

Dealing with the Effects of Concrete Volume Changes on Concrete Structures — A Designer's View

By Max Zar

Synopsis: Creep, shrinkage, and temperature effects on concrete structures are discussed from a design perspective. Research into these problems and various solutions to these problems are looked at. Also emphasized is the importance of complex, sophisticated techniques of analysis for special structures, such as nuclear reactor containments.

Keywords: concretes; creep properties; failure; fatigue (materials); shrinkage; structural design; volume change.

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Some decades ago, interest in the creep, shrinkage and temperature effects on concrete structures was almost totally confined to the work of researchers, in spite of the well-documented list of failures attributed to these volumetric changes.

At that time, the concrete structural design techniques that were borrowed from the well-established design techniques for steel structures assumed elastic concrete behavior. Later, the non-elastic properties of concrete and its volume changes were accounted for almost entirely by experience and judgment.

Most experiences were gained the hard way; that is, from failures and unexpected behavior, which, perhaps, could have been anticipated in the original design, with greater knowledge of concrete behavior. The inexperienced designer and those who tried to extrapolate the state-of-the-art were and are usually the most affected by the lack of data on design for these effects.

The construction of large, mass concrete structures and the development and subsequent use of prestressed concrete increased interest of the designers in this subject; however, in both cases, the interest from the designer standpoint was confined to the designers and designer-researchers directly involved with those types of structures. It is interesting to mention that structures like these were extreme cases that pointed out the limitations of

the design techniques, the lack of designers' experience and judgment and the limitations of our knowledge on concrete volume changes. Two types of solutions were developed for these extreme cases. One solution deals basically with the material properties; that is, avoid or reduce the effects by reducing the causes. Mass concrete technology, as developed for the construction of big dams, is the best example. The second solution is basically analytical. Where the effects cannot be avoided, they must be considered. Analytical techniques combined with empirical formulation and "expansion" joints have been applied successfully to a wide range of prestressing problems, regardless of the actual concrete properties.

The large research projects on columns, started in the early 30's at the University of Illinois and at Lehigh University, indicated clearly the dependency of steel and concrete stresses on the amount of shrinkage and creep in the concrete and the loading history. The early abandonment of the elastic method for design of columns initiated the slow switch in emphasis from service loads to ultimate strength loads in the ACI 318 Building Code. At the same time, shrinkage and creep effects began to be incorporated into the code, either in a hidden form, that is, as part of the non-elastic coefficient and provisions, or in "motherhood" statements cautioning the designer that concrete volume changes shall be properly accounted for, but without being specific as to how this is to be accomplished.

This approach had worked out fairly well for most structures designed under ACI 318, UBC and AASHTO Codes; however, the designer has been confronted with the fact that even up to a few years ago, only a

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general qualitative analysis was possible in most cases and only recently, rigorous quantitative analysis techniques became available. Moreover, these techniques are not accepted unanimously and, hence, are not found in the textbooks and manuals used by most designers. The designer has difficulty locating recommended solutions and sorting these out to find the one that best suits his situation. In general, these are simplified methods of analysis which yield reasonably good but not precise results, especially when compared with the method of analysis used for the applied loads.

Special structures, such as nuclear reactor containments, bridges and shells of record spans, require more complex and sophisticated techniques of analysis which are still in the process of development.

Let's consider, for example, the case of prestressed nuclear containments. Because of their dimensions, loading, discontinuities and reinforcement, they do not fit into the definition of mass concrete as generally accepted. At the same time, they also do not fit into the definition of common prestressed structures. Those structures are generally thinner, geometrically simpler and designed for simpler loading. Containments are pressure-tested (structural integrity test at 115% of the design pressure) and the ungrouted tendons are periodically inspected in service, tested and the losses are determined. Prototype containments are fully instrumented to measure strains, stresses and deformations at critical sections and, of course, the results are to be compared with the theoretically predicted values at different stages of the pressure test. It is

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easy to figure out that the long-term concrete volume changes are no longer a secondary problem, as considered in most other structures. Since no prediction is better than the assumptions, the analysis techniques, the material parameters versus time, the loading and environmental histories used, it is not difficult to imagine the complexity of the predictions and the importance of the creep, shrinkage and temperature effects on these predictions.

As designers, we have to develop analytical techniques consistent not only with the design requirements but with the long-term data. Also, elaborate concrete long-term test programs are being performed for each one of the containments under design and construction. The abundant data from the actual determination of prestressing losses, the structural integrity tests and the inservice surveillance of the tendons are used as feedback data to further refine the techniques used in the design and predictions. At the same time, provisions in specifications are enforced to minimize the effects by minimizing the causes.

As the development of mass concrete and prestressed concrete types of solutions contribute to the better design and construction techniques for concrete structures in general, the present effort on containment designs is and will be extremely useful in expanding our knowledge of the effects of creep, shrinkage and temperature on concrete structures.

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ACI Committee 209 which sponsored sessions and symposiums in 1956, 1964 and 1970, made substantial contributions to the design for volume changes on concrete structures. Today, as a designer, I would like to thank all the participants in this symposium for their contribution in making our work easier and for adding credibility to our results.

New Model for Practical Prediction of Creep and Shrinkage

By Zdenek P. Bazant and Liisa Panula

Synopsis: A new model for the prediction of creep and shrinkage (which is presented in full detail elsewhere), along with a large scope verification by test data, is outlined in simple terms, explained and illustrated in this paper. In this model, the total creep strain is separated into the basic and drying creep components, but not into "reversible" and "irreversible" creep components. The effect of environmental relative humidity is modeled by vertical scaling of the drying creep term. The effect of specimen size is modeled by a horizontal shift of the drying creep term in the logarithmic time scale, and the basic creep term is unaffected by humidity and specimen size. The effects of humidity and size upon the drying creep are modeled completely analogously to those on shrinkage.

The dependence of shrinkage as well as drying creep on the size of the cross section is introduced by means of shrinkage-square halftime, which is the same for both shrinkage and drying creep. Finally, the basic creep component of total creep strain is characterized by double power law.

Keywords: building codes; concretes; creep properties; deformation; humidity; mathematical models; shrinkage; strains; structural analysis; structural design; volume change.

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INTRODUCTION

With the exception of creep buckling of thin shells, a poor prediction of creep and shrinkage does not cause structural collapse, but produces cracking, damage, excessive deflections, i.e., endangers serviceability and economy. The question of optimum creep and shrinkage prediction is, therefore, of great interest for the formulation of building codes and standard recommendations.

However, what is the optimum model for creep and shrinkage? This is a difficult question which has been during the past eight years the subject of lively polemics, the source of which has been the lack of quantitative argument.

Creep is a phenomenon of great variability, influenced by many factors which can hardly be considered in a deterministic way. Quantitative evaluation of test data, therefore, requires that many, essentially all, available test data be considered. An exhaustive program aimed at collecting, organizing and evaluating usable creep and shrinkage data that exist in the literature has been launched at Northwestern and it led to a formulation of new model which allows a greatly improved prediction of creep and shrinkage compared to the existing models (see in detail references 1 and 2). The theoretical structure of this model was based on previous work in Ref. 3, 4, and 5 in which the mechanics and mathematical aspects of the model were analyzed in depth.

The purpose of this brief paper is to present, in simple terms, an instructive explanation of how the model works and what are the reasons behind its structure, as well as the advantages compared to the existing models.

CREEP FUNCTION

Let ϵ be the uniaxial strain of concrete, t the time, t' the instant of load application, $t = t - t' =$ duration of load, Δ_d the delay of the time of loading after the start of drying, and h the relative humidity of the ambient air. Considering a unit normal stress applied at time t' and constant in time, the strain ϵ at time t , or the so-called creep function, can be expressed according to the new model [1,2,3] as follows:

$$\epsilon = \underbrace{\frac{1}{E_o}}_{\text{(Constant)}} + \underbrace{A(t')F(\bar{t})}_{\text{(Basic Creep)}} + \underbrace{H(h)B(t')P(\Delta_d)\bar{S}\left(\frac{\bar{t}}{\tau_{sh}}\right)}_{\text{(Drying Creep)}} \quad (1)$$

$= \epsilon_{b.c.} \qquad \qquad \qquad = \epsilon_{d.c.}$

(Constant) (Basic Creep) (Drying Creep)

Here the first term represents the elastic deformation, the second term represents the basic creep and the third term represents the drying creep. $A, F, h, B, P, \bar{S}$ are functions of the variables indicated, and τ_{sh} is called shrinkage-square half time.

The most important aspect of the model is that the basic creep strain and the drying creep strain are separated, as is illustrated in Fig. 2c. An essential point to note is that the basic creep term involves no effect of humidity and no effect of the size of the cross-section of specimen. These effects are involved only in the second, drying creep term and they enter through function H and function $\bar{S}$, respectively.

For comparison it is useful to indicate the expressions for the strain due to long time loading according to Branson's Model adopted by ACI Committee 209, and according to the 1978 CEB-FIP Model Code (7-9):

ACI 209:

$$\epsilon = \frac{1}{E_c(t')} (1 + c_1 c_2 A(t') F(\bar{t})) \quad (2)$$

CEB-FIP:

$$\epsilon = \underbrace{\frac{1}{E_c(t')}}_{\text{("Elastic")}} + \underbrace{\frac{\beta_a(t')}{E_{c28}}}_{\text{("Rapid Irr.")}} + \underbrace{\frac{\phi_d \beta_d(t, t')}{E_{c28}}}_{\text{("Reversible")}} + \underbrace{\frac{\phi_{f1} \phi_{f2} [\beta_f(t) - \beta_f(t')]}{E_{c28}}}_{\text{("Irreversible")}} \quad (3)$$

↑ ↑
hum. size

We see that the ACI model is given by a considerably simpler equation, whereas the CEB model is about equally involved as the present model (the reader should note that the numerous graphs which are used to define the functions in the CEB model would require involved mathematical expressions if they should be described by formulas).

