An Investigation into the Drying Shrinkage of Cement Treated Mixtures

by

R.K.M. Bhandari*

Introduction

A considerable amount of research has been carried out on the strength properties of cement stabilized soils. It may be possible to prepare a stabilized soil which should meet certain strength specifications but if these materials possess large volume changes, cracking may soon occur defeating the very purpose of the project.

Extensive shrinkage cracking of cement stabilized soils has been observed in some instances where such materials were used in the pavement structure and as a result, this type of construction has not been an unqualified success (N.R. Board, 1970; J.J. Marshall, 1954 and J.F. Redus, 1958).

The volume reductions in cement stabilized soils are caused by shrinkage resulting from loss of moisture content on drying. The results of some pilot studies conducted in the initial stages of this investigation indicated that shrinkage in soil-cement occurs also during curing. In addition, contraction of the cement stabilized soil may be caused by reduction in ambient temperature. The total expansion or shortening due to variations in temperature depends upon the coefficient of expansion or contraction of the stabilized material. The data available on the coefficient of expansion as determined by various workers is summarised in Table I. Considering the range of soils and cement contents used (Table I), the variation in coefficient of expansion does not appear to be very large and therefore an average value of 6×10^{-6} in/in/°F may be assumed without appreciable error.

The shrinkage of soil blócks prepared at water of maximum plasticity takes place in distinct stages. The different shrinkage phases as first distinguished by Hains (1923) are (*i*) Normal shrinkage, (*ii*) Residual shrinkage and (*iii*) No shrinkage. Stirk (1954) defined an additional phase of shrinkage which precedes normal shrinkage and is common with soils possessing crumb structure. He termed this additional phase as "Structural Shrinkage". In agricultural practice, this preliminary stage is considered to be an important attribute of natural soil as distinct from the moulded blocks since it assists aeration.

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* Pool Officer, Soils Division, Central Road Research Institute, P.O., C.R., R.I., New Delhi-20.

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TABLE I

Coefficient of expansion of a variety of stabilized soils.

Description of soil	Cement content %	Coefficient of Thermal Expansion in/in/°F	Reference No.
Sandy Loam	2.5—10	4.5—5.8	
Silty Loam	2.5—10	4.1—5.6	
Silty Clay Loam	2.5—10	3.9—6.1	6
Loam	2.5—10	4.6—6.3	
Clay	12	5.7	7
Several Types (South African Soils)	Not given	5.1—8.7	8

The purpose of this paper is to compare the shrinkage occurring due to various causes and in addition, it is examined whether a cement stabilized soil would show distinct stages of shrinkage process as indicated above for an untreated soil. Also presented is the relationship between drying shrinkage and time.

TABLE II

Factors and their levels.

Factor	Levels				
	1	2	3	4	5
Curing Period (T)	3	7	14	28	84 days
Cement Content (C)	3	6	9%	—	— by dry wt. of soil
Degree of Saturation (S)	73.3	83.3%	—	—	—
Dry Density (D)	114.5 Standard	119.5 Intermediate	124.5 Modified	—	— pcf

This investigation formed a part of the work aimed at evaluating the effect of various factors on drying shrinkage of soil-cement material. The levels of various factors included in this study are shown in Table II. The relationships mentioned above have been discussed in the light of these factors. Only typical results have been presented in this report.

Preparation and Curing of Specimens

The soil selected for this investigation consisted of Botany Sand and a commercially available Kaolin (60 : 40 by weight, respectively). The properties of this sand-clay mixture are shown in Table III.

