# Factors Influencing Shrinkage of Soil-Cement

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Linear shrinkage of 2- × 2-in. diameter molded soil-cement spec-
imens was measured at prescribed intervals during curing. Four
soils were used: a standard graded Ottawa sand with no clay, an
Iowa dune sand and an Iowa loess silt with 2.8 and 16 percent mont-
morillonitic clay, respectively, and a North Carolina clay with 30
percent kaolinitic clay. Effects of varying the cement content, ini-
tial water content, and curing method were evaluated. Results show
no relation between total shrinkage and cement content in the ranges
investigated. The initial water content had some effect on shrinkage
of the silt and the clay but not of the sands; compaction below opti-
mum moisture content gave slightly less shrinkage. Montmoril-
lonitic clay in a mix greatly increased total shrinkage, kaolinitic
clay increased shrinkage less, and total linear shrinkage ran as
high as 1 percent. Shrinkage occurred mainly on drying, and pro-
longed curing before drying slightly increased total shrinkage.

•SOIL-CEMENT is a hardened material formed by curing a tightly compacted mixture
of soil, portland cement, and water. Use of soil-cement as flexible pavement base
course is steadily increasing; last year's rate of construction was over 10,000 lane-
miles (1), rivaling the construction rate of portland cement concrete pavement.

A soil-cement problem which is probably more damaging to public relations than
to the pavement is shrinkage cracking. Soil-cement commonly contracts slightly
following construction; the resulting cracks may be as much as $\frac{1}{8}$ in. across, although
are usually much less. At worst the cracks have about the same effect as joints on the
load-carrying capacity; they are a problem only if left unsealed, permitting water to
infiltrate and weaken the subgrade. Subgrade pumping through the cracks is not
common, perhaps because of small slab size, bridging by slab interlocking, and low
traffic volumes. The cracks are usually sealed or are allowed to form before applica-
tion of the final bituminous surfacing, which acts as a seal. Sealing of individual cracks
by maintenance crews is costly, looks unsightly, and affects riding qualities of the sur-
face.

The present study was undertaken to learn the causes of shrinkage and its relation-
ship to fundamental variables including soil, cement content, and method and time of
curing and drying.

## REVIEW OF PREVIOUS WORK

Factors influencing shrinkage of portland cement paste and concrete have been
studied extensively for many years (2, 3). Shrinkage of concrete relates to drying of
the cement paste (2). Aggregate reduces shrinkage, theoretically by acting as rigid
inclusions in the shrinking matrix, the more inclusions, and the more rigid the inclu-
sions, the less the shrinkage. Based on this assumption is a relationship derived by
Pickett (5):

$$S = S_o (1 - g)^\alpha \qquad (1)$$

where S and $S_O$ are unit linear shrinkages of concrete and cement pastes, respectively, g is the volume fraction of the aggregate, and $\alpha$ depends on Poisson's ratio and Young's moduli of the paste and aggregate. Subsequent tests verified the relationship; $\alpha$ for sand mortars is about 1.7 [5].

Drying shrinkage of neat cement pastes relates to water/cement (w/c) ratio, although shrinkage of concrete is reported to be little influenced by the w/c ratio after a day of hardening [3]. High w/c ratios mean higher initial water content and consequent shrinkage; however, as water content is lowered, either through drying or because of initially low w/c ratio, shrinkage per unit loss of water is increased. This is believed to be due to much higher tensile stresses that result from water lost from the gel instead of from the larger capillaries. Increasing the cement content tends to increase shrinkage by providing more gel. However, increasing the cement content without correspondingly increasing the amount of water first increases shrinkage until the w/c ratio is about 0.5 to 0.4, and then decreases shrinkage [9] at lower w/c ratios, perhaps because of incorporation of unhydrated particles. Increasing the size of gel particles into the noncolloidal range, as by steam curing, also reduces tension and shrinkage [2]. Use of coarse grind cement reduces shrinkage, perhaps partly because of included unhydrated particles [2]. Prolonged curing before drying should increase shrinkage because of the higher proportion of gel; however, this appears to be offset by increasing structural rigidity [4], perhaps causing stress relief by microcracking with correspondingly less relief through shrinkage [2].

Carbonation of the $Ca(OH)_2$ liberated by hydrating cement causes irreversible shrinkage, for reasons not yet understood. However, either water-saturated or oven-dry specimens absorb little $CO_2$ and, therefore, are not affected. Carbonation shrinkage is maximum at a relative humidity of about 55 percent [2].

Application of these factors to soil-cement suggests that the latter should have less shrinkage than concrete, soil-cement contains relatively little cement gel, and its use compared to most uses of concrete should cause it to undergo relatively little carbonation. However, the importance of clay content is indicated by Hveem and Tremper [6], who emphasize the utility of cleaning the clay from aggregates to reduce concrete shrinkage. Shrinkage of mortar bars was found to be in linear relation to the sand equivalent, a sedimentation value showing relative amount of plastic fines (AASHO Designation: T 175-56). In terms of shrinkage, it has been suggested that the clay fraction should be considered part of the shrinking or gel phase rather than of the rigid or aggregate phase [2] because clay aggregate would shrink more than the matrix.

Shrinkage of relatively pure clays in the manufacture of ceramic products is commonly measured for specimens dried from the water-of-plasticity (slightly more than plastic limit) to ovendry (105° C) [10, p. 75 ff]. Therefore, shrinkage relates to water-of-plasticity requirements, which depends on the kind of clay mineral, particle size distribution, and adsorbed ions.