In the ACI model the humidity effect enters through coefficient c_1 and the size effect enters through coefficient c_2 . In the CEB model these effects are introduced by coefficients ϕ_d and ϕ_{f2} , respectively. Here we see an essential difference.

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These models made no distinction between the basic creep and the drying creep and the coefficients introducing the humidity and size effects multiply a term which is supposed to represent both the drying and basic creeps. This is not justified by the present understanding of the humidity effects in creep.

The CEB model does separate the total strain in several parts; the third term in equation (3) represents the so-called "reversible" strain, the fourth term represents the so-called "irreversible" strain, and the second term represents the so-called "rapid irreversible initial" creep strain. But there exists no good reason for the humidity effect and the size effect not entering the third, "reversible", term and at the same time applying to the last, "irreversible", term that involves both the basic and drying creeps.

The drying creep term in equation (1) is characterized by function $\bar{S}$ which is a shrinkage-like function and depends on τ_{sh} , the shrinkage-square half time, which brings in the size effect.

The fact that the creep strain is made dependent on the shrinkage corresponds to what experimentalists have been saying all the time. The shrinkage and creep of concrete are not simply additive (10); shrinkage affects creep. It is for this reason that the shrinkage-like function $\bar{S}$ is included in equation (1).

SHRINKAGE

As has been said, drying creep cannot be properly described without reference to shrinkage. The formula giving the shrinkage strain ϵ_{sh} at time t is:

$$\epsilon_{sh} = k_h S\left(\frac{\hat{t}}{\tau_{sh}}\right) \quad (4)$$

$$\tau_{sh} = \frac{D^2}{C_1(t_o)} \quad (5)$$

Here $\hat{t}$ represents the duration of drying, i.e., $\hat{t} = t - t_o$, where t_o is the age at the start of drying. Coefficient k_h depends on relative humidity h , as sketched in Fig. 1e.

According to diffusion theory, which is the governing physical model for the drying process of concrete, the shrinkage-square half time τ_{sh} must be proportional to the square of cross-section thickness D (or a characteristic dimension of the cross-section of specimen).

Furthermore, also according to the diffusion theory, τ_{sh} should be inversely proportional to moisture diffusivity C_1 , which itself is a function of the age of concrete at the start of drying t_o as illustrated in Fig. 1f. This introduces the

The time shape of shrinkage is characterized by function S chosen to run from 0 to 1.0; see Fig. 1d, where the shrinkage-square half time τ_{sh} characterizes the time for which one half of the final shrinkage-square value is attained. This time is characteristic of the rate of the shrinkage process in a given cross-section (or specimen).

Fig. 1g illustrates the humidity effects on shrinkage. It consists in vertical scaling (reduction of ordinates) according to coefficient k_h . Note that τ_{sh} is not affected by this effect.

Fig. 1h illustrates the effect of the size or thickness. This effect is altogether different and consists in a horizontal shift of the shrinkage curve in the log-time scale. The middle curve in Fig. 1h is for some medium thickness, the curve shifted to the right is for a thin specimen. These shifts are indicated by the changes in the τ_{sh} value, and they are equal to the logarithms of the squares of the ratios of thicknesses. The square comes out from the diffusion theory and agrees very well with available test data.

The size or thickness effect is thus seen to be completely different from that used in the ACI and CEB formulations. The horizontal shifting of the shrinkage curve, rather than vertical scaling used by ACI and CEB, results in rather different time shapes when specimens of different thicknesses are considered.

Fig. 2a is pertinent in this regard. The dashed line represents the correct shifted shrinkage curve while the solid scaled-down curve represents what is indicated by ACI and CEB formulations. The cross-hatched areas in the figure represent the error introduced by the vertical scaling for the size effect. We see that for short times the shrinkage values are overpredicted and for long times they are underpredicted. This is especially undesirable when we have shrinkage test data of limited duration, say, one year, and want to extrapolate them to long times, such as forty years. Obviously if we used the vertically scaled time shape we would grossly underpredict the long time shrinkage values.

As far as the size effect in CEB shrinkage formulation is concerned, the different shrinkage curves used for different thicknesses do correspond roughly to the horizontal shift required. However, using a number of curves to achieve it is a crude and unnecessarily complicated approach. It is much simpler to use a single time curve and leave the size effect to the dependence of τ_{sh} upon D^2 .

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DRYING CREEP

Having considered shrinkage we are ready to discuss the drying creep. It is given basically in the form:

$$\epsilon_{d.c.} \sim H(h) \bar{S}\left(\frac{\bar{t}}{\tau_{sh}}\right) \quad (6)$$

(Humidity) (Size)

in which function $\bar{S}$ is similar but not exactly the same as the shrinkage time curve S illustrated in Fig. 1d; $\bar{t}$ is the duration of loading and τ_{sh} is the same shrinkage-square half time as used for shrinkage curves. In this manner we introduce the fact that according to the diffusion theory the size effect, and the effect of different diffusivities in different concretes as well as their dependencies on age t_0 , ought to be the same for shrinkage and for drying creep.

The humidity effect is given by function $H(h)$ which may be visualized as vertical scaling of the ordinates of the drying creep term, as sketched in Fig. 2b.

Similarly as for shrinkage, the size or thickness effect consists in a horizontal shift of the curve representing the drying creep term, as illustrated in Fig. 2c where the middle curve corresponds to some medium thickness, the curve shifted to the right corresponds to a thicker cross-section, and the curve shifted to the left corresponds to a thinner cross-section as indicated by the change in the values of τ_{sh} .

It is important to realize that Figs. 2b and 2c, analogous to Figs. 1g and 1h for shrinkage, correspond to the drying creep term alone. When we consider the total strains ϵ we see the picture in Fig. 2d and 2e. In Fig. 2d the basic creep curve does not move; it is independent of h . It is only the drying creep term that is added on top of the basic creep curve which is scaled vertically according to the environmental humidity, preserving the same value of τ_{sh} . The horizontal shift which describes the thickness or size effect on the drying creep term is manifested by the sliding of the curve that represents drying creep on top of the basic creep curve, as illustrated in Fig. 2e. The basic creep curve is again independent of D and the middle curve added on top of it refers to some medium thickness, whereas the curve obtained by sliding to the right corresponds to a thick cross-section and the curve obtained by sliding to the left on top of the basic creep curve corresponds to a thin cross-section.

These effects of humidity and thickness are entirely different from those given in ACI and CEB formulations. The dashed line in Fig. 3a represents a curve obtained by vertical scaling of the drying creep term added on top of the basic creep curve.

However, for a thicker specimen the curve should rather be transformed by sliding it to the right and up on top of the basic creep curve, as indicated by the solid curve.

The error indicated by the cross-hatched areas in Fig. 3a means overprediction of creep of the thicker cross-section for short times, and underprediction for long times. This is especially undesirable if we have short time creep data, say, for a six months duration, and want to extrapolate them to forty years. We then greatly underestimate the long time creep value.

The situation is the opposite for a thinner cross-section. In this case the dashed curve obtained by vertical scaling, as in ACI or CEB formulations, underpredicts the short time creep and greatly overpredicts the long time creep for a thinner specimen for which the proper creep curve is obtained by sliding to the left and downward (see Fig. 3a).

The effects of humidity and thickness according to the new model and the ACI and CEB formulations are visually contrasted in Fig. 3b. Note again in this figure that the vertical scaling for both humidity and thickness effects, used by ACI and CEB, does not correspond to reality. The situation is slightly better, although less simple, in the CEB formulation which does distinguish between the shapes of the creep curve for specimens of different thicknesses (Fig. 3b). However, when humidity is changed, the entire value of the "irreversible" strain, comprising both the basic and drying creep parts, is scaled vertically, whereas what should be scaled is only the drying creep part (see Fig. 3a left).

Thus we see that to get the proper formulation of the thickness effect in the CEB Model Code, it would be necessary to have a different set of creep curves for each different humidity. Moreover, these curves would have to be formulated not only for the irreversible creep parts but also for the reversible creep part because the latter one also consists of both basic and drying components.

BASIC CREEP

The form of the basic creep term from equation (1) is extremely simple and is given by the product form:

$$\epsilon_{b.c.} = A(t')F(\bar{t}) \quad (7)$$

$\nearrow$
 (Age at
loading)

$\uparrow$
 (Load
duration)

in which t' is the age at loading and $\bar{t}$ is the load duration. The shapes of functions A and F are illustrated in Fig. 4a and 4b in the logarithmic time scales.

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It is noteworthy that the time-shape curve F exhibits an ever increasing slope in the log-time scale. The lack of a downturn of the slope is confirmed by virtually all basic creep data (1). This means that the basic creep exhibits no final value. This is however only of academic interest; we may of course call the thirty, or forty, or fifty year creep value the "final" value and the precise choice of the time makes no difference. For example, if we would call a hundred year value the final value, the creep would be only some 7% larger.

The time shape of functions A and F is well described by power curves. Therefore, equation (7) has been called the double power law. The product form used for the basic creep is like the creep formula of ACI, equation (2), and unlike the creep formula of CEB, equation (3). The double power law is the simplest among all formulas for basic creep of concrete for different ages of loading.

A further comment is in order regarding the power curve in the load duration, Fig. 4c. A power curve has been proposed long ago (by Shank, in 1940) and has been used by many subsequent investigators. The value of the exponent has always been obtained roughly as $n = 1/3$. This exponent is, however, much too large. Correctly its value should be around 0.13. This is an essential difference which explains why in previous papers and books the power law was dismissed finding that it overpredicts long time creep. It has recently been shown that this overprediction of the long-time creep was caused by an unsuitable choice of the short-time creep value from which the ordinates described by the power curve are to be measured; see the horizontal line in Fig. 4c (4).

