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Synopsis

Portland cement concrete pavements tend to become rougher with time. To a degree the development of roughness is initiated by curling of the ends of the slabs. In California, at least, slabs curl upward more than downward because shrinkage due to drying is more pronounced in the upper part of the slab. When curled upward, the slabs are not supported uniformly by the subgrade and the ends deflect more under load. Under heavy traffic, crack and faulting develop and the pavement becomes progressively rougher. The integrity and smoothness of the pavement can be prolonged if the characteristic shrinkage of concrete can be reduced.

Both Portland cement and aggregates affect the amount of shrinkage. Some of the factors contributing to the influence of Portland cement are known, although not adequately restricted in standard specifications. The contribution of clay in aggregates to shrinkage has not received the attention it warrants and national specifications do not guard adequately against excessive amounts of clay.

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Some Factors Influencing Shrinkage of Concrete Pavements*

By F. N. HVEEM and BAILEY TREMPER†

SYNOPSIS

Portland cement concrete pavements tend to become rougher with time. To a degree the development of roughness is initiated by curling of the ends of the slabs. In California, at least, slabs curl upward more than downward because shrinkage due to drying is more pronounced in the upper part of the slab. When curled upward, the slabs are not supported uniformly by the subgrade and the ends deflect more under load. Under heavy traffic, cracks and faulting develop and the pavement becomes progressively rougher. The integrity and smoothness of the pavement can be prolonged if the characteristic shrinkage of concrete can be reduced.

Both portland cement and aggregates affect the amount of shrinkage. Some of the factors contributing to the influence of portland cement are known, although not adequately restricted in standard specifications. The contribution of clay in aggregates to shrinkage has not received the attention it warrants and national specifications do not guard adequately against excessive amounts of clay.

The California Division of Highways has developed simple, short field tests that evaluate both the quantity and activity of clay contained in aggregates. These are known as the "sand equivalent" and "sedimentation" tests. Data are presented to show that a high degree of correlation exists between the results of these tests and the drying shrinkage of mortar and concrete. With suitable specification limits, these tests are effective in securing important reductions in drying shrinkage.

It is not a particularly difficult matter for an engineer today to construct a pavement or any structure from portland cement concrete. When the work is completed and ready for use, the pavement or structure usually conforms to the plans and specifications. In other words, it is exactly where it should be within close tolerances. However, experience has shown that while a pavement may be constructed that is true to line and grade for all practical purposes, there is no assurance that it will stay that way. While change in contour or surface roughness or riding quality is not peculiar to any one type of pavement, one of the factors which may cause a smooth,

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relatively perfect concrete pavement to become rough and wavy within a few years is the shrinkage of the concrete.

EXAMPLES OF PAVEMENT CURLING

Fig. 1 represents a profilogram illustrating typical changes and movements in concrete pavement slabs that are of daily occurrence.

Fig. 2 is a profilogram showing another pavement where early morning and afternoon recordings were made at intervals during the life of the project. The profilograms represent the pavement 2 months, 1 year, and 2 years after construction.

Fig. 3 is a drawing of an individual pavement slab showing the differences in shape between the early morning and the afternoon on a warm day. The magnitude of slab deflection under a heavy truck load is also indicated. Note that the deflection at the slab end is about four times as large in the early morning when it has the greatest upward curl, and that there is no greater deflection at the end than elsewhere when the slab is "flattened down" to make contact with the subgrade.

