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The shrinkage of fine-grained soil-cement

by

H. E. Bofinger, H. O. Hassan and R. I. T. Williams

TRANSPORT and ROAD RESEARCH LABORATORY
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THE SHRINKAGE OF FINE-GRAINED SOIL-CEMENT

Authors H E Bofinger, H O Hassan and R I T Williams

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The incidence of cracks not associated with traffic loads is a feature of roads with soil-cement bases. The consequent problem of such cracks reflecting through a bituminous road surfacing has caused concern for many years. The cracks result from restrained thermal and shrinkage movements but, when the stabilized soil is fine-grained, it is believed that this cracking is mainly attributable to shrinkage.

An examination of the shrinkage behaviour of soil-cement mixed from Littlehampton brickearth was carried out to provide a better understanding of one of the major causes of cracking in soil-cement road bases. The effects of the following factors on the shrinkage of this mixture were investigated in this study:

i) the method of compaction used to mould the specimens

ii) the cement content of the mixture

iii) the moisture content of the mixture when the specimen is moulded

iv) the average density of the specimens

v) the moisture content of the soil immediately before it is mixed with cement and the moulding water

vi) the effect of drying after a period of autogenous curing.

Three methods of compaction were used to mould specimens, namely static compaction, kneading compaction and dynamic compaction using the British Standard laboratory compaction rammer. The shrinkage of specimens moulded by static compaction was measured parallel to the direction of the compactive force and perpendicular to it. When the other methods of compaction were used, the shrinkage was only measured parallel to the direction of the compactive force. The specimens were sealed to prevent loss of moisture thereby simulating ideal conditions of curing.

The main conclusions drawn from this investigation are listed below:

1. The shrinkage of laboratory specimens is anisotropic and is also markedly influenced by the method used to compact them. Hence the prediction of the shrinkage behaviour of full-scale pavements on the basis of tests on laboratory specimens must take account of the methods used to prepare these specimens, and the direction in which the shrinkage is measured.

2. Autogenous shrinkage in the direction perpendicular to the compacting force reduces when higher proportions of cement are added to clays. It is this type of laboratory test that most closely simulates the structure of a soil-cement pavement layer.

3. Volume changes in clay-cement are thought to be caused by the interaction of soil-moisture suction, the re-orientation of water adsorbed on the clay particles, the expansion of cement gel as it hydrates, the self desiccation caused by the hydration of the cement and the increase in the strength of the cemented soil skeleton.

4. Shrinkage of clay-cement specimens is profoundly affected by the initial condition of the soil prior to moulding, by the moisture content at which they are compacted and by their final density.

The shrinkage will be minimised if the soil is processed from a dry state and all the water required for compaction and hydration is added during mixing. In addition, to minimise shrinkage, the mixture should be compacted as quickly as possible to the minimum density that will ensure that the material will attain adequate strength.

5. If clay-cement specimens are exposed to a drying atmosphere, their shrinkage potential is increased but the longer the period of time they are kept sealed before drying commences, the smaller is the total shrinkage.

The work described in this Digest forms part of the programme carried out by the Overseas Unit of TRRL for the Ministry of Overseas Development but any views expressed are not necessarily those of the Ministry.

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H E Bofinger, H O Hassan and R I T Williams

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THE SHRINKAGE OF FINE-GRAINED SOIL-CEMENT

ABSTRACT

The incidence of cracks not associated with externally applied loads is a feature of soil-cement roadbases, and the consequent problem of reflection cracking through the superimposed surfacing has caused concern over the years. The cracks result from restrained thermal and shrinkage movements but, when the stabilized soil is fine-grained, it is believed that the cracking is mainly attributable to shrinkage.

The paper describes a study of the autogenous shrinkage of such a material aimed at improving the understanding of its susceptibility to cracking. In the investigation, specimens were cured under ideal conditions, but, because conditions in the field are often far from ideal, the influence of drying on shrinkage was also studied.

The principal finding of the investigation is that the measured value of shrinkage is greatly affected by the test conditions imposed. In particular, major differences were observed in specimens compacted by different methods and, furthermore, the mode of compaction had a striking influence on the way in which the cement content of mixes influenced shrinkage.

A tentative explanation for the results obtained is presented in terms of the pore pressure in the specimens, the hydration of the cement and the particle orientation. It is clear, however, that further work is necessary before the general validity of the results can be determined.

1. INTRODUCTION

In a number of areas of the world traditional road building materials of adequate quality are not readily available within a reasonable haulage distance of road construction projects. In such situations the stabilization of local soils and gravels can produce an economical material for building road-bases. Cement has been widely used as a stabilizing agent for locally-occurring materials but cement-stabilized road-bases have a reputation for cracking. Cracks formed in the base often reflect through the bituminous surfacing unless a considerable thickness of bituminous material is provided. The extent and effects of these cracks concern engineers because they may seriously affect the performance of roads if they permit the ingress of water to the sub-base and sub-grade.

Many factors influence the degree of cracking of soil-cement in terms of the spacing, direction and width of cracks. Among the more important are:

(i) the susceptibility of the material to shrinkage as a result of moisture loss or the internal redistribution of moisture as the cement hydrates,

(ii) the contraction of the material as the ambient temperature falls,

(iii) the restraint imposed on the roadbase by the sub-base or subgrade,

(iv) the tensile properties of the hardening soil-cement in terms of its strength, its strain capacity, modulus of elasticity and the ability to relieve critical conditions through creep.

The extent to which cracks in the soil-cement ultimately reflect through the surfacing depends on a number of factors but principally on the type and thickness of the bituminous surfacing, the effect of climate and age on the viscosity of the binder, and the volume and magnitude of the axle loads of commercial vehicles using the road. (However, not all cracks in bituminous surfacings are attributable to cracks in the base).

This paper considers one factor only that contributes to cracking, namely the shrinkage characteristics of soil-cement, which are of particular importance in the case of fine-grained soil-cement[1,2,3].

The ideal curing condition which allows soil-cement to achieve the maximum increase in strength and to minimise cracking due to differential drying shrinkage is to enclose totally the soil-cement with an impermeable material so that no moisture can escape. Under these ideal conditions the shrinkage that occurs has been called 'autogenous'shrinkage. At the other extreme, when moisture is allowed to dry freely from soil-cement, 'drying' shrinkage occurs and the potential strength of the material is then substantially reduced and the likelihood of cracking is increased.

Desirably, the curing conditions for soil-cement road bases should approach as closely as possible the conditions of autogenous shrinkage. In practice, however, this is difficult to achieve, and frequently inadequate attention is paid to retaining moisture in the material.

To provide a better understanding of a major cause of cracking in soil-cement roadbases, an investigation has been undertaken of the shrinkage properties of clayey soil-cement.

The following factors (which affect the shrinkage of soil-cement) were investigated in this study:

(i) the method of compaction used in moulding the specimens,
(ii) the cement content of the mixes,
(iii) the moisture content of the mixture when the specimen is moulded,
(iv) the average density of the specimens,
(v) the moisture content of the soil immediately before it is mixed with cement and the moulding water,
(vi) the effect of drying after a period of autogenous curing.

2. PREVIOUS RESEARCH

A number of laboratory studies of the shrinkage of soil-cement under various conditions have been conducted, some of the more important being those undertaken by Nakayama and Handy[1], George[2], Wang[4], Pretorius and Monismith[5] and Dunlop[6].

Shrinkage of soil-cement is generally held to be caused by loss of water due to self desiccation and evaporation. Evaporation from unprotected surfaces causes the largest changes in volume but good curing practices can minimise this loss. Self desiccation causes volume changes of a smaller magnitude Thermal shrinkage is believed to be insignificant in soil-cement, George[2].

Plummer and Dore[7] have suggested that the drying shrinkage in bodies which undergo volume changes smaller than the corresponding loss in the volume of moisture is caused by a capillary phenomenon and, therefore, that the shrinkage obeys capillary tension theory. Means and Parcher[8] and Czernin[9] have associated the drying shrinkage of cement paste with the same theory.

When cement paste is cured under sealed conditions it first expands[10] but after some time, recrystallization occurs which results in a loss of intracrystalline or adsorbed water, thus reducing the volume of the material Bernal[11].

George[2] has proposed three hypotheses to explain drying shrinkage in soil-cement. At high humidities he suggests that the capillary tension effect predominates whereas at intermediate humidities, the decrease of the adsorbed water film causes contraction and, when the humidity is reduced further, shrinkage is due to the loss of water from the crystal lattice of the soil.

In a later study, Wang and Kremmydos[12] proposed that the lattice shrinkage in clay would occur as soon as evaporation begins, contrary to George's third hypothesis.

Expansion has been measured in sealed specimens of sand-cement[13]. These mixtures are composed of volumetrically stable sand particles surrounded by a cement gel which expands when it hydrates, thus causing the overall expansion of the specimen. If the gel in clay-cement mixtures expands similarly, it follows that the shrinkage within the clay fraction must be greater than the expansion of the cement gel for autogenous shrinkage to occur.

3. DETERMINATION OF SHRINKAGE

In this Paper the term 'shrinkage' is used to describe autogenous shrinkage or shrinkage under sealed conditions. When the specimens are permitted to dry the term 'drying shrinkage' is used.

One of the important aspects of this study was the examination of the anisotropic nature of the shrinkage of soil-cement. Most researchers who have studied the shrinkage characteristics of soil-cement have measured the axial deformation of cylindrical specimens compacted in moulds developed for producing compression strength test specimens. Specimens prepared and monitored in this way do not simulate the critical shrinkage conditions experienced by soil-cement in roadbases since the shrinkage measured will reflect the vertical shrinkage of roadbases. Shrinkage in this direction, which causes a change in the thickness of the layer, is probably not very relevant to the formation of the cracks that significantly affect the performance of soil-cement bases. In this study cylindrical shrinkage specimens were prepared using static compaction, kneading compaction and impact compaction, and the shrinkage was measured in the direction in which the compacting force was applied. In addition, prismatic specimens were compacted statically and the shrinkage was measured at right angles to the direction of the compacting force.

Most previous researchers in this field have concentrated on the measurement of the drying shrinkage of specimens initially cured in a moist condition for some period of time. This approach does not enable measurements to be made of the volume changes that occur immediately after compaction is completed or during the early stages of the curing period. The behaviour of soil-cement during this early stage of curing may have an important effect on the subsequent performance of the material. In this investigation, shrinkage measurements were therefore commenced immediately after the compacted specimen had been sealed in wax.

4. MATERIALS AND LABORATORY PROCEDURES

4.1 *Materials*

The majority of the tests in this investigation were conducted on specimens prepared from Littlehampton brickearth. In addition two other types of soil were used to check certain of the results obtained with the brickearth. These additional soils were Bagshot sandy clay and Wainscott brown clay. The properties of all three soils are shown in Figure 1 and Table 1. Table 1 also includes test results of the ordinary Portland cement used in all the tests.

TABLE 1a

Properties of soils

Soil property	Little-hampton brickearth (L.B.E.)	Bagshot sandy clay (B.S.C.)	Wainscott brown clay (W.B.C.)
1. Particle sizes			
Sand %	23	45	12
Silt %	51	18	39
Clay %	26	37	49
2. Specific gravity	2.73	2.72	2.73
3. Atterberg limits			
Liquid limit	39	34	75
Plastic limit	19	18	31
Plasticity index	20	16	44
Compaction:			
(i) B.S. light(14)			
Max. dry density lb/ft^3	111	112	97
Mg/m^3	1.78	1.79	1.55
Optimum moisture content	17%	15%	21%
(ii) B.S. heavy[14]			
Max. dry density lb/ft^3	123	123	-
Mg/m^3	1.97	1.97	
Optimum moisture content	13%	12%	
California bearing ratio (C.B.R.) %	13	-	-
Linear shrinkage %	12.4	-	16

TABLE 1b

Properties of the cement

(BS12)[15]

Setting times			
Water	26.3%		
Initial	120 min		
Final	165 min		
Fineness			
Specific surface	348 sq m/kg		
Expansion			
Le Chatelier	2.5mm		
Compressive strength			
Vibrated mortar cubes	3 days	31	MN/m^2
	7 days	45	MN/m^2

4.2 *Preparation of the soil*

The clays were air-dried and then pulverised until they passed the No 7 (2.36 mm) sieve. Water was mixed with the pulverised soil to raise its moisture content to a level 2 per cent below the optimum for compaction. The moist soil was then sealed in containers and stored for a minimum period of one month to allow the moisture to distribute uniformly throughout the soil.

4.3 *Preparation of specimens*

Pre-wetted soil and cement were mixed, the additional moulding water added, the whole thoroughly mixed and then moulded into specimens as quickly as possible.

Three shapes of specimens were used:

(i) 4" x 2" Ø cylinders
(101.6 x 50.8 mm)

(ii) 4.6" x 4" Ø cylinders
(116.6 x 101.6 mm)

(iii) 1½" x 1½" x 6" bars
(38.1 x 38.1 x 152.4 mm)

The 4" x 2" cylinders were moulded by vertical static compaction or by kneading compaction using a plunger similar to the type developed for the Havard miniature compaction apparatus. The 4.6" x 4" diameter cylinders were compacted in accordance with the BS 2.5 kg rammer method (BS 1377-1975)[14].

The 1½" x 1½" x 6" bars were moulded horizontally by static compaction in three equal layers, each layer being compacted separately under a pressure of 227 psi (1560 kN/m^2). This pressure was chosen because it produced approximately the same dry density as BS compaction with the 2.5 kg rammer(14).

Immediately after they had been compacted, the specimens were mounted on carriers, sealed in wax, set up on stands, and the shrinkage measured by dial gauges reading to 0.001 mm as shown in Plate 1. Shrinkage measurements were made at fixed time intervals over a period of 28 days, during which time the temperature of the specimens was maintained at $20^{\circ} \pm 2^{\circ}C$. At the end of the 28 day testing period, the weight of each specimen was remeasured to check that the wax-seal was intact.

When drying shrinkage measurements were required, the autogenous shrinkage was first measured during the initial period of moist curing, the wax was then removed and the drying shrinkage measured at the same ambient temperature.

5. RESULTS

The results of the shrinkage tests are shown in Figures 2 to 5 and 7 to 15, in which shrinkage strain is plotted against time. Each curve is plotted through the average points obtained from five separate tests, and examples of the variability of the complete results of typical groups of tests are given in the Appendix.

5.1 *The effect of the method of compaction*

Figures 2 to 5 show the results of shrinkage tests carried out on samples of Littlehampton brickearth stabilized with various percentages of cement.