One should fit the power curve to test data without selecting a short-time strain value in advance. In this manner we obtain a power curve of a much smaller exponent which tends on the left side to a horizontal asymptote corresponding to infinitely fast loading, that is, a zero creep duration, or a creep duration which is far less than 0.001 seconds. The modulus value corresponding to this asymptote is called asymptotic modulus E_0 . If the ordinates to be fitted by the power law are measured from this asymptotic value, then an exponent much smaller than $1/3$ is obtained. The power curve is then found to fit not only the creep data for medium load durations but even for very long time durations, and, which is not really of interest for creep, also for extremely short time durations including the static elastic modulus E_c and the dynamic modulus E_{dyn} (which corresponds roughly to load duration 0.001 sec.). Moreover the age dependence of the creep curve at the same time happens to give in this manner also about the proper age dependence of the elastic modulus, and even of the dynamic modulus (see Fig. 4d).

Important points to note are:

(1) According to equation (7) and Figs. 4a and 4b, the time shapes of the creep curve and the age effect are given by independent and different functions, which is like the ACI model and unlike the CEB model in which, unfortunately, the same function of time is used to define both the irreversible creep and the age effect. The use of the same function has been identified as the cause of a significant error.

(2) No separation of "reversible" and "irreversible" total strain ϵ is used, which is again like the ACI model and unlike the CEB model. There exists no theoretical justification for this separation. What is done instead in our new model is to separate the drying and basic creep terms.

The fact that the initial strain $1/E_0$ in equation (1) is independent of age is a significant simplification compared to ACI and CEB formulations, in which $1/E_c$ depends on age t' . This simplification is made possible by the fact that E_0 represents the asymptotic modulus, not the elastic modulus E_c . The value of E_c may, however, be calculated from equation (1) if a load duration of about $t - t' = 0.1$ day is substituted. The conventional creep coefficient, defined by the relation $\epsilon = (1 + C_t)/E_c(t')$, may then be calculated as

$$C_t = \epsilon E_c(t') - 1$$

METHOD OF EXPERIMENTAL VERIFICATION AND STATISTICAL SCATTER

Because of the great scatter and variability of creep and shrinkage, any model must be compared to test data in the statistical sense. The situation is illustrated in Fig. 1a in which the deviations from the mean creep curve in log-time are sketched by the cross-hatched band. Also shown is a normal Gaussian distribution which may be adopted for the frequency of the deviations from the mean creep values at a certain fixed time. As statistical parameters one can use either the standard deviation ω or, which is more indicative for design purposes, the 95% confidence limits, ω_5 , representing the values which are exceeded with a 5% probability.

In Ref. 1 an unprecedentedly large amount of data collected from literature has been fitted and analyzed. It included 80 different data sets from various laboratories, pertaining to different concretes (shrinkage, basic creep, drying creep). Optimum fits have been obtained with the aid of the computer, and the confidence limits for these optimum fits are indicated in Table 1. They are listed separately for the complete version of the model and for a simplified version of the model.

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For comparison Table 1 also lists the values of the 95% confidence limits obtained for these 80 data sets for the ACI model and the CEB model Code. We see that these values are significantly larger. The comparisons of the ACI and CEB model predictions with many of these data can be found in Ref. 2.

Prediction of creep as well as shrinkage can be greatly improved if one short-time measured value is available; for example, the initial elastic deformation, or the short-time shrinkage of a very thin specimen. The 95% confidence limits for such cases are vastly reduced, as is indicated also in Table 1 (see Ref. 2).

It should be further pointed out that the 60% value indicated for the CEB Model Code is a value after computer optimization of this Code which was carried out at Northwestern University and was subsequently adopted as the final version of this Code. This optimization resulted in adding to equation (3) the second term, the "rapid irreversible initial" creep, whose time shape is based on the proposal from Ref. 6.

The need for including all careful measurements reported in the literature cannot be overemphasized. This may be illustrated by the case reported in Ref. 1 where, for shrinkage, twelve data sets were available and the fits indicated a coefficient of variation of 23%. If only four of these twelve data sets were left out, the coefficient of variation would have been reduced to 13%. How false an impression would this convey!

The comparison with the existing models would not be complete without considering the degree of simplicity, which is an equally important aspect to the designer. In the order of decreasing simplicity we have:

1. ACI 209 Model 1971 (Branson);
2. Our model - simplified version;
3. CEB-FIP Model Code 1978, and our model - full version.

We see that the ACI model does have a great advantage in its simplicity. The same cannot be said of the CEB Model Code which has about equally poor confidence limits yet does not afford any advantage in simplicity over the proposed new model.

By analyzing 80 different data sets the parameters of all functions involved in the new model have been determined as functions of standard strength f'_c , water-cement ratio, aggregate-cement ratio, sand-gravel ratio and cement type. These dependencies are used in the full version of the model. In the simplified version the material parameters are expressed mainly but not exclusively as a function of standard strength f'_c . For details, see Refs. 1 and 2.

Before concluding, it must be emphasized that the present model cannot be regarded as a rejection of the ACI 209 (Branson's) model. Within its own degree of simplicity, and given the common time shape is chosen to describe all creep curves, the ACI

209 formulation appears to represent just about the best possible model sufficient for many practical situations.

SUMMARY

A new model for the prediction of creep and shrinkage, which is presented in full detail elsewhere, is outlined in simple terms, explained and illustrated in this paper. Its principal features are:

1. The total creep strain is separated into the basic and drying creep components, but not in "reversible" and "irreversible" creep components.
2. The effect of environmental relative humidity is modeled by vertical scaling of the drying creep term. The effect of the size of the specimen is modeled by a horizontal shift of the drying creep term in the logarithmic time scale. The basic creep term is unaffected by humidity and size of specimen. The effects of humidity and size upon the drying creep are completely analogous to those on shrinkage.
3. The dependence of shrinkage as well as drying creep on the size of the cross-section is introduced by means of shrinkage-square half time, which is the same for both shrinkage and drying creep. Furthermore this also brings in the effect of diffusivity, along with its dependence on the age of concrete at the start of drying.
4. The basic creep component of total creep strain is characterized by double power law.
5. The dependence of the material parameters of the model on concrete strength and composition have been established elsewhere and the model has been verified by a data set of unprecedented scope.

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Table 1 Approximate 95% Confidence Limits
of Available Models

	shrinkage	basic creep	drying creep	overall
ACI 209 (1971)	65%	52%	42%	63%
CEB Model Code (1978)	118%	47%	32%	76%
Present model				
- Simplified (Ref. 2)	37%	45%	29%	37%
- Full Version (Ref. 1)	27%	39%	27%	31%
- Full Version if one initial value is known (Ref. 1)	22%	13%	16%	18%

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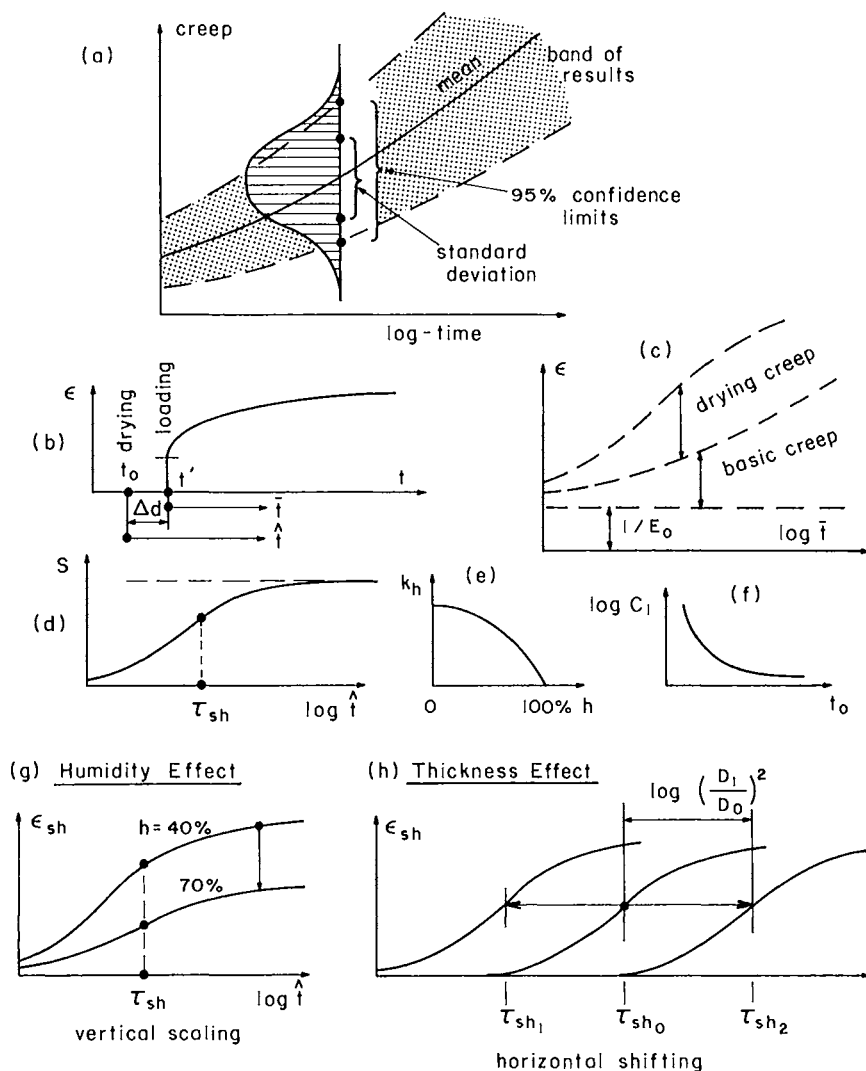