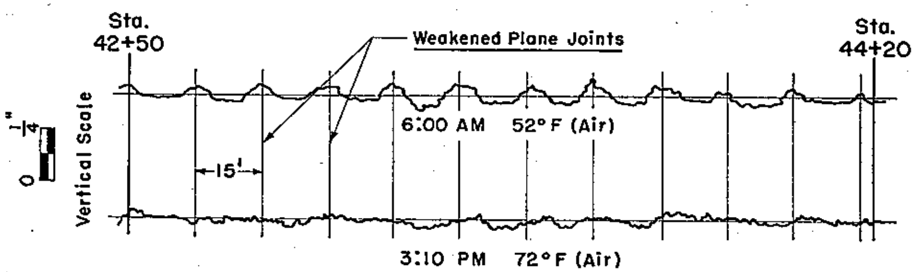

Fig. 1—Effect of temperature on profile of pavement

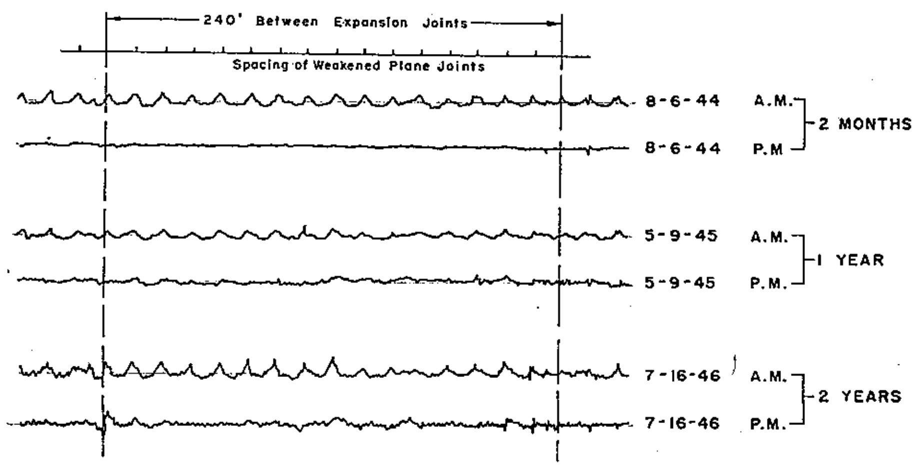

Fig. 2—Effect of time on profile of pavement

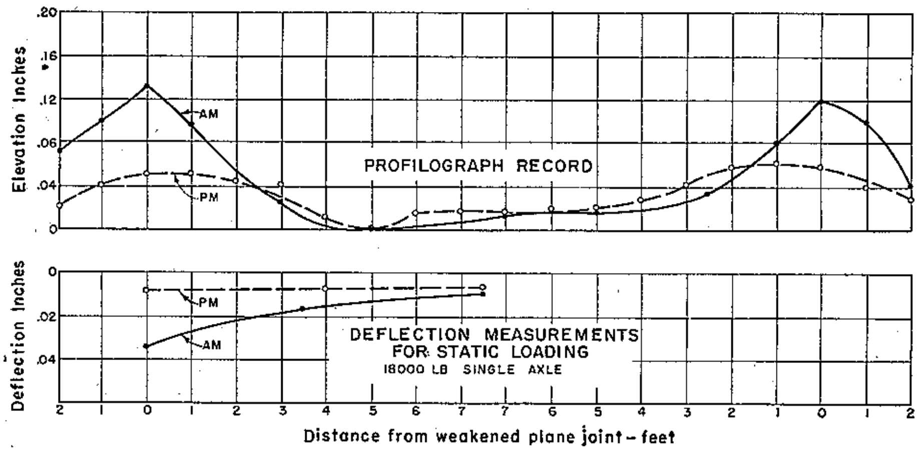

Fig. 3—Effect of curling on deflection under load

CAUSES OF CURLING

Failures near joints in portland cement concrete pavement may be attributed to one or more causes; either the subgrade is yielding under the passing loads or the slab is being deflected when not supported by the subgrade. While the character of the supporting soils is undoubtedly a factor, it seems evident that much of the roughness in concrete pavements would not develop even over a comparatively poor subgrade if the concrete pavement remained in contact with the subgrade at all times and at all points beneath the slab. This particular discussion, therefore, deals primarily with the properties and characteristics of portland cement concrete which lead to slab warping or curling.

A curled slab is an unstable mechanism that, in effect, creates a pumping machine where the concrete slab is a movable diaphragm under each passing heavy wheel load. To determine the reasons for this change in shape, an investigation was carried out on concrete pavements in California and some of the results were presented in a paper entitled "Slab Warping Affects Paving Joint Performance."[1] Fig. 8 from that paper is reproduced here as Fig. 4, illustrating that the expansion of dry concrete due to absorption of moisture is in many cases greater than the thermal expansion resulting from a 90-deg rise in temperature. The magnitude of shrinkage could be equally great.

It is obvious from an examination of the contour of the curled slabs, that either the underside of the pavement has become longer or the upper surface has become shorter. While it is probable that both forms of volume change are present, nevertheless, the underside of the slab was wet when laid and being in contact with the subgrade probably never dries out or loses an appreciable amount of moisture. The upper surface, on the other hand, does dry out and will shrink according to the characteristics of the particular concrete. When this surface shrinkage is combined with contraction due