TABLE III

Properties of the Soil		40% Kaolinite + 60% Sand
Liquid Limit	...	26.2 %
Plastic Limit	...	16.2 %
Plasticity Index	...	10.0 %
Shrinkage Limit	...	15.5 %

The various mixes were prepared in a mixer having saddle shaped shell with two rotating Z-shaped horizontal blades. The materials were dry mixed for 8 minutes and then wet mixing was continued in the mixer for 10 minutes. A predetermined quantity of the mixed materials to give a specimen 3.8 cm (1.5 in.) diameter and 7.6 cm (3 in.) high was placed in the moulds and compacted statically by a hydraulic jack powered by a pneumatic pump. Immediately after compaction, the specimens were selected at random, marked, their initial height determined by a comparator apparatus described later and then sealed in air tight jars big enough to accommodate one specimen. These jars were stored for a period of 3, 7, 14 28 and 84 days in an air-conditioned room at 70°F. The measurement of moist cured shrinkage was taken at the end of these curing periods and the specimens thereafter dried using calcium chloride in air tight containers. The measurements of drying shrinkage for the specimens exposed after various moist curing periods were taken at 2, 4, 6 hours, 1, 2, and 3 days of drying.

There seems little point in continuing the period or drying out with calcium chloride beyond 3 days because that will produce moisture contents well below those likely to occur in the field.

Measurement of Shrinkage

In this investigation, the shrinkage characteristics of cement stabilized specimens were evaluated by measuring the length changes in the vertical direction. The apparatus which was fabricated to measure the vertical length changes of 3.8 cm (1.5 in.) diameter and 7.6 cm (3 in.) high specimens is shown in Figure 1.

A special feature of this apparatus was a top plate supported on the base plate with three bolts so that the top plate could be adjusted in a plane truly perpendicular to the plane of the dial spindle. The zero of the dial-gauge was checked with a standard before starting each run. Prior to

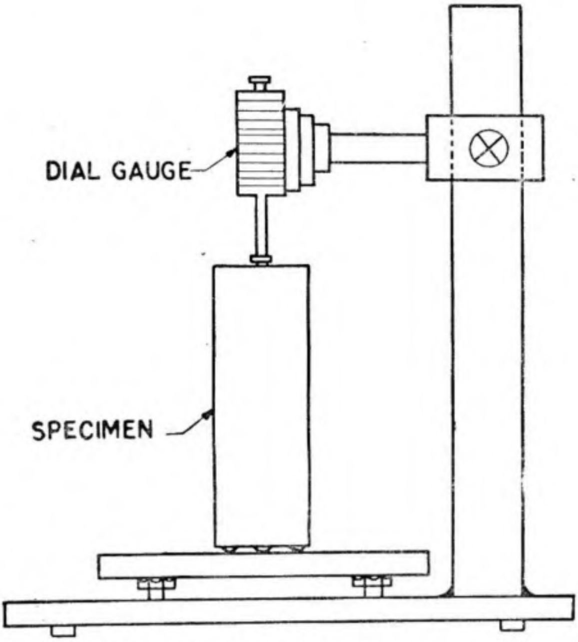

FIGURE 1 : **Shrinkage test apparatus.**

demoulding the specimens, cadmium plated three index pins were embedded in one end of the specimen to provide a reference plane and one index pin embedded in the centre of the other end which provided a reference point for the length measurement. The bottom three index pins ensured that the specimen rested in a plane perpendicular to the top plate while the top index pin was covered uniformly by the spindle flat which was of the same diameter as the pin head (1.77 cm).

A further precaution was taken by marking a black line among the middle of one of the pins at the lower end of each specimen and bringing it infront every time a length measurement was taken. This ensured an exact reproduction of the same position of the specimen for each successive measurement. The measurements of length changes on the cylindrical specimens showed a remarkable repeatability with this piece of equipment. All contact surfaces of this instrument were hard chromed to avoid abrasion.

Resuts and Discussion

COMPARISON OF THE VARIOUS TYPES OF SHRINKAGE

The values obtained from measurement of shrinkage resulting from drying out enable the magnitude of this type of shrinkage to be compared with that of shrinkage occurring during curing and with the contraction resulting from drop in temperature of the soil-cement.

The shrinkage of various types has been compared in Figure 2. In this figure the line '*ab*' represents the estimated contraction for a 50°F. The curve '*cd*' is the time dependent shrinkage observed during moist curing and curves *ef*, *gh*, *ij*, *kl* and *mn* indicate the shrinkage due to drying out after various periods of moist curing.

