SOIL-CEMENT: RECENT RESEARCH BY THE OVERSEAS UNIT OF TRRL*

H.E. BOFINGER, M.E., Ph.D., F.I.H.E., Principal Scientific Officer, Overseas Unit, Transport and Road Research Laboratory, Department of the Environment, Department of Transport

ABSTRACT

This paper describes some of the research which has been conducted recently by the Transport and Road Research Laboratory (TRRL) into the behaviour of soil-cement and considers the implications for its use in pavement layers. The laboratory studies have concentrated on the volumetric changes in the material and on the effectiveness of curing membranes. Shrinkage in clay-cement mixtures has been shown to be anisotropic. When it is measured in the direction appropriate for estimating the horizontal shrinkage in pavements, shrinkage is inversely proportional to the cement content provided that the material is properly cured. As the cement content is increased up to 15 per cent the shrinkage of horizontally compacted specimens decreases. The effects of the method of compaction, density and pretreatment moisture content on the shrinkage of clay-cement is considered. Curing methods commonly used in the field have been studied under controlled conditions and their effectiveness on three different types of soil-cement (sand-cement, clay-cement and gravel-cement mixtures) has been evaluated. It is apparent that some common methods for curing soil-cement pavement layers are ineffective.

INTRODUCTION

1. Many road pavements with soil-cement bases or sub-bases have given excellent service in a wide variety of climatic conditions. In tropical countries soil-cement is often used for the main structural layer of a pavement, sometimes because sources of traditional materials such as crushed rock are scarce or are completely absent in a region, and sometimes because the cost of winning and transporting such materials substantially exceeds the cost of cement-stabilisation of locally occurring materials.

2. In some tropical countries roads with soil-cement bases have earned a reputation for premature failure. Often such failures can be attributed to poor construction techniques and inadequate construction control, but some failures do occur where the quality of the soil-cement, in terms of accepted standards, is high. Engineers often attribute such failures to the 'shrinkage' of the soil-cement used, and suggest that this can be minimised by placing an upper limit on the cement content. Recent investigations by the Overseas Unit, TRRL, have concentrated on finding out more about the shrinkage characteristics of soil-cement, and on the factors that influence shrinkage, in particular the effectiveness of different methods of curing soil-cement layers. It should be recognised however that whilst the shrinkage characteristics of cement-stabilised materials do indeed contribute to the initial cracking of soil-cement pavement layers, several other important factors contribute to the long-term performance of such layers. These factors are the strength of the material, its modulus and strain capacity, the restraint of the underlying layer, the stresses induced by traffic or fluctuations in termperature or moisture content, and the creep properties of the material. A considerable volume of knowledge exists about the influence of these factors on pavement performance, and hence the recent investigations by the Overseas Unit have concentrated on the shrinkage characteristics of soil-cement, about which relatively little quantitative information is available.

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SHRINKAGE OF SOIL-CEMENT

3. Studies of the shrinkage of soil-cement under various conditions have been conducted in a number of institutions. Among the more important studies are those by Nakayama and Handy (1965), George (1968), Wang (1973), Pretorius and Monismith (1971), and Dunlop (1973). Each of these investigations was carried out using specimens that were unsealed against loss of moisture during part or all of the period of observation. Nakayama and Handy (1965), George (1968), and others have shown that the shrinkage is maximised when the material is allowed to dry, particularly within the first few days. It is important, therefore, that efficient methods are used to cure soil-cement layers in order to minimise the loss of moisture and the effects of drying shrinkage. Hypotheses to explain the mechanism of drying shrinkage have been proposed by George (1968) and Wang and Kremmydos (1970).

4. An investigation of the volumetric changes in hardening sand-cement mixtures has been carried out at TRRL (Bofinger and Duffell 1973). When these mixtures were sealed to prevent loss of moisture, expansion occurred, indicating that the hydrating gel expands and its structure has sufficient strength to retain the expanded dimensions of the specimen when the volume of the cement paste decreases due to recrystallisation (Bernal 1952).