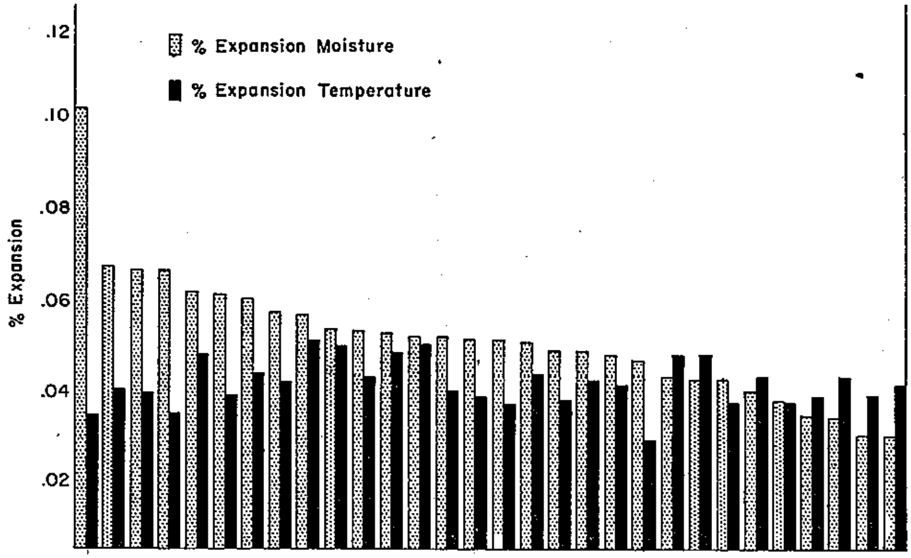

Fig. 4—Comparison of moisture and thermal expansion of concrete

to low temperatures of the upper surface, then the pavement slab will manifest its utmost curl.

The following discussion deals with some of the factors that can be responsible for abnormal shrinkage of portland cement concrete. These relationships may explain some of the differences in pavement performance which have been observed, although no data are available concerning the properties of the particular cements and aggregates used in some of the older projects.

CAUSES OF DRYING SHRINKAGE

R. W. Carlson[2] has shown that drying shrinkage is affected by many factors. Among these are the characteristics of the two major constituents, cement and aggregates.

Portland cements have been found to produce variations in shrinkage of as much as 50 percent. William Lerch[3] has shown that these variations can be reduced substantially by controlling the gypsum content of the cement to an optimum value. To date, however, a workable method of securing optimum gypsum content by means of purchase specifications has not been developed. This subject is still under study in ASTM Committee C-1 and it is hoped that a solution to this important problem will be obtained.

The influence on drying shrinkage of clay in aggregates has not received the attention it warrants. The term "clay" is here used in the layman's sense. Nationally recognized specifications do not provide adequate retrictions against clay. The specified determination of clay lumps does not include clay as coatings or clay in finely divided form. The usual test for material finer than the No. 200 sieve does not distinguish between clay and inert fine particles.

The California Division of Highways has developed rapid field tests for the quantity and activity of clay in aggregates that correlate well with the development of drying shrinkage in mortar and concrete. These tests are known as the "sand equivalent" test which is applied to fine aggregate and the "sedimentation" test which is used on coarse aggregate. Although differing in details of manipulation because of particle size, both methods are based on the same principle. Clay, if present in the sample either as a coating or in the form of discrete particles, is brought into suspension in a dilute solution of calcium chloride which causes a moderate controlled flocculation of colloidal particles. The suspension is allowed to settle for a definite period of time and its height is measured. The particular solution used produces a greater settled volume of the more active clays such as montmorillonite than it does with kaolin for example.

SAND EQUIVALENT TEST

Fig. 5 shows the relationship between drying shrinkage and the sand equivalent of a series produced by increments of washing of a dirty pit run sand. Note that shrinkage of concrete follows trend shown for mortar.