It is seen that the contraction due to changes in ambient temperature is less than the moist curing shrinkage and that the action of drying results in even greater shrinkage. The contraction due to drop in temperature undoubtedly contributes to cracking of soil-cement. In this connection Soures (1961) reported that cracking often tends to appear during the first spell of cold weather. However, the results of shrinkage measurements indicate that the influence of moisture changes may be of relatively greater importance than the temperature associated contraction in producing shrinkage cracks.

It appears that for soil-cement mixtures studied, the most significant volume change is that produced by drying out, especially if drying takes place after short curing periods. It follows that the most effective means of controlling the shrinkage stresses and associated cracking lies in controlling the drying out shrinkage.

DRYING SHRINKAGE VERSUS MOISTURE LOSS

The relationship between shrinkage and moisture loss for kaolinitic soil without cement is shown in Figure 3 while the same relationship for kaolinitic soil-cement has been shown in Figure 4.

It is seen that in the case of untreated soil (Figure 3), the relationship between drying shrinkage and percent moisture loss is linear (line AB) until a certain amount of moisture is lost. Beyond the point B, a larger loss of moisture causes a much smaller shrinkage and the relationship becomes curved. The two shrinkage zones represented by lines AB and BC are identical to normal and residual shrinkage respectively observed in soil blocks prepared at water of maximum plasticity (Hains, 1923).

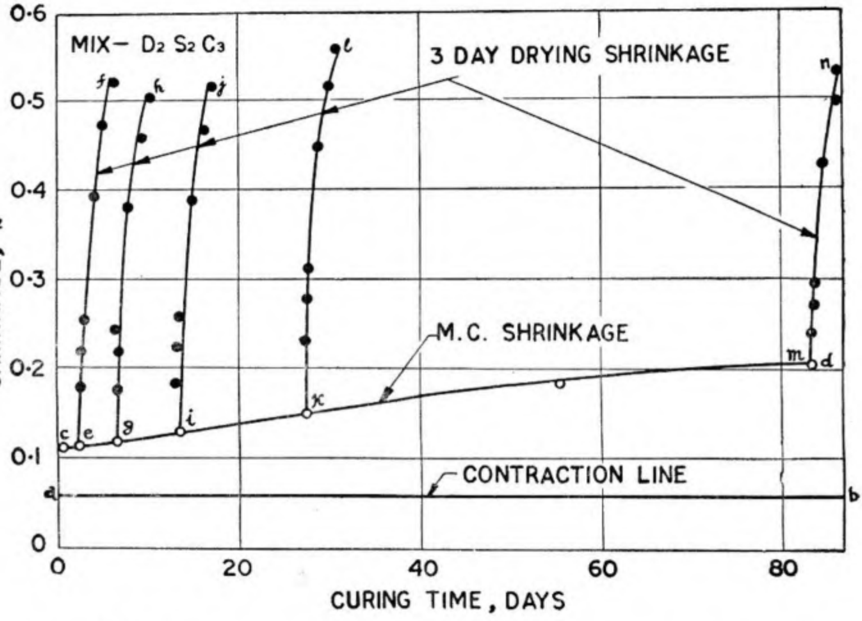

FIGURE 2 : Comparison of relative magnitudes of the various types of shrinkage.