Specimens were moulded in four different ways: by vertical static compaction in 4" x 2" cylinders, by horizontal static compaction in 1½" x 1½" x 6" bars, by kneading compaction in 4" x 2" cylinders and by impact compaction in a BS standard compaction mould[14]. For each of these tests the total shrinkage strains after twenty-eight days are listed in Table 2 to summarise the overall pattern of behaviour.

The development of shrinkage with time follows a similar pattern for each type of specimen and for most values of cement content, except for specimens with cement contents of 10 and 15 per cent moulded horizontally by static compaction in which some expansion occurred. Generally, the rapid shrinkage during the first few hours was followed by a null zone which continued for up to 1 day before further shrinkage occurred.

It is clear from Table 2 that the method of compaction has a major influence on the magnitude of shrinkage, the greatest amount of shrinkage being measured on specimens moulded by impact compaction and the smallest amount by kneading compaction. Specimens moulded by vertical static compaction and horizontal compaction have a similar magnitude of shrinkage.

TABLE 2

Total shrinkage strains x 10^{-6} after 28 days of curing for specimens moulded at O.M.C. to B.S.light density by different methods of compaction

Soil	Method of compaction	Cement content %					
		0	4	6	8	10	15
Little-hampton brickearth	Vertical static compaction (cylinders)	1850	1300	300	400	600	-
	Kneading compaction	-	960	50	500	-	-
	Dynamic compaction	-	4500	3900	4090	-	-
	Horizontal static compaction (bars)	2100	1230	640	580	440	330
Bagshot Sandy Clay	Vertical static compaction (cylinders)	-	1250	850	950	-	-
	Horizontal static compaction (bars)	-	1450	1350	950	-	-
Wainscott Brown Clay	Vertical static compaction (cylinders)	-	2900	1900	3250	-	-
	Horizontal static compaction (bars)	-	4150	3850	3500	-	-

5.2 *The effect of the cement content*

The effect of the cement content on the shrinkage behaviour was influenced by the method of compaction. When the specimens were moulded in vertical cylinders, either by static compaction or by kneading compaction, there was a critical cement content at which the shrinkage was a minimum. In contrast, specimens that were moulded horizontally by static compaction showed a progressive reduction in shrinkage when the cement content was increased. At high values of cement content there was an initial expansion rather than shrinkage. Finally, when specimens were compacted by the standard impact hammer, the results (Figure 5) are less well defined but they suggest that the shrinkage is relatively insensitive to the cement content.

It is evident from the shrinkage of sealed specimens which contained no cement that the addition of cement to clayey soils reduced the autogenous shrinkage (Figure 6). This is in contrast with the widely held view that shrinkage will be reduced by reducing the cement content.

The results obtained from specimens moulded horizontally by static compaction (which most closely model conditions in roadbases) thus differ from vertically compacted specimens, and , thereby, from previously published results which have been obtained using cylindrical 'compression' specimens. To determine whether this effect was peculiar to specimens moulded from Littlehampton brickearth, comparative tests were made with Bagshot sandy clay and Wainscott brown clay. The results of these tests are shown in Figures 7 to 10. It is clear from these figures that the reduction in shrinkage with increasing cement content for specimens moulded horizontally by static compaction is not peculiar to soil-cement made from Littlehampton brickearth.

5.3 *The effect of the moulding moisture content*

The influence of the moisture content of the moulded mixture on the shrinkage of soil-cement was studied on specimens which were moulded vertically by static compaction at 2 per cent above and 2 per cent below the optimum moisture content for BS compaction (2.5 kg rammer method[14]). The target density was the maximum density for BS compaction (2.5 kg rammer) and groups of specimens were moulded at various cement contents. Additional tests were conducted on specimens containing 8 per cent cement, moulded horizontally by static compaction at the same moisture contents and density. The values of total shrinkage measured after 28 days of curing are summarised in Table 3.

TABLE 3

Total 28-day shrinkage strain x 10^{-6} at various moisture contents

Type of compaction	Cement content %	Moisture content		
		2% below OMC	OMC	2% above OMC
Vertical Static Compaction	4	740	1300	1590
	6	280	300	320
	8	420	410	450
	10	560	600	650
Horizontal Static Compaction	8	460	580	700

5.4 *The effect of the level of compaction*

A series of tests was conducted to assess the effect that the magnitude of the compacted density has on the shrinkage characteristics of soil-cement. In the initial tests, specimens containing various percentages of cement were moulded vertically by static compaction at the optimum moisture content and to the maximum dry density for the BS 4.5 kg rammer method for compaction. Two additional sets of specimens containing 8 per cent of cement were moulded horizontally at the same optimum moisture content, to the same density and to 95 per cent of that density. The results are shown diagrammatically in Figures 11 and 12 and a summary of the total shrinkages after 28 days is included in Table 4, together with values obtained from specimens moulded at the optimum moisture content and to the maximum dry density for the BS 2.5 kg rammer method.

TABLE 4

Total 28-day shrinkage strain x 10^{-6} at different densities and optimum moisture contents

Type of compaction	Cement content %	Moulding conditions		
		BS light density and OMC (17%)	BS heavy density and OMC (13%)	95% of BS heavy and 13% moisture content
Vertical Static Compaction	4	1300	1700	-
	6	300	1850	-
	8	410	1950	-
	10	600	2150	-
Horizontal Static Compaction	8	580	2100	1200

There was a marked increase in the shrinkage at the high density, even though the heavier compactive effort is associated with a lower optimum moisture content. It should be noted, however, that when the density was varied without changing the moisture content, shrinkage was greater at the higher density. The shrinkage behaviour of the more dense specimens differed in other respects too. In specimens moulded vertically by static compaction, the shrinkage increased with increasing cement content and it continued to increase progressively with time without going through a 'null' period. Specimens moulded horizontally by static compaction also exhibited this latter type of behaviour.

5.5 *Influence of the pre-treatment moisture content of the soil*

It was expected that the moisture content of the soil immediately before it was mixed with cement and moulding water would affect the shrinkage of soil-cement. To investigate this, a small study was conducted on specimens containing 6 per cent of cement which were compacted vertically by static compaction.

The results of these tests are shown in Figure 13 and they indicate that the pre-treatment moisture condition has a marked effect on the shrinkage of soil-cement. When oven-dry soil was used, the specimens developed a small shrinkage strain during the first few hours followed by expansion for up to 7 days before they started to contract again. Specimens prepared from soil which was pre-wetted to the optimum moisture content showed progressive shrinkage with time. When the soil was used at the standard pre-treatment moisture condition of 2 per cent below the optimum moisture content for compaction, the 'typical' null period was observed for curing periods of 2 hours to 1 day.

5.6 *The influence of drying*

The major part of this investigation was directed towards the autogenous shrinkage of soil-cement. However, because a number of researchers have reported studies on specimens which were moist cured for a short period of time and then were exposed to allow drying to occur, some specimens were treated similarly for comparison.

Specimens containing 8 per cent of cement were moulded vertically by static compaction and then immediately sealed in wax for periods of 1 hour, 1 day and 7 days. The wax seal was then stripped, the drying shrinkage observed and the results compared with the shrinkage of specimens which were sealed in wax for the full period of the test. The results of these tests are shown in Figure 14. It can be seen that, regardless of the initial period of moist cure, almost all of the drying shrinkage occurs within 7 days and its magnitude is reduced as the period of moist cure is increased. In all cases the drying shrinkage is much greater than the autogenous shrinkage.

6. SUPPLEMENTARY TESTS

The results obtained from the foregoing studies could not be entirely explained by the hypotheses proposed by previous research workers. Accordingly further tests were undertaken in an attempt to provide an explanation for the unexpected shrinkage behaviour that was observed.

When the compactive force is removed from an unsaturated clay specimen, suction or negative pore pressure is induced (Lambe[16,17], Aitchison[18]). Furthermore Lambe has suggested that surface chemical phenomena give clay the capacity to imbibe water and if the water content of a clay mass is less than this capacity, a water deficiency will exist, increasing the magnitude of the suction. The intergranular stress will be increased by this suction, causing consolidation in the material.

The pattern of shrinkage behaviour that was measured on specimens moulded by each of the methods of compaction suggest that the pore pressure condition contributes to the rapid initial shrinkage.

Tests were therefore carried out to assess the development and dissipation of pore pressure during and after the compaction of three specimens, one containing no cement and the other two containing 8 per cent of cement. The specimens were moulded at the optimum moisture content for BS compaction with the 2.5 kg rammer and also at two per cent above this value for specimens containing cement. A small piezometer was placed in the middle of the specimens which were compacted vertically by static compaction.

The pore pressure of the specimens was measured for 24 hours and the results are shown in Figure 15. The limited number of tests made do not permit quantitative conclusions to be drawn but it is clear that during the compaction phase a positive pore pressure developed in all three specimens. This dropped to zero within 9 minutes of the specimens being extruded. Thereafter, a pore suction was measured and this remained until the end of the period of observation of 24 hours, although, in each case, the maximum pore suction was measured after 5 to 6 hours.

7. DISCUSSION OF RESULTS

7.1 *Pore pressure and suction in unstabilized clay*

An unexpected result from the investigation was the magnitude of the shrinkage of sealed specimens of untreated clay and the fact that this shrinkage was still increasing at the end of the observation period of 28 days.

The pore suction that develops in the specimens shortly after they are extruded from the mould would be expected to contribute to their shrinkage only during the initial life for the following reasons:-

1. When the soil skeleton is subjected to constant additional stress, the maximum drainage path in specimens of this size is 1 inch (25.4 mm). Based on standard laboratory consolidation tests, one would expect

that the primary consolidation of these specimens should effectively be completed within 24 to 48 hours.

2. At any age of 5 to 6 hours the pore suction in the specimens reaches a maximum after which it tends to reduce towards zero. It follows that intergranular stress due to pore suction will fall after about 6 hours and the specimens could possibly rebound if the suction reduces sufficiently, resulting in an increase rather than a decrease in their volume.

It is suggested that the development and dissipation of pore suction in untreated clay will cause shrinkage of the form shown diagrammatically in Figure 16 and hence that another mechanism must contribute to the shrinkage observed, particularly over periods of time greater than 24 hours after the material has been compacted.

7.2 *Changes in the structure of the water in the clay*

The water in clays is not always in a liquid state which is characterised by a complete lack of orientation or structure. Rosenquist[19], Low[20] and others have suggested that the water immediately surrounding the clay particles has an orientated structure but researchers cannot agree(21) whether the density of this non-liquid water is greater or less than 1.0.

Grim[21] hypothesised that when clays are in an 'undisturbed' state, the non-liquid water contributes to their shear strength. During the process of remoulding he postulated that the structure in the orientated water is disrupted, thus reducing the shear strength of the clay and causing the phenomenon of 'sensitivity'.

The change from non-liquid to liquid water during the remoulding process is not irreversible. Disturbed soils gradually regain strength and eventually return to the 'undisturbed' state. This change in state suggests a mechanism for the longer term shrinkage of unstabilized clay specimens.

When water is added to adjust the moisture content of a sample of soil and it is mixed and compacted, the soil is in a highly disturbed condition. In a recently moulded specimen, the water immediately surrounding the clay particles gradually becomes re-orientated, a condition in which it probably has a higher density and, therefore, a lower volume[21]. The gradual reduction in the volume of water in the clay causes it to shrink slowly and this process continues for some time as the clay tends to resume the undisturbed state. A possible timing for the shrinkage associated with this process is illustrated in Figure 17, but obviously the hypothesis implies that the density of non-liquid water is greater than 1.0.

7.3 *The effect of additions of cement on the behaviour of untreated clay*

When cement is added to the soil, the material is modified in several ways. The first effect is an increase in the strength and volume stability of the soil skeleton. In the first few hours this effect is produced by the cement flocculating the structure of the clay fraction but the more permanent and more significant effects are attributable to the hydration of the cement which occurs over a much longer period of time. After the initial set has occurred in the cement paste, a more rigid soil structure develops and continues to increase in strength and rigidity as the hydration progresses. The pore suction which develops in a specimen immediately after it is extruded would cause less 'consolidation' shrinkage in the stronger, stabilized specimen than occurs in the untreated material. Likewise, less shrinkage can be expected to be caused by re-orientation of the water immediately surrounding the clay particles in the stabilized material.

According to Taylor[22], ordinary Portland cement contains approximately 45 per cent of tricalcium silicate (C_3S) and approximately 27 per cent of dicalcium silicate (C_2S). The C_3S hydrates relatively quickly while the C_2S takes a considerable time, suggested values being some 10 hours and 1000 hours respectively.

In sealed specimens the water for hydration is drawn from the moist clay and as hydration proceeds, the amount of adsorbed water in the clay will steadily decrease, thus increasing the suction in the pores and consequently, the intergranular stress. Sherwood[23] has shown that when Harmondsworth brickearth is stabilized with 10 per cent of cement, approximately 13 per cent of water (based on the dry weight of cement in the mixture) will be used in the hydration reaction within the first 7 days. This increases the pore suction by 1.09 and there is a similar increase in the intergranular stress. When the cement content is lower there would be a smaller but still significant increase in the intergranular stress.

Littlehampton brickearth is generally similar to Harmondsworth brickearth and soil-cement specimens moulded from it would be expected to exhibit a similar increase in the intergranular stress while hydration is proceeding, thereby causing consolidation or shrinkage.

Another important effect is the expansion in the cement gel while it hydrates. Tests on cement pastes[10,11] have shown that expansion ceases after a certain time and the hydrated gel starts to shrink as recrystallisation occurs. A similar type of behaviour was observed when sealed specimens of cement paste were moulded at 17 per cent moisture content to the same density as the soil-cement specimens. The maximum value of expansion occurred after 1 day of curing and this was followed by a reduction in the volume of the paste[24].

Bofinger and Duffell[13] showed that sand-cement mixtures, which have volumetrically stable soil particles, expand when they are sealed and do not subsequently shrink. This is probably because the strength of the cemented sand matrix is sufficiently large to resist the shrinkage stresses in the paste after one day.

7.4 *The shape of the shrinkage-time curve*

The results of the experiments clearly indicated that the four methods of compaction used in the study produced specimens that exhibited different magnitudes of shrinkage but which had similar time-dependent patterns of shrinkage behaviour.

During the first phase, which lasts for up to one day, the rate of shrinkage is rapid and is thought to be dominated by the pore suction that develops when specimens are extruded. As the pore suction dissipates, the resultant shrinkage will also diminish and within 24 hours this process will be complete.