Fig. 1--Statistical scatter and functions involved in shrinkage

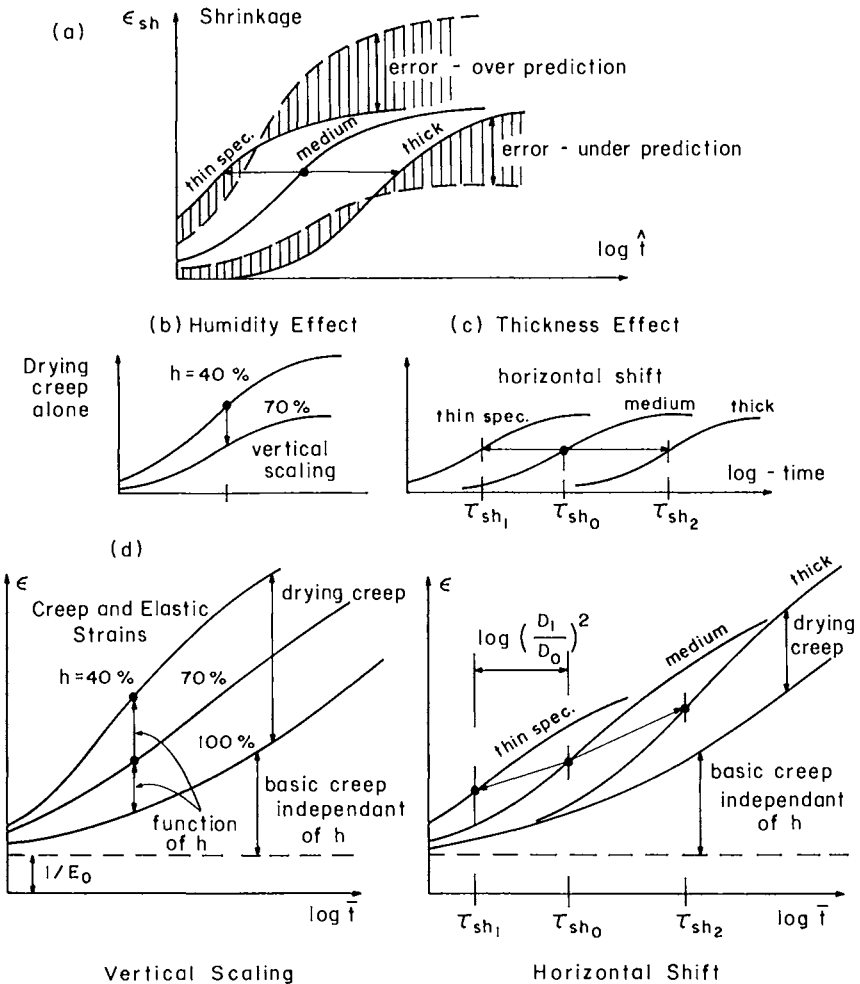


Fig. 2--Thickness and humidity effects in shrinkage and creep

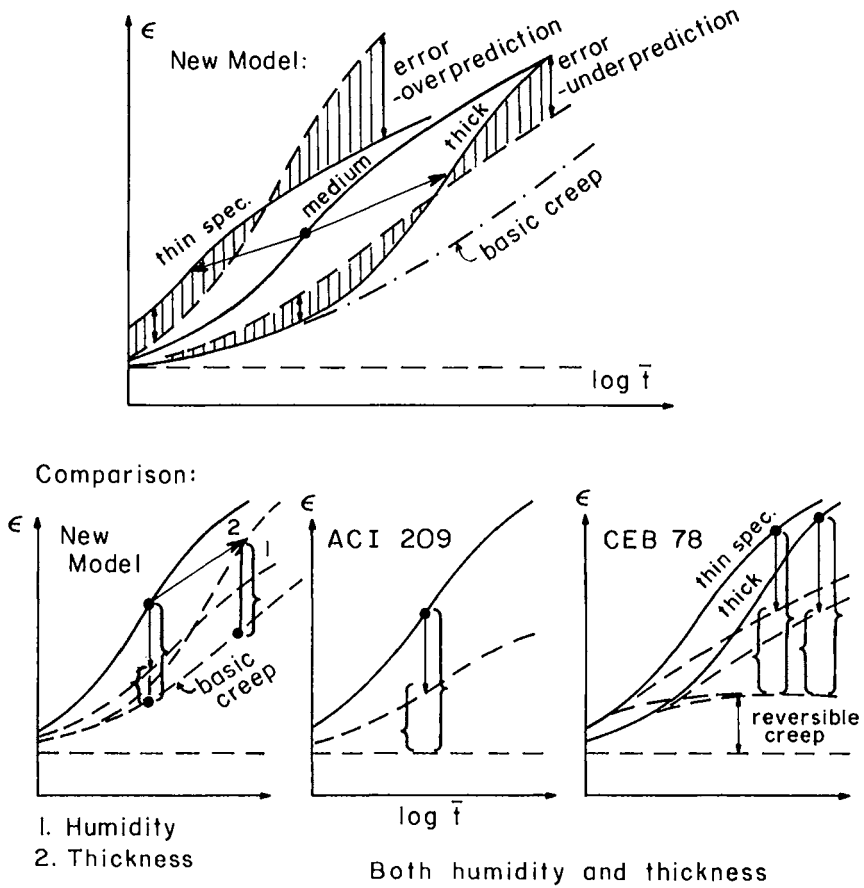


Fig. 3--Differences in modeling thickness and humidity effects

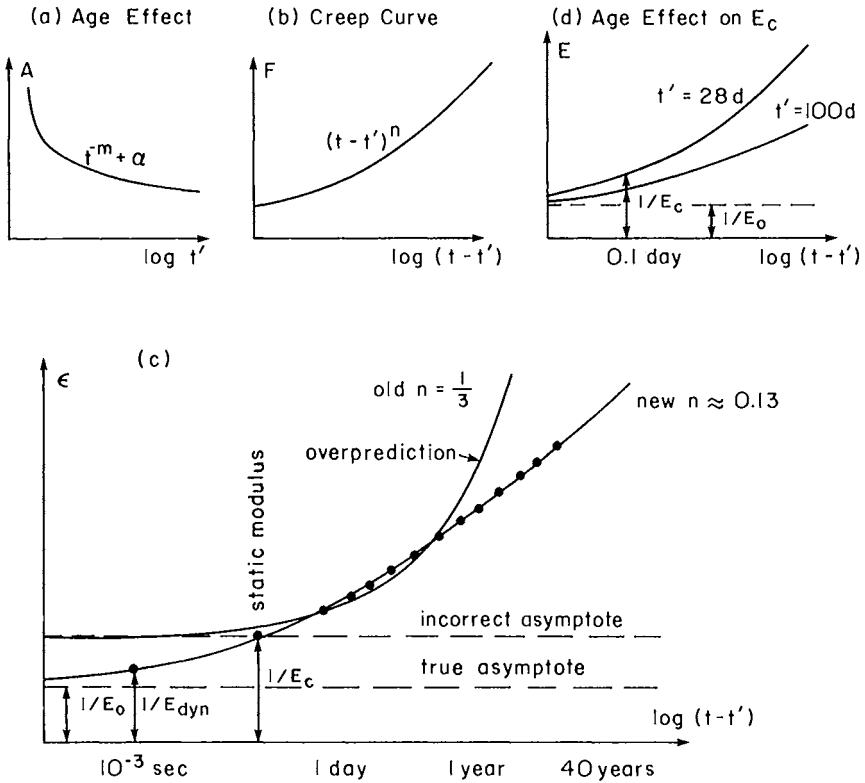


Fig. 4--Functions involved in basic creep

Concrete Drying Shrinkage: Facts or Fallacies

By Paul P. Kraai

Synopsis: Concrete drying shrinkage, as measured by ASTM C-157--Length Change of Hardened Cement Mortar and Concrete, represents a total value which is influenced by the cement type, aggregate source, and the test method. Based on available test data, percentage values can be assigned to each of the above contributions. One purpose of this paper is to show that ASTM C-157 is primarily a laboratory test and not a field test. A second purpose is to relate laboratory shrinkage to structure shrinkage. A third purpose is to relate the above shrinkage data to the volume change of field concrete which is also significantly influenced by ambient conditions.

Keywords: aggregates; cement types; concretes; cracking (fracturing); drying shrinkage; plastic shrinkage; tests.

During the past fifteen years, one of the primary methods of attempting to minimize the magnitude and frequency of concrete cracking was the application of a field shrinkage specification based on ASTM C-157. The lack of uniformity in specifications, product performance, and the lack of a relationship between laboratory and field shrinkage (either ASTM C-157 or structure) has produced a mass of factual and fallacious data which can be confusing.

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Facts or Fallacies:

This section covers a brief review of several ideas with which the average engineer may or may not be familiar. Most of the ideas are not new but they bear repeating primarily for emphasis.