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| Soil Class.[a] | AASHO Class.[b] | Sample No. | Horizon | Sampling Depth (ft) | Textural Composition (%)[c] | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Gravel (>2mm) | Sand (2-0.074 mm) | Silt (0.074-0.005 mm) | Clay | |
| | | | | | | | | (<0.005 mm) | (<0.002 |
| Fine Sand[g] | A-3(0) | S-6-2 | C | 6-11 | 0.0 | 95.5 | 1.5 | 3.0 | 2.8 |
| Silt loam[i] | A-4(8) | 20-2 VII | C | 35-36 | 0.0 | 0.4 | 80.0 | 19.6 | 16.( |
| Clay[j] | A 7-6(11) | AR-6 | B | 2[k] | 0.0 | 45.2 | 18.3 | 36.5 | 30.( |

[a]Triangular chart developed by U. S. Bureau of Public Roads, using 0.074 mm, instead of 0.05 mm, as the division between silt-size particles and sand.
[b]AASHO Method M 145-49.
[c]ASTM Method D 422-54T.
[d]ASTM Methods D 423-54T and D 424-54T.
[e]Ammonium acetate (pH = 7) method on soil fraction < 0.42 mm (No. 40 sieve) for sand and silt, and on soil fraction < 2 mm (No. 10 sieve) for clay.
[f]Versenate method for total calcium.

## PROCEDURE

### Soils

Four soils were selected to represent a range in size gradations and mineralogy: graded Ottawa pure silica sand meeting gradation requirements of ASTM Designation: C 109-56; an Iowa A-3(0) dune sand and an Iowa A-4(8) loess silt loam with about 2.8 and 16 percent $-2\mu$ montmorillonitic clay, respectively; and a North Carolina A-7-6(11) clay containing about 30 percent $-2\mu$ kaolinitic clay. Pertinent properties of the natural soils are given in Table 1.

### Cement and Water

Type I portland cement for the study (Table 2) was stored in a sealed container until used. Distilled water was used for mixes.

### Mixes

Cement requirements and optimum moisture contents for the soils were determined by standard soil-cement freeze-thaw test procedures (7). Additional shrinkage measurements were made with cement contents above and below the estimated minimum requirements (Table 3) and with the moisture contents above and below optimum (Table 4) to determine the effects of these variables.

### Specimens

Measurements of soil-cement shrinkage presents problems not encountered in concrete or mortars because of the differing method of sample compaction. Soil-cement is molded relatively dry by ramming into a mold. This procedure makes it difficult to obtain long specimens of uniform density throughout. Greater precision in measurements is required for short specimens, but they are less subject to cracking from shrinkage differentials.

Soil cylinders 2.00 in. in diameter by $2.00 \pm 0.05$ in. in height were molded to approximately standard Proctor density by dynamic compaction procedures using 10 blows from a 5-lb rammer dropping 12 in. (13). Before extrusion with an hydraulic jack, a double-pointed index pin was pushed through a plastic guide tube into the top center of each sample. The sample was then extruded and turned over, and another index pin was pushed into the other end for later optical measurements of the distance between the tips of the two pins.

### Measurements

In initial trials, measurements were attempted with a 1/10,000-in. dial gage, but error was introduced by inconsistent spring pressure from the stem of the dial and by

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| Colloids (<0.001 mm) | Atterberg Limits (%)d | | | Chemical Properties | | | | Predominate Clay Material |
|---|---|---|---|---|---|---|---|---|
| m) | L.L. | P.L. | P.I. | C.E.C. (m eq/100 g)e | Carbonates (total Ca++, %)f | pH | Organic Matter (%) | |
| 2.6 | 12.7h | - | non-plastic | 1.0 | 0.4 | 6.6 | 0.1 | Montmorillonite (trace) |
| 14.5 | 30.8 | 24.6 | 6.2 | 13.4 | 10.2 | 8.7 | 0.17 | Montmorillonite |
| 25.0h | 51.0 | 25.5 | 25.5 | 8.4 | 0.1 | 5.7 | 0.1 | Mica-kaolinite |

[g] Wisconsin-age eolian sand, fine-grained, oxidized, leached; sampling location, Benton Co.,
[h] Iowa; soil series, Carrington.
[i] Extrapolated data.
[i] Wisconsin-age loess, oxidized, calcareous friable; sampling location, Harrison Co.,
[j] Iowa; soil series, Hamburg.
[j] Residual soil over medium-grained biotite granite; sampling location, Durham Co., N.C.;
[k] soil series, Durham.
[k] Below A horizon.

TABLE 2
PROPERTIES OF PORTLAND CEMENT[a]

| Properties | Value |
|---|---|
| Chemical (%): | |
|   $SiO_2$ | 22.14 |
|   $Al_2O_3$ | 4.90 |
|   $Fe_2O_3$ | 2.80 |
|   MgO | 2.68 |
|   $SO_3$ | 2.04 |
|   Loss on ignition | 0.64 |
|   Insoluble residue | 0.14 |
|   $3\,CaO \cdot SiO_2$ | 49.2 |
|   $2\,CaO \cdot SiO_2$ | 26.5 |
|   $3\,CaO \cdot Al_2O_3$ | 8.3 |
|   CaO | 63.92 |
|   Free lime (CaO) | 0.15 |
|   $4\,CaO \cdot Al_2O_3 \cdot Fe_2O_3$ | 8.5 |
| Physical: | |
|   Fineness, specific surface (sq cm/g) | |
|     Wagner (turbidimeter) | 1,896 |
|     Blaine (air permeability) | 3,468 |
|   Setting time | |
|     Gillmore needles | |
|       Initial | 3 hr 20 min |
|       Final | 5 hr 25 min |
|     Vicat needle | |
|       Initial | 2 hr 40 min |
|   Soundness | |
|     Autoclave expansion (%) | 0.060 |
|   Compressive strength, 1:2.75 G.O.S. (psi) | |
|     1-day | 883 |
|     3-day | 1,883 |
|     7-day | 3,221 |
|     28 day | 5,304 |
|   Air entrained in standard mortar (%) | 7.7 |

[a]Penn-Dixie Cement Corporation, West Des Moines, Iowa.
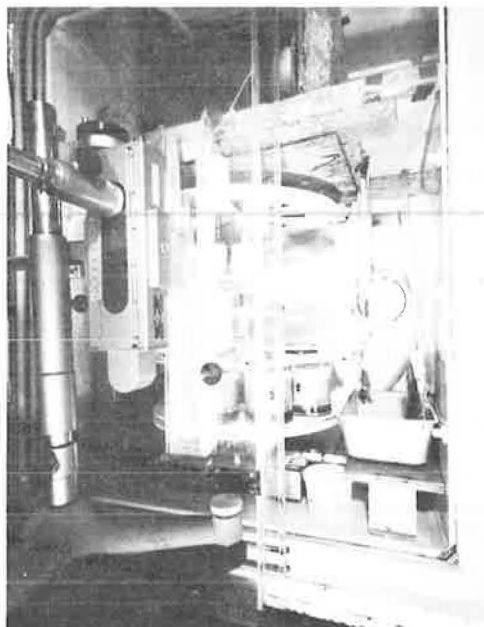


