

Properties and proportions of mix constituents, age of concrete at loading, storage conditions, stress-strength ratio, and other factors affecting creep are discussed. Various expressions for the creep-time relation are discussed, and prediction curves for creep of concrete of different properties and stored under different condition are presented.

Creep of Concrete: Influencing Factors and Prediction

By Adam M. Neville and Bernard L. Meyers

■ CREEP IS AN INCREASE with time in the strain of concrete subjected to stress; it is conveniently expressed at a constant stress. This definition is not adequate because concrete exhibits a change in strain with time when no external stress is acting—when drying (or swelling) takes place. This is of course drying shrinkage.

How are shrinkage and creep analyzed when they occur simultaneously? The common practice is to consider the two phenomena to be additive. The over-all increase in strain of a stressed and drying member is assumed to consist of shrinkage (equal in magnitude to that of a similar unstressed member) and of a change in strain due to stress (creep). This approach has the merit of simplicity but not of accuracy. Creep and shrinkage are not independent phenomena to which the principle of superposition can be applied, and in fact the effect of shrinkage on creep is to increase the magnitude of creep. In the case of many actual structures, however, creep and shrinkage occur simultaneously and the treatment of the two together is from the practical standpoint often convenient.

For this reason, and also because the great majority of the available data on creep were obtained on the assumption of the additive properties of creep and shrinkage, the discussion in this paper will, for the most part, consider creep as a deformation in excess of shrinkage. However, where a

more fundamental approach is warranted, distinction will be made between creep of concrete under conditions of no moisture movement to or from the ambient medium (true¹ or basic creep) and the additional creep caused by drying (drying creep).

The dependence of the stress-strain relation on time is shown not only by creep, as defined earlier, but also by relaxation. This is the change in stress in a member subjected to a constant strain. Creep and relaxation are closely inter-related but there is no simple way of translating creep values into relaxation values or vice versa.

For the sake of accuracy it should be noted that since the modulus of elasticity of concrete increases with time, the elastic strain decreases with time. Thus, strictly speaking, creep should be reckoned as strain in excess of the elastic strain at the time considered and not in excess of a fixed value of elastic strain.

The terms and definitions involved are illustrated in Fig. 1

FACTORS INFLUENCING CREEP

Since the mix constituents are the main variables in concrete as a material, it is not surprising that nearly all the early studies on creep were concerned with the influence of the variation in the properties and quantities of the mix ingredients. Unfortunately, however, and this of course is well known, it is not possible to alter one constituent of concrete without altering at least one other. To give an example, a change in the water-cement ratio is accompanied by a change either in the content of the cement paste or in workability or in both.

A great volume of test results on creep of concretes of different composition is available but the interpretation of the data requires considerable skill. It should not be surprising to find, in some cases, that the interpretation of test results in the light of the information now available may differ substantially from the investigator's original conclusions.

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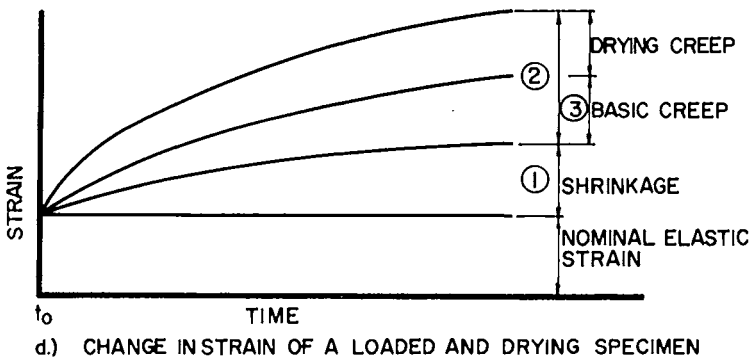
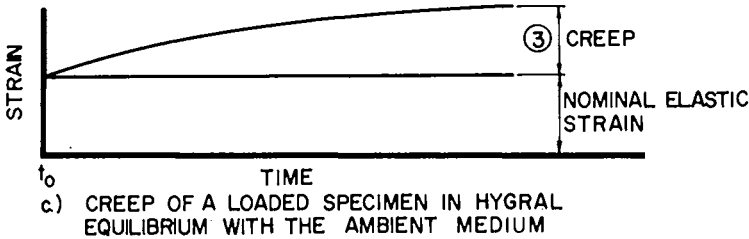
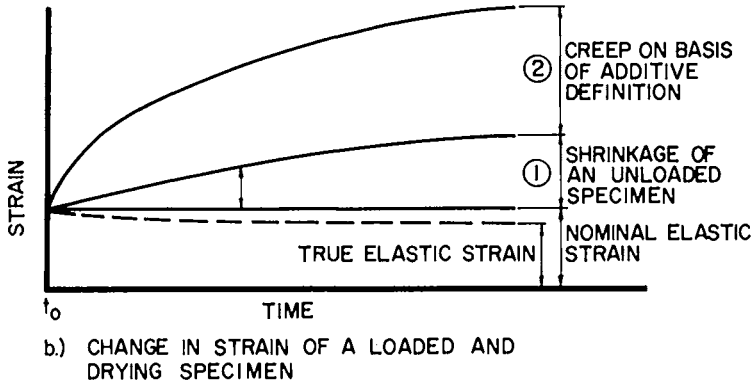
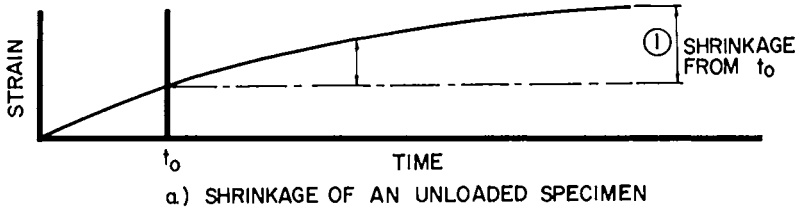


Fig. 1—Definitions of terms (t_0 is the time of application of load)

Aggregate

The usual normal weight aggregate used in concrete is not liable to creep to an appreciable extent,* so that it is reasonable to assume that the seat of creep is in the cement paste, but this does not mean that the aggregate does not influence the creep of concrete. The influence is in fact two-fold.

Aggregate content

Firstly, because the cement paste is subject to creep and the aggregate generally is not, the effect of the aggregate is to reduce the effective creep of concrete. Creep is thus a function of the volumetric content of cement paste in concrete, but the relation is not linear. Recent work⁶ indicates that creep of concrete, c , and the volumetric content of aggregate, g , are related by:

$$\log \frac{c_p}{c} = \alpha \log \frac{1}{1-g} \quad \dots \dots \dots (1)$$

where c_p is creep of neat cement paste of the same quality as used in concrete, and

$$\alpha = \frac{3(1-\mu)}{1+\mu+2(1-2\mu_a)\frac{E}{E_a}} \quad \dots \dots \dots (2)$$

Here, μ_a = Poisson's ratio of aggregate, μ = Poisson's ratio of surrounding material, E_a = modulus of elasticity of aggregate, and E = modulus of elasticity of the surrounding material.

Fig. 2 illustrates the relation between creep of concrete and its aggregate content. It may be noted that in the majority of the usual mixes, the variation in the aggregate content and therefore in creep is small.

The grading, maximum size, and shape of the aggregate have been suggested as factors in creep. It is now⁶ believed, however, that their main influence lies in the effect that these properties have directly or indirectly on the aggregate content. As shown earlier for a given water-cement ratio, the higher the content of aggregate, the lower the creep. The above statements and those to follow assume that in all cases the mix proportions are such that full consolidation can be obtained and that such consolidation has in fact been obtained.