Two other factors, namely the pore suction caused by the hydration of the cement, and the expansion of the cement paste, will contribute to the overall dimensional changes during this first phase. However, their influence is thought to be less significant than the pore suction developed after extrusion, although further work is required in order to confirm this.

The initial rapid shrinkage is followed by a null zone which lasts for up to 7 days during which it seems likely that the increasing pore suction caused by the hydration of the cement tends to counterbalance the dissipation of the pore suction developed during the extrusion process. After approximately 10 hours the consumption of water in the hydration reaction is well advanced but the water will be taken first from the larger pores, thus causing only a relatively small increase in the pore suction which is insufficient to overcome the strength that the soil structure has attained at that time.

As hydration proceeds and water is removed progressively from finer and finer pores, the suction will build up sufficiently to cause the third stage of shrinkage which commences after approximately 7 days of moist curing.

7.5 *Influence of the method of compaction on the magnitude of shrinkage*

The method of compaction was found to have a major influence on the magnitude of shrinkage, the largest amount of shrinkage being measured on specimens moulded by impact compaction. It is likely that the mode of compaction affects both the structure in the material and the pore suction when the specimen is extruded.

It is expected that the pore pressure developed during compaction and, in consequence, the pore suction developed after the sample is extruded, will be greatest when a standard Proctor hammer is used and least when the samples are moulded by static compaction. During the first 24 hours, therefore, specimens moulded by Proctor hammer will probably shrink more than specimens moulded by kneading or static compaction.

El Rawi et al[25] found that the method of compaction influences the magnitude of cohesion in soil-cement specimens as well as its rate of increase with time. Specimens that were moulded by kneading compaction had higher cohesion values than those moulded dynamically. It can be surmised that the greater the cohesion, the greater will be the resistance to shrinkage stresses that develop in the soil-cement.

The difference in the total shrinkage of specimens moulded statically in the vertical and horizontal directions supports the view that there is some degree of anisotropy in the specimens, particularly in those moulded from Wainscott brown clay. Of more practical significance is the relationship between the cement content and shrinkage of specimens moulded in each direction. If randomly orientated plate-shaped particles are compacted, they tend to align themselves at right angles to the direction in which the compacting force is applied and tend to adopt a structure similar to a disordered pile of cards (see Figure 18). When a suction is developed internally in such a structure, movement of the particles can be achieved more easily in the horizontal direction than in the vertical direction. One would expect, therefore, that the shrinkage measured at right angles to the compacting force would be greater than in the direction of compaction.

In a roadbase, the compacting force is at right angles to the direction in which the shrinkage is critical, ie, the behaviour in the field is more closely modelled by the horizontally compacted specimens. The results of tests on horizontally-moulded specimens should therefore be considered very carefully when the behaviour of a soil-cement roadbase is being predicted from laboratory tests.

The method of compaction influences the pore suction, the cohesion and the orientation of particles, and thus contributes to the shrinkage characteristics of soil-cement specimens. It is suggested that they provide an insight into the large differences in the magnitude of the shrinkage of soil-cement specimens compacted by the four methods studied in this investigation.

7.6 *The effect of the cement content*

Variations in the cement content affected the shrinkage characteristics of the different types of specimens in different ways. For vertically compacted specimens moulded statically or by kneading, there was a critical cement content at which the autogenous shrinkage was a minimum. George[2] noticed a similar trend in the drying shrinkage of soil-cement. No completely satisfactory explanation can be offered for this behaviour especially since it is completely different from the behaviour of specimens moulded horizontally by static compaction which displayed lower shrinkage with progressive increase in cement content. Furthermore, the shrinkage of specimens compacted dynamically was found to be insensitive to cement content, although the conditions leading to the relatively large shrinkage of specimens compacted in this way may have masked the effect of differences in cement content.

An increase in the cement content will increase the volume of expanding gel and provide a stronger and more stable soil structure to resist the higher pore suction caused by self-desiccation. When the cement content is increased sufficiently one would expect the rigidity of the soil aggregates to approach that of the sand in sand-cement, leading to continued expansion instead of autogenous shrinkage. There is evidence that this is starting to occur when the cement content of the horizontally-moulded specimens is 10 and 15 per cent (Figure 3).

7.7 *The effect of the moisture content at which the soil-cement is moulded*

The shrinkage pattern was not altered by compacting the specimens at moisture contents 2 per cent greater or less than the optimum but the initial shrinkage was higher in the wettest specimens. Figure 15 shows that moulding a specimen at 2 per cent above the optimum moisture content will increase the pore suction developed after extrusion to nearly double the values obtained from a specimen moulded at the optimum moisture content. Consequently the higher initial shrinkage in the wetter specimens is probably due to this increase in the pore suction.

7.8 *The influence of the density*

The specimens compacted to a higher density, where the particles are closer together and the strength is higher, exhibited greater shrinkage than the specimens compacted to the lower density. This was a most unexpected result, and the probable explanation is that the water required for the hydration of the cement in a more dense specimen will be taken from finer capillaries and hence a higher pore suction will be induced. One must also consider the increased strength of the matrix due to the closer contact within the cemented skeleton but the results suggest that this higher strength is not sufficient to counteract the shrinkage forces. This is clearly a finding that merits further investigation.

It should be remembered that strength and durability, which are also affected by the density of the material, can be even more important in practice than shrinkage.

7.9 *The effect of the pre-treatment moisture content*

An explanation for the results shown in Figure 13 can be offered in terms of the competition between the soil and the cement for the moulding water.

In specimens prepared from dry soil, the water coating the soil aggregates is simultaneously attracted both by the soil particles and the cement. The cement will start to hydrate and expand, the clay fraction in the soil will swell but, in the initial stage, the tendency for the constituents to expand will not completely counteract the reduction in volume caused by the removal of water from the film surrounding the soil aggregates. As the hydration proceeds and as more water is adsorbed by the clay, expansion of the cement gel and swelling of the clay will predominate and there will be an overall expansion in the material. Eventually water for cement hydration will be extracted from the clay, self-desiccation will exceed the expansion in the cement gel, and the material will shrink.

When specimens are prepared from soil pre-treated at the optimum moisture content, the water for hydration will be taken entirely from within the soil causing shrinkage in the clay fraction which is unlikely to be offset by the expansion in the gel.

If the soil is pretreated at 2 per cent less than the optimum moisture content, the behaviour is intermediate between the two extremes described above.

7.10 *The effect of drying*

There was an initial sharp rise in the drying shrinkage when the wax was stripped from the specimens, but in every case it was completed within 7 days of the beginning of the drying cycle. The magnitude of the drying shrinkage decreased when the period of moist curing was increased, supporting the findings of George[2] but contrary to the results of Nakayama and Handy[1].

If soil-cement specimens are allowed to dry, the self-desiccation is augmented by the loss of moisture to the atmosphere, emptying smaller capillaries and increasing the pore suction and shrinkage forces. Ultimately, most of the capillary water will be lost, the shrinkage forces will reach a maximum and no further shrinkage strain will occur. The loss of water due to evaporation is greater than the amount of water required by cement for hydration and, therefore, evaporation drying will contribute more to shrinkage than will self-desiccation.

When specimens are moist cured for a longer period of time before being allowed to dry out, more cementation and bonding occurs, thereby decreasing the shrinkage potential in the clay fraction.

8. IMPLICATIONS FOR ROAD PAVEMENT LAYERS

This study has produced data which have important practical implications for minimising the shrinkage in pavement layers constructed from clayey soil-cement. The spacing, and more importantly, the width of cracks in a soil-cement pavement layer are important factors influencing overall performance. Under ideal curing conditions, the spacing of cracks is primarily governed by the strength of the material and the subgrade restraint, while the width of the cracks during the early life of the soil-cement layer can mainly be attributed to the shrinkage characteristics of the material. Subsequent changes in the width of the cracks will be influenced by changes in temperature and in the moisture within the layer. In the following discussion the effects of the cement content, moisture content, compaction and curing on the shrinkage of soil-cement are considered, but the way in which the strength and stiffness of soil-cement affects the spacing and width of cracks is not discussed here.

8.1 *Cement content*

It is often suggested that the problem of shrinkage cracking in soil-cement can be reduced by lowering the cement content provided that an adequate minimum strength is maintained.

Horizontally moulded specimens are appropriate for estimating the shrinkage behaviour of a soil-cement layer because the orientation of the soil particles is similar to that in a pavement layer. The study showed that, contrary to the traditional ideas, autogenous shrinkage of horizontally moulded specimens is minimised by increasing the cement content [traditional thinking has usually assumed that shrinkage is caused by drying]. However the full implications of increasing cement content and the consequent increase in strength on the spacing between the cracks should be considered together with the crack width. Further work is needed to study drying shrinkage after a number of months of moist curing in an attempt to simulate the field conditions to which a well-cured base may be subjected.

8.2 *Moisture content*

The magnitude of the shrinkage can be significantly reduced if the soil is kept in the driest practicable state before it is mixed. The most effective way to achieve this is to use a single-pass mixer and compact the stabilized material as soon as possible after mixing, before any significant swelling occurs within the soil aggregates. An added advantage of using this method is that the moisture will be sucked into the soil aggregates, carrying hydrated cementitious material with it, thus helping to stabilize the interior of the soil lumps.

The target moisture content should be the optimum for compaction but it is preferable to err on the low side rather than the high if the criterion to be satisfied is that of minimising shrinkage. Other criteria, such as minimising the air voids in the compacted material, would then be more difficult to meet.

8.3 *Compaction*

Ideally, compaction plant should induce a low pore pressure in the upper part of the layer on which it is working, when compacting a clayey soil-cement material. Probably the best plant for this purpose is a pneumatic-tyred roller, and the least suitable is likely to be a vibrating roller because the shock loading it would impose would cause a large immediate increase in pore pressure.

It would appear from the results obtained that compacting clay-cement mixtures to a high density will increase the shrinkage as well as the strength of the material, resulting in a large spacing between cracks. As a consequence of both strength and shrinkage considerations, the crack formed will therefore be very wide.

This is a controversial finding that requires further investigation.

8.4. *Curing*

It is difficult to prevent the gradual loss of moisture from a soil-cement pavement layer into the underlying material, but evaporation from the surface of a layer can be prevented by sealing it immediately after it has been compacted. Any period of curing is beneficial in reducing the shrinkage and the longer the layer can be maintained in this condition, the smaller will be the final total shrinkage.

9. CONCLUSIONS

The results obtained in this investigation enable the following main conclusions to be drawn:

1. The method of compaction and the anisotropy induced in specimens has a major influence on the magnitude of shrinkage and hence the prediction of the shrinkage behaviour of full-scale pavements on the basis of laboratory tests must be made with caution. Shrinkage was a maximum in specimens moulded by dynamic compaction (BS compaction[14]) and a minimum when static compaction was used.

2. The higher the proportion of cement that is added to clays, the smaller will be the autogenous shrinkage of horizontally moulded specimens in which the structure of a soil-cement pavement layer is most closely simulated. Vertical compaction methods which do not simulate field conditions allow other conclusions to be drawn but these should be treated with reservation. When the clay is unstabilized, the larger values of shrinkage that occur are probably due to the combined effects of the soil moisture suction which develops when the specimen is extruded from the mould and the gradual re-orientation of the water adsorbed on the clay particles. The addition of cement introduces other factors, the most important being the expansion of the cement gel as it hydrates, the self-desiccation caused by the hydration of the cement and the increase in the strength of the cemented soil skeleton.

3. Shrinkage of clay-cement specimens is profoundly affected by the initial moisture condition of the soil prior to moulding, by the moisture content at which they are compacted, and by their final density. Specimens moulded to a high density shrink more than those with lower densities and the shrinkage increases when the moulding moisture content is increased. The shrinkage of clay cement will be minimised if the soil is processed in a dry state and the water required for compaction and hydration is added during mixing. Additionally, to minimise shrinkage the mixture should be compacted as quickly as possible to the minimum density that will ensure that the material will attain adequate strength.

4. If clay-cement specimens are exposed to a drying atmosphere at any time after moulding the shrinkage will be greater than that of sealed specimens, but the longer the period of time they are kept sealed before drying commences, the smaller is the total shrinkage.

10 ACKNOWLEDGEMENTS

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11. REFERENCES

1. NAKAYAMA, H and R L HANDY, 1965. Factors influencing shrinkage of soil-cement. Highway Research Record 86; Washington DC (Highway Research Board) pp15-27

2. GEORGE, K P, 1968. Shrinkage characteristics of soil-cement. Highway Research Record 255. Washington DC (Highway Research Board) pp42-57

3. WEBB, T L, T P CILLIERS and N STUTTERHEIM, 1950. The properties of compacted soils and soil-cement mixtures for use in buildings. South African Council for Sci and Indust Research, Natal Building Research Institute.

4. WANG, J W H, 1973. Use of additives and expansive cement for shrinkage crack control in soil-cement. Highway Research Record 442. Washington DC (Highway Research Board) pp11-20.

5. PRETORIUS, P C and C L MONISMITH, 1971. Prediction of shrinkage stresses in pavement containing soil-cement bases. Highway Research Record 362. Washington DC (Highway Research Board) pp63-86.

6. DUNLOP, R J, 1973. Shrinkage and creep characteristics of soil-cement. Unpublished Ph.D Thesis, Univ of Canterbury, Christchurch, New Zealand.

7. PLUMMER, F L and S M DORE, 1940. Soil mechanics and foundation. Pitman, New York, pp60-61.

8. MEANS, R G and J V PARCHER, 1963. Physical properties of soils. Merrill Books Inc., Columbus.

9. CZERNIN, W, 1962. Cement chemistry and physics for civil engineers. London. Crosby Lockwood.

10. HANSEN, T C 1958. Creep of concrete. Research Institute Bulletin No. 33.

11. BERNAL, J D, 1952. The structure of cement hydration compounds 3rd Intern. Symp. on the Chemistry of Cement. London 1952. pp216-236.

12. WANG, J W H and A H KREMMYDOS, 1970. Use of sodium chloride in reducing shrinkage in montmorillonitic soil-cement. Highway Research Record 315. Washington DC (Highway Research Board) pp81-90.

13. BOFINGER, H E and C G DUFFELL, 1973. The effect of filler on the characteristics of sand-cement mixtures. Department of the Environment, TRRL Report LR 527. Crowthorne, 1973 (Road Research Laboratory).

14. BRITISH STANDARDS INSTITUTION. Methods of testing soils for civil engineering purposes. London 1975 (British Standard Institution). British Standard No. 1377.