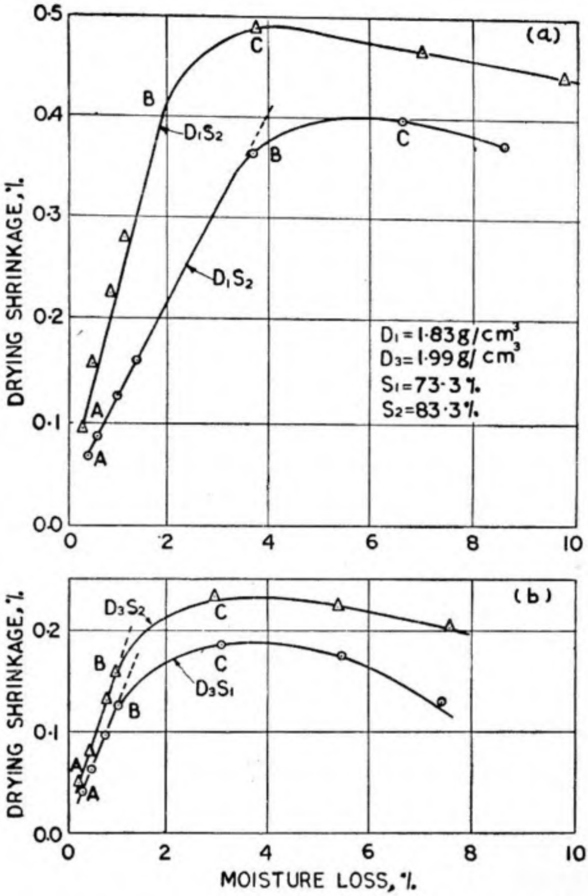

FIGURE 3 : **Relationship between moisture loss and drying shrinkage of untreated soil for various mixes.**

Means and Parcher attributed the increase in shrinkage with moisture loss to the force arising from pressure difference across the curved air-water interfaces. This type of force increases with decrease in menisci diameter in accordance with the following equation :

$$P = T\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad \text{...(1)}$$

where, P=pressure deficiency inside the meniscus
T=surface tension of the liquid
r_1 and r_2=radii of curvature of the moisture film in each of its principal directions.

As long as the resistance of clay particles to closer approach, i.e., to shrinking is greater than the force due to pressure difference, the relationship between shrinkage and moisture loss is linear. As drying proceeds, the water films become progressively thinner and particles eventually come in contact at which stage the shrinkage with further moisture loss is reduced causing the relationship to deviate from the straight line and become curved with further evaporation. It may be noted that the moisture loss corresponding to maximum shrinkage (Point C, Figure 3) depends both upon the degree of saturation and dry density.

In the case of soil-cement, however, it appears that the shape of the curve relating moisture loss and drying shrinkage (Figure 4) is continuous and it is seen that in no instance, the point of inflexion is as clearly and sharply defined as for the untreated soil. Hains (1923) pointed out that in the case of sandy soils, part AB is much smaller and the shrinkage process is mainly represented by the part BC (Figure 3). It is realized that the addition of cement to a clayey soil converts the clay into relatively large floccules Chadda, (1971) which may then behave like "sand size" particles and consequently the part AB in cement treated soil is generally indistinguishable.

It may be noted that after the soil specimens (Figure 3) had shrunk maximum, they have shown some "residual expansion". Henry & Siefert, (1941) attributed this expansion to the relaxation of clay particles. This relaxation occurs when the last thin film of water is broken due to extremely high tensile stresses in water induced by drying and thus resulting in the removal of the force which pulled the particles together and thereby causing a slight rebound. Yong and Warkentin, (1966) also observed this expansion in kaolinite and attributed it to the same cause as Henry, et.al. It should be noted, however, that despite this expansion, the specimens continue to lose water. This is because the particles are maintained in a moist state inside the specimen though the continuity of the water films has been ruptured.

It is seen that as drying is related to moisture loss, the control of moisture offers a possible method of affecting the nature of shrinkage cracks which occur in a cement stabilized pavement.

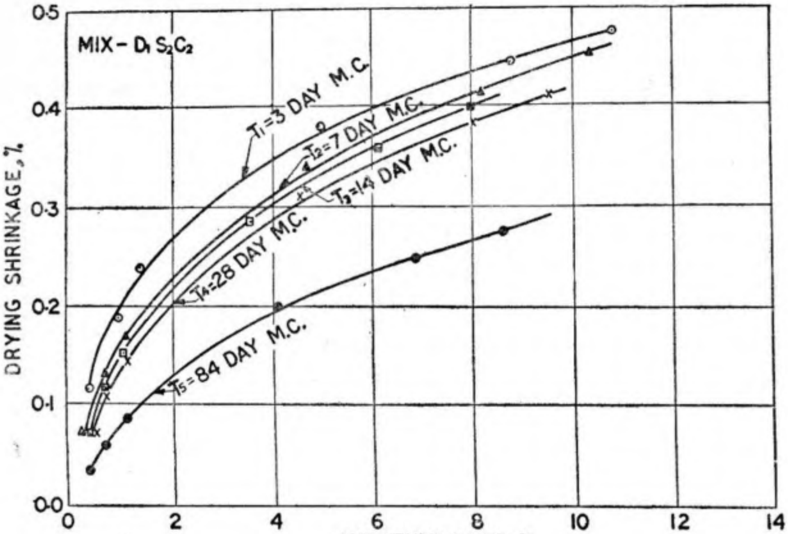

FIGURE 4 : **Relationship between moisture loss and drying shrinkage at each curing time level for a typical cement treated mix.**