Physical properties of aggregate

There are, however, certain physical properties of aggregate which influence the creep of concrete. The modulus of elasticity of aggregate is probably the most important factor. The higher the modulus, the greater

*Some aggregates are, however, liable to creep at stresses of no more than several hundred psi: McHenry³ demonstrated this for a volcanic agglomerate; the Bureau of Reclamation reported creep of the Glen Canyon sandstone⁴ and Taiwan greywacke.⁵

the restraint offered by the aggregate to the potential creep of the cement paste; this is evident from Eq. (2).

Porosity of aggregate has also been found to influence the creep of concrete but since aggregates with a higher porosity generally have a lower modulus of elasticity, it is possible that porosity is not an independent factor in creep. On the other hand, it can be visualized that the porosity of aggregate, and even more so its absorption (Fig. 3), plays a direct role in the transfer of moisture within concrete; this transfer may be associated with creep.

Because of the great variation in aggregate within any mineralogical or petrological type, it is not possible to make a general statement about the magnitude of creep of concrete made with aggregates of different types. However, as no more than an illustration, the findings of two investigators are quoted. In 1930 Davis and Davis⁷ found the aggregates in the order of increasing creep to be: limestone, quartz, granite, gravel, basalt, and sandstone. After 20 years' storage at a relative humidity of 50 percent, concrete made with sandstone aggregate exhibited creep more than twice as great as concrete made with limestone.⁸

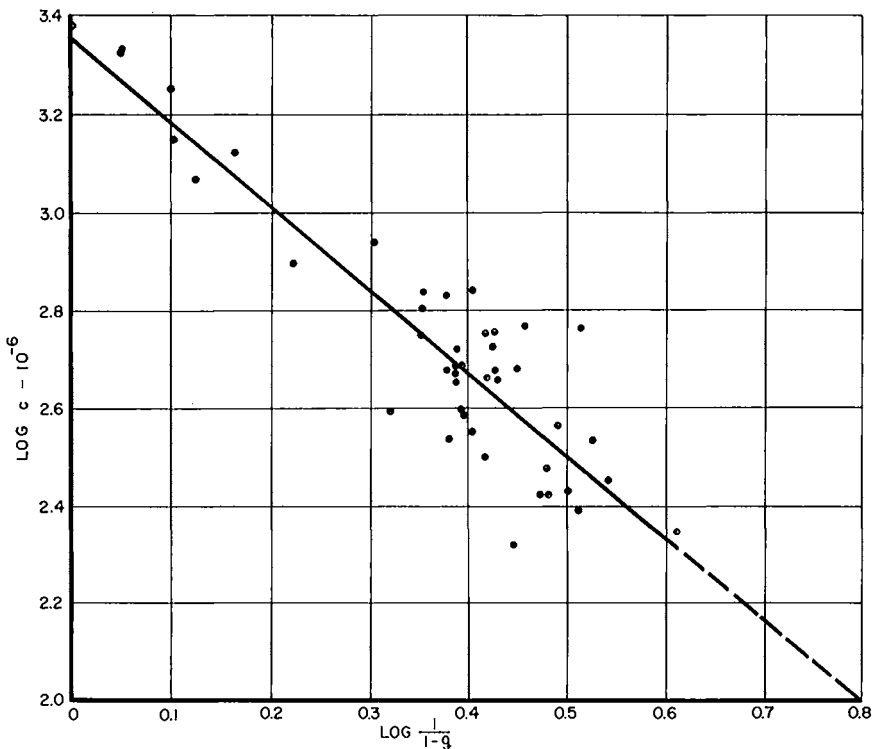


Fig. 2—Relation between creep c after 28 days under load and content of aggregate g for wet-stored specimens loaded at the age of 14 days to a stress-strength ratio of 50 percent.

An even greater difference between creeps of concretes made with different aggregates was found by Rüsch, Kordina, and Hilsdorf⁹ in 1962. After 18 months under load at a relative humidity of 65 percent, the maximum creep was five times the minimum value, the aggregates in the increasing order of creep being: basalt; quartz; gravel, marble and granite, and sandstone.

Rüsch's⁹ tests indicate that the influence of the petrological type of aggregate on creep acts primarily through the modulus of elasticity of aggregate. The latter affects also the elastic deformation of concrete, and indeed a good correlation between creep and elastic deformation of concrete was obtained. At the same time, the absorption of aggregate and its modulus of elasticity were definitely related (Fig. 3) so that the pattern of the creep-elasticity-absorption relation, mentioned earlier, is confirmed.

Lightweight aggregate deserves a special mention because of the rather common belief that it leads to substantially higher creep than normal weight aggregate. Lightweight aggregate is increasingly used in structural concrete and the knowledge of its creep properties is important. Recent work both at the University of Missouri and elsewhere indicates that there is no fundamental difference between normal and lightweight aggregates as far as the creep properties are concerned, and the higher creep of concretes made with lightweight aggregates reflects only the lower modulus of elasticity of the aggregate. There is no inherent difference in the behavior of coated and uncoated aggregates or between those obtained by different

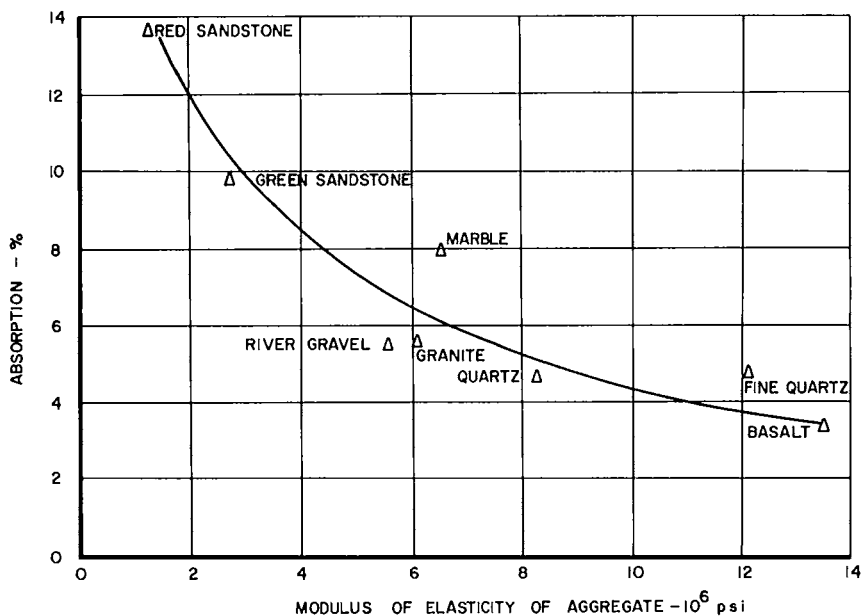


Fig. 3—Relation between absorption and modulus of elasticity of different aggregates.

manufacturing processes, but this of course does not mean that all the aggregates lead to the same creep.

Cement

The usual portland cements differ from one another primarily in the rate of hydration but not in the ultimate strength. Any comparison of creep behavior must therefore take into account the degree of hydration at the time of application of the load. Unqualified statements such as "Type IV cement creeps more than Type I cement" are almost meaningless.

In conventional concrete design, the permissible stress forms a fixed proportion of the concrete strength at the time of application of the load or, more commonly, at some arbitrary age such as 28 days. For this reason, it is logical to compare concretes made with different cements under a load where the stress-strength ratio* is the same in all cases. Under these conditions, the type of cement (i.e., its composition or fineness) does not, in the first approximation, influence creep.^{10†} The composition is meant to include the major cement compounds, C_3S , C_2S , C_3A , C_4AF , and also the alkalis whose presence in cement tends to increase the creep and also to lower the gain in strength.¹²

The amount of gypsum in the cement may affect creep in a manner similar to the influence on shrinkage. This was suggested by Davis and Troxell¹³ and observed experimentally by Neville.¹⁰ The influence of gypsum is apparent when cements are reground in the laboratory without gypsum being added. With the vast majority of commercial cements, the gypsum content is near the optimum value for shrinkage and probably also for creep.