15. BRITISH STANDARDS INSTITUTION. Part 2: Specification for Portland Cement (Ordinary and rapid hardening). London 1971 (British Standards Institution). British Standard No. 12.

16. LAMBE, T W, 1961. Residual pore-water pressure in compacted clays. Proc. 5th Intr. Conf. on Soil Mech. and Found. Engng. Vol 1. Paris pp207-212.

17. LAMBE, T W, 1958. The structure of compacted clays. Jour. of Soil Mech and Found. Div. Proc. of ASCE, May 1958.

18. AITCHISON, G D, 1961. Relationship of moisture stress and effective stress functions in unsaturated soils. Pore-pressure and suction in soils, Soil Mech. and Found. Engng. Butterworth.

19. ROSENQUIST, I T, 1959. Physico chemical properties of soils: Soil water system. Proc. ASCE 85 SM2.

20. LOW, P F, 1959. Viscosity of water in clay systems: Proc. 8th Nat. Conference Clays and Clay Minerals, London.

21. GRIM, R E, 1962. Applied clay mineralogy. McGraw-Hill Book Coy.

22. TAYLOR, H F W, 1964. The chemistry of cement, Vol 1. Academic Press, London, New York.

23. SHERWOOD, P T, 1968. The properties of cement stabilized materials. Ministry of Transport, RRL Report LR 205. Crowthorne, 1968 (Road Research Laboratory).

24. HASSAN, H O, 1975. Shrinkage and creep in soil cement. Unpublished PhD Thesis. University of Surrey.

25. EL RAWI, N M, T A HALIBURTON and R L JANES, 1968. Effect of compaction method on strength parameters of soil-cement mixtures. Highway Research Record 255, Washington DC (Highway Research Board) pp72-80.

12. APPENDIX

TABLE 1

Typical shrinkage strains vs time of L.B.E. sealed specimens moulded to B.S. light density and O.M.C. by vertical static compaction

Cement content	8%					
	Shrinkage strain x 10^{-6}					
Spec No	1	2	3	4	5	Average
Time						
15 mins	0	0	0	0	0	0
30 mins	92	46	36	32	46	50
1 hr	96	46	38	36	46	52
2 hrs	96	46	40	38	48	54
4 hrs	126	58	48	44	60	67
1 day	480	232	386	336	272	341
2 days	512	276	406	358	312	373
3 days	512	278	410	358	312	374
7 days	512	278	410	360	318	376
14 days	520	280	416	364	322	380
28 days	542	296	424	386	356	401
72 days	856	536	686	746	716	708

TABLE 2

Typical shrinkage strains vs time of L.B.E. sealed specimens moulded to B.S. light density and O.M.C. by horizontal static compaction

Cement content	8%					
	Shrinkage strain x 10^{-6}					
Spec No	1	2	3	4	5	Average
Time						
15 mins	17	67	25	31	42	36
30 mins	53	81	59	58	70	64
1 hr	95	95	84	87	96	91
2 hrs	123	108	95	106	114	109
4 hrs	124	108	95	108	118	111
1 day	147	167	181	162	176	167
2 days	143	160	173	162	170	162
3 days	127	143	173	162	150	151
7 days	251	231	271	260	258	254
14 days	378	283	438	374	364	367
28 days	547	475	614	557	533	545
56 days	867	760	814	848	827	823

TABLE 3

Typical shrinkage strains vs time of L.B.E. sealed specimens moulded to B.S. light density and O.M.C. by kneading compaction

Cement content	8%					
	Shrinkage strain x 10^{-6}					
Spec No	1	2	3	4	5	Average
Time						
15 mins	275	316	298	257	363	302
30 mins	400	439	431	389	553	442
1 hr	440	468	463	431	601	481
2 hrs	443	468	465	437	605	484
4 hrs	443	468	460	433	600	481
1 day	380	385	379	403	508	411
2 days	380	381	373	398	427	392
3 days	380	381	373	398	427	392
7 days	380	381	373	398	427	392
14 days	380	387	382	426	460	407
28 days	450	473	488	560	543	503

TABLE 4

Typical shrinkage strains vs time of L.B.E. sealed specimens moulded to B.S. light density and O.M.C. by dynamic compaction

Cement content	8%					
	Shrinkage strain x 10^{-6}					
Spec No	1	2	3	4	5	Average
Time						
15 mins	126	142	119	136	130	131
30 mins	260	304	263	293	279	280
1 hr	500	446	468	470	493	475
2 hrs	678	740	683	706	718	705
4 hrs	786	900	800	831	853	834
1 day	960	1070	1013	1043	1056	1028
2 days	1018	1124	1080	1113	1128	1093
3 days	1150	1260	1186	1209	1237	1208
7 days	2060	2920	2217	2500	2660	2471
14 days	2420	3230	2650	2936	3086	2864
28 days	3980	4340	4015	4209	4256	4160

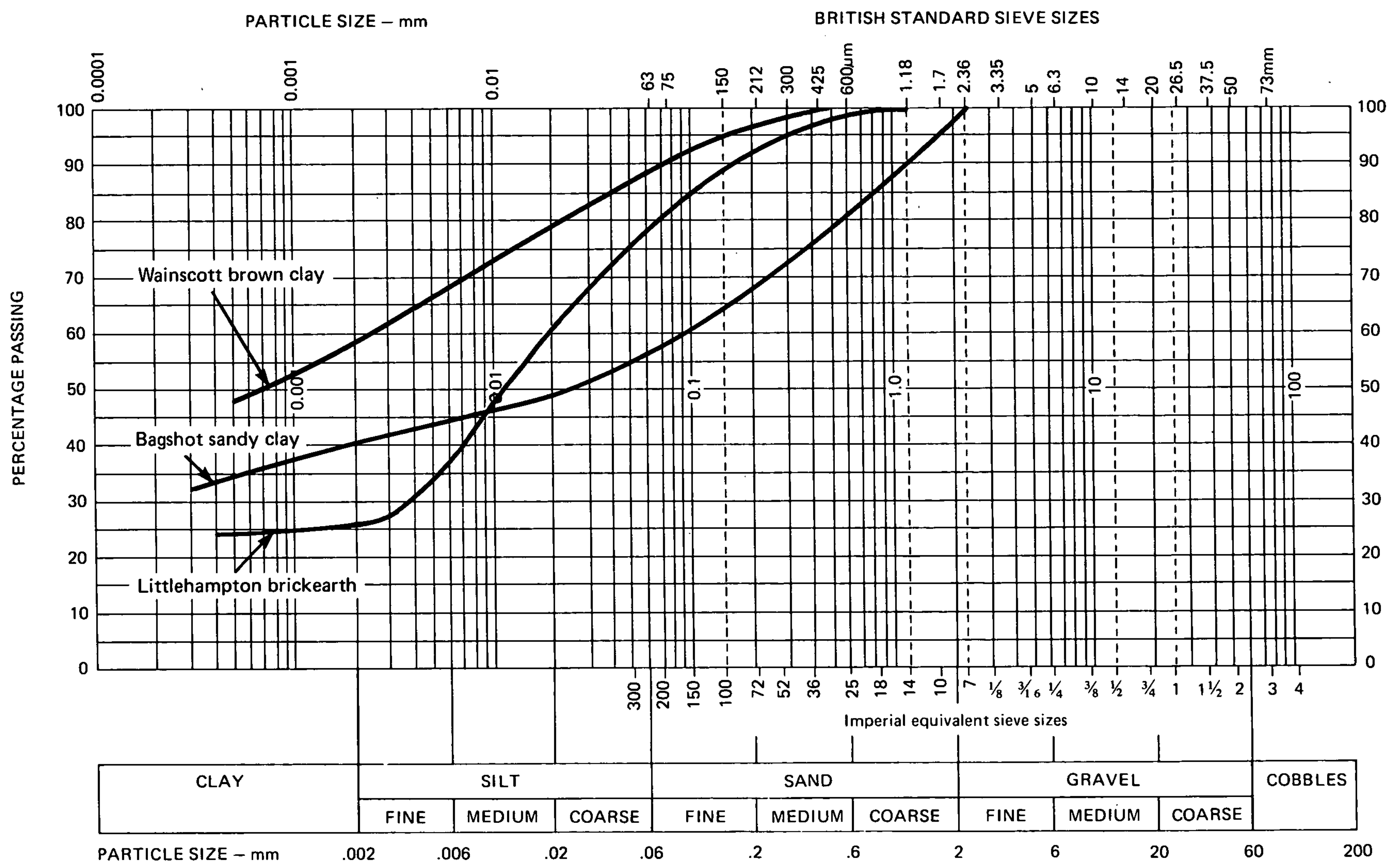

Fig. 1 PARTICLE-SIZE DISTRIBUTION

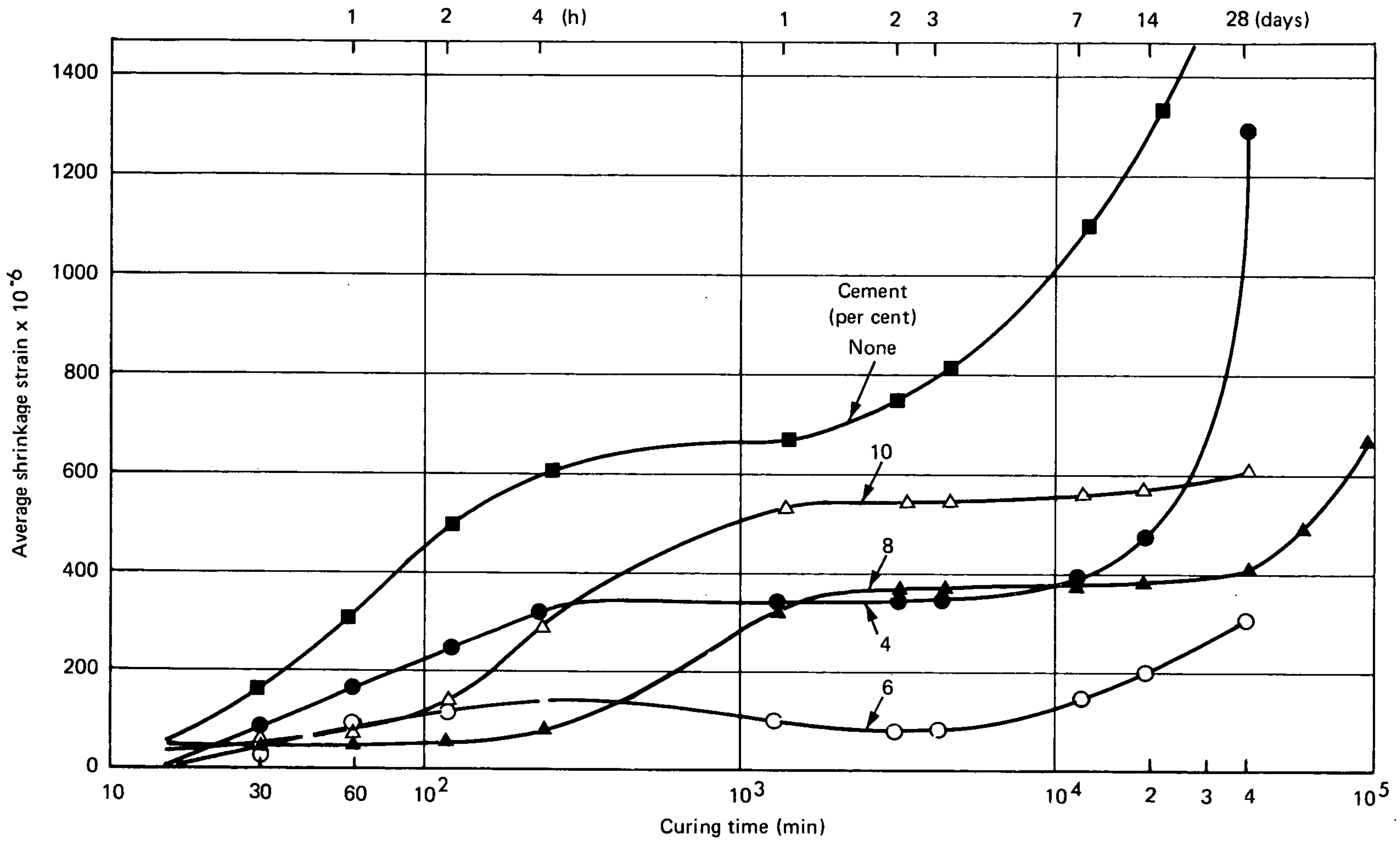

Fig. 2 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF L.B.E. SOIL-CEMENT. VERTICAL STATIC COMPACTION

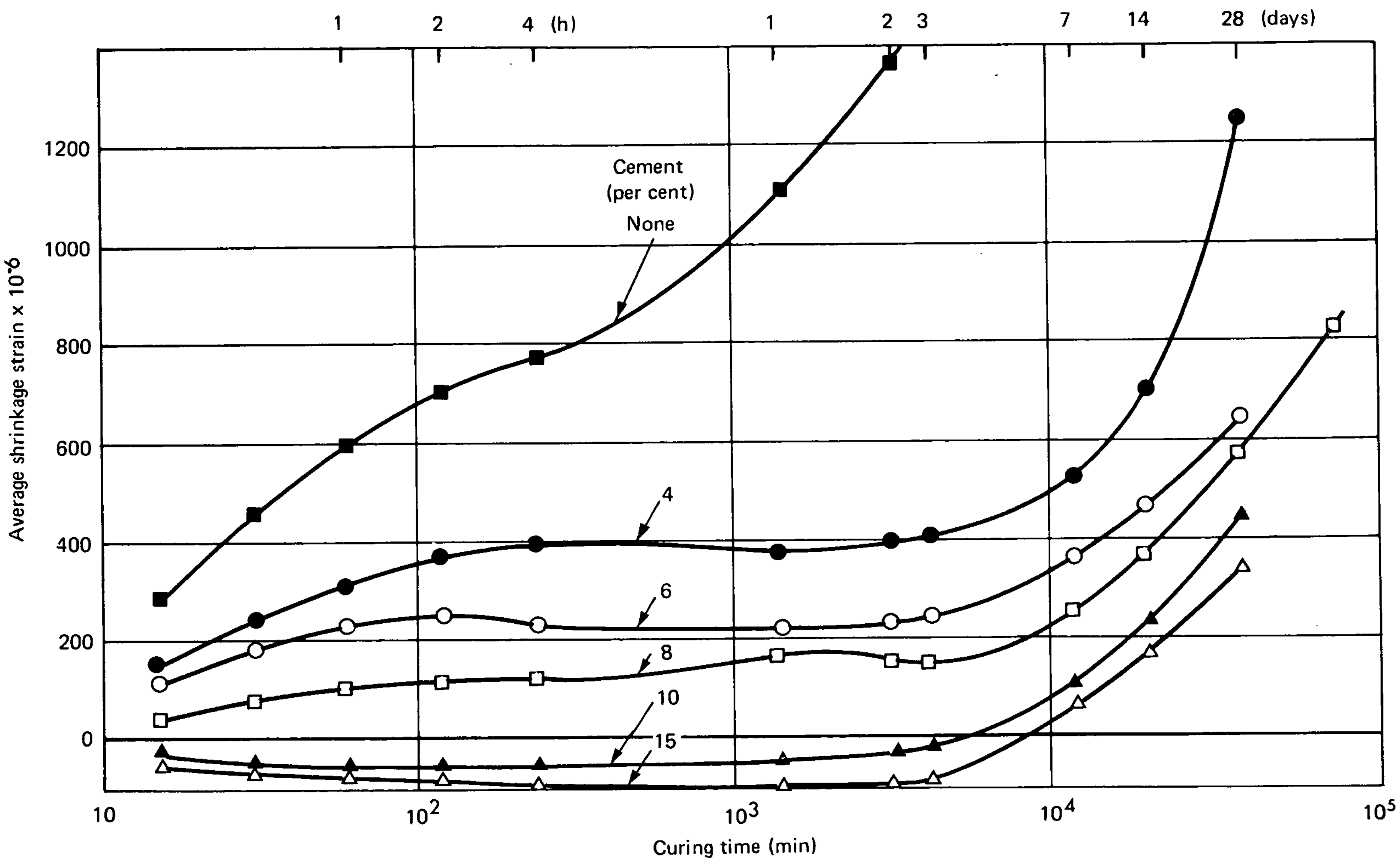

Fig. 3 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF L.B.E. SOIL-CEMENT. HORIZONTAL STATIC COMPACTION