1. The size of the test specimen definitely influences the magnitude of quantitative results. An accepted relationship between sizes is based on the ratio of square area to volume. (Graph No. 1) (page 20)
2. The larger the test specimen, the better the relationship is to the actual shrinkage values of the concrete in the structure.
3. The loss of water (based on the total mixing water) is considered one of the prime causes of concrete cracking. The end result, based on ASTM C-157, does not discriminate between a 2" slump concrete and a 6" slump concrete. The 28-day shrinkage values are the same. (Ref. #3) (page 19)
4. Based on C-157 procedures, variations in cement factors do not influence shrinkage results. A 4-sack mix will perform in the same manner as a 8-sack mix. Research done by R. W. Carlson (1) indicates that cement paste will shrink 5 to 15 times that of concrete. Shouldn't the 8-sack mix increase the shrinkage over the 4-sack? (Ref. #1) (page 19) (Ref. #3) (page 19)
5. Field testing versus laboratory testing, based on ASTM C-157, can be quite confusing. Field testing, using the same concrete



components, can produce shrinkage values that range from 100 to 200+% of laboratory testing. This condition has been recognized by The SEAONC Committee on drying shrinkage. (Ref. #2) (page 19)

6. The drying shrinkage value that is usually specified is really the overall shrinkage value which is the total effect derived from the concrete components. Cement, plus water, plus aggregate, and plus the test method (procedures, casting, curing, facilities, personnel, etc.) are the major contributors to the total value.
7. The writer believes that an aggregate shrinkage characteristic is relatively constant when the variations of the cement and the test method are eliminated. It is a physical characteristic similar to specific gravity, the L.A. Rattler Abrasion Loss, and absorption. Wide variations in shrinkage tests, due to specific aggregate sources, are not very probable.
8. ASTM C-157 does differentiate between low shrinkage aggregate and medium shrinkage aggregate (total basis). When corrections are made for the effect of cement and test method variations, the difference in magnitude becomes considerably less. In large specimens, this difference is negligible.
9. Northern California, primarily the Bay Area, is the only part of the United States where the drying shrinkage specification is used to try to control concrete. Southern California considered a 2-year moratorium in order to re-evaluate the subject. Cal-Trans does not use this test for control purposes.
10. A study of various rock types (National Sand and Gravel Association) indicate that an average concrete would have a value of

0.043% (3" x 4" x 16" prism). This is equivalent to 0.047% on 4" x 4" x 11" prism basis. The Livermore Valley aggregates (Aver. = 0.043%) would be considered average for the country as a whole. (Ref. #4) (page 19)

ASTM C-157 - Laboratory Research Program

Concrete drying shrinkage literature has generally emphasized the effect of aggregates; very little similar information is available on the effect of cement. In order to put the effects of aggregates and cements into proper perspective, a research program was developed which measured the following characteristics:

1. Variability of a constant brand of cement
2. Variability of a constant source of aggregate
3. Variability of the test method - ASTM C-157

The laboratory personnel, facilities and mix design (5.5 sacks/yard and 4 + 1/2" slump) were held constant.

Step No. 1 - Product Variability - Cement Vs. Aggregate

This phase of the investigation was based on two laboratories, designated as A and B. In order to meet the above requirements, test results from Laboratory A were used in the statistical analysis. The comparative laboratory testing was based on a constant cement, a constant aggregate, variable cements and variable aggregates. The constant samples were split 24 times. Each laboratory received 12 sets of each (constant or "controlled") sample. Batch plant samples of cement and aggregates were taken on a monthly basis.

These variable samples were also split between Laboratories A and B and tested in concrete with their respective constant counterpart. All the test data for drying shrinkage and compressive strength has been listed in Table No. 1. (page 25)

PRODUCT VARIABILITY

	Variable Cement		Variable Aggregate	
	Shrinkage	Strength	Shrinkage	Strength
Average	0.045%	4425 psi	0.043%	4487 psi
Range	.036-.059%	3930-4910 psi	.039-.049%	4180-4700 psi
Stan. Deviation	±0.007%	±303 psi	±0.003%	±178 psi
Coef. of Variation	15.6%	6.8%	7.0%	4.0%

Note: The above evaluation is based on overall values.

Step No. 2 - Test Method Variability

A third factor, which should be considered, is the variability of the test method. This criteria includes laboratory personnel, equipment, test procedures, and curing conditions. Laboratory A has been inspected by the Cement and Concrete Reference Laboratory of the National Bureau of Standards.

At this time, the shrinkage test method variability was also compared with the compressive strength test method variability (See Table No. 2). The program consisted of 10 split samples of cement and 10 split samples of aggregates. The 10 batches of concrete were tested for compressive strength and drying shrinkage.

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This program was designed to measure the inherent variability of the test method that can occur when a single laboratory (constant personnel, equipment curing facilities, etc.) does the testing.

	ASTM C-39	ASTM C-157
	Compressive Strength	Drying Shrinkage
Average	4629 psi	0.0518%
Standard Deviation	<u>±</u> 77 psi	<u>±</u> 0.0025%
Coeff. of Variation	1.7%	4.8%

The above data indicates that the variability of C-157 could be 280 percent greater than the variability of C-39.

Step No. 3 - Analysis of Variance

The analysis of variance is a mathematical method of isolating individual causes for variation. This method will be used in

determining the percent contribution of each component. The basic equation can be set up in the following manner:

$$\sigma_o^2 = \sigma_c^2 + \sigma_A^2 + \sigma_W^2 + \sigma_T^2$$

σ_o = Overall Standard Deviation

σ_c = Cement Standard Deviation

σ_A = Aggregate Standard Deviation

σ_W = Water Standard Deviation

σ_T = Testing Standard Deviation

- Note:** 1. Water is considered a constant in all cases. (Minor variations in W/C ratios were considered insignificant.)
2. Same water source - Temperature Range 66° - 70°F.

The following calculations are based on the values developed in Step No. 1 and Step No. 2.

Step No. 1a - Cement Variability; $(\sigma_c^-) = +0.0070\%$

Overall standard deviation due to cement variability = $(\sigma_o^-)_c$

Step No. 2b - Aggregate Variability; $(\sigma_A^-) = \pm 0.0030\%$

Overall standard deviation due to aggregate variability = $(\sigma_o^-)_A$

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Step No. 2 - Test Method Variability; $(\sigma_{o_T}) = \pm 0.0025\%$

Corrected overall standard deviation due to test method variability

Since $\sigma_C = \sigma_A = \sigma_W = 0$; then $\sigma_T = (\sigma_{o_T}) = \pm 0.0025\%$

Cement Variability

$$\begin{aligned} \sigma_o^2 &= \sigma_C^2 + \sigma_A^2 + \sigma_W^2 + \sigma_T^2 \\ (0.007)^2 &= \sigma_C^2 + 0 + 0 + (0.0025)^2 \\ \sigma_C^2 &= 0.0000428 \quad \sigma_C = \pm 0.0065\% \text{ (Corrected)} \end{aligned}$$

Aggregate Variability

$$\begin{aligned} \sigma_o^2 &= \sigma_C^2 + \sigma_A^2 + \sigma_W^2 + \sigma_T^2 \\ (0.003)^2 &= 0 + \sigma_A^2 + 0 + (0.0025)^2 \\ \sigma_A^2 &= 0.0000028 \quad \sigma_A = \pm 0.0017\% \text{ (Corrected)} \end{aligned}$$

(1) Corrected - Other variables are held constant

Percent Distribution

Variance, σ_o^2 , is equal to the sum of the individual parts squared

$$\begin{aligned}\sigma_o^2 &= \sigma_C^2 + \sigma_A^2 + \sigma_W^2 + \sigma_T^2 \\ \sigma_o^2 &= (0.0065)^2 + (0.0017)^2 + 0 + (0.0025)^2 \text{ (Corrected values)} \\ \sigma_o^2 &= \frac{\text{(Cement)}}{.0000423} + \frac{\text{(Aggregate)}}{.00000289} + \frac{\text{(Test)}}{.00000625} = .0000514\%\end{aligned}$$

The variance that occurs in the development of overall drying shrinkage values is influenced by the following distribution:

$$\begin{aligned}\text{Cement} &= (.0000423 / .0000514) (100) = 82.2\% \\ \text{Aggregate} &= (.00000289 / .0000514) (100) = 5.6\% \\ \text{Test Method} &= (.00000625 / .0000514) (100) = 12.2\% \\ \text{Total} &= 100.0\%\end{aligned}$$

ASTM C-157: Used as a Quality Control Tool

It is common practice to use the ASTM test method as a field quality control tool. When field data is compared with laboratory data, the field data can range from 100 to 200% of the laboratory data. Graph No. 2 contains data on a major concrete project which had a field shrinkage specification. It is interesting to note that the majority of test results (57%) failed.

The range in field shrinkage values - Random Projects (Graph No. 2) (page 21) indicates that the high variability of the field test

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method tends to mask any significant difference in shrinkage characteristics between low shrinkage and medium shrinkage aggregates.

Based on the above data, it is possible to compare the variability of the field test results with the variability of the laboratory test results. The following equation is based on the analysis of variance:

$$\begin{aligned}\sigma_{\text{Field}}^2 &= \sigma_C^2 + \sigma_A^2 + \sigma_{T(\text{field})}^2 \\ (0.0084)^2 &= (0.0065)^2 + (0.0017)^2 + \sigma_{T(\text{field})}^2 \quad (\text{page 8}) \\ \sigma_{T(\text{field})}^2 &= 0.000025; \sigma_{T(\text{field})} = \pm 0.0050\%\end{aligned}$$

The variability of the field ASTM C-157 test method ($\pm 0.0050\%$) was twice the variability of the laboratory test method ($\pm 0.0025\%$). (page 6)

Primary Cause of Shrinkage Based on ASTM C-157

The section on Analysis of Variation indicates that the cement is responsible for 82% of the drying shrinkage value.

If we apply the corrected statistical data from the Analysis of Variation study, it is also possible to make the following comparisons:

$$\begin{aligned}\text{Aggregate Variability} &= \sigma_A = \pm 0.0017\%; 2\sigma = \pm 0.003\% \quad (\text{page 8}) \\ \text{Cement Variability} &= \sigma_C = \pm 0.0065\%; 2\sigma = \pm 0.013\% \quad (\text{page 8}) \\ 95\% \text{ Conformance Limits} &= \bar{X} \pm 2\sigma\end{aligned}$$

	<u>Lower Control</u>	<u>Upper Control</u>	<u>$\bar{x}$</u>
Aggregate Influence	0.040%	0.046%	0.043%
Cement Influence	0.032%	0.058%	0.045%

Kaiser Sand and Gravel Company has made a long term study of concrete drying-shrinkage comparisons; the details are listed on Graph No. 3. It is interesting to note that the high points occur during the winter and the low points occur in the summer. (Graph No. 3) (page 22)

Graph No. 3 actually shows a range of 0.033% to 0.055%. Based on a normal distribution, 58% of the values fall outside the aggregate influence range and 100% fall within the cement influence range. This also indicates that the cement is the controlling factor.