The statement that creep is not influenced by type of cement is believed to be of importance, but should be refined by considering the change in strength of concrete while under load. Therefore, concretes made with different cements and loaded at the same age at a constant stress-strength ratio should be considered. The increase in strength beyond this age will be different for different cements; being least for Type III cement and greatest for Type IV cement. It has been suggested that the decrease with time in the rate of creep is a function of the increase in strength, the decrease in the rate being greater, the greater the increase in strength.⁶ A quantitative verification of this relation is in progress (1964) at the University of Alberta, Calgary. In general terms it can be stated, with the qualifications made, that creep increases for cement Types IV, I, and III, respectively. There is no doubt, however, that for a constant applied stress at a fixed (early) age, creep increases in order for cement Types III, I, and IV. These two statements bring out clearly the need for a full qualification of statements about factors in creep.

*The ratio of the applied stress to the strength at the time of loading.

†This statement does not apply to cements other than Types I to V and white portland cement. For instance, portland blastfurnace cement results in a higher creep¹¹ than the cements mentioned above.

Entrained air

Sufficient information on the influence of entrained air on creep is not available but there are indications that the presence of air increases creep. It is logical to treat entrained air as aggregate with a modulus of elasticity of zero, and thus to consider air as materially contributing to creep. This statement is valid, however, only if we compare mixes which differ solely by the presence or absence of air. In practice, a mix designed to contain entrained air has properties such as workability and strength which are comparable with those of an air-free mix of different proportions. On this basis of comparison the influence of the air content on creep may not be significant.

Admixtures and pozzolans

No systematic tests on the influence of admixtures on creep have been made and no reliable information is available. This statement is hardly helpful, and all that can be recommended is that the behavior of untried admixtures be studied in the laboratory before field use.

Pozzolans probably do not directly affect creep. If they are used as a partial replacement of cement and the load is applied before the pozzolanic action has been fully developed, an increase in creep should be expected.

Mix proportions

The quality of the cement paste has a direct influence on creep, and this can be expressed approximately by saying that for a constant cement paste content, and the same applied stress, creep is inversely proportional to the strength of concrete. Thus strength is a convenient, but approximate, measure of the state of the cement paste, i.e., its composition and degree of hydration.

Creep, therefore, increases with an increase in the water-cement ratio* but the relation between creep and the water content of the mix is not basic. What happens depends on the influence of the water-cement ratio and aggregate-cement ratio, as these two factors control the water content of the mix. (The influence of the aggregate-cement ratio is the lesser of the two.)

Viewing creep as a function of water-cement ratio and aggregate-cement ratio gives a correct general picture of the influence of mix proportions on creep, and is worth emphasizing, for in the older literature there exist numerous misleading statements. For example: creep is proportional to the aggregate content of the mix (which can be explained by a concomitant increase in the water-cement ratio); or, creep is proportional to the water content of the concrete (which can be explained by the fact that for a constant workability an increase in water content must be accompanied by an increase in the aggregate-cement ratio, with a consequent

*Creep being approximately proportional to the square of the water-cement ratio, as suggested by Lorman.¹⁴

increase in the water-cement ratio; the effect of the latter on creep is greater than that of the aggregate-cement ratio for usual ranges of practical mixes). If both the aggregate content and water-cement ratio are varied, the net effect on creep would depend on the relative magnitude of the effects of variation in the paste content and its quality.

For these reasons, and also because the strength of structural concrete is a practical concern, relating creep to strength is thought to be both

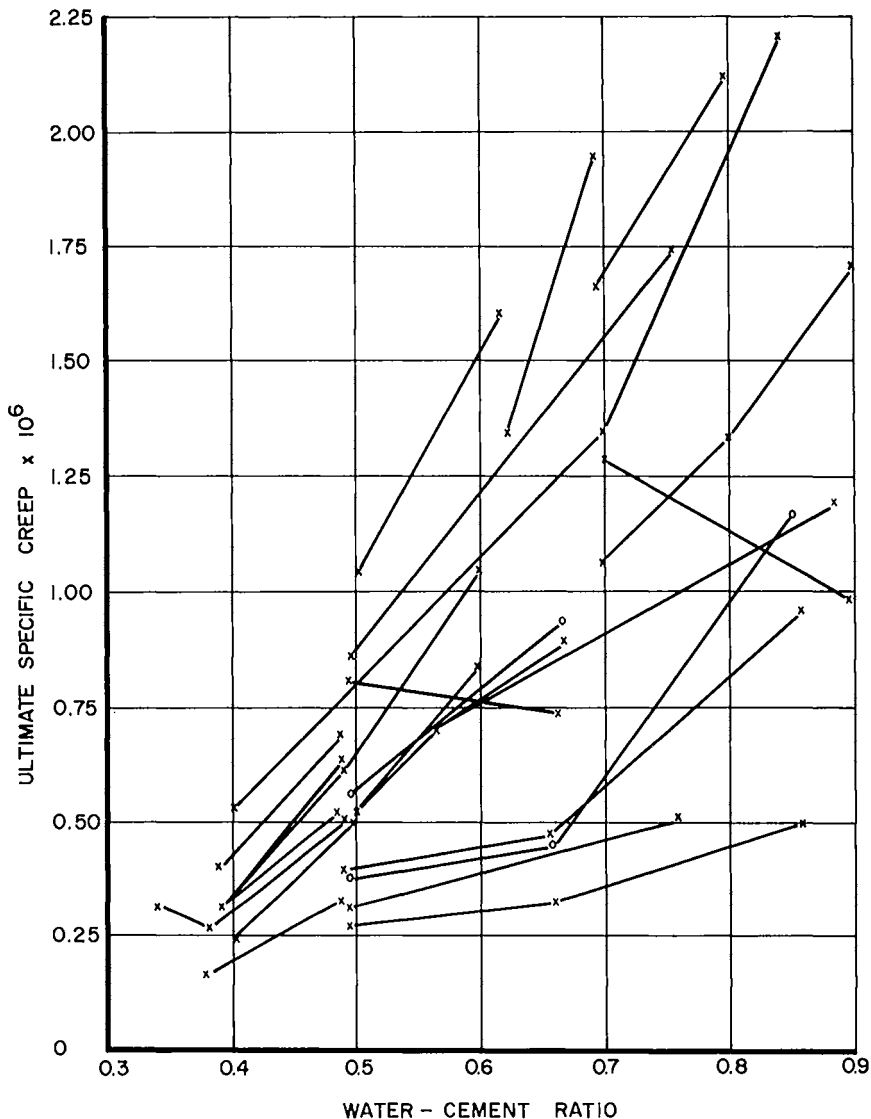


Fig. 4—Relation between specific creep and water-cement ratio in the tests of various investigators¹⁶

convenient and fairly reliable. As an example, Klieger's¹⁵ data on creep of concrete can be expressed in terms of strength, as shown in Table 1.

A good illustration of the general situation is given by Wagner's data.¹⁶ Fig. 4 shows the relation between specific creep (creep per psi) and water-cement ratio; there is no clear-cut pattern, and indeed the trend of some investigations is opposite to that of others. However, when a correction for the cement paste content has been made (by reducing the observed creep values to those which would exist if the content of cement paste were 20 percent by weight), the influence of the water-cement ratio becomes clear, as shown in Fig. 5. The ordinate of this figure represents the ratio of the actual creep to the creep of a mix with a water-cement ratio of 0.65. Such a relation exists both for long- and short-term creep.