5. Recently, studies at the TRRL (Bofinger, Hassan and Williams 1978) have concentrated on examining the anisotropic nature of shrinkage and the relationship between shrinkage and the cement content of specimens moulded from fine-grained soil. Additional tests were made to assess the effect on shrinkage of the method used to compact the specimen, the average density of the specimen and the pretreatment moisture content of the soil, i.e. the moisture content of the soil before it is processed into soil-cement.

6. Some properties of the fine-grained soil that was used in these tests, a brickearth from Littlehampton, are listed below.

(a)	Particle sizes	sand	23%
		silt	51%
		clay	26%
(b)	Atterberg limits	liquid limit	39%
		plastic limit	19%
		plasticity index	20%
(c)	Linear shrinkage		12.4%
(d)	Compaction		
	BS (2.5 kg rammer)	OMC	17%
	(1975)	MDD	1.78 Mg/m^3
	BS (4.5 kg rammer)	OMC	13%
	(1975)	MDD	1.97 Mg/m^3
(e)	CBR at OMC		13%

7. In the TRRL studies specimens of Littlehampton brickearth were moulded by one of three methods of compaction. Static compaction was used to make cylindrical specimens 100 mm x 50 mm diameter in which the compacting force was applied along the longitudinal axis of the cylinder (i.e. moulded vertically), and also to make 150 mm x 38 mm x 38 mm bars in which the compacting force was applied at right angles to the axis (i.e. moulded horizontally). Kneading compaction was carried out in the same cylindrical moulds using a tamper based on the Harvard miniature compaction apparatus. The standard compaction hammer, BS 1377 (1975), was used to mould another type of specimen in the standard compaction mould.

8. All of the specimens were sealed in wax immediately they were extruded from the mould and measurements of axial shrinkage were commenced within two minutes. A minimum of five specimens was used in each group of tests.

RESULTS

9. The results of the tests to examine the effects of anistropy and the method of compaction on autogenous shrinkage are listed in *Table I.*

TABLE I

Total Shrinkage Strains (x 10^{-6}) after 28 days of Curing for Specimens Moulded at OMC to BS (2.5 kg) Density by Four Methods of Compaction

Method of Compaction	*Cement Content (%)*					
	0	*4*	*6*	*8*	*10*	*15*
Vertical static compaction	1850	1300	300	400	600	—
Kneading compaction	—	960	50	500	—	—
Dynamic compaction	—	4500	3900	4090	—	—
Horizontal static compaction	2100	1230	640	580	440	330

NOTE: — denotes mixtures that were not tested

ANISOTROPY

10. The autogenous shrinkage of specimens moulded vertically was similar in magnitude to the shrinkage of specimens moulded horizontally but there was, however, a significant difference in the effect of the cement content on the shrinkage of each type of specimen. When specimens were moulded vertically, there was an optimum cement content at which the shrinkage was a minimum, confirming the results of George (1968). In contrast, when specimens were moulded horizontally, the magnitude of the shrinkage progressively decreased as the cement content increased. These horizontally-moulded specimens most closely model soil-cement in a pavement layer. Two other soils were also tested to confirm that this effect was not peculiar to soil-cement made from Littlehampton brickearth.

METHOD OF COMPACTION

11. Vertically moulded specimens in which kneading compaction or dynamic compaction (using the BS compaction method (1975)) was used, also exhibited an optimum cement content at which shrinkage was minimised, but the magnitude of the shrinkage of dynamically compacted specimens was very large. In this type of specimen the shrinkage strains were up to six times greater than those in the other types of specimen.

DENSITY

12. It has often been shown that there is a marked increase in the strength and stiffness of soil-cement when its density is increased. Both of these properties contribute to the initial spacing of cracks in a stabilised road base. It is important, therefore, to know how the shrinkage characteristics of soil-cement are related to the density of the material.