Figure 1. Microscope-slide-cathetometer in place (left) to measure length changes of 2- × 2-in. diameter cylindrical specimens inside constant temperature cabinet (right).

thermal length changes in the gage support. Instability was also found from placing specimens on Plexiglas plates. A micrometer was tried (8) but was inconvenient for measuring 2-in. specimens. The problems from elastic strain suggested an optical measurement method, and a microscope-slide-cathetometer was used. The microscope is focused on an index point at one end of the sample, then it is moved to an index at the other end by a screw arrangement, and the distance was measured to the nearest 0.001 mm (Fig. 1). Later a linear variable differential transformer (LVDT) method was tried with some success.

Curing

As indicated in Table 5, several curing programs were selected:

1. Immediate air drying at 70.5 F and 50 percent RH;
2. Moist curing for 7 days (100 percent RH), then air drying (50 percent RH);
3. Moist curing for 60 days, then air drying; and
4. Moist curing for 3 days, continuous immersion in distilled water for 60 days, then air drying.

Curing chambers were constructed to allow length measurements to be made without disturbing the specimens.

Moist-curing chambers were seal-top polyethylene cups, 5 in. in diameter by 4 in. high, large enough for three specimens. Each specimen rested on a Plexiglas plastic platform with a hole in it for the index pin (Fig. 2a and b). Optical glass windows (made from microscope cover glasses) were cemented in the outside wall of the cups to allow the pins to be viewed for measurements. Nearly 100 percent RH was maintained by having free water in the bottom of the cups.

Specimens for immediate air drying were protected under polyethylene covers during transfer from the molding room to a controlled atmosphere for drying.

TABLE 3

TOTAL SHRINKAGE DURING MOIST CURING[a]

| Soil | Cement (%)[b] | Molding M.C. (%)[c] | Linear Shrinkage (%) 7 days | Linear Shrinkage (%) 60 days |
|------|------|------|------|------|
| Ottawa sand | 8 | 11.1 | 0.000(0.006) | 0.00 |
| | 10 | 10.4 | 0.018(0.000) | 0.018 |
| | 12 | 10.6 | 0.010(0.010) | 0.018 |
| | 10 | 7.4 | 0.000 | -- |
| | 10 | 11.4 | 0.000 | -- |
| Fine sand | 8 | 10.7 | 0.000(0.000) | 0.000 |
| | 10 | 10.4 | 0.000(0.000) | 0.000 |
| | 12 | 10.3 | 0.000(0.000) | 0.000 |
| | 10 | 7.4 | 0.00 | -- |
| | 10 | 11.4 | 0.00 | -- |
| Silt | 10 | 19.9 | 0.016(0.016) | 0.020 |
| | 12 | 19.5 | 0.048(0.024) | 0.050 |
| | 14 | 19.3 | 0.024(0.020) | 0.024 |
| | 12 | 16.5 | 0.008 | -- |
| | 12 | 22.5 | 0.060 | -- |
| Clay | 10 | 17.3 | 0.120(0.120) | 0.120 |
| | 12 | 17.0 | 0.122(0.122) | 0.120 |
| | 14 | 17.3 | 0.140(0.140) | 0.140 |
| | 12 | 14.0 | 0.050 | -- |
| | 12 | 20.0 | 0.180 | -- |

[a] Data taken from curing procedures 3 and 2 (latter data underlined).
[b] By weight of ovendry soil.
[c] By weight of ovendry soil + cement.


TABLE 4

TOTAL SHRINKAGE WITH INITIAL MOISTURE CONTENT VARIABLE[a]

| Soil | Cement (%) | Mix Water (%) | Shrinkage (%) M.C. | Shrinkage (%) Air Dry | Shrinkage (%) Total |
|------|------|------|------|------|------|
| Ottawa sand | 10 | 7.4 | 0.000 | 0.022 | 0.022 |
| | | 10.4[b] | 0.000 | 0.028 | 0.028 |
| | | 11.4 | 0.000 | 0.020 | 0.020 |
| Fine sand | 10 | 7.4 | 0.000 | 0.048 | 0.048 |
| | | 10.4[b] | 0.000 | 0.064 | 0.064 |
| | | 11.4 | 0.000 | 0.050 | 0.050 |
| Silt | 12 | 16.5 | 0.000 | 0.636 | 0.636 |
| | | 19.5[b] | 0.024 | 0.670 | 0.694 |
| | | 22.5 | 0.064 | 0.642 | 0.706 |
| Clay | 12 | 14.0 | 0.050 | 0.454 | 0.504 |
| | | 17.0[b] | 0.122 | 0.526 | 0.648 |
| | | 20.0 | 0.180 | 0.820 | 1.000 |

[a] Seven-day moist curing, then air drying.
[b] Optimum moisture content for standard Proctor compaction.