It may be relevant to note that this mix with a water-cement ratio of 0.65 and a cement paste content of 20 percent by weight is used as a reference mix when the prediction of creep for mixes of different proportions by Wagner's method¹⁷ is considered later in the paper.

Mixing time and consolidation

No tests have been made on the influence of the mixing procedure and time on creep. These factors may affect the strength of concrete, and it

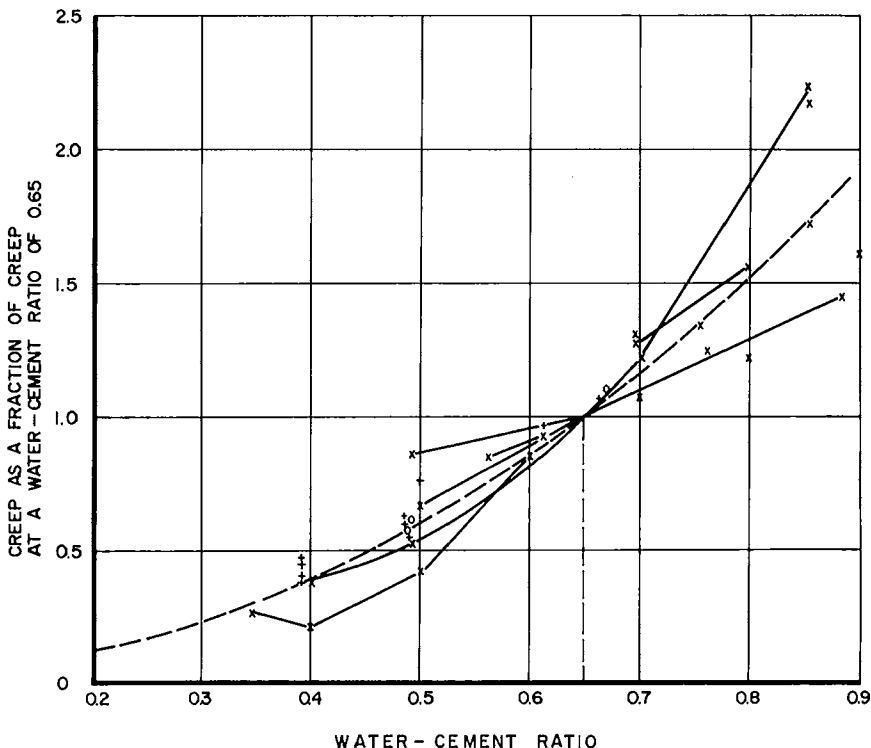


Fig. 5—Data of Fig. 4 adjusted for the content of cement paste (to a value of 20 percent) and expressed in terms of creep at a water-cement ratio of 0.65¹⁶

TABLE 1—CREEP OF CONCRETES OF DIFFERENT STRENGTHS

Compressive strength at time of application of load, psi	Ultimate specific creep, 10^{-6} per psi	Ultimate creep at a stress-strength ratio of 30 percent, 10^{-6}
2000	1.40	933
4000	0.80	1067
6000	0.55	1100
8000	0.40	1067

would therefore be logical to expect a corresponding influence on creep. In some cases, the influence on strength is transitory and may cease to be present at the age at which the sustained load is applied; no influence on creep would then be expected.

The influence of consolidation on creep is related to the strength which the concrete has developed. Voids due to incomplete consolidation affect creep in a manner similar to the capillary voids whose presence is reflected by the influence of the water-cement ratio on creep. It is, therefore, believed that experimental results relating the method of consolidation to creep should be interpreted in terms of the degree of consolidation achieved by the various means of consolidation. From the practical point of view, proper consolidation of concrete is of great importance.

Age of concrete

When the influence of the strength of concrete at the time of application of the load on creep was discussed, the variation in strength was considered to arise from the type of cement and mix proportions used. Age of concrete at loading acts in the same way, i.e., it is a factor in creep in so far as it influences the degree of hydration and development of strength. Thus creep has been found to correlate well with maturity.^{17,18}

Under conditions such that no sensible variation in the degree of hydration occurs, the age at loading ceases to influence creep. For instance, the influence of the age at which the load is applied is much smaller in the case of dry-cured concrete. Also, at later ages the rate of creep becomes independent of the age at loading.

Level of stress

In various experimental results there exists substantial evidence of the proportionality between creep and the applied stress, with a possible exception of specimens loaded at an early age. What is not certain is the upper limit of proportionality. (The lower limit is virtually at zero stress as creep is exhibited by concrete even at low stresses.) In terms of the stress-strength ratio, an upper limit between about 30 and 75 percent¹⁹ has been suggested.*

*Freudenthal and Roll²⁰ found the limit to be as low as 23 percent.

It is known that severe internal cracking takes place in a concrete compression specimen at a stress-strength ratio of 40 to 60 percent,²¹ and it is not surprising that, once the cracking has started, the creep behavior also changes. It is possible that the onset of cracking depends on the degree of heterogeneity of the concrete; for instance, mortars are less grossly heterogeneous than concrete containing a large-size aggregate and exhibit proportionality between creep and stress-strength ratio up to a higher limit, possibly 85 percent.¹⁰

It appears safe to conclude that within the range of working stresses the proportionality holds good and, with one exception,²² creep expressions and prediction diagrams (discussed later in the paper) assume this to be the case.

Above the limit of proportionality, creep increases with an increase in stress at an increasing rate, and there exists a stress level above which creep produces time failure. This level is in the region of 70-80 percent of the short-term static strength. Creep increases the total strain until this reaches a limiting value corresponding to the ultimate strain of the given concrete. This statement implies a limiting strain concept of failure of concrete, which the authors believe to be the case.¹²

Ambient humidity

Numerous tests have shown that creep increases with a decrease in the relative humidity of the surrounding medium. For instance, at a relative humidity of 50 percent creep may be 2 to 3 times greater than at 100 percent (Fig. 6). However, careful qualification is necessary because a statement that creep is higher the lower the relative humidity of the ambient medium may be misleading. Two points should be noted.

Firstly, the ambient relative humidity affects creep if drying takes place while the specimen is under load. But if the concrete has reached hygral equilibrium prior to loading, the magnitude of creep is independent of the relative humidity of the surrounding medium. This was reported by Neville,¹⁰ and confirmed by Kesler's tests on mature concretes. It appears thus that it is not the ambient humidity that is a factor in creep but the process of drying while the concrete is subject to creep. This is confirmed, for instance, by the fact that at later ages the rate of creep becomes sensibly independent of the ambient relative humidity (Fig. 6); by that time, shrinkage has virtually ceased.

The second point is really an extension of the first. Hansen²³ observed (1958) that alternating the ambient relative humidity between two limits results in a creep which is higher than that obtained at a constant humidity within the given limits. This was confirmed by L'Hermite²⁴ in 1960. The phenomenon was in fact first noticed as far back as 1942²⁵ but since no explanation was available it was simply ignored and forgotten. One effect of this behavior is that laboratory tests performed at a constant relative

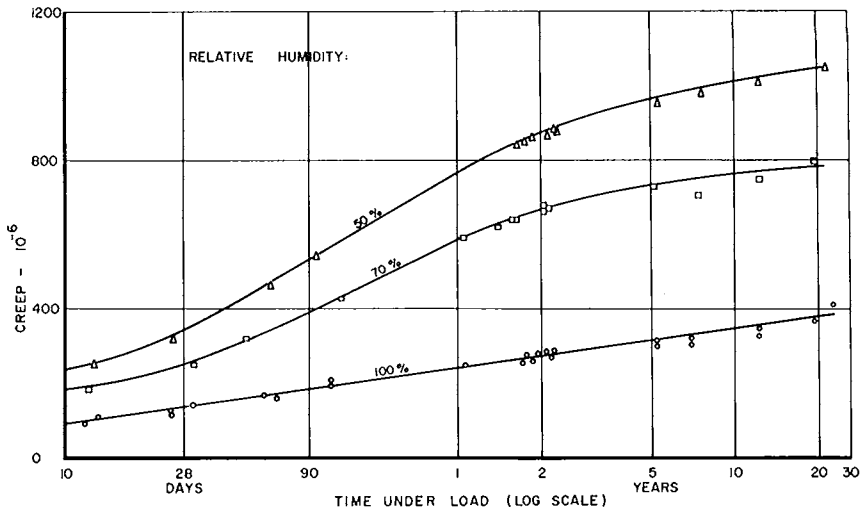


Fig. 6—Creep of concrete cured in fog for 28 days, then loaded and stored at different relative humidities⁸

humidity underestimate the creep under conditions of practical exposure in many countries.