13. In the initial tests, specimens containing various percentages of cement were moulded vertically by static compaction at optimum moisture content (OMC) to maximum dry density (MDD) for the BS 4.5 kg rammer method (1975) and their shrinkage was compared with previous results obtained from specimens compacted to the lower maximum dry density given by the BS 2.5 kg rammer method. Two additional sets of specimens containing 8 per cent of cement were moulded horizontally at the OMC to the MDD for the BS 4.5 kg rammer method and also to 95 per cent of this MDD and their shrinkage was compared with similar specimens moulded to the MDD given by the BS 2.5 kg rammer method. A summary of the total autogenous shrinkage strains after 28 days is given in *Table II.*

14. The autogenous shrinkage of all specimens was greater at the higher density than at the lower density, even though the higher density specimens were moulded at a lower moisture content. It should be noted that when specimens were compacted horizontally at the same moisture content but to different densities, the specimens with the lower density had the smallest shrinkage strains, thus indicating that this phenomenon is not dependent on the moisture content.

PRETREATMENT MOISTURE CONTENT

15. Rallings (1971) has shown that the pretreatment moisture content can have a significant effect on the strength and swell potential of clays stabilised with cement. The effect of pretreatment moisture content on

TABLE II

Total 28 day Shrinkage Strain (x 10^{-6}) at Different Densities and Optimum Moisture Contents

Type of Compaction	Cement Content (%)	*Moulding Conditions* BS (2.5 kg) MDD & OMC (17%)	95% BS (4.5 kg) at 13% MC	BS (4.5 kg) MDD & OMC (13%)
Vertical static compaction	4	1300	—	1700
	6	300	—	1850
	8	410	—	1950
	10	600	—	2150
Horizontal static compaction	8	580	1200	2100

NOTE: — denotes mixtures that were not tested

the autogenous shrinkage of specimens of Littlehampton brickearth stabilised with 6 per cent of cement and moulded vertically by static compaction was evaluated in this investigation.

16. The results illustrated in *Fig. 1* show that the pretreatment moisture content has a profound effect on the shrinkage of soil-cement. Samples prepared from air-dried soil actually expanded rather than shrank, even though the moulding moisture content of all of the specimens was the same.

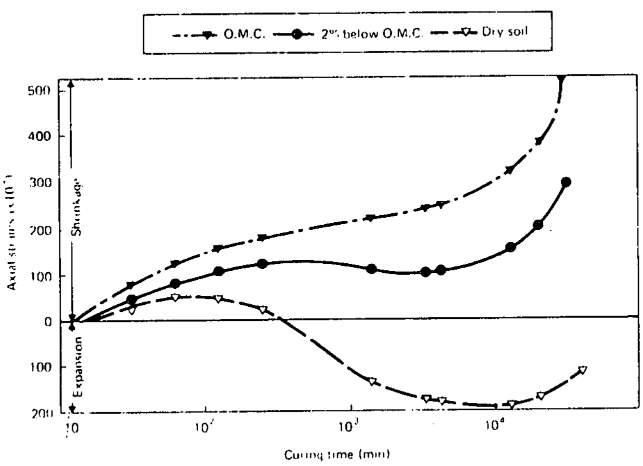

Fig. 1 — Influence of pre-treatment moisture content on shrinkage of specimens containing 6% cement

DISCUSSION OF SHRINKAGE RESULTS

17. The results of these tests raise several issues that have important implications for the construction of road bases from fine-grained soil-cement mixtures. The reduced shrinkage of horizontally-moulded specimens when higher quantities of cement are incorporated is contrary to the increased shrinkage at higher cement contents when specimens are moulded vertically. It is likely, however that the horizontally-moulded specimens most closely resemble the shrinkage conditions in the field, which implies that the adoption of an upper limit for cement content will not reduce the incidence of shrinkage cracking. The effects on shrinkage of the method of compaction, the density and the pretreatment moisture content, should be considered carefully when soil-cement layers are being designed and constructed. Laboratory compaction procedures embodying dynamic techniques are recognised as being poor replicates of field compaction processes. Nevertheless the possibility should not be ignored that the shock loading associated with vibratory rollers may cause larger shrinkage strains in soil-cement layers than compaction by dead weight rollers. The most suitable roller for minimising shrinkage in a soil-cement layer at a particular target density is likely to be a pneumatic-tyred roller.