Relationship of ASTM C-157 to Structure Concrete

There is a significant difference between laboratory shrinkage values and actual field shrinkage values based on slabs or structure concrete (measuring studs placed in field concrete). Graph No. 4 represents a long term study. Field data indicates that there is very little difference between high shrinkage aggregate (Centerville) and low shrinkage aggregate (Granite).

Graph No. 5 Slab and Structure Concrete also illustrates the similarity in magnitude of values between low shrinkage aggregates (Limestone) and medium shrinkage aggregate (Livermore Valley).

Table No. 3 tabulates some long term shrinkage values. (Graphs Nos. 4 and 5, page 23, 24) (Table No. 3, page 26)

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Cracking Tendencies

The phenomenon of concrete drying shrinkage starts as soon as the concrete is placed. The initial volume change during the plastic state is a major contributor to the total volume change which directly influences the tensile stresses that cause cracking. One of the purposes of this report is to relate ASTM C-157 drying shrinkage values to the potential volume change that occurs during the plastic state.

Mr. Robert Tobin, Professional Engineer, has reported: "The potential volume change (and cracking tendency) in fresh concrete may be as much as 200 times greater than it is on hardened concrete.

"It is true that these volume changes occur at different times and a direct comparison is not entirely valid. However, the order of magnitude is tremendous and we may well be paying insufficient attention to the really big shrinkage problem and the original source of many cracks." (Ref. #5)

While there is no positive method of determining the initial (plastic) volume change due to water loss, it is possible to make an estimate based on published data. Let us assume that we have a completely unrestrained concrete slab (20' x 20' x 4") with an exposed surface area of 400 square feet. The ambient conditions during placing, finishing and curing were: Temperature = 70°F.; wind velocity = 10 mph; the drying tendency would then be 0.062 lbs. water/sq. ft./hr. (Ref. #6) Let us also assume that the total volume change, due to

Concrete Drying Shrinkage 37

water loss, would be expressed in a single potential crack width.

At this time, we would also like to compare the effects of ASTM C-157 and pinned structure values on the same size slab.

Table 4

Condition	Aggregate	Shrinkage %	Location	Crack Width (In.) (3)	Relative Comparison (%)
Ambient	L.S. & M.S. T=70°F; Wind 10 m/hr.	-	-	0.733 (4)	100
ASTM C-157	L.S.	0.030	Laboratory	0.073 (5)	10.0
ASTM C-157	M.S.	0.043	Laboratory	0.108 (5)	14.8
Meas. Studs	L.S.	0.012	Structure	0.029	4.0
Meas. Studs	M.S.	0.015	Structure	0.036	4.9

Note: 1. L.S. = Low Shrinkage
2. M.S. = Medium Shrinkage
3. Basic Calculations Ref. #3
4. Based on 1 hour of exposure
5. Based on 7 days wet and 28 A.D.

The writer has observed concrete slabs, in California, that have developed many cracks (width = 1/8" to 1/4" 2-7 days) under adverse ambient conditions whose total volume-loss/area would approximate the above calculated value.

Since the above assumptions and end results could represent several points of contention, the writer decided to develop some additional supporting

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data as to potential water-loss effect. Two small concrete forms (16 1/2" x 34 1/2" x 3") were made and sealed with a bond-breaker. The forms were filled with a 5.5 s/y 1" max. concrete (5.5" slump); each form required 0.85 cu. ft. of concrete and had an exposed area of 4 sq. ft. After the forms were filled, vibrated, and screeded, Slab A was coated twice with an evaporation inhibitor and the other (Slab B) was untreated; final finish consisted of a light steel troweling. There was no additional curing. This data is listed in Table 5.

Table 5

Exposure Hrs.	Temperature °F	Relative Humidity	Wind Velocity mph	Water-Loss				
				Pounds			Percent (1)	
				Slab A	Slab B	Ratio B/A	Slab A	Slab B(2)
1	78	56	8	0.3	1.0	3.3	2.9	9.8
2	79	56	11	1.0	1.6	1.6	9.8	15.7
3	78	52	11	2.0	2.5	1.3	19.6	24.5
4	78	58	11	2.6	3.2	1.23	25.5	31.4
5	76	62	10	3.0	3.8	1.26	29.4	37.2
20	62	80	10	3.8	4.4	1.16	37.2	43.1
24	69	62	10	4.3	4.6	1.07	42.1	45.1

- (1) Percent of total water in mix = Added + Absorbed water
- (2) Slab A = Treated, 127.5 lbs (net), 123.2 lbs (net, 24 hrs)
Slab B = Untreated, 127.6 lbs (net), 123.0 lbs (net, 24 hrs)
- (3) Bleed water was insignificant.

Analysis of Data

A. The preceding data indicates that 40 to 45% of the total water can be removed from the slab concrete under severe ambient conditions which cover the most critical period in the life of the concrete. The following calculations, indicate that the above water-loss in 24 hours, due to poor curing, is quite possible.

1. Moisture samples were taken from each slab. (24 hrs)

Slab A = 1.0; Slab B = 1.1; Average = 1.05%

2. Test Data - Cement/Slab = 16.28 lbs/0.85 cu. ft.

Water/Slab = 10.24 lbs/0.85 cu. ft.

3. Estimated non-evaporable water in concrete @ 24 hours (Ref. #7 & #8) (page 19)

$16.28 \times 0.25 (+) = 4.07 \text{ lbs/slab}$

4. Potential free water available in slab after 24 hours:

$10.24 - 4.07 = 6.17 \text{ lbs}$

5. Water-loss by evaporation = 4.6 lbs (Slab B)

6. Free water in slab (24 hrs) = $6.17 - 4.6 = 1.57 \text{ lbs}$

7. Percent of available water that was lost in 24 hours (Slab B) =

$(4.6/6.17) \times 100 = 74.5\%$

8. Cross Check

a. Estimated available moisture content of Slab B = 1.28%

$\frac{1.57}{123} \times 100 = 1.28\%$

b. Actual measured moisture content of Slab B = 1.10%

9. Evaporation Rate

	Slab A	Slab B
Water-loss, lbs/sq ft/hr		
1 Hour Basis	0.075	0.250
24 Hour Basis	0.045	0.048

- B. The water loss, indicated in the preceding Section A is based on the total water/slab (10.24 lbs); if we take into consideration the non-evaporable water then we would only have 6.17 lbs of water/slab available for curing. On this basis the evaporated water-loss at 24 hours would be (4.6/6.17) 75%; that is, the slab would have approximately 25% of the original mixing water available for any additional curing.
- C. The importance in the control of water-loss was illustrated in crack patterns between Slab A and Slab B. Slab A (one transverse crack) ranged from 0.008" to a hair-line. Slab B had two major cracks that ranged from 0.010" to 0.020". The total length of cracks for Slab A was between 10 to 20% of that for Slab B (Age = 3 days). At three months, Slab B cracks had a maximum width of 0.050".
- D. In order to complete the above picture, two additional slabs were prepared. Slab C was treated with the evaporation inhibitor. At 5 hours, Slab C and Slab D were coated with the recommended rate

of a commercial resin-based curing compound. At 5 hours, the untreated Slab D had developed a Y-shaped hair-line crack. During the next 3 months, the treated Slab C essentially did not crack; the Slab D hair-line crack developed a crack width of 0.002".

Comparative Costs

The use of a low shrink aggregate, in place of a medium shrink aggregate, will increase the cost of concrete approximately 12% (Oakland-San Francisco area). If we use a typical concrete structure in this area which contains 15,000 yards of low shrink aggregate, the additional cost would be approximately (15,000 x \$4) \$60,000.

The project listed in Graph No. 2 - "Field Shrinkage Values" has approximately 65,000 yards of low shrink aggregates. In addition, 224 field shrinkage tests were made. At current commercial laboratory prices, the field tests cost \$112 + \$40/hour (assume 1 hour test). The added cost would be:

$$\begin{array}{rcl} 65,000 \times \$4 & = & \$260,000 \\ 224 \times \$152 & = & \underline{\underline{\$34,048}} \\ \text{Total Extra Cost} & = & \$294,048 \end{array}$$

The data on the preceding graph shows that 35% were below the specification line, 8% borderline, and 5% that failed to meet the field quality control requirement. The concrete, in place, was excellent regardless of the low and high shrinkage values. The range in values above the spec line (0.035 to 0.071%) would be similar to the range for medium shrink aggregates. Was the extra cost justified?

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Conclusions

1. Concrete drying shrinkage is primarily effected by the cement influence (ASTM C-157).
2. ASTM C-157 should not be used as a field control test.
3. Control of water-loss during placement and curing is essential in the prevention and minimization of future cracking.
4. The volume change, as measured by ASTM C-157 is minimal when compared to the volume change during the first 48 hours (field concrete).

Recommendations

1. ASTM C-157 should not be used as a field quality control tool.
2. Field shrinkage tests should be based on large samples such as 4' x 4' x 8" sections (flat or vertical) or pinned structures.
3. The use of an evaporation inhibitor during the first two hours of placement prior to the application of a sprayed-on curing membrane is an excellent method of water-loss control during the most critical volume-change period in the life of the concrete.