It may be relevant at this stage to observe that the apparent influence of ambient humidity on creep does not act through the medium of an additional loss of water from the concrete. Numerous tests* have shown that an external load does not increase water loss to the surrounding air in excess of that which takes place under similar conditions without an external load acting. Alternating humidity, whether the concrete be under load or not, leads to moisture movement into and out of concrete. This appears to enhance creep²⁸ but creep does not enhance the moisture movement. An explanation of these apparently contradictory phenomena is offered in the second paper in this symposium.

We should note also that the ambient humidity affects the rate of hydration and of gain of strength. This influence is smaller in the case of Type III cement, and indeed the creep of concrete made with this cement is less influenced than when Type I cement is used. This is apparent, for instance, from Glanville's data.²⁹ The order of magnitude involved is given in Table 2.

Temperature

The influence of temperature on creep is of interest in connection with the use of concrete in the construction of prestressed concrete nuclear pressure vessels. The topic is thus rather specialized. Work of Ross and England³⁰ shows that creep increases with temperature, the increase being greater in the range 68 to 180°F (say, fourfold after 80 days under load) than for higher temperatures up to 280°F (when creep is about five times

*See References 26 and 27 for examples.

TABLE 2—INFLUENCE OF AMBIENT RELATIVE HUMIDITY ON CREEP

Relative humidity, percent	Creep of concrete as a fraction of creep at 70 percent relative humidity	
	Type I cement	Type III cement
100	0.50	0.70
85	0.77	0.87
70	1.00	1.00
55	1.22	1.10
45	1.34	1.17
35	---	1.22

the creep at 68F). This broad pattern was found both for concrete stored in air and for concrete under simulated conditions of mass curing. These results are in qualitative agreement with Theuer's findings³¹ but he observed also that the creep of desiccated concrete is independent of temperature. Experimental work being conducted by Nasser and Neville shows that the temperature effect is present also when concrete is stored in water.

Temperature influences creep even within the normal range (say, up to 100F) and this effect should not be neglected.

The difference between the temperature during the period while under stress and during the preceding period must be recognized; the latter influences the basic principles of concrete, its maturity, the structure of gel, etc., and should be viewed in that light.

Size of member

Several investigations have indicated an influence of the size of the specimen on creep. The measured creep decreases with an increase in the size of the specimen, but when the specimen thickness exceeds about 3 ft, the size effect is no longer noticeable. Some typical results are shown in Fig. 7.³²

This apparent influence of the size of the concrete member on creep complicates an evaluation of the test results of different investigators but the importance of the phenomenon lies in its causes. Why does size affect creep? The first observation which should be made is that the influence of size on creep is greatest during the initial period after the application of the load. Beyond, say, several weeks the rate of creep is the same in specimens of all sizes.

The original explanation of the size effect in terms of the loss of water to the ambient medium (which would be relatively greater in a smaller specimen) is not correct for it is now known that loss of water does not play a significant role in creep. However, in actual tests, creep and shrinkage operate simultaneously. As shown earlier these two phenomena are not independent and concurrent shrinkage enhances creep. Thus in a small specimen a greater part of the concrete is subjected to creep while drying

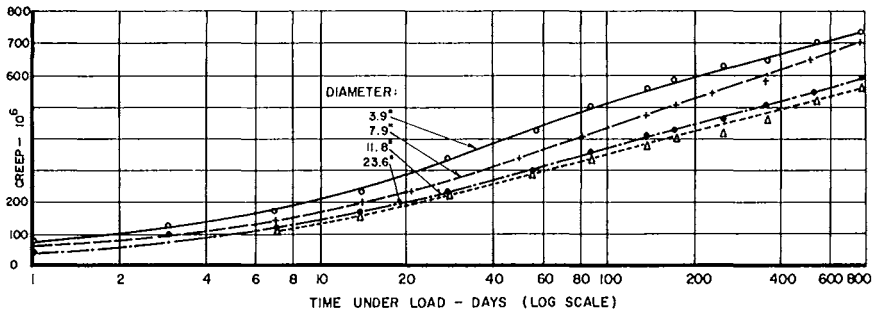


Fig. 7—Influence of specimen size on creep³²

takes place, and a greater creep is therefore recorded. The converse is true in a larger specimen, and even if with time the drying effect reaches the core, the concrete there will have changed substantially from the state which existed when load was first applied. A greater degree of hydration will have taken place and a higher strength will have been developed in the core so that the creep response to the creep-while-drying condition will be small. The size effect applies not to true creep or basic creep but to the increase in creep due to drying.

Recent work at the Portland Cement Association Laboratories indicates that both creep and shrinkage are functions of the surface-volume ratio of the member. Thus the size effect is an indirect one, involving the surface of the specimen, and it may be concluded that when a free surface is absent, creep is unaffected by the size of the member. In fact, in concrete cured under mass conditions, size effects do not appear to be present.

CREEP UNDER DIFFERENT STATES OF STRESS

The preceding discussion referred to uniaxial compression but creep also occurs in other loading situations and information about creep behavior under these situations is especially helpful in establishing the nature of creep. Unfortunately, the volume of experimental data is small and in many cases quantitative evaluation and comparison with the behavior in compression is not possible. For this reason no more than broad qualitative statements will be made.

Creep takes place under uniaxial tension; its magnitude is of the same order as creep in compression, and the creep-time curves for the two conditions are similar. Drying enhances creep in tension as well as creep in compression.

Creep occurs under torsional loading, and is affected by stress, water-cement ratio, and ambient relative humidity in qualitatively the same manner as creep in compression. The creep-time curve is also of the same shape.³³

Creep in a direction normal to the applied load can be expressed in terms of a creep Poisson's ratio. There are strong indications that this ratio is zero,³⁴ i.e., that axial creep produces no increase in the lateral

TABLE 3—AVERAGE INCREASE IN CREEP⁸

Creep after 1 year	1.00
Creep after 2 years	1.14
Creep after 5 years	1.20
Creep after 10 years	1.26
Creep after 20 years	1.33
Creep after 30 years	1.36

deformation, but this can be so only for loads which produce a stress-strength ratio not greater than, say, 40 to 50 percent because splitting may take place at higher stresses.²¹

Biaxial and triaxial stresses could thus be expected to lead to creep deformations which are sums of creeps caused by component uniaxial stresses. This appears to be the case but further work in this area is necessary.

END VALUE OF CREEP

The definition of creep refers to the increase in strain with time but says nothing about the presence or absence of a terminal value. All creep-time curves (with the exception of those for extremely high stress-strength ratios which lead to time failure) show a progressive decrease in the rate of creep with time. This is particularly noticeable in the early stages after the application of the load but it is not certain that the decrease continues throughout.