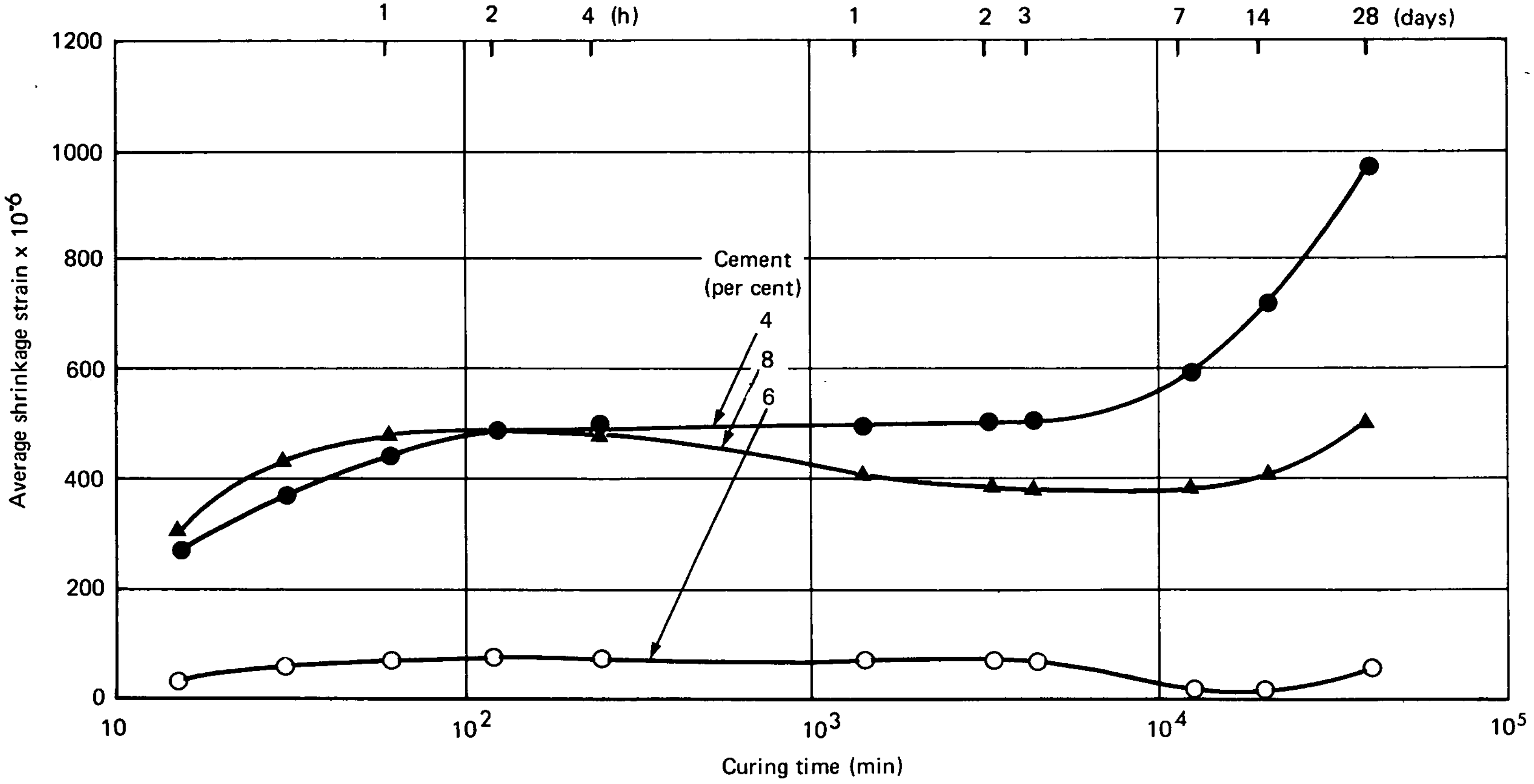

Fig. 4 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF L.B.E. SOIL-CEMENT. KNEADING COMPACTION

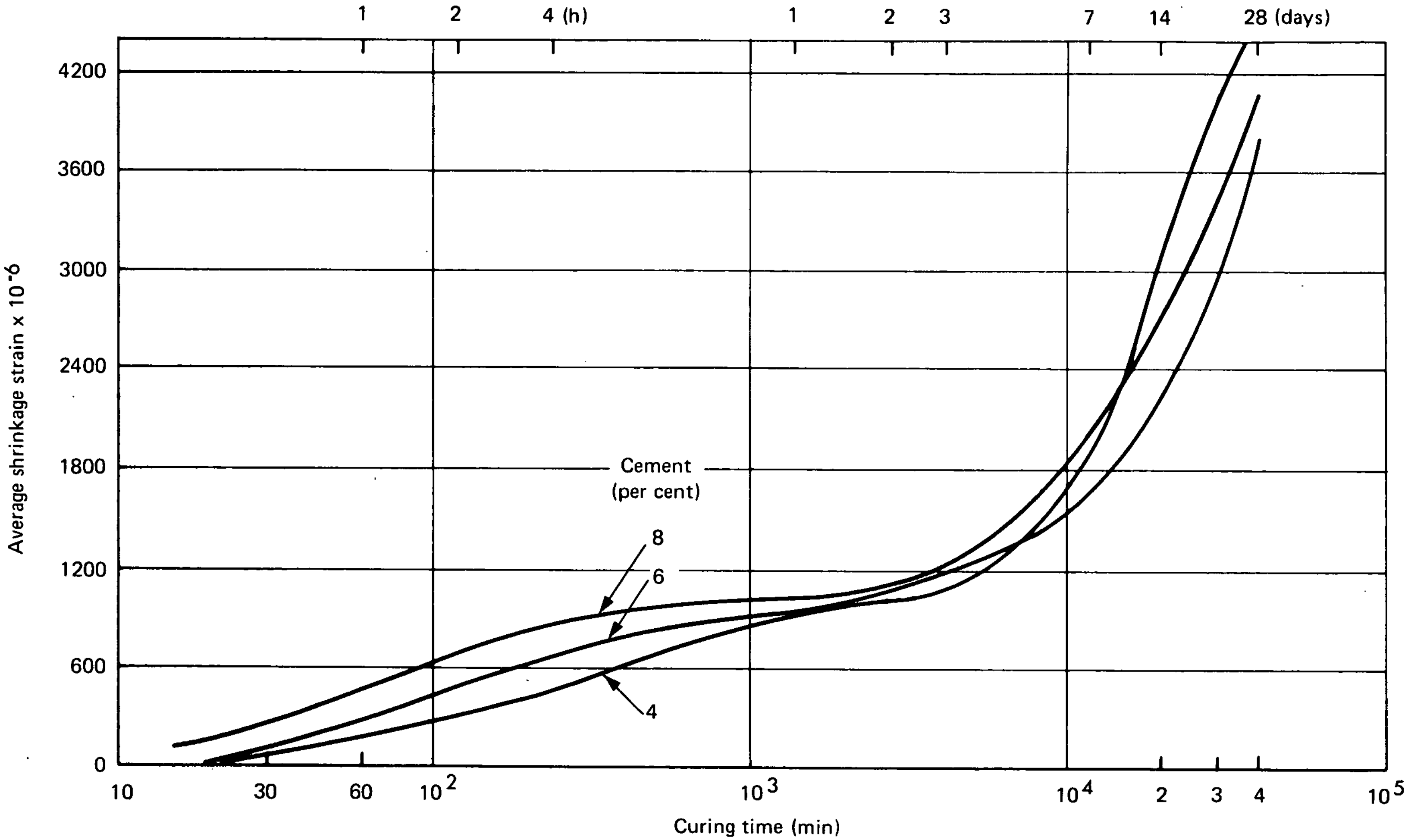

Fig. 5 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF L.B.E. SOIL-CEMENT. DYNAMIC COMPACTION