18. The results of this investigation indicate that the selection of the target density for a stabilised base is a complex matter. The Highway Research Board (1961) and others, have shown that the strength and stiffness of soil-cement increase progressively as the density is raised, but unnecessarily high densities appear to cause difficult cracking problems. As the density, and hence the strength and stiffness, of fine-grained soil-cement are increased, the spacing between shrinkage cracks in a pavement layer of the material will increase. Correspondingly for the same shrinkage strain, the cracks formed will be wider and will have a greater probability of being reflected through the bituminous surfacing of a pavement. If, however, the density is kept at a low value to reduce the cracking problem, the strength and durability of the soil-cement will be adversely affected, and its ability to resist crack propagation due to traffic and temperature stresses will be significantly impaired. The best compromise is probably to aim for a durable material, accepting that it will crack at regular intervals, and to take steps to seal the cracks when they appear.

19. The tests to assess the effects of the pretreatment moisture content of the soil show that for best results it should be processed in the driest practicable condition. In addition to reducing the autogenous shrinkage, this practice will improve the transport of cementitious material into lumps of soil and will increase their stability.

20. The foregoing study was confined to the autogenous shrinkage of a fine-grained soil-cement and the results are appropriate only when the material is cured under ideal conditions without loss of moisture. This ideal is not possible in practice because there will always be a delay between the completion of the compaction and the placing of a curing seal on the layer. Recent work by May Loh (1977) on a laboratory scale indicates that shrinkage increases significantly when there is a delay before a curing membrane is applied. She has shown that if one day elapses the shrinkage will be approximately the same magnitude as that of completely uncured material. Some consideration should be given, therefore, to arranging the construction procedure so that a curing seal is applied immediately after the layer has been finally trimmed and compaction has been completed.

21. The efficiency of common curing methods is considered in the next section of the paper.

CURING EFFICIENCY

22. Various methods are used to reduce loss of moisture from the upper surface of newly constructed

soil-cement pavement layers. Some methods attempt to seal the surface with an impermeable membrane, while other methods reduce the loss of moisture from the layer by keeping the surface wet.

23. The Overseas Unit of TRRL has investigated the efficiency of some of the common methods of curing soil-cement. In the investigation, specimens were made from three different types of soil, viz a sand, a clay and a gravel. Some of the properties of the three soils are listed below.

Soil Type	*Particle Size*	*Percentage*
Chertsey Sand	> 300 μm	2
	300-150 μm	88
	< 150 μm	10
Iver Brickearth*	Sand	15
	Coarse silt	48
	Medium silt	14
	Fine silt	5
	Clay	18
Malawi Gravel†	20-10 mm	7
	10-5 mm	7
	5-2.36 mm	11
	2.36 mm-425 μm	33
	425-75 μm	22
	< 75 μm	20

* MDD (8% cement) is 1826 kg/m³ at OMC of 15.5%. (BS 2.5 kg rammer (1975).) LL = 37%, PL = 19%, PI = 18%

† MDD (4% cement) is 2162 kg/m³ at OMC of 8%. (BS 4.5 kg rammer (1975).) LL = 35%, PL = 19%, PI = 16%

24. Specimens were compacted statically in three layers in steel moulds with internal dimensions of 300 x 75 x 75 mm and the top surface of the specimens was treated with one of several curing techniques. The loss of moisture from the samples was then measured at regular intervals during exposure to different conditions of temperature and humidity.

25. One of the most common curing techniques is to apply a bituminous prime such as a fluid cut-back, on the assumption that this material will also act both as a curing membrane and a prime for subsequent surface dressing. Alternatively, the soil-cement layer is sprayed with water at regular intervals (say twice each day) to keep the surface moist. A modification of this method uses a layer of loose sand spread on the soil-cement layer to retard the rate of drying and to prevent water from being sprayed directly onto the soil-cement surface. Each of these curing techniques was examined in the investigation and, in addition, the sealing efficiency of 55 per cent anionic bituminous emulsion was tested. One set of specimens was left completely unprotected to measure the rate of loss of water under the worst conditions.