The problem is of fundamental importance for if this be the case creep approaches asymptotically a limiting value. If, on the other hand, the rate becomes stabilized at some value, creep increases indefinitely. There is no doubt, however, that even in the latter case the rate of increase would be so low that with a practical limit of duration of load, say 100 years, the long-term increase in creep would not bring about a large or dangerous defor-

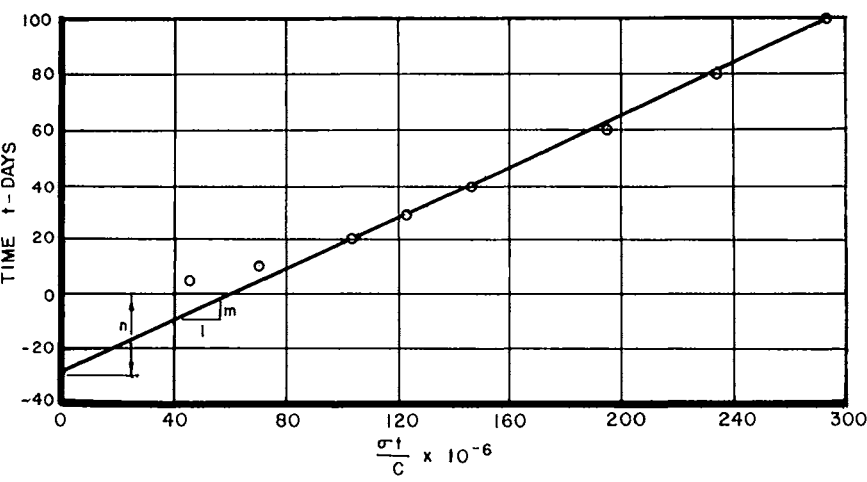


Fig. 8—Creep constants according to Lorman

mation. The practical significance of the problem is thus smaller. Table 3 shows average increase in creep⁸ beyond 1 year's duration of load.

The longest period for which creep data are available is less than 30 years⁸ and here a small but measurable rate of creep was observed. It is not possible to say whether this rate will vanish to zero. Flügge's interpretation³⁵ of various tests is that after about a year under load, creep continues at a constant rate so that no finite limit of creep can exist. These tests include the earlier tests of Davis and those of Glanville²⁹ who postulated a limiting value of creep. It seems that only time will resolve the problem.

CREEP EXPRESSIONS

It is convenient to express the creep-time relation in the form of an equation so that values of creep may be predicted without performing long-time tests. About a dozen equations have been suggested, most of these of a hyperbolic or an exponential type. In some cases creep is expressed by a "standard" curve, which is modified by a number of factors to allow for properties of a particular mix and storage conditions.

Among the equations which make creep tend toward a finite limit are those of Lorman, Ross, and Thomas. Lorman¹⁴ proposed a hyperbolic expression

$$c = \frac{mt}{n+t} \sigma \dots \dots \dots (3)$$

where, t = time since the application of load, σ = applied stress, and m and n are constants in appropriate units.

Eq. (3) can be written in the form

$$t = \frac{m\sigma t}{c} - n \dots \dots \dots (4)$$

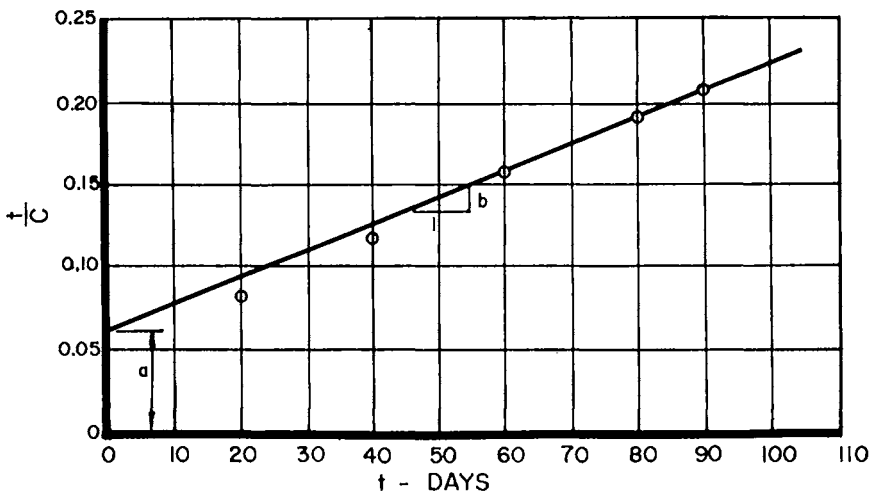


Fig. 9—Creep constants according to Ross

and hence, m and n can be obtained as the slope and intercept respectively of the plot of $\sigma t/c$ against time. This is shown in Fig. 8.

The ultimate creep, c_{∞} , is creep when $t = \infty$. From Eq. (3)

$$c_{\infty} = m \sigma \dots \dots \dots (5)$$

It is interesting to note that when $t = n$, $c = \frac{1}{2} m \sigma$, i.e., one-half of the ultimate creep is realized at time $t = n$.

Ross³⁸ suggested a similar equation about 3 years before Lorman

$$c = \frac{t}{a+bt} \dots \dots \dots (6)$$

where a and b are constants.

A plot of t/c against t is a straight line, and the constants can be easily evaluated (Fig. 9). The ultimate creep is

$$c_{\infty} = \frac{1}{b} \dots \dots \dots (7)$$

and the ease with which this value can be obtained is an advantage of the hyperbolic expressions, Eq. (3) and (6).

It should be noted that in drawing the straight lines in Fig. 8 and 9 a greater weight is given to the points for larger values of t because this gives a better prediction of creep values for long periods under load and of the ultimate creep. This procedure is used throughout this paper.

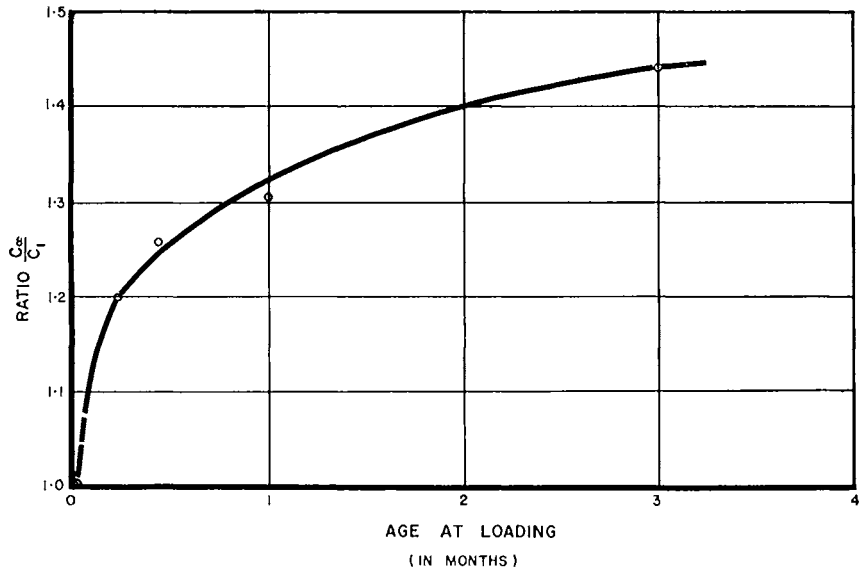


Fig. 10—The influence of the age at loading on the ratio of the ultimate creep, c_{∞} , to creep after 1 year under load, c_1

The values of c_{∞} given by Eq. (6) agree closely with those given by Thomas³⁸ exponential expression

$$c = c_{\infty} \times \sigma \left(1 - e^{-A(t+df-dg)} \right) \dots \dots \dots (8)$$

where, A , d , and g are constants determined experimentally, and c_{∞} represents now the ultimate specific creep.