TABLE 5

TOTAL SHRINKAGES IN PERCENT WITH VARIABLE CEMENT CONTENTS AND METHODS CURING

| Soil | Cement (%) | Envir. 1 | Envir. 2 | | | Envir. 3 | | | Envir. 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Air Dry (50% RH) | M.C. 7 Days | Air Dry | Total | M.C. 60 Days | Air Dry | Total | Moist Cure 3 Days | Immerse 60 Days[a] | Air Dry | Total[a] |
| Ottawa sand | 8 | 0.030 | 0.006 | 0.008 | 0.014 | 0.000 | 0.020 | 0.020 | 0.000 | -0.050 | 0.040 | -0.010 |
| | 10 | 0.046 | 0.000 | 0.028 | 0.028 | 0.018 | 0.040 | 0.058 | 0.000 | -0.040 | 0.028 | -0.012 |
| | 12 | 0.032 | 0.010 | 0.026 | 0.036 | 0.018 | 0.038 | 0.056 | 0.000 | -0.030 | 0.044 | +0.014 |
| Fine sand | 8 | 0.078 | 0.000 | 0.050 | 0.050 | 0.000 | 0.080 | 0.080 | 0.000 | -0.040 | 0.088 | 0.048 |
| | 10 | 0.080 | 0.000 | 0.064 | 0.064 | 0.000 | 0.080 | 0.080 | 0.000 | -0.038 | 0.080 | 0.042 |
| | 12 | 0.082 | 0.000 | 0.066 | 0.068 | 0.000 | 0.054 | 0.054 | 0.000 | -0.040 | 0.080 | 0.040 |
| Silt | 10 | 0.600 | 0.016 | 0.652 | 0.668 | 0.020 | 0.790 | 0.810 | 0.000 | -0.030 | 0.800 | 0.770 |
| | 12 | 0.720 | 0.024 | 0.670 | 0.694 | 0.050 | 0.860 | 0.910 | 0.032 | 0.000 | 0.980 | 1.012 |
| | 14 | 0.610 | 0.025 | 0.732 | 0.756 | 0.024 | 0.840 | 0.864 | 0.018 | -0.068 | 0.840 | 0.798 |
| Clay | 10 | 0.688 | 0.120 | 0.544 | 0.664 | 0.120 | 0.660 | 0.780 | 0.140 | -0.070 | 0.656 | 0.726 |
| | 12 | 0.656 | 0.122 | 0.526 | 0.648 | 0.120 | 0.580 | 0.700 | 0.140 | -0.080 | 0.640 | 0.700 |
| | 14 | 0.652 | 0.140 | 0.600 | 0.740 | 0.140 | 0.610 | 0.750 | 0.140 | -0.050 | 0.670 | 0.760 |

[a] Data erratic.

Specimens for continuous immersion were placed singly in 7-oz polyethylene cups, each with an optical glass window cemented in the side near the bottom. The top pin was allowed to project through a hole in the lid. Another hole in the lid allowed occasional replenishing of the distilled water. Because air bubbles interfered with viewing the lower pin and a carbonate crust sometimes obscured the tip of the upper pin, a glass cup with open top and a reference baseplate was later substituted (Fig. 2c). This proved unsatisfactory for long-term measurements because of excessive carbonation.

A special curing cabinet was built from a 6-cu ft household refrigerator. Constant temperature and near 50 percent RH were maintained with a cooler-heater arrangement and continuous recirculation of air within the cabinet. The door was replaced with a Plexiglas door having a dead air space and a 1.5- $\times$ 17.5-in. vertically arranged optical glass window. Inside the cabinet at different levels were three 14-in. diameter revolving steel shelves mounted on a vertical shaft which could be turned by a worm gear. Each shelf could hold 16 air-drying or continuous-immersion specimens. Moist-cured specimens were placed on the middle shelf, which had revolving subtables for each three-specimen container so that each container could be rotated to bring the specimens successively into view.

An initial checkout of cabinet temperatures was made with thermocouples feeding a 16-channel recording potentiometer, and temperature was found to be constant with time in all positions to $\pm 0.6$ F. Most of this temperature fluctuation was cyclic due to on-off cycles of the refrigerator, and the average temperature in all positions varied from 70.3 to 70.7 F. Checks of the humidity showed an inverse relationship to temperature, the average relative humidity being held in the neighborhood of 50 percent by the heater-cooler closed air circulation system.

During measurements, observation windows in the cups were quite often found to be fogged over, so a small heater was constructed to blow a jet of warm air on a window before measurement.

In general, after each change in environment, measurements were made on a geometric time-increment basis. That is, measurements were usually made after 0, 20, 40, 60, 90, 120, 150 and 180 minutes; 4, 5, 6, 8, 10, 13, 16, 20, 24, 32, 40, 48, and 60 hours; and 3, 4, 5, 6, 7, 9, 11, 14, 17, 21, 28, 35, 42, 56 and 90 days. Moving a specimen to a new environment, as from moist cure to air dry, initiated a new series of measurements starting from time zero.

<div align="center">RESULTS</div>

Shrinkage and Time

Shrinkage-vs-time graphs are shown in Figures 3 to 5. The nominal specimen length of 2.00 in. was used to calculate percent shrinkage. Each point is the average from three specimens molded from a single batch.

Start of Shrinkage. —As shown in Figure 3, the clay soil-cement specimens with no moist curing began to shrink almost immediately on air drying. In other specimens, and in the clay soil-cement after moist or immersion curing, shrinkage was delayed for
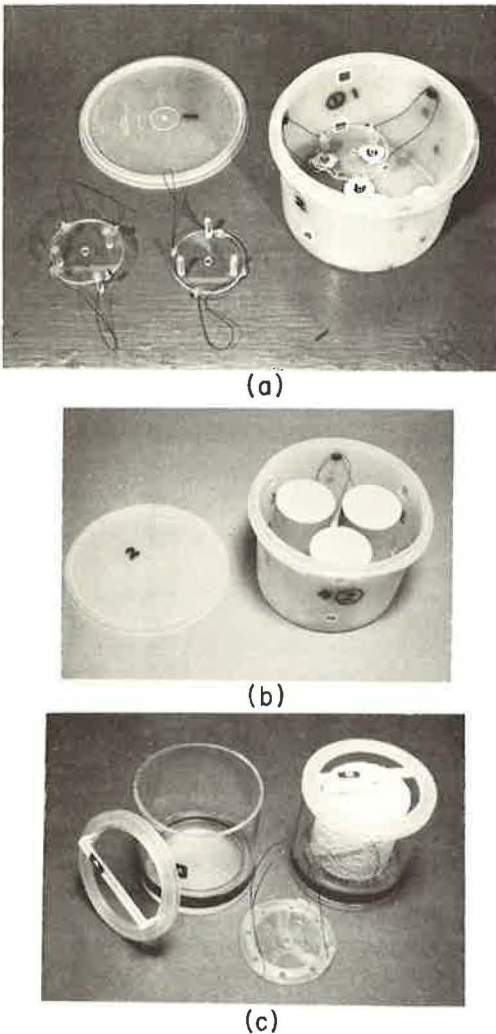
(a)