DRYING SHRINKAGE VERSUS DRYING TIME

Based on theoretical considerations, Nakayama (1965) et.al. gave the following relationship between shrinkage and drying time :

$$S = c.t^{B} \qquad \ldots(2)$$

where, S = Drying shrinkage
t = Drying time
B and c = Constants.

However, when drying shrinkage was plotted against drying time in accordance with the above relationship, the relationship did not plot as a straight line on log-log graph and therefore the above model was considered inadequate for the present data. The curves, plotted, however, gave indication of some complex exponential function.

For the purpose of investigating a new exponential function at a particular level of a factor, the observations were grouped over the levels of factors other than the one under consideration. Typical relationship which better described the data (Figure 5) was of the following form :

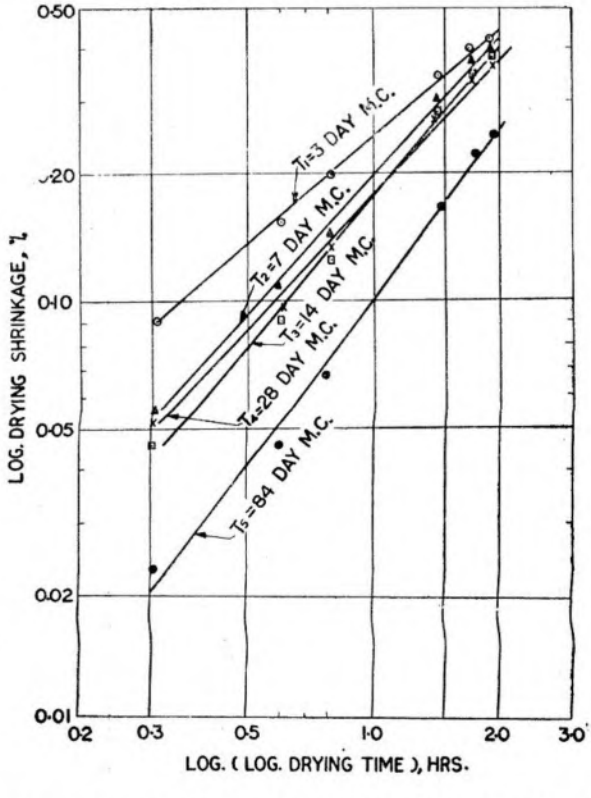

FIGURE 5 : **Effect of drying time on drying shrinkage at each curing time level.**

TABLE IV

Comparison of straight line slopes, Figure 5.

Slope Factor	b_1	b_2	b_3	b_4	b_5	$\bar{b}$	Significant level of difference between slopes
Period of Curing	0·85866	1·11528	1·18837	1·08190	1·32770	1·11438	N.S.
Degree of Saturation	1·16741	1·06138	—	—	—	1·11439	N.S.
Dry Density	1·02026	1·12148	1·20142	—	—	1·11439	N.S.
Cement Content	1·08876	1·11427	1·14014	—	—	1·11439	N.S.

N.S.=Non-significant at a level higher than 20 percent.

$$\text{Log } S_d = a + b \log(\log t) \qquad \ldots(3)$$

where,
S_d = Mean percent drying shrinkage
t = Drying time varying from 2 to 72 hours
a = Intercept
b = a dimensionless constant.

In call cases, the regression was very highly significant at a probability level lower than 0·1 percent.