Thomas found that the ratio of the limiting creep to that occurring during the first year under load varies little and suggested that it does not exceed 4/3 for specimens loaded at the age of 28 days. For specimens loaded at later ages the creep after 1 year will be smaller and thus the ratio is an increasing function of the age at loading, as shown in Fig. 10. The figure is useful but in order to find the value of the limiting creep it is necessary to know the value of creep after the first year under load; such a period may not be convenient in practice. Furthermore, the value of 4/3 may be too low, as a value of 1.36 has been actually obtained (Table 3).

McHenry's³ exponential expression also assumes that creep is proportional to the amount of potential creep remaining. The specific creep is given by

$$c = (\alpha + \beta e^{pT}) (1 - e^{-rt}) \dots \dots \dots (9)$$

where, T = age at the time of application of load ($T > 5$ days), t = time since the application of load, and α , β , p , and r are constants determined experimentally.

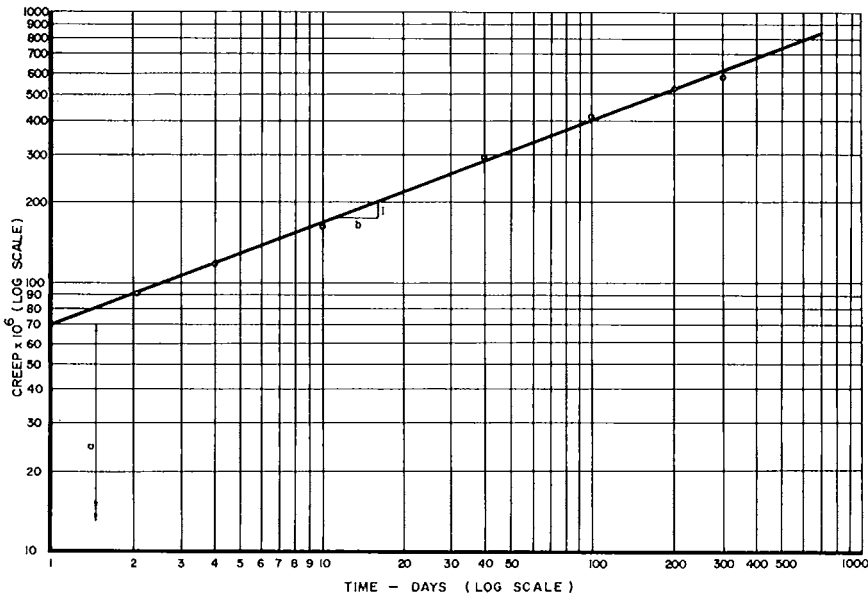


Fig. 11—Creep constants according to Shank

At an early stage, a transient creep may exist but this disappears at a rate proportional to itself. Thus,

$$c = \alpha(1 - e^{-qt}) + \beta e^{-qt} (1 - e^{-qt}) \quad \dots \dots \dots (10)$$

where, q = an experimental constant. If $q = r$, Eq. 10 reduces to Eq. 9.

A simple exponential equation was suggested by Shank,³⁹ the specific creep is given by

$$c = at^{1-b} \quad \dots \dots \dots (11)$$

where, a is a constant, and b is a coefficient depending on the properties of concrete.

The values of a and b can be obtained from a plot of $\log c$ against $\log t$ (Fig. 11) since the latter two plot as a straight line.

Eq. (11) can be used for estimating creep up to about 1 year under load only, as for longer periods under load creep increases at too great a rate. Furthermore, the expression postulates an indefinite increase in creep.

A similar approach is adopted by Saliger⁴⁰ who expresses creep approximately as

$$c = \alpha_t \times \sigma \quad \dots \dots \dots (12)$$

where α_t is a creep coefficient of the form

$$\alpha_t = A \sqrt[3]{T} \quad \dots \dots \dots (13)$$

and is plotted in Fig. 12.

Eq. (12) does not approach a finite limit, but Saliger assumes that maximum creep is reached at the age of 30 months. This would mean that concrete loaded at the age of 30 months will show no creep, which is not

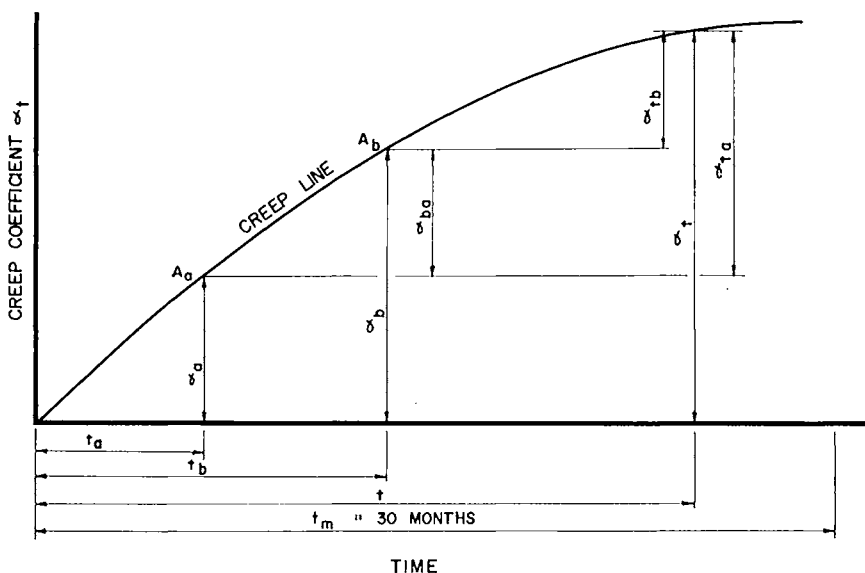


Fig. 12—Saliger's creep coefficient

the case, and for this reason Eq. (12) cannot be used for loading ages greater than a few months.

Saliger assumes that concrete subjected to a sustained load responds elastically to the action of live loads additional to the sustained load, i.e., that live loads produce only elastic deformations corresponding to the instantaneous modulus of elasticity at the time of application of the live load.

The creep coefficient, α_i , has been obtained empirically for a "standard" age at loading. If a sustained stress σ_a is imposed at time t_a greater than the standard age, creep should be calculated as if the curve showing the relation between the creep coefficient and time started from point A_a (Fig. 12). Now, if after time t_b an additional sustained stress σ_b begins to act, the additional creep is calculated as if the creep line started at A_b .

Saliger postulates that strains produced at any given time by a stress applied at the time t_o are independent of any stress applied either earlier or later than t_o . This principle of superposition was first postulated by McHenry,³ who applied it also to creep recovery by considering a relief of