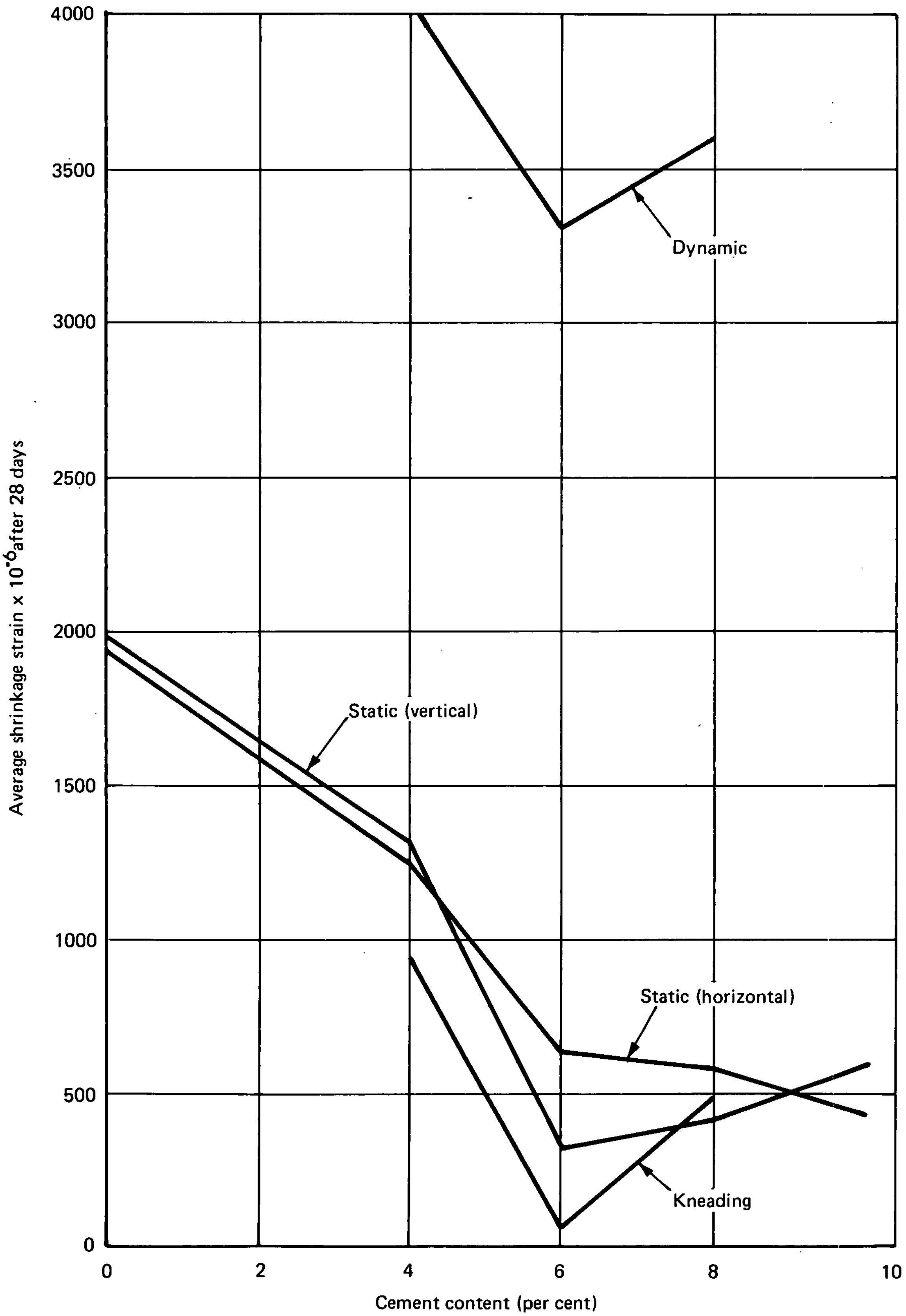

Fig. 6 INFLUENCE OF CEMENT CONTENT ON SHRINKAGE OF SPECIMENS MOULDED FROM L.B.E. BY VARIOUS METHODS OF COMPACTION

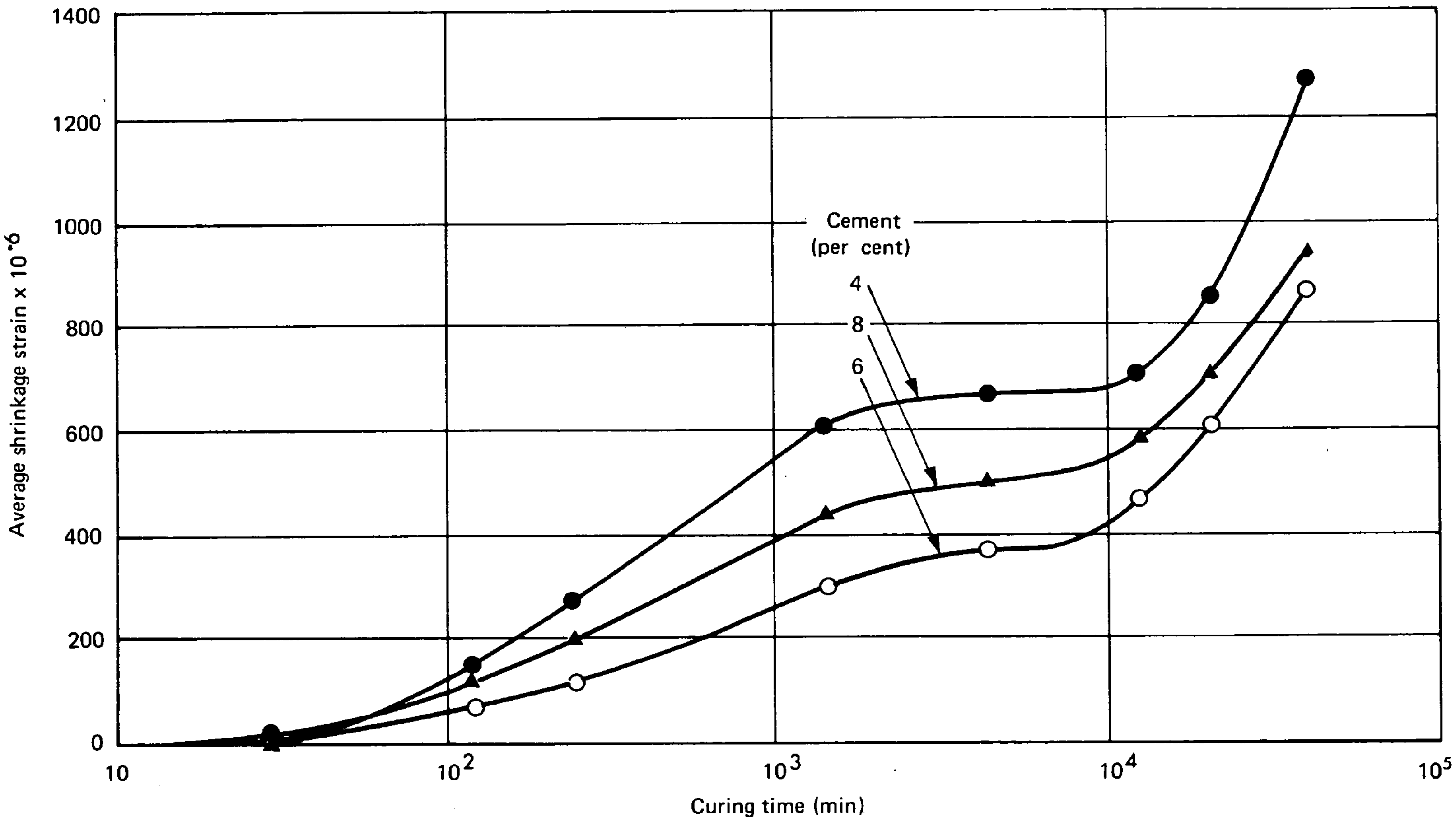

Fig. 7 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF BAGSHOT SANDY CLAY SOIL-CEMENT. VERTICAL STATIC COMPACTION

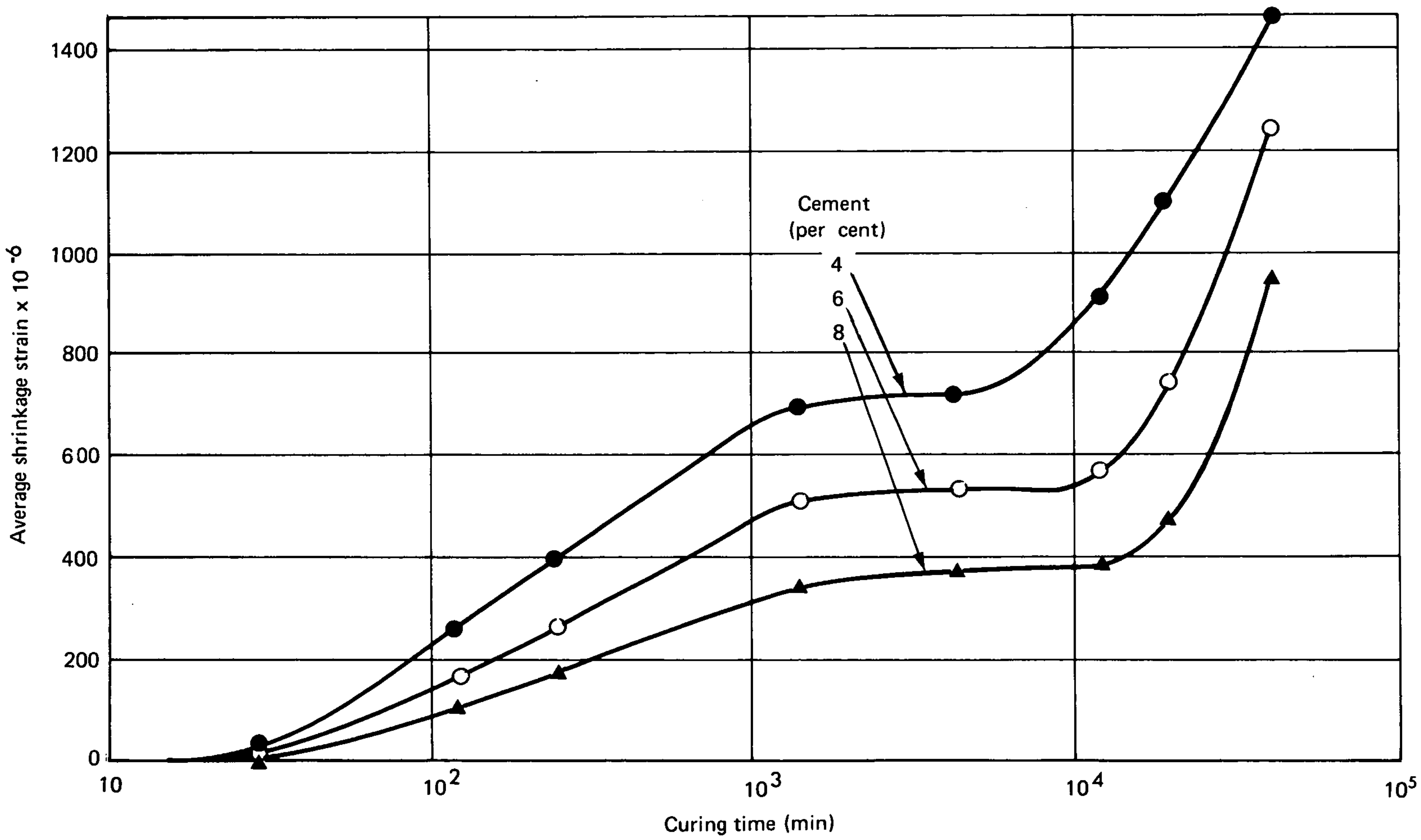

Fig. 8 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF BAGSHOT SANDY CLAY SOIL-CEMENT. HORIZONTAL STATIC COMPACTION

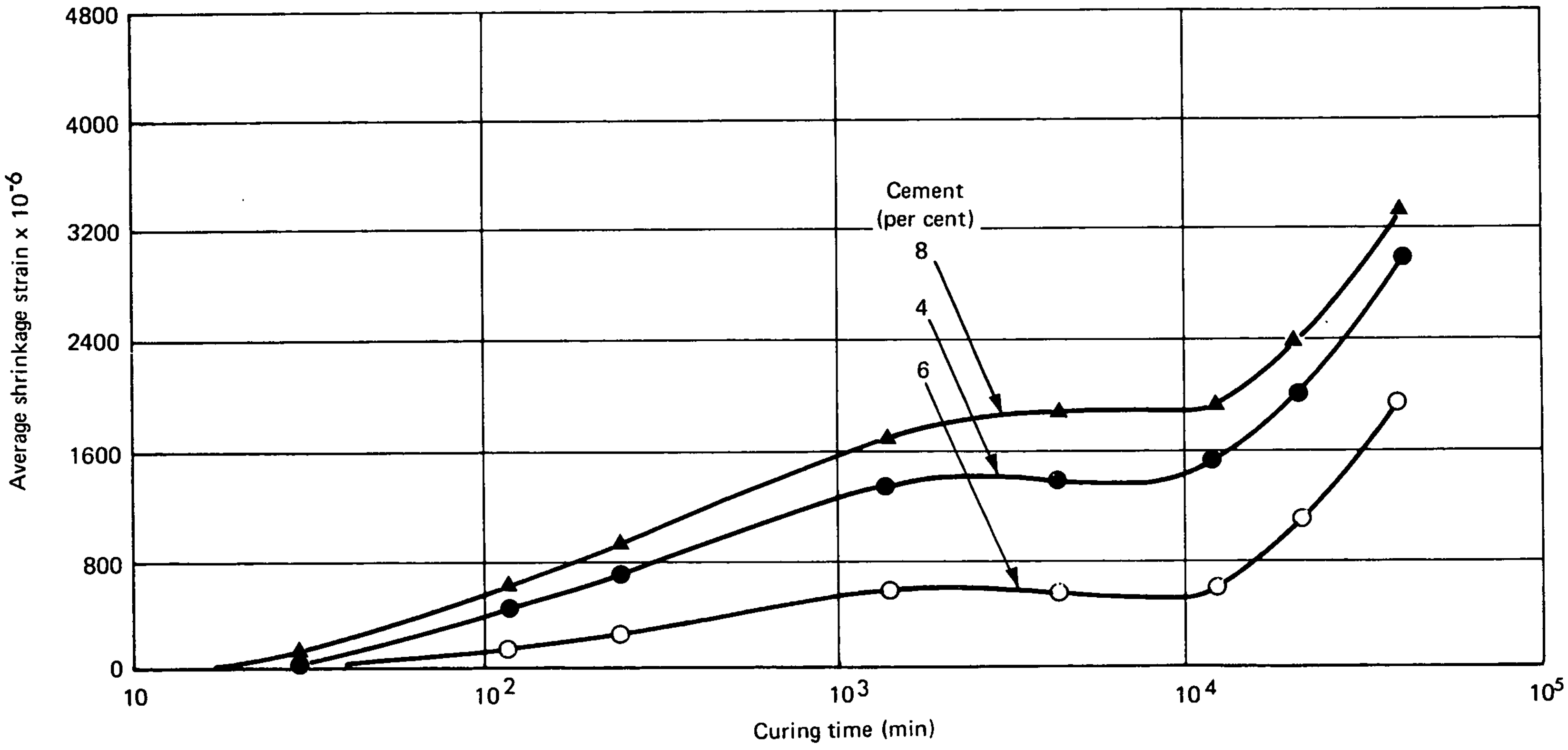

Fig. 9 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF WAINSCOTT BROWN CLAY SOIL-CEMENT. VERTICAL STATIC COMPACTION

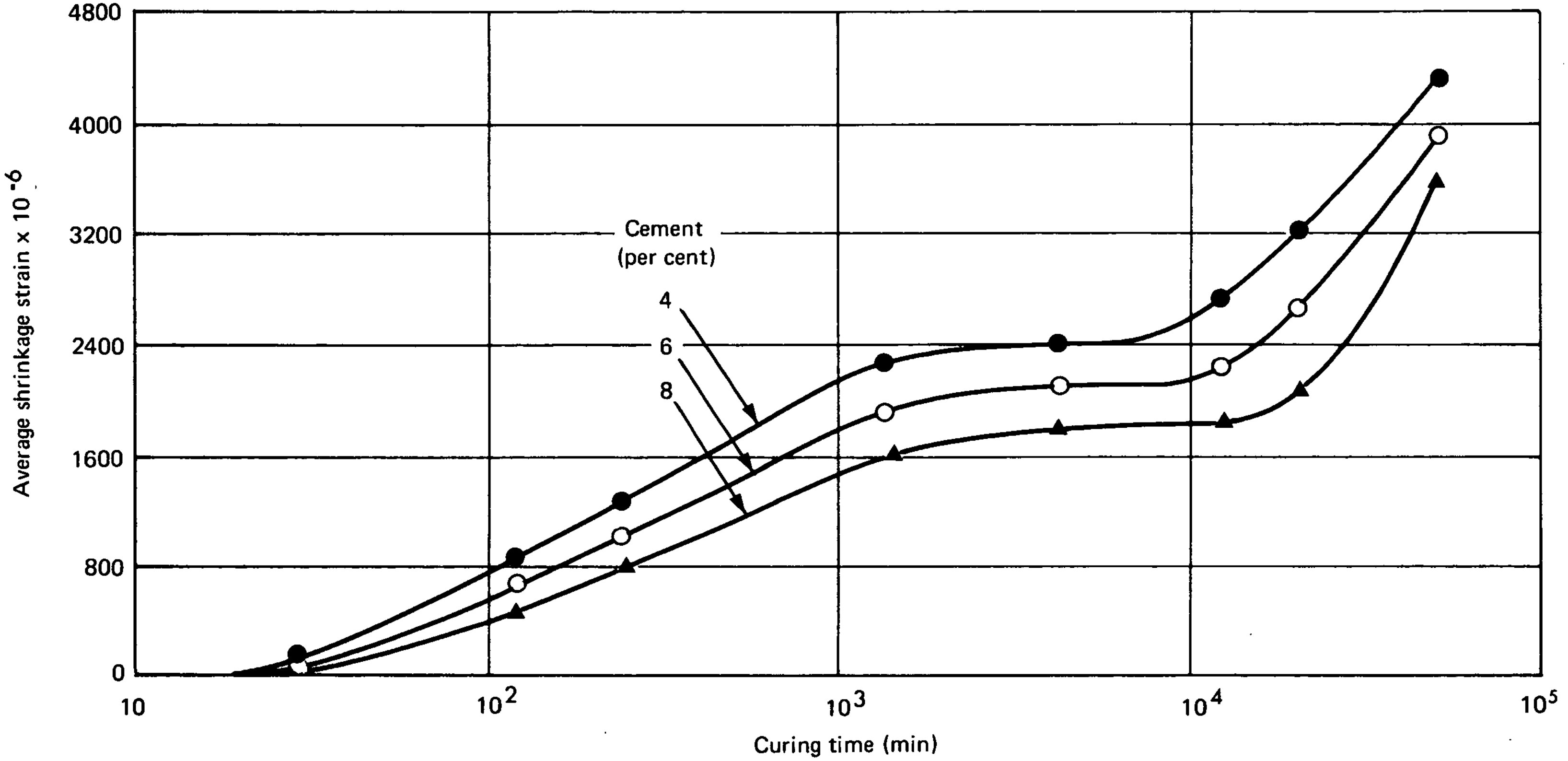

Fig. 10 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF WAINSCOTT BROWN CLAY SOIL-CEMENT. HORIZONTAL STATIC COMPACTION