(b)



(c)

Figure 2. Test equipment: (a) container for moist curing three specimens at 10 percent RH; (b) specimens in place in the moist-cure container (note index pins in tops of specimens, and glass windows for length measurements); and (c) containers for measurements during continuous immersion curing.

periods ranging from several hours to one day, giving an initial flat portion to the shrinkage-log time curves (Fig. 4). Presumably the time delay was necessary for shrinkage tensions to build up and overcome internal restraints in the hydrated cement gel (5). These restraints were apparently absent only in the uncured, high clay content specimens, indicating that the clay with little or no such internal restraint must have participated in the shrinkage.

Rate of Shrinkage. —Before proceeding with the data, we may theorize that in a simplified system, shrinkage should be proportional to amount of evaporation, and drying rate should be uniform. Shrinkage then will be a direct function of time; this can be illustrated by the steady evaporation and shrinkage of a glass of water exposed at constant conditions. It was not found to be the case for the soil-cement.

First, the rate of evaporation probably is not constant, because the binding energy of the water increases with decreasing moisture content, affected by such factors as decreasing size of remaining filled capillaries, increasing concentration of salts in solution, and finally a relatively high-energy function due to decreasing number of water layers adsorbed. This would tend to put evaporation as a function of some root of time.

Second, shrinkage is not proportional to evaporation, because increased bonding energy also means increased internal tensions as water is removed. As has been shown for concrete, less evaporation of held water is required to cause the same amount of shrinkage. This would tend to put shrinkage in proportion to some power function of time.

The two departures from the ideal glass-of-water concept may be expressed by

$$S = ct^\beta \qquad (2)$$

where S is shrinkage, t is drying time, and c and $\beta$ are constants. If $\beta$ is less than one, reduced evaporation rate is the dominant factor; if $\beta$ is more than one, increased internal tension and high shrinkage per unit loss of water dominate.

The silt and the clay mixes showed shrinkages large enough to test the equation. Plots are shown in Figures 4 and 5, and there is a considerable straight-line portion in most graphs. The straight-line portions intersect low or zero-shrinkage portions at later ages, presumably as drying rate comes under a new control. Only the clay mixes with no moist curing failed to show the early log time function, perhaps a result of curing changes brought about with drying.

The slope $\beta$ in the graphs appears to be related to beginning time of shrinkage, which as previously discussed is later for better cured samples. In all except one (0 day m.c.)
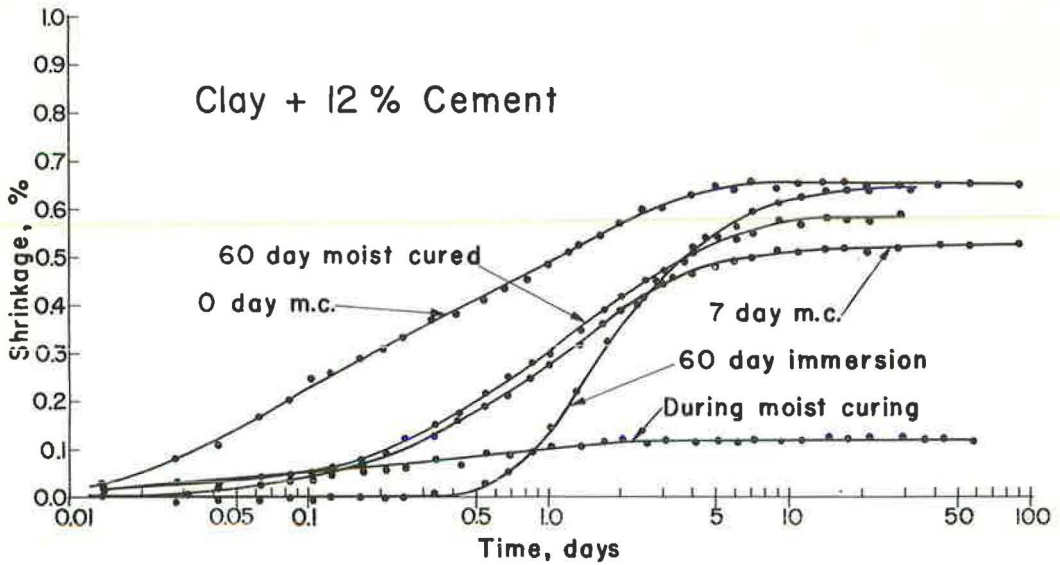
Figure 3. Shrinkage data for typical mix under different curing conditions.

silt mix and in the 60-day-immersed clay mixes, $\beta$ exceeded 1.0; in others, $\beta$ was less than 1.0. An inverse relation found between $\beta$ and C gives

and

$$\text{Clay: } S = ct^{(2.5 - 2.6c)} \tag{3}$$

$$\text{Silt: } S = ct^{(2.0 - 5.6c)} \tag{4}$$

where c is the percent shrinkage after one day. Therefore, low early shrinkage means higher $\beta$ and a faster rate of shrinkage once it starts. This should be indicative of stronger gel structure, which restricts gel reorganization at early ages until a certain level of tension is reached, then becomes volumetrically very sensitive to water loss because of the high tensions in the well-bonded gel.

Evaluation of c and $\beta$ in Eq. 2 is readily done by measuring shrinkage of 2- × 2-in. samples after 7.6 hours and after one day, representing, respectively, log t = -0.5 and log t = 0. Application of the shrinkage rate equations to field situations would re-quire consideration of the much lower rate of moisture loss with the lower surface/volume ratio, and particularly under a bituminous cover.