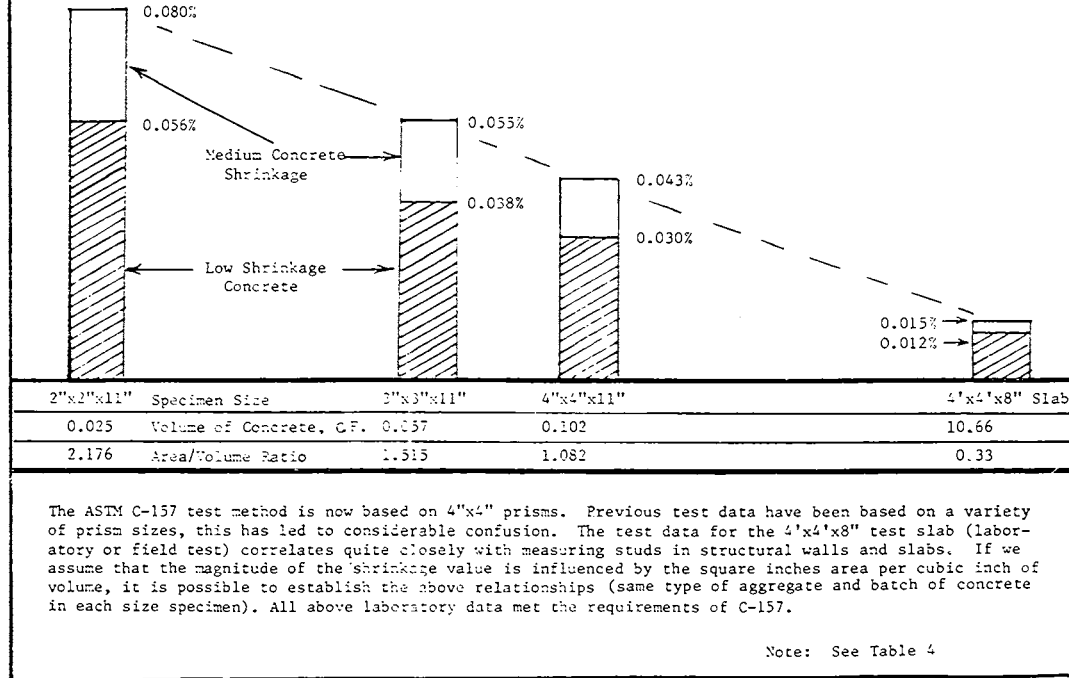


References

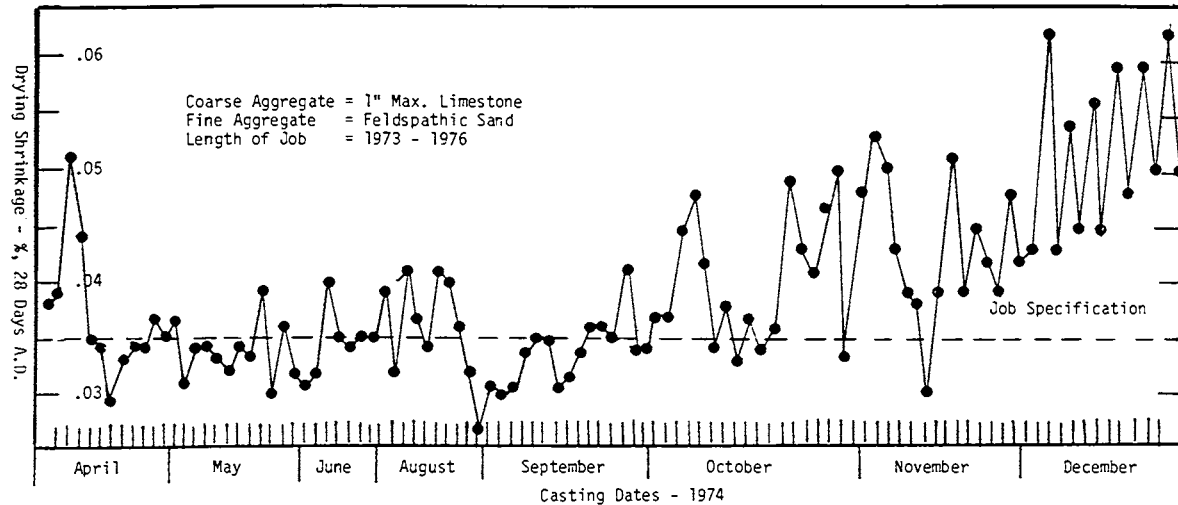
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5. R. E. TOBIN, Structural Engineers Association of California, Special Committee on Concrete Shrinkage, 1966
6. Portland Cement Association, Prevention of Plastic Cracking in Concrete
National Sand and Gravel Ready Mixed Concrete Association, Plastic Cracking of Concrete
7. LEA and DESCH, Chemistry of Cement and Concrete, pg 211
8. NEVILLE, Properties of Concrete, pg. 35

The non-evaporable water contains nearly all chemically combined water and also some water not held by chemical bonds.

GRAPH NO. 1

DRYING SHRINKAGE RESULTS - EFFECT OF SPECIMEN SIZE

GRAPH NO. 2

FIELD DRYING SHRINKAGE VALUES - LOW SHRINKAGE AGGREGATESDetails

Method = ASTM C-157
 Specimen Size = 4" x 4" x 11"
 Constant Cement Brand
 Constant Source of Aggregate

Statistics

Number of Tests = 224
 Standard Deviation = +0.0084%
 Range = 0.025 - 0.071%
 Coef. of Variation = 22%

Shrinkage Specification = 0.035%

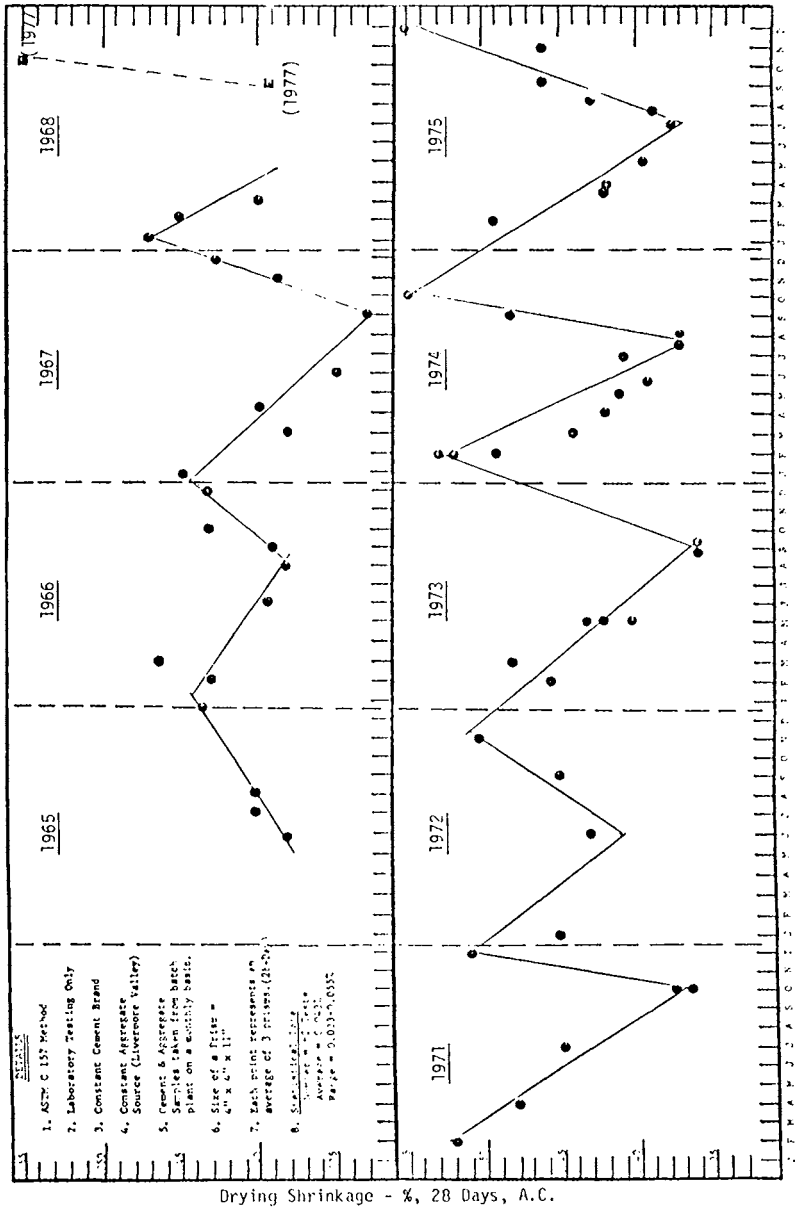
Passing = 35%
 Borderline = 8%
 Failing = 57%

Range in Field Shrinkage Values - Random Projects

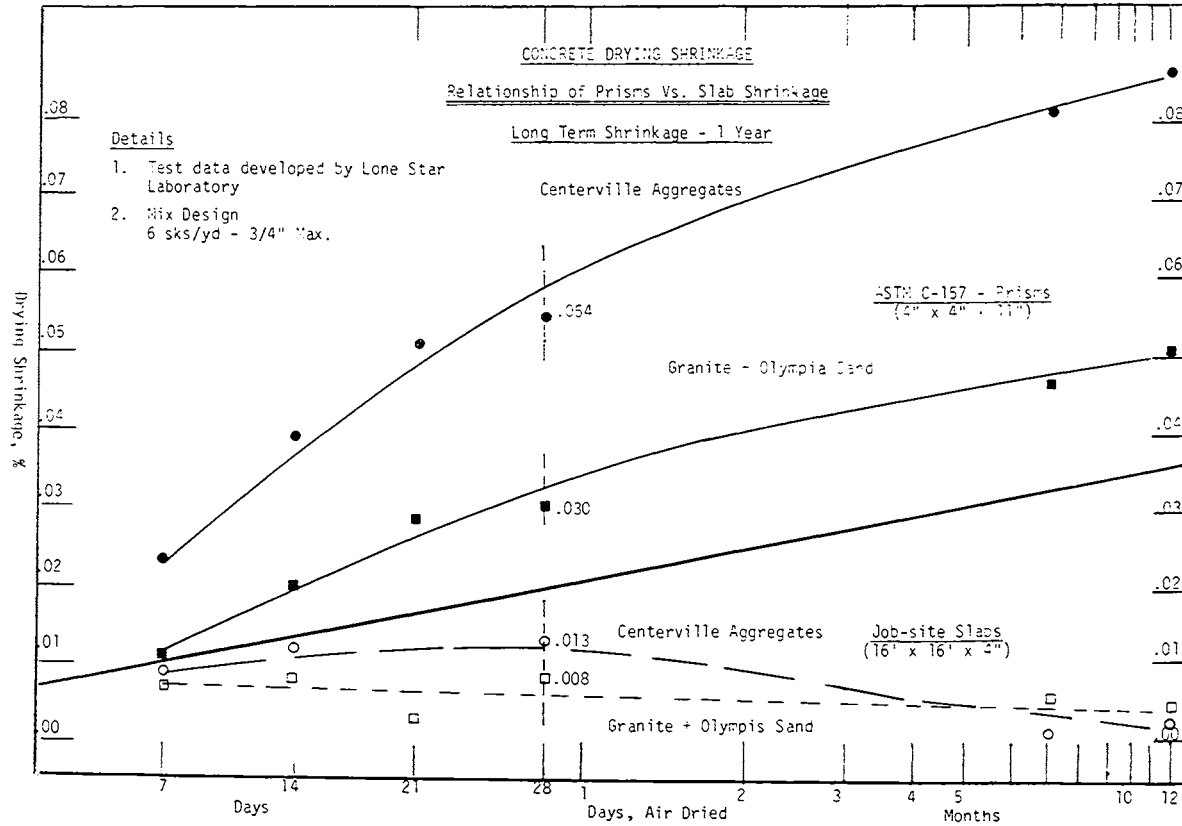
Type	Aggregate	Percent	Data Information	
Low Shrinkage	Limestone	0.025 - 0.071	Lab C	N = 224
Low Shrinkage	Granite	0.033 - 0.073	Various Labs	N = 28
Medium Shrinkage	Livermore Valley	0.036 - 0.078	Lab D	N = 152
Medium Shrinkage	Russian River	0.036 - 0.066	Lab E	N = 194
				598