Fig. 6 shows the relationship between drying shrinkage of mortar and the

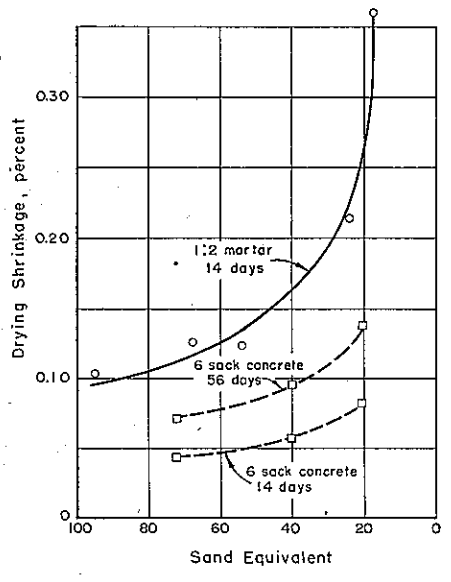

Fig. 5—Influence of sand equivalent on drying shrinkage

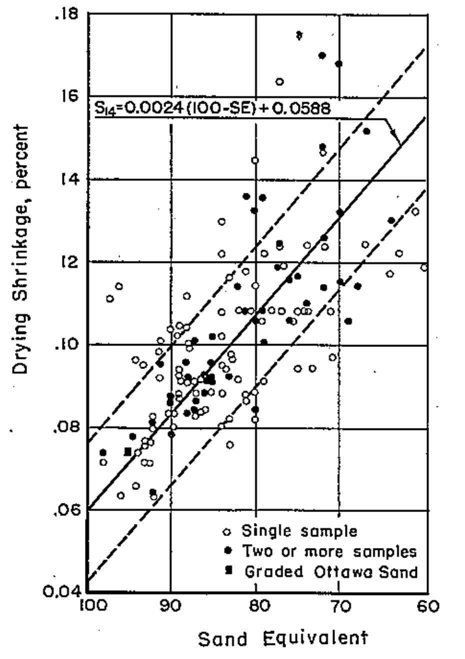

Fig. 6—Influence of sand equivalent on drying shrinkage

sand equivalent of 248 samples of commercially produced concrete sands from 142 sources of supply in California. Test specimens were 1 x 1 x 10-in. gage length bars of 1:2.75 mortar cured moist for 7 days at standard temperature and then subjected to drying in an atmosphere maintained at 100 F and 70 percent relative humidity.

The equation relating sand equivalent and drying shrinkage is:

$$S_{14} = 0.0024\,(100 - SE) + 0.0588 \pm 0.017 \qquad (1)$$

where S_{14} is the percentage of drying shrinkage at 14 days, SE is the sand equivalent, and the last term is the standard error of estimate (shown by broken lines in Fig. 6).

The coefficient of correlation of this equation is 0.66 which, for the number of tests involved, indicates a probability of better than 99 to 1 that the observed relationship is not due to chance.

A substantial number of the sands produce shrinkage that departs from the general equation by more than the standard error of estimate. Many of these sands come from a few limited areas in the state. This fact indicates that performance may be related to mineralogical composition. Carlson[2] found this to be the case and concluded that the normal shrinkage of the cement paste is resisted by the aggregate, the more compressible particles offering less restraint. He also found that apparent compressibility of the aggregate is a function of porosity, and that drying shrinkage is related to the absorption of the aggregate as determined by the standard test.

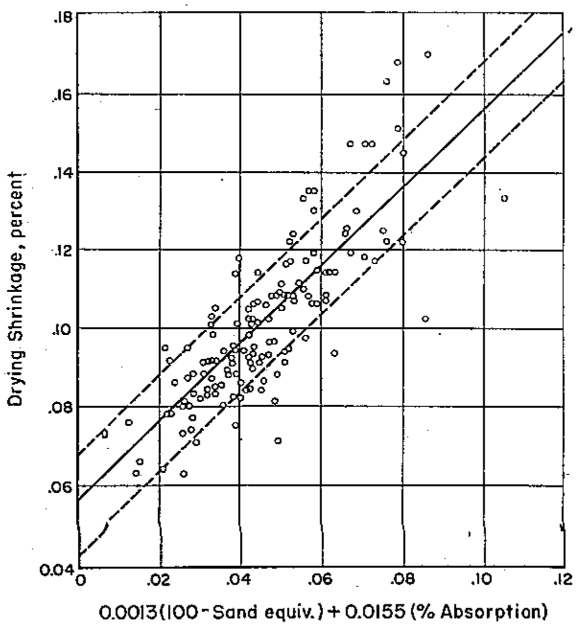

Fig. 7—Influence of absorption and sand equivalent combined on drying shrinkage

For the sands considered in the present study, the relationship between drying shrinkage and absorption is:

$$S_{14} = 0.0198A + 0.0723 \pm 0.0516 \qquad (2)$$

where A is the percent absorption of the sand.

A multiple relationship between sand equivalent and absorption combined and drying shrinkage has been computed and is expressed by the following equation:

$$S_{14} = 0.0013\,(100 - SE) + 0.0155A + 0.0561 \pm 0.0121 \qquad (3)$$

The coefficient of correlation is 0.83, a very significant value indicating that the contribution of the sand to drying shrinkage is dependent to a high degree on sand equivalent and absorption. Fig. 7 is a plot of the multiple relationship. Some of the points that fall well below the plotted curve represent sands of high absorption due to vesicular lava. Evidently the rigidity of such rock is not seriously affected by its pores.