Shrinkage during Moist Curing. —All samples shrank slightly during moist curing; clay shrank the most. The shrinkage delay time was about the same as during straight drying, suggesting that moist-cure shrinkage might be due to partial drying. However, calculation of evaporation necessary to saturate air in the containers (0.003 g $H_2O$) and account for water absorption by the polyethylene cups (0.024 g) and Plexiglas sample supports (0.15 g) accounts for a maximum linear shrinkage of about 0.02 per-cent. The amounts measured are shown in Table 3. Repeated runs showed a large variation only in one silt mix, suggesting a container leak. The kaolinitic clay, there-fore, appears to undergo a considerable shrinkage without loss of water. As shown in Table 3, this shrinkage was reduced from 0.13 to 0.05 percent by decreasing the mix water, and was increased to 0.18 percent by increasing mix water, perhaps by increas-ing the mix plasticity and ease of deformation. Possibly cement hydration was robbing clay of water; this could be checked by measuring specimens with zero cement.

Cessation of Shrinkage. —Shrinkage of the 2-in. specimens departs from the log time plot after about 1 to 3 days drying, but appears to continue at a greatly reduced rate. Slight shrinkages may be seen in Figures 4 and 5 at ages up to 100 days, again following a log time relationship.
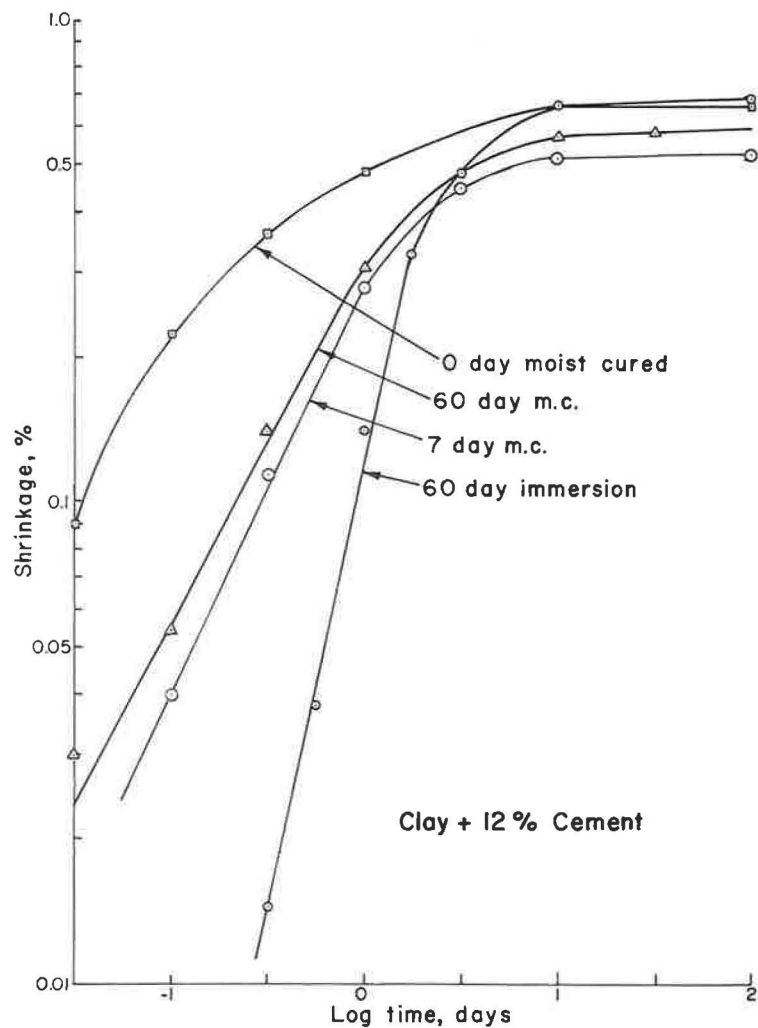
Figure 4. Shrinkage curves for a kaolinitic clay mix; points read from smoothed curves (Fig. 3).
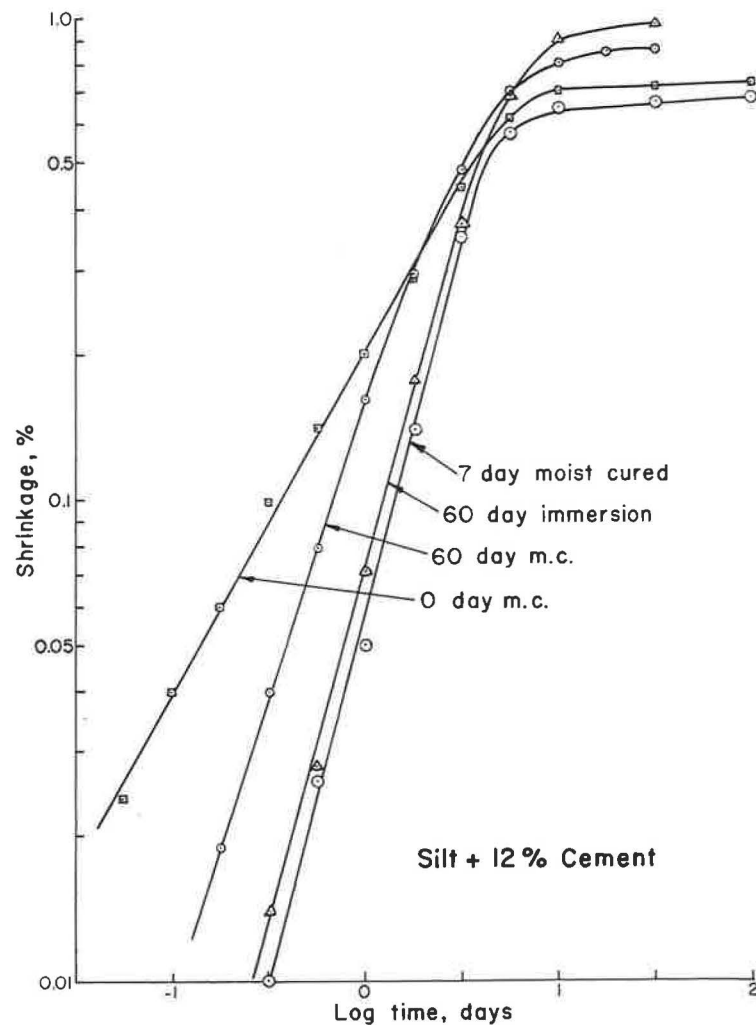
Figure 5. Shrinkage curves for montmorillonitic silt mix.