The variation of the slope of the straight line (Figure 5) with changes in the levels of a factor was tested by applying F-test to the results of regression. This test indicated that the regression coefficients which give the slope between drying shrinkage and drying time did not change significantly with curing period, degree of saturation, dry density and cement content (Ref. Table IV). The best available estimate of the slope, $\log S_d/\log(\log t)$, was an overall average of 1·1144. It was, therefore, concluded that within the range of factors considered the rate of drying shrinkage was not influenced by changes in the factors.

It was further examined if the relationship derived in Equation (3) was true also for drying periods greater than 72 hours. For this purpose the data available from a pilot study was used. The specimens having saturation=83·3 percent, standard density=1·83 g/cm^3 (114·5 pcf) and cement content=6 percent were moist cured before drying for 0 day (i.e., no moist curing following compaction) and 7 days. After the expiry of these curing periods, the specimens were exposed in a room at 50 percent R.H. and temperature of 70°F. The measurement of drying shrinkage was taken at 1/2, 1, 2, 4, 6, 8 hour, 1, 2, 3, 7, 21 and 28 day of drying.

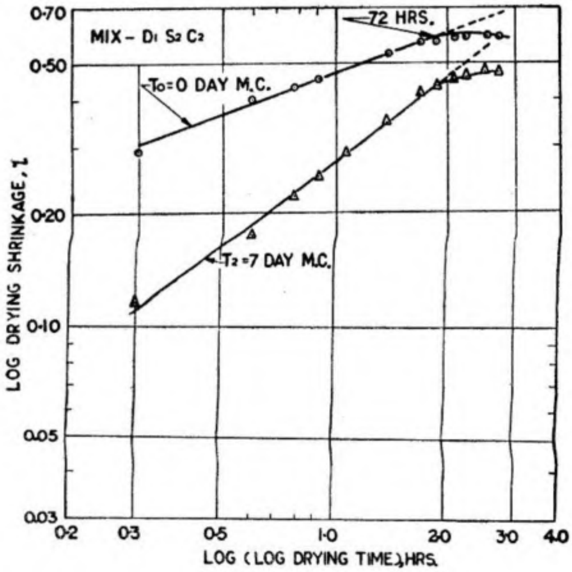

FIGURE 6 : Effect of drying time on drying shrinkage at each curing time for specimens dried in air at 50 percent R.H. and 70°F.

The results of this series of experiments plotted in Figure 6 show that Equation (3) is obeyed only up to 3 days of drying and that with further drying periods, progressive departure from this relationship takes place. However, since shrinkage almost ceases after 3 days of drying (Figure 6), the relationship developed in Equation (3) furnishes a good means for prediction of drying shrinkage at any time within the range of drying periods from 2 to 72 hours.

It is also apparent from Figure 6 that specimens with no moist curing showed substantially higher shrinkage especially in the early drying periods, as compared with those moist cured for 7 days prior to drying. Presumably the non-availability of the opportunity to cure in the uncured samples causes inhibition of clay-cement interaction. The presence of this interaction in cured samples alters the clay to cementitious products (Herzog and Mitchell, 1963) and apparently reduces the shrinkage of those specimens which received moist curing of 7 days.

A general observation may be recorded from the results shown in Figures 2, 4, 5 and 6 that period of moist curing before drying influences the magnitude of drying shrinkage. This aspect shall be dealt with in detail elsewhere.

Conclusions

(*i*) It has been shown that the drying shrinkage is significantly greater than moist cured shrinkage as well as volume reduction caused by temperature drop and therefore drying shrinkage probably represents a potential cause of cracking of cement treated bases.

(*ii*) The relationship between drying shrinkage and moisture loss for the cement treated soil cannot be distinguished to be taking place in district stages as is the case for untreated soil. The formation of large sized floccules in cement stabilized soil appears to cause this difference in behaviour.

(*iii*) As drying shrinkage is related entirely to moisture loss, the control of moisture offers a possible method of affecting the nature of shrinkage cracks which occur in a cement stabilized pavement.

(*iv*) A new exponential relationship has been developed between drying shrinkage and drying time (Equation 3) and the rate of drying shrinkage is independent of the curing period, dry density, degree of saturation and cement content of the mix (Table IV).

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