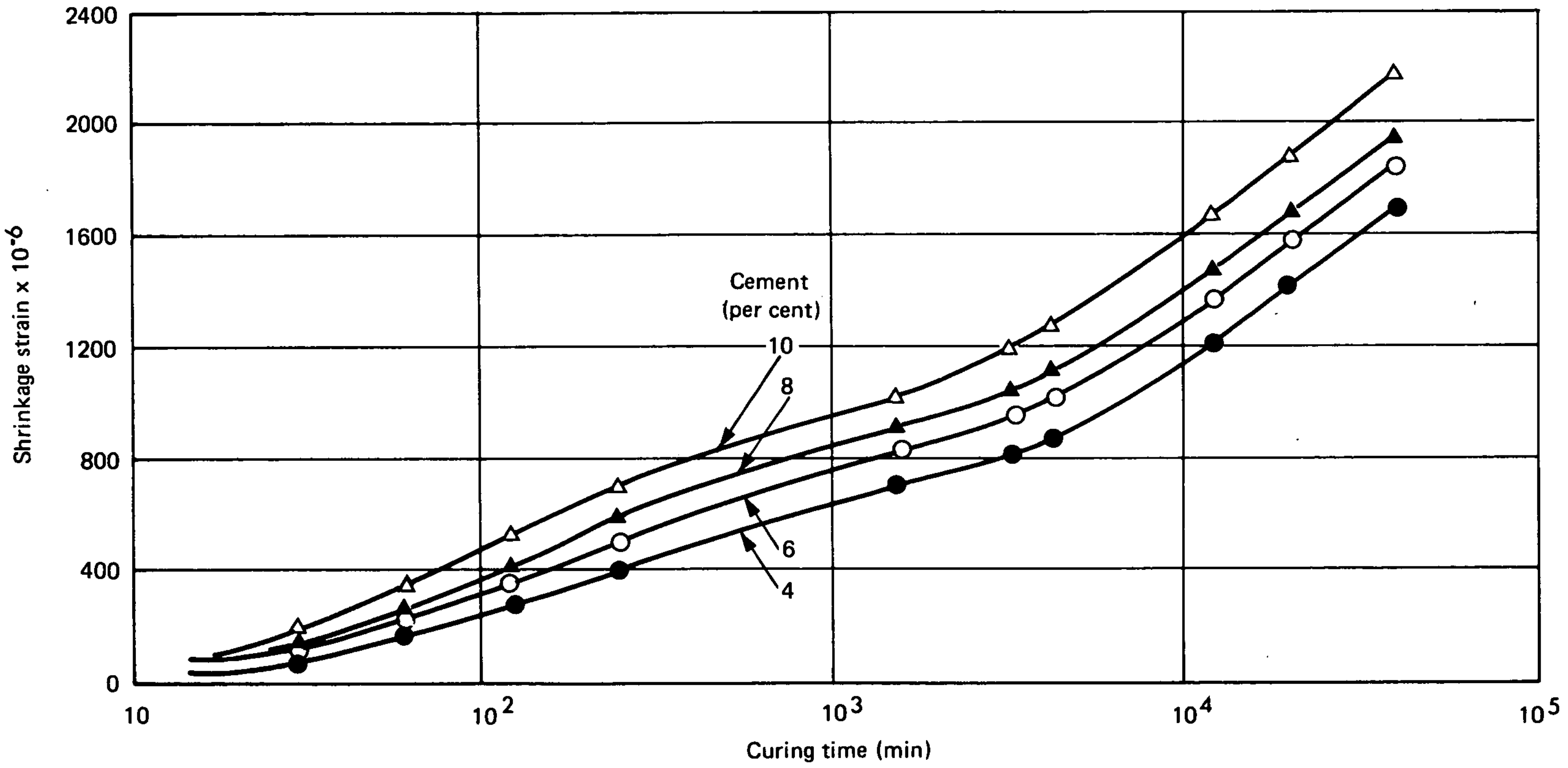

Fig. 11 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF L.B.E. SOIL-CEMENT. B.S. HEAVY DENSITY AND RELEVANT O.M.C. VERTICAL STATIC COMPACTION

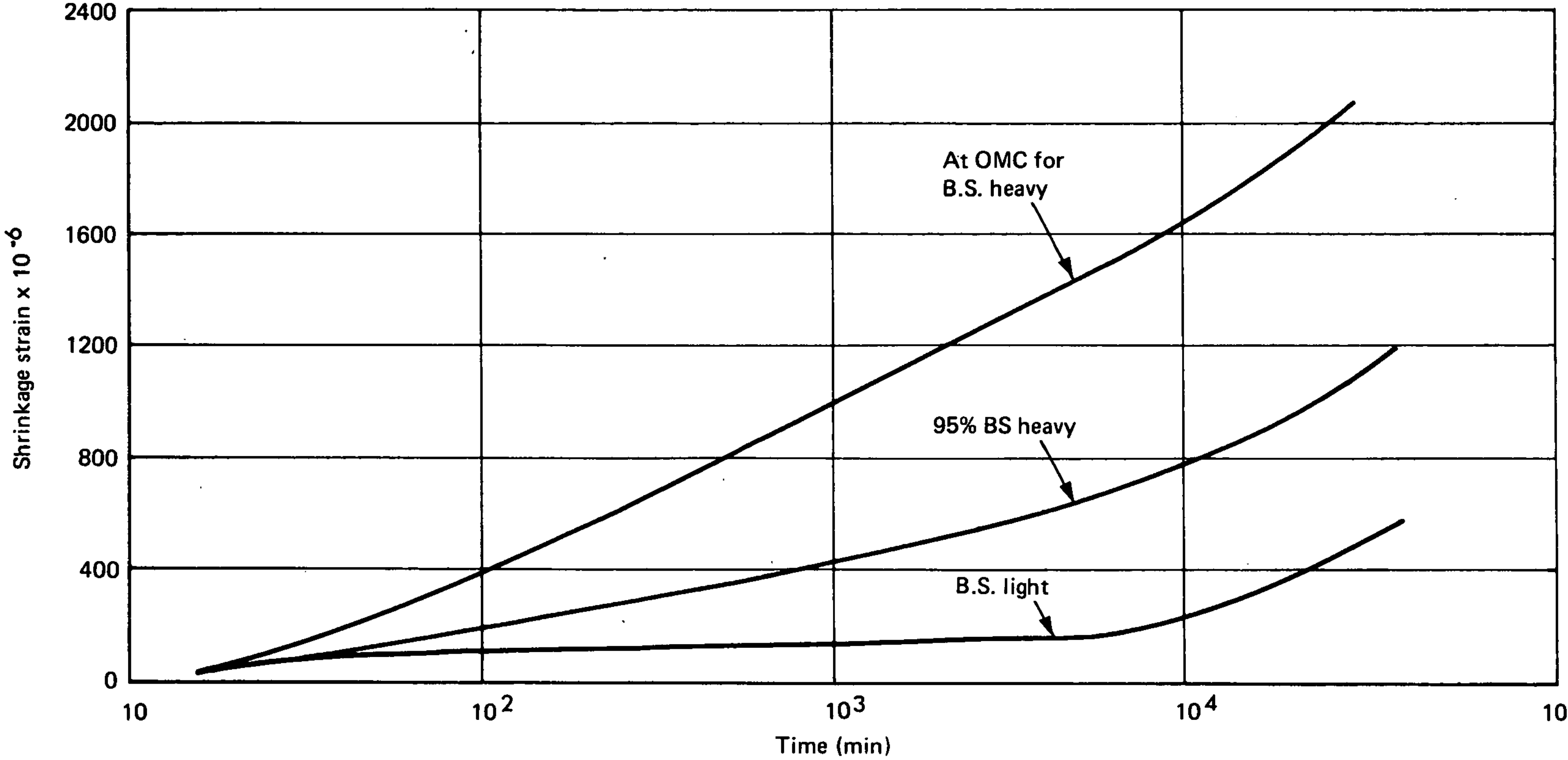

Fig. 12 RELATIONSHIP BETWEEN SHRINKAGE AND LOG. TIME OF L.B.E. SOIL-CEMENT CONTAINING 8 PER CENT CEMENT MOULDED AT VARIOUS DENSITIES. HORIZONTAL STATIC COMPACTION

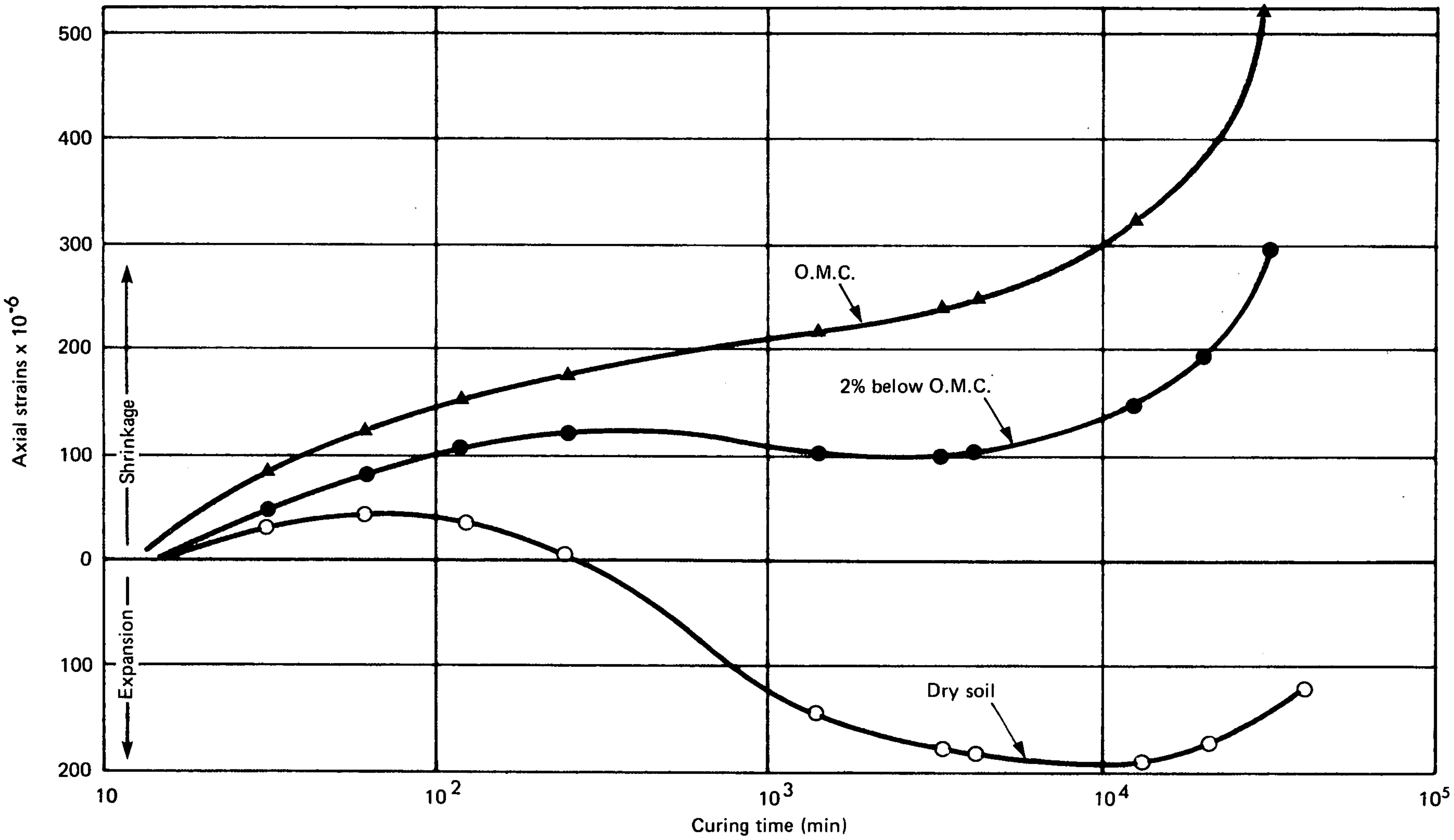

Fig. 13 INFLUENCE OF PRE-TREATMENT MOISTURE CONTENT ON SHRINKAGE OF SPECIMENS CONTAINING 6 PER CENT CEMENT COMPACTED AT OPTIMUM MOISTURE CONTENT TO THE (2·5kg RAMMER TEST) MAXIMUM DRY DENSITY