GRAPH NO. 3

CHRONOLOGICAL CONCRETE SHRINKAGE



GRAPH NO. 4



GRAPH NO. 5

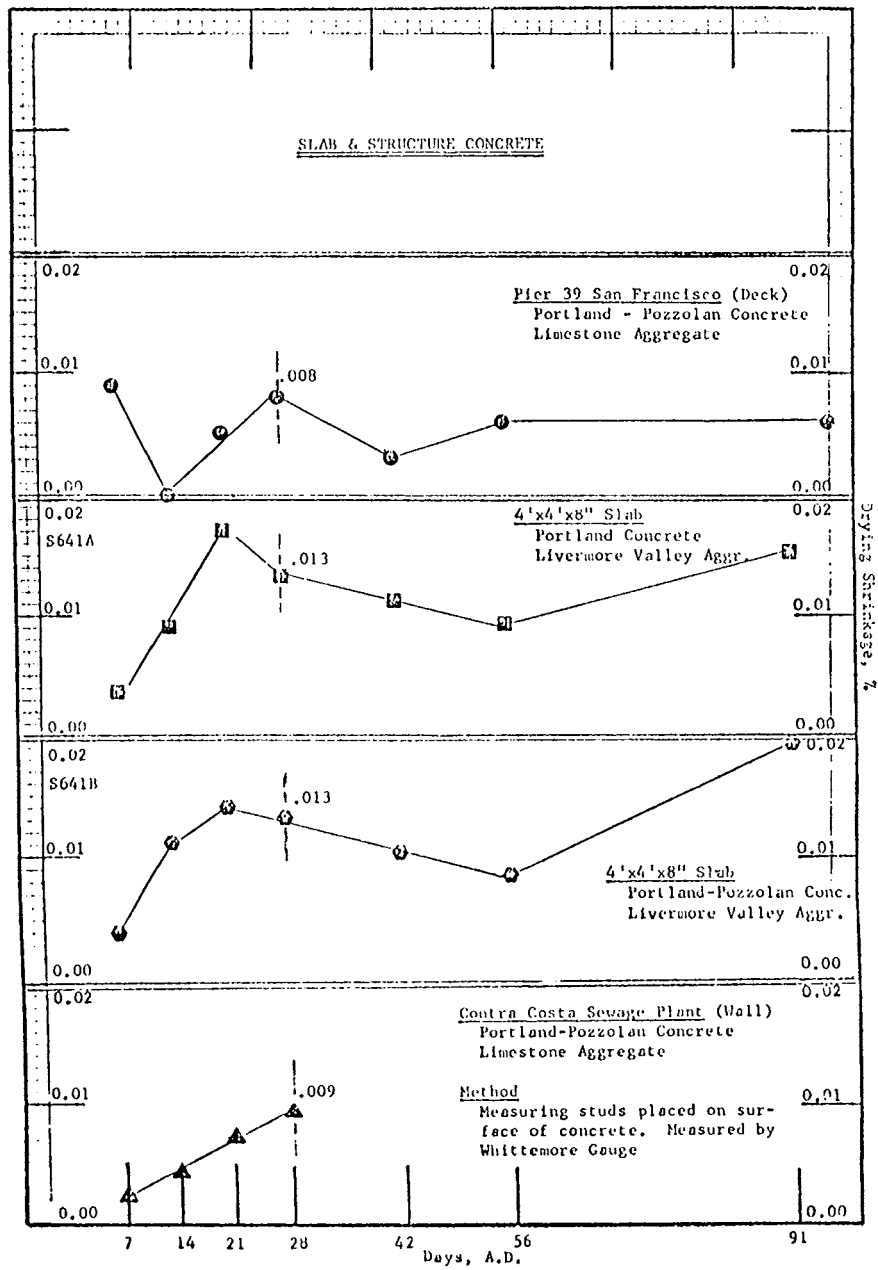


TABLE NO. 1
Product Variability
Cement Versus Aggregates

Conditions	Variable Cement / Constant Aggregate				Variable Aggregate / Constant Cement			
	Compressive Strength psi		Drying Shrinkage %		Compressive Strength psi		Drying Shrinkage %	
Test Lab	A	B	A	B	A	B	A	B
March (1975)	4700	4520	0.042	0.037	4700	4520	0.042	0.037
April	4910	4110	0.058	0.057	4620	4530	0.045	0.042
May	4380	4110	0.040	0.043	4560	4080	0.041	0.041
June	3930	--	0.038	0.045	4480	--	0.041	0.043
July	4100	4150	0.038	0.043	4180	3890	0.043	0.048
August	4015	3580	0.043	0.049	4280	4190	0.039	0.048
September	4410	4730	0.046	0.040	4400	3890	0.045	0.040
October	4320	4010	0.036	0.039	4270	4530	0.040	0.043
November	4410	--	0.046	--	4480	4120	0.042	0.037
December	4540	--	0.045	--	4640	--	0.048	--
January (1976)	4580	4610	0.047	0.046	4660	4420	0.043	0.046
February	4770	--	0.059	--	4630	--	0.049	--
Average	4425	4228	0.045	0.049	4487	4240	0.043	0.043
Stan. Deviation	+303 psi	+375 psi	+0.007%	+0.006%	+178 psi	+266 psi	+0.003%	+ 0.004%
Coef. of Variation	6.8%	8.9%	15.6%	13.6%	4.0%	6.3%	7.0%	9.3%

Note: Strength = Average of 2 Cyls. - Shrinkage = Average of 3 Prisms

Table No. 2

Set No.	Compr. Strength, psi 28-Days - Aver. 2	Drying Shrinkage, % 28-Days A.D. Aver. 3
1.	4755	0.049
2.	4555	0.050
3.	4630	0.052
4.	4730	0.055
5.	4590	0.056
6.	4645	0.049
7.	4595	0.051
8.	4520	0.050
9.	4575	0.053
10.	4695	0.053
	ASTM C-39	ASTM C-157
Average	Compressive Strength 4629 psi	Drying Shrinkage 0.0518%
Range	235 psi	0.007%
Standard Dev.	+77 psi	+0.0025%
Coef. of Variation	1.7%	4.8%

TABLE NO. 3

SLAB AND STRUCTURE SHRINKAGE

Aggregates	Type	Date Cast	Age-Months, %			
			1(28)	2	3	12
Centerville	M.S.	1/64	0.013	0.009	-	0.004
Granite	L.S.	1/64	0.008	0.004	-	0.002
Limestone	L.S.	4/75	0.009	-	-	-
Livermore Valley	M.S.	1/77	0.013	0.009	0.015	-
Livermore Valley	M.S.	7/77	0.013	0.008	0.018	-
Limestone	L.S.	9/77	0.008	0.006	0.006	-
Livermore Valley	M.S.	11/77	0.020	0.024	0.029	-
Limestone	L.S.	11/77	0.017	0.021	0.025	-
Granite	L.S.	11/77	0.017	0.022	0.026	-
			Average Monthly Values, %			
			1	2	3	12
			0.015	0.013	0.021	0.004
Medium Shrinkage (M.S.)			0.012	0.013	0.019	0.002
Low Shrinkage (L.S.)						

TABLE NO. 4

RELATIONSHIP OF SPECIMEN SIZES

TABLE OF FACTORS FOR APPROXIMATE CONVERSION OF DRYING SHRINKAGE VALUES FROM ONE PRISM SIZE TO ANOTHER.						
GIVEN PRISM SIZE	FACTORS TO OBTAIN APPROXIMATE EQUIVALENT					
	2X2X11 1/4	3X3X11	4X4X11	4X5X18	5X6X16	5X6X40
2x2x11 1/4	1.00	0.70	0.54	0.46	0.39	0.36
2.178**						
3x3x11	1.44	1.00	0.78	0.67	0.57	0.52
1.515						
4x4x11	1.84	1.28	1.00	0.86	0.73	0.66
1.182						
4x5x18	2.15	1.50	1.17	1.00	0.85	0.77
1.011						
5x6x16	2.54	1.77	1.38	1.18	1.00	0.91
0.858						
5x6x40	2.78	1.94	1.51	1.29	1.10	1.00
0.783						

** SQUARE INCHES OF SURFACE AREA PER CUBIC INCH OF VOLUME.