen in a direct tension test, so that the measured tensile strength measured by this test could also be unreliable.

In this paper, an attempt has been made to explain the differences observed in the three types of tests by using analytic simulations and actual experiments.

## METHOD OF ANALYSIS

The cement-treated material was assumed to be linearly elastic with a modulus in compression that might differ from the modulus in tension. The finite-element method of analysis was used to determine the stresses and deformations for a specific test configuration (Figures 1 and 2) resulting from particular load. A planar stress condition was assumed, and a successive-approximation technique was used to include the bimodular material properties (i.e., $E_c \neq E_t$). In this procedure, the modulus in compression was used for all elements on the first