TABLE 6

AVERAGE SHRINKAGES[a]

| Method | Ottawa Sand | Fine Sand | Silt | Clay |
|---|---|---|---|---|
| No curing | 0.04 | 0.08 | 0.64 | 0.66 |
| After 7-days m. c. | 0.03 | 0.06 | 0.71 | 0.68 |
| After 60-days m. c. | 0.05 | 0.07 | 0.86 | 0.74 |
| After 60-days immersion | 0.00 | 0.08 | 0.86 | 0.73 |

[a]From Table 5.

Total Shrinkage. — Total shrinkages are shown in Table 5. The data are less consistent than in the log time plots, probably because more factors are involved in stopping shrinkage than in establishing its rate during drying.

Shrinkage vs Cement Content. — No consistent or significant trends are shown by shrinkage totals vs percent cement (Table 5). Therefore, the shrinkage percentages for the same soil with different cement contents were averaged to strengthen the data for later comparisons (Table 6). In road bases, cement content in part determines tensile strength at time of shrinkage and, therefore, should influence crack spacing; higher cement contents should give larger cracks farther apart but with about the same total shrinkage per unit length. This trend has been observed in field studies (11).

Shrinkage vs Curing. — Average silt-cement shrinkage increased about one-tenth (from 0.064 to 0.71 percent) if shrinkage took place after 7 days of moist curing instead of immediately after molding (Table 6). After 60 days of moist or immersion curing, shrinkage further increased about two-tenths. A similar trend is seen for the clay, and the trend is present but much less pronounced for the sands. Apparently with longer curing before drying, there is more shrinking of the gel and less internal restraint from unhydrated cement particles.

Swelling. — Measurements during continuous immersion were hindered by air bubbles on the container windows, and immersion swelling data in Table 5 are only approximate. Two repeated tests with the newer type of container showed swelling of 0.046 percent for Ottawa sand + 8 percent cement, and 0.080 percent for silt + 10 percent cement. Swelling is expected from hydration of the cement. It is interesting that the silt montmorillonite, with its large potential for swelling, apparently came into equilibrium with water and free lime mixing and exhibited no appreciable further swelling. Swelling during immersion is only partly reversed by later shrinkage.

Shrinkage vs Clay Content. — Shrinkage of the 7-day moist-cured fine sand samples, with about 3 percent montmorillonite, is approximately twice the shrinkage of the similar specimens made with Ottawa pure silica sand. Shrinkage of the silt specimens, with about 16 percent montmorillonite, is over 10 times that of the Ottawa sand. But shrinkage of the clay with 30 percent kaolinite is less than that of the silt. The only correlation to soil property data listed in Table 1 appears to be to plastic limit, which cannot be tested on sands. Total shrinkage in percent about equals P. L. $\times$ 0.03.

Shrinkage vs Initial Moisture Content. — Table 4 shows shrinkages of intermediate cement-content specimens molded above and below the optimum moisture content. No consistent trend is shown for the sands, but shrinkage of the silt and clay does relate to the amount of initial mix water; i.e., the more water, the more shrinkage. A 6 percent weight difference in initial water gives only 0.5 percent difference in linear shrinkage for the clay and about 0.07 percent for the silt. These correspond to changes in volumetric shrinkage of about 1.5 and 0.21 percent, respectively, indicating that much of the excess mix water is probably capillary water which may be lost without shrinkage. Control of mix water is, therefore, relatively ineffective for reduction of shrinkage, even for clay, where compacting 3 percent below optimum moisture content reduced total shrinkage only from 0.65 to 0.50 percent.

Cracks. — Shrinkage cracks were observed only in the silt mixes, typically in a rectangular pattern with hexagonal elements near the middle of the specimens. Cracking usually started about $2\frac{1}{2}$ to 8 hours after drying began. The cracks reached a maximum width of 0.04 to 0.12 mm after 1 to 2 days, and usually healed on the third to ninth day. More cracking was observed after longer initial curing and with higher contents of cement. Cracking did not cause any abrupt change in the shrinkage-time curves and probably relates to moisture gradient in the drying samples.

## DISCUSSION

### Comparison with Portland Cement Mortar

If the two sand mixes are considered to be very lean concrete, 10 percent cement and 10.4 percent water (both by weight of the sand) nominally correspond to 1.8 sk/cu yd and a w/c ratio of 1.04, assuming zero air. Comparison with representative concrete data ($\underline{4}$, Fig. 30) shows that the Ottawa sand shrinkage conforms to expectations. The cement paste shrinkage should be relatively large, probably on the order of 0.4 percent at this high w/c ratio, but, by way of counterbalance, there is relatively little paste to shrink. The latter effect from Eq. 1 gives a predicted shrinkage of 0.05 percent for both sand mixes, which is about correct for the Ottawa sand.

In the silt and clay mixes, w/c ratios are 1.6 and 1.4, respectively. If the clay is considered part of the shrinking phase, w/c + cl equals 0.78 and 0.45, respectively, but S from Eq. 1 comes out only about 0.1 percent for the silt and clay soils if $S_O$ (gel shrinkage) and $\alpha$ stay the same. It is very likely that $S_O$ is larger for cement-clay pastes than for pure cement pastes. By substituting measured shrinkages in Eq. 1, and assuming the exponent to be 1.7, shrinkage $S_O$ for the cement + clay gel phase of the silt soil is 2.3 and for the clay soil is 1.9. Assuming a linear relationship to clay content, with 0.4 as the contribution of the cement gel,

$$S = S_O (1 - g)^{1.7} = S_O (c + w + cl)^{1.7} \tag{5}$$

where

$$S_O = 0.4 + 0.12 \, Pm \tag{6}$$

or

$$S_O = 0.4 + 0.05 \, Pk \tag{7}$$

where c, w, and cl are the volume fractions of cement, water, and clay; Pm and Pk are the percentages of $-2 \, \mu$ montmorillonitic or kaolinitic clay, respectively. Predicted shrinkage of the fine sand mix for Eqs. 5 and 6 is 0.1 percent which approximates data in Table 6. An example of the calculation is shown in the Appendix.