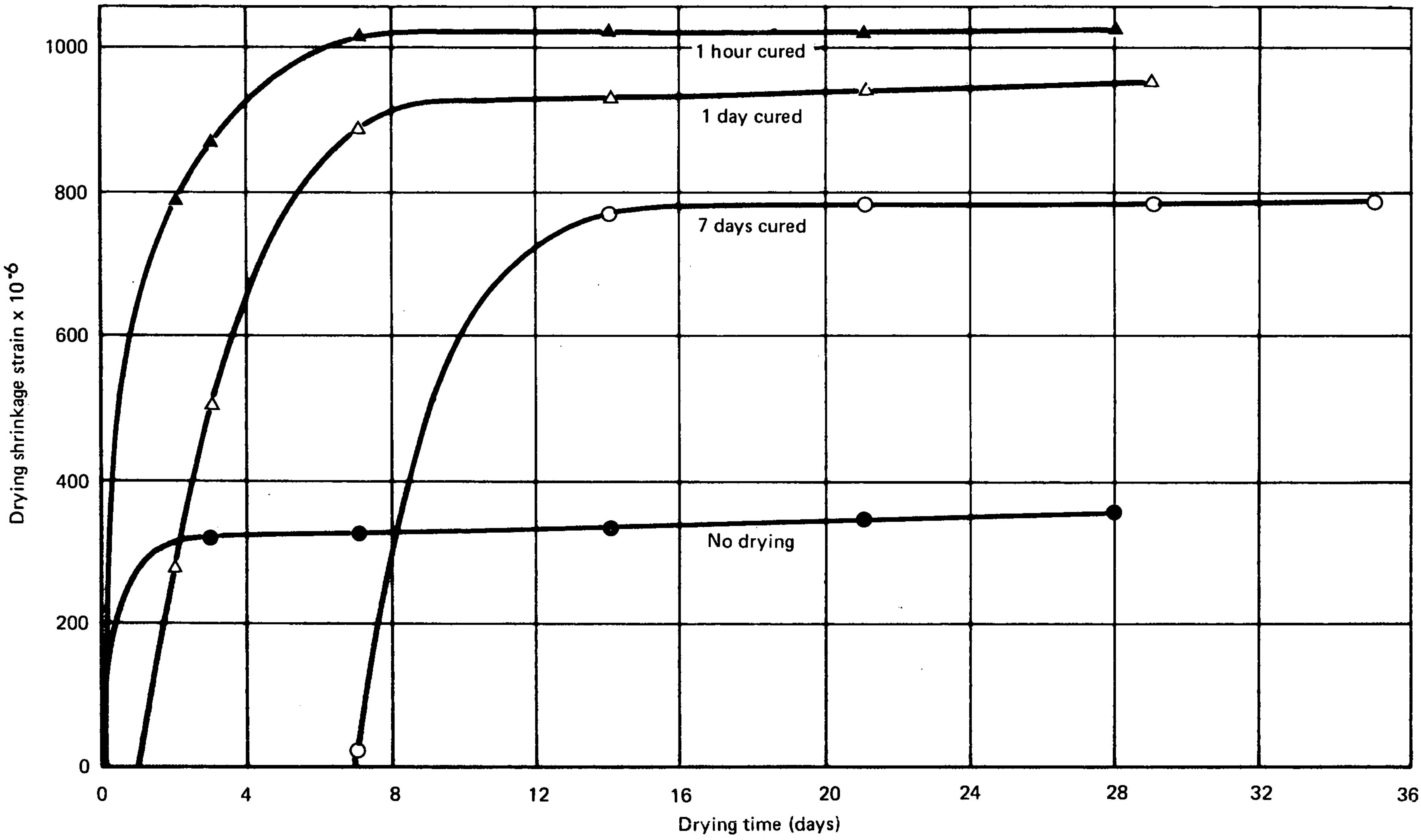

Fig.14 INFLUENCE OF DRYING ON SHRINKAGE OF L.B.E. SPECIMENS CONTAINING 8 PER CENT CEMENT MOULDED AT O.M.C. FOR B.S. LIGHT COMPACTION

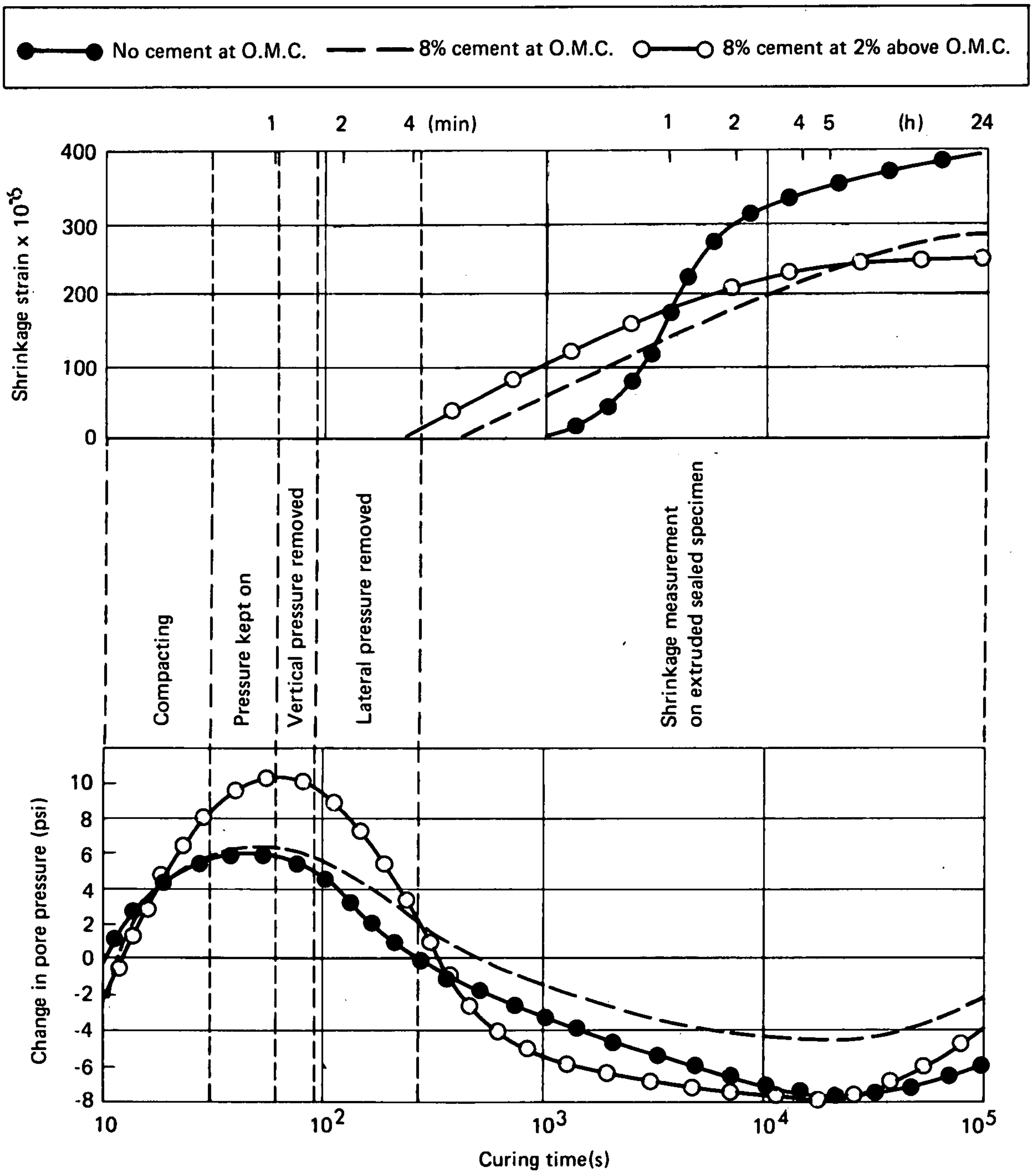

Fig. 15 CHANGES IN PORE PRESSURE AND AXIAL STRAIN WITH TIME

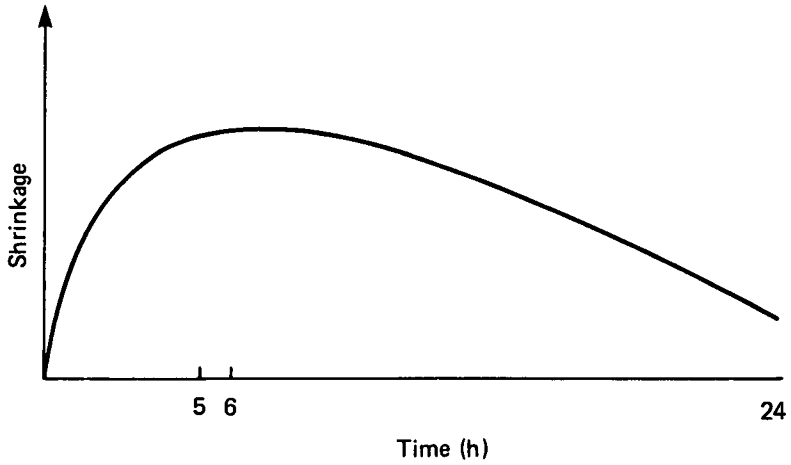

Fig. 16 POSSIBLE SHRINKAGE OF CLAY WITH TIME DUE TO DEVELOPMENT AND DISSIPATION OF PORE SUCTION

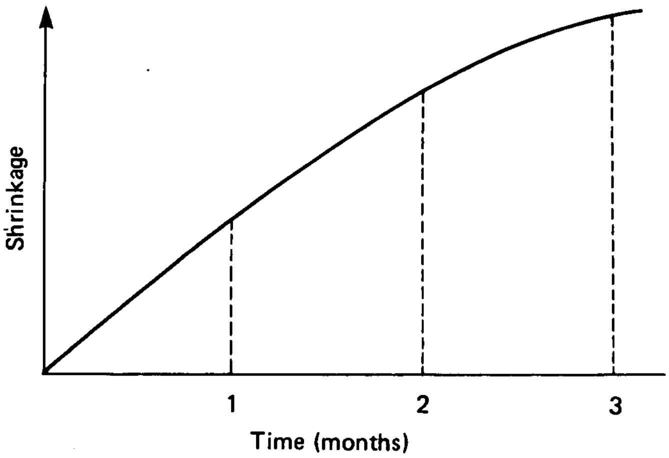

Fig. 17 POSSIBLE SHRINKAGE OF CLAY WITH TIME DUE TO RE-ORIENTATION OF ADSORBED WATER

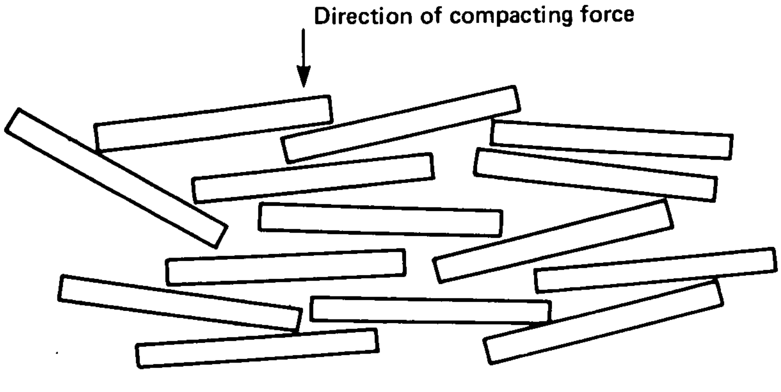

Fig. 18 CLAY STRUCTURE AFTER COMPACTION

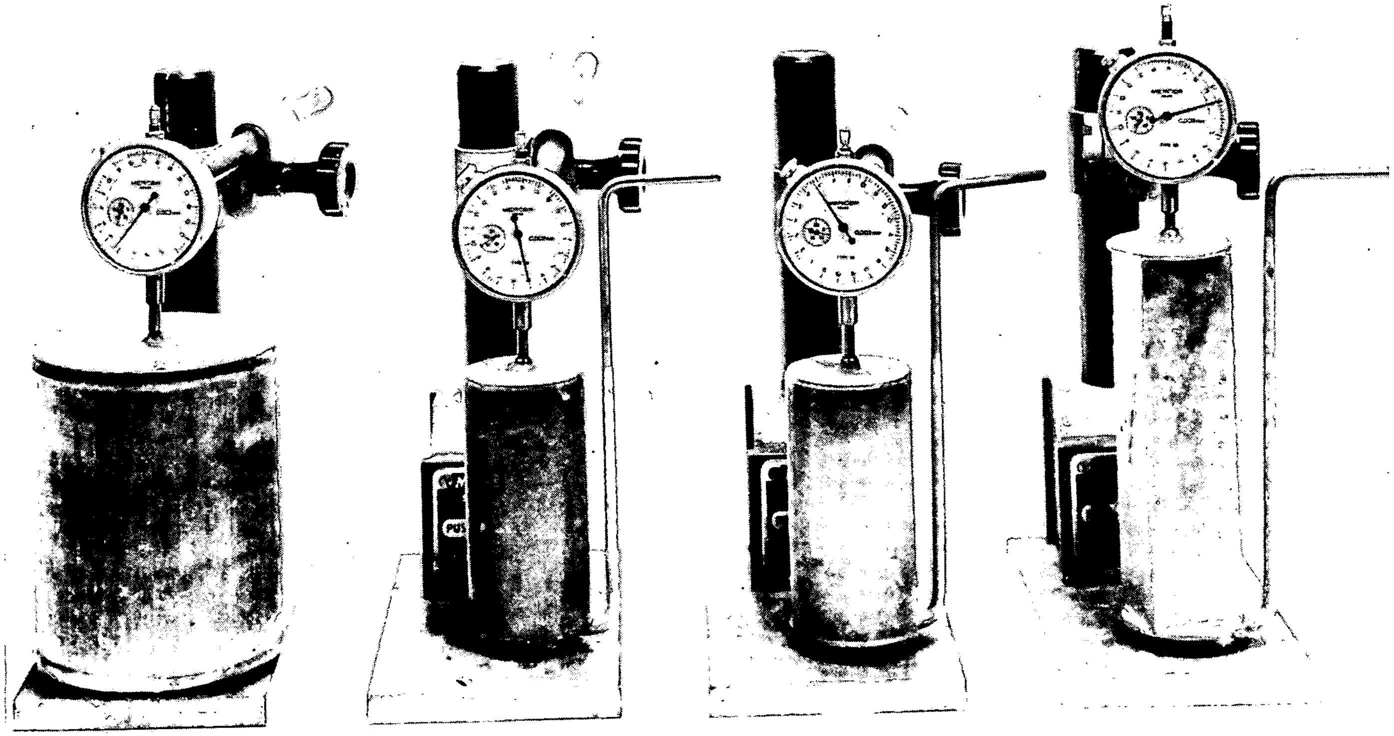

Plate 1 SHRINKAGE SPECIMENS MOULDED BY DYNAMIC, KNEADING, VERTICAL STATIC AND HORIZONTAL STATIC COMPACTION

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ABSTRACT

THE SHRINKAGE OF FINE-GRAINED SOIL-CEMENT: *H E Bofinger, H O Hassan and R I T Williams:* Department of the Environment Department of Transport TRRL Supplementary Report 398: Crowthorne, 1978 (Transport and Road Research Laboratory). The incidence of cracks not associated with externally applied loads is a feature of soil-cement roadbases, and the consequent problem of reflection cracking through the superimposed surfacing has caused concern over the years. The cracks result from restrained thermal and shrinkage movements but, when the stabilized soil is fine-grained, it is believed that the cracking is mainly attributable to shrinkage.

The paper describes a study of the autogenous shrinkage of such a material aimed at improving the understanding of its susceptibility to cracking. In the investigation, specimens were cured under ideal conditions, but, because conditions in the field are often far from ideal, the influence of drying on shrinkage was also studied.

The principal finding of the investigation is that the measured value of shrinkage is greatly affected by the test conditions imposed. In particular, major differences were observed in specimens compacted by different methods and, furthermore, the mode of compaction had a striking influence on the way in which the cement content of mixes influenced shrinkage.

A tentative explanation for the results obtained is presented in terms of the pore pressure in the specimens, the hydration of the cement and the particle orientation. It is clear, however, that further work is necessary before the general validity of the results can be determined.

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