26. Pairs of specimens were subjected to relative humidities of 33, 50, 75 and greater than 96 per cent at a temperature of 25°C, and also to a relative humidity of 50 per cent at a temperature of 45°C. The loss of moisture expressed in terms of the percentage loss after seven days of the total water in the mixture when the specimen was moulded is shown in *Table III*.

DISCUSSION OF RESULTS OF THE INVESTIGATION OF CURING TECHNIQUES

27. The results shown in *Table III* indicate that some curing techniques in common use, such as spraying with water or spraying a thin cut-back bitumen on to the surface of the soil-cement, have only a very limited effect in preventing loss of moisture. Some of the results obtained did not follow the general trends (these are marked with an asterisk in the table), but the general conclusions that can be drawn are clear. These are that the best methods for curing soil-cement layers (from among those studied) are by sealing the surface with bitumen emulsion or by spreading a layer of loose sand on the soil-cement which must then be kept damp by spraying with water.

TABLE III

Average Percentage Loss of Moisture After 7 Days

Soil	*Curing*		*Drying Conditions (Relative Humidity & Temp.)*				
	Type	*Spray Rate l/m²/day*	*50%/45°C*	*33%/25°C*	*50%/25°C*	*75%/25°C*	*96+%/25°C*
Chertsey sand	Nil	—	81	72	68	59	46
+	MC0	1.1	69	40	31	23	19
6% cement	MC2	1.1	36	26	13*	22	13
	55% Emulsion	1.1	2.7*	6.2*	10	7.4	6.5
	Damp Sand	2.2	—	24*	10	6.9	6.5
Iver	Nil	—	46	38	36	32	19
Brickearth	MC0	0.54	28	8.9	6.6	8.0	2.0
+	MC2	0.54	13	6.8	4.8	2.4	2.0
8% cement	55% Emulsion	0.54	12	4.4	4.8	4.8	3.0
	Water Spray	2.2	40	31	23	18	9.6
Malawi gravel	Nil	—	37		29	19	
+	MC0	0.54	37		19	13	
4% cement	MC0	1.1	40		18	14	
	55% Emulsion	0.54	33*		9.5	7.2	
	Damp Sand	2.2	11		9.5	5.6	

* For explanation of asterisks see para. 27

28. In tropical and sub-tropical countries the results obtained under conditions of 50 per cent relative humidity and a temperature of 45°C are likely to be more appropriate than the other values listed in the Table. As the relative humidity drops, there is a marked increase in the loss of water through the curing membrane. Hence in very dry regions, particular attention must be given to the speed with which the curing membrane is applied and to the quality of the curing method. The most difficult material to cure with bituminous membranes is sand-cement, whereas it is the easiest of the materials to prime for subsequent surface dressing (see Highway Research Board 1949).

29. In general it seems likely that bituminous emulsions and damp sand offer engineers satisfactory methods for curing soil-cement, and the choice of method will obviously depend on the relative costs of each method for the particular project. It must be stressed, however, that it is essential to commence curing the material as soon as possible so that the shrinkage is kept to a minimum.

CONCLUSIONS

30. The shrinkage of soil-cement is anisotropic and contrary to previously published data, the autogenous shrinkage measured in the appropriate direction (e.g. horizontally) is progressively reduced when the cement content is increased. Hence the commonly accepted thesis that increasing the cement content of soil-cement pavement layers above a certain optimum value tends to increase shrinkage, is open to serious doubt.

31. Some methods of compaction induce very high shrinkage strains in soil-cement, and these strains cannot be attributed to the differences in density or moisture content associated with particular compaction methods.

32. Compacting soil-cement to a high density will increase its propensity to shrink, but it will also increase the strength and durability of the material.

33. Soil-cement should be processed when the soil is in its driest practicable condition. No attempt should be made to raise its moisture content over a period of time prior to construction but all of the water needed for compaction should be added during the mixing process.

34. Bituminous emulsion curing seals or blankets of damp sand retain most of the moisture in the soil-cement layer and are satisfactory curing techniques. They should be applied as soon as possible after compaction is complete. If curing is delayed for one day, the total shrinkage of soil-cement will be nearly as great as if no curing measures were taken at all.

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