Extrapolation of Eqs. 6 and 7 to 100 percent clay gives S = $S_O$ = 12 percent for montmorillonite and S = 5 percent for kaolinite, which represents the clays in the presence of excess free lime. No data have yet been obtained for pure lime-treated clays, but linear drying shrinkage ranges of 3 to 10 percent for kaolinite and 12 to 23 percent for montmorillonite have been reported ($\underline{10}$, Tables 3-6). The range reported therein for illite is about the same as that for kaolinite.

In the foregoing calculations, initial air content was assumed to be zero. As can be seen from Table 7, this is not true. The effect of air content should depend on its relation to the system. For example, concrete shrinkage increases appreciably with percent entrained air ($\underline{14}$); however air entrained in concrete mainly occurs as tiny bubbles in the paste, probably reducing internal shrinkage restraints and $S_O$. In soil-cement, air is mainly in capillary-sized voids, surrounded by a skeletal structure of air and cement paste. This would simulate air entering into concrete as the first capillary water is lost during drying and should not influence shrinkage. This was verified for compacted cylinders of calcium and sodium montmorillonite, where percent voids had no effect on percent expansion ($\underline{12}$).

### Effect of Density

Density or degree of compaction was not investigated as an independent variable. Calculations from the densities obtained with different soils show that the influence of air content must be small compared with that of clay and initial water contents (Table 7).

The effect of higher compaction, such as to modified Proctor density, should be investigated. However, since total amount of shrinkage appears to be mainly related to constitution of the gel, the effect may be indirect, by decreasing the initial moisture content.

<div align="center">

TABLE 7

COMPACTED DENSITIES OF SELECTED TEST MIXTURES

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| Soil | Cement Content (%) | Water Content (%) | Dry Density (pcf) | Volume Percent Air[a] | Shrinkage (%) |
|------|-----|-----|-----|-----|-----|
| Ottawa sand | 10 | 10.4 | 114 | 15.0 | 0.028 |
| Fine sand | 10 | 10.4 | 112 | 15.7 | 0.064 |
| Silt | 10 | 19.9 | 99 | 10.3 | 0.668 |
| | 12 | 19.5 | 99 | 11.2 | 0.694 |
| | 14 | 19.3 | 99 | 11.7 | 0.756 |
| | 12 | 16.5 | 97 | 18.5 | 0.636 |
| | 12 | 22.5 | 99 | 6.3 | 0.706 |
| Clay | 10 | 17.3 | 99 | 14.5 | 0.664 |
| | 12 | 17.0 | 101 | 14.3 | 0.648 |
| | 14 | 17.3 | 98 | 17.3 | 0.740 |

[a]S. G. of cement = 3.15; S. G. of soil = 2.70.

## Shrinkage Control

The data suggest that shrinkage is unavoidable and the main control that can be exercised is timing. Prolonged moist curing or prolonged wetting before drying increase rather than decrease total shrinkage. Compaction below optimum moisture content has some beneficial effect, but not much; however, except with sands, moisture in excess of optimum is damaging and should be avoided.

About the same total shrinkage occurs on drying, regardless of when drying takes place. From the standpoint of riding qualities, many fine cracks may be preferable to a few large ones, but the spacing is a function of tensile strength at the time of drying; therefore, a sacrifice in strength would be required to obtain a better crack distribution. An alternative is to prevent drying until the soil-cement has sufficient tensile strength to crack at intervals scribed as joints. But with linear shrinkages as high as 0.5 to 1 percent, the joints would be rather wide.

A third alternative is to try to reduce shrinkage of the clay. A question needing immediate answer is whether the high shrinkage contribution of montmorillonite relates to its fine particle size or to a slight change in interlayer water. The latter should be more susceptible to control by trace additives or pretreatment. However, the relatively high shrinkage of the kaolinitic soil appears partly due to matrix reorganization taking place during moist curing (Table 4) and probably during drying; this might be more difficult to control.

In summary, minimization of shrinkage requires reduction of the initial water content and, more important, the amount of clay.

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CONCLUSIONS

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1. Drying shrinkage usually proceeds as an exponential function of time (Eqs. 2, 3 and 4).

2. Longer curing of soil-cement causes a late start in shrinkage, but a faster rate after shrinkage has started.

3. Longer curing generally increases the total shrinkage.

4. The (kaolinitic) clay soil-cement shrinks appreciably during moist curing; the wetter mixes shrink most.

5. Within the cement content ranges investigated (8 to 12 and 10 to 14 percent), no relation was found between rate or total percent of shrinkage and percent cement.

6. Total shrinkage is very sensitive to the amount and kind of clay (Eqs. 5, 6 and 7), montmorillonite contributing most.

7. Compaction at above or below optimum moisture content has no appreciable effect on shrinkage of the sands and only a small effect on shrinkage of the silt and clay.

8. Immersion caused only slightly more swelling of samples high in clay than of those with little or no clay.

## ACKNOWLEDGMENTS

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## *Appendix*

EXAMPLE OF SHRINKAGE PREDICTION CALCULATION

| Fraction | Wt (per 100 g soil) | S. G. | Rel. Vol | Vol (%) |
|----------|--------------------|-------|----------|---------|
| Soil: | | | | |
| Sand + cement | 97.2 | 2.7 | 36.0 | 69.7 |
| Clay (mont.) | 2.8 | 2.7 | 1.0 | |
| Cement | 10 | 3.15 | 3.2 | |
| Water | 10.4 × 1.10 | 1.0 | 11.4 | |
| | | | 51.6 | |

$$S_O = 0.4 + 0.12 \, Pm \tag{6}$$
$$= 0.4 + 0.12 \, (2.8) = 0.736$$
$$S = S_O (1-g)^{1.7} \tag{5}$$
$$= 0.736 \, (1-0.697)^{1.7}$$
$$= \underline{0.096\%}$$