SEDIMENTATION VALUE

Tests made to date to determine the effect of the sedimentation value of coarse aggregate on drying shrinkage are rather limited. Results are shown in Fig. 8. Drying shrinkage was measured on 3 x 3 x 10-in. gage length bars of 6-sack concrete, 3- to 4-in. slump, using ¾-in. maximum size of aggregate. The same cement and sand were used throughout and the coarse aggregate comprised 50 percent by absolute volume of the total aggregate.

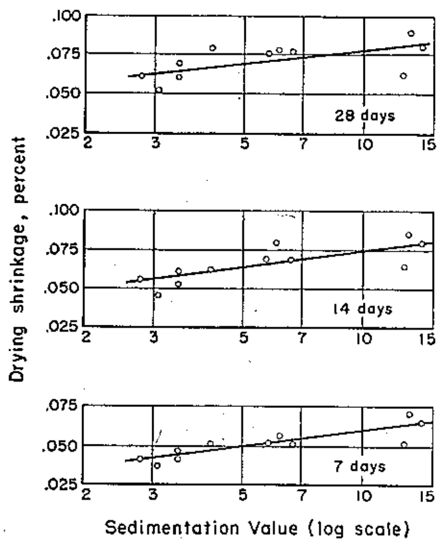

Fig. 8—Influence of the sedimentation value of coarse aggregate on drying shrinkage

The equations of the curves plotted in Fig. 8 are:

$$S_7 = 0.0333 \log SV + 0.0262 \pm 0.0059 \quad (4)$$

$$S_{14} = 0.0359 \log SV + 0.0391 \pm 0.0070 \quad (5)$$

$$S_{28} = 0.0298 \log SV + 0.0489 \pm 0.0073 \quad (6)$$

where S_7, S_{14}, and S_{28} are the percentages of drying shrinkage at 7, 14, and 28 days, respectively, and SV is the sedimentation value.

The coefficients of correlation for Eq. (4), (5), and (6) are 0.84, 0.78, and 0.70, which indicate a high level of significance.

The water-cement ratio required for equal slump increased with increasing sedimentation value and, therefore, drying shrinkage is shown to be related to water-cement ratio. Coefficients of correlation for the latter relationship, however, are relatively low, from 0.50 to 0.59. It is indicated, therefore, that the sedimentation value measures a property of the coarse aggregate that is of greater influence than the water demand alone with respect to the development of drying shrinkage.

EFFECT ON WORKABILITY

The more thorough removal of clay tends to produce lower workability in concrete. The demand for "fat" mixes with a low cement content by the building trades in California has created a problem in specifying a value of sand equivalent as high as considered desirable for highway work. The slightly higher cost of cleaner sand is not considered to be of moment, but the difficulty of securing a special sand for highway use in urban areas served by established commercial plants is a major problem.

Loss in workability, if important, can be restored by air entrainment, which has been shown[4] to have little effect on drying shrinkage. It is hoped that the dissemination of information on the adverse effects of clay will result in greater appreciation of the benefits of more thorough washing of the aggregates.

Although beyond the scope of this paper, it is worthy of note that the removal of clay as measured by the sand equivalent and sedimentation tests also results in important gains in compressive and flexural strength of concrete.

PRACTICAL SIGNIFICANCE

The practical significance of the data presented is that the more thorough removal of clay by better washing of aggregates will result in important reductions in the drying shrinkage of the resulting concrete. Reductions of up to one-third to one-half may be obtained when "borderline" aggregates are cleaned to a degree that is entirely feasible economically. A higher level of improvement is possible by also placing a limitation on the maximum percentage of absorption. But, since absorption is more or less an inherent property of the aggregate from a given source and cannot easily be reduced by processing, the inclusion of a limitation on this property in specifications may be difficult to justify economically.

CONCLUSIONS

Drying shrinkage is an important property of concrete for all purposes. In pavements, low shrinkage is believed to be a major contributing factor to the maintenance of structural integrity and good riding qualities.

Important reductions in drying shrinkage are feasible by more thorough removal of clay in the processing of aggregates. Rapid means of estimating clay content are afforded by the sand equivalent and sedimentation tests. These are the only quick tests presently available that can be used to determine whether aggregates are really clean.

More thorough washing of aggregates may tend to result in less workable concrete, but this can be offset by air entrainment which has little effect on drying shrinkage.

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