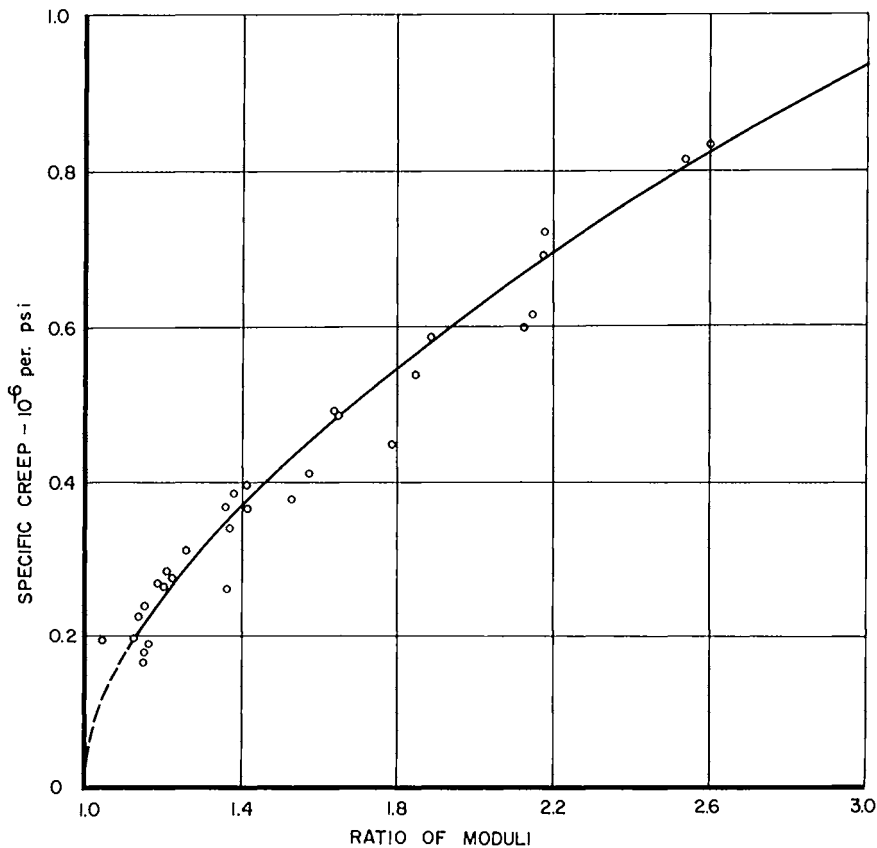


Fig. 13—Relation between specific creep at any time and the ratio of the modulus of elasticity at that time to the modulus at the time of application of load¹¹

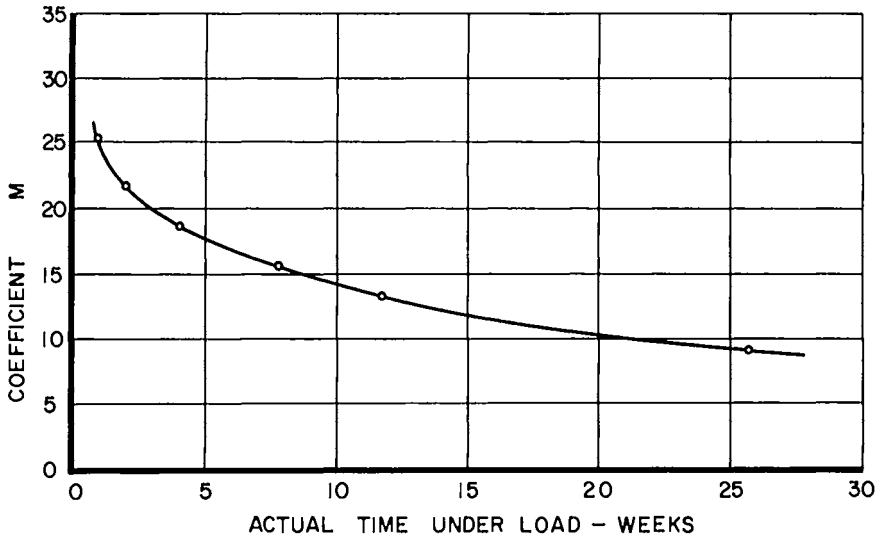


Fig. 14—Accuracy of predicting creep after 1 year under load from short-time tests

stress as a negative stress. In actual fact, the application of the principle of superposition introduces a fixed bias but is nevertheless convenient for most practical purposes.

The U. S. Bureau of Reclamation, which has made an extensive study of creep of concrete dams and of methods of predicting creep, has found that specific creep can be represented by the expression

$$C = F(T) \log (t+1) \quad \dots \dots \dots (14)$$

where T is the age at which the load is applied, $F(T)$ is a function representing the rate of creep with time, and t is reckoned in days.

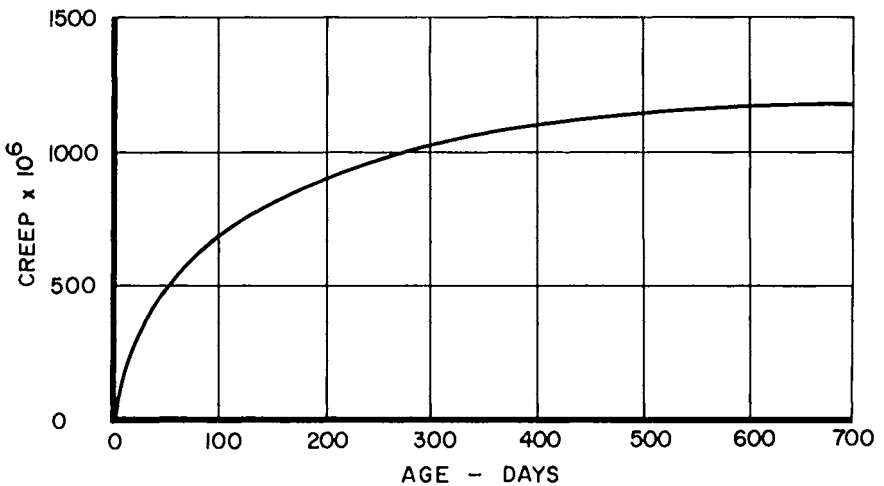


Fig. 15—“Standard” creep curve⁴²

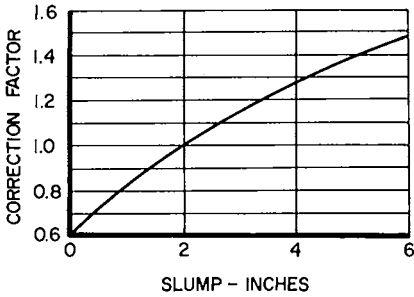


Fig. 16—Correction factor for slump

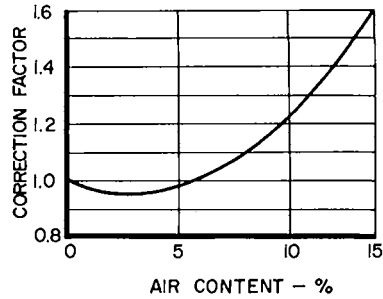


Fig. 17—Correction factor for air content

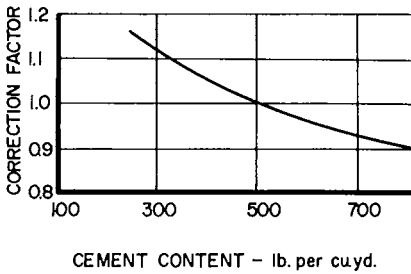


Fig. 18—Correction factor for cement content

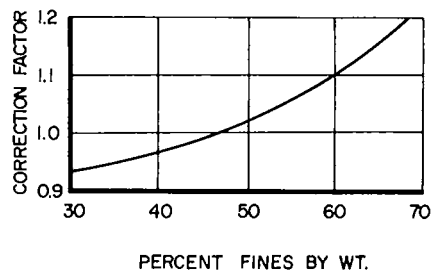


Fig. 19—Correction factor for percent fines

Creep plots thus as a linear function of the logarithm of the time under load (or, strictly speaking, $t + 1$), but values for short periods under load depart from the straight line (see discussion of Fig. 8 and 9).

In the Bureau studies,⁴¹ it was also shown that creep can be estimated from the change in the elastic properties of concrete. Fig. 13 shows the specific creep at any time plotted against the ratio of the modulus of elasticity at that time to the modulus at the time of application of the load; the data cover a wide range of ages at which the load was applied. Such a relation indicates that for a given mix, the modulus of elasticity of concrete (as a function of time) is a useful parameter in estimating creep. While the modulus is easier to determine than creep, the necessary information can be obtained only after a long period.

GENERAL PREDICTION DATA

In all the equations mentioned in the preceding section the constants have to be determined empirically, i.e., limited time creep tests must be made using the actual mix and storage conditions. The longer the time over which creep is actually measured the better the prediction. This can be seen from Fig. 14, which shows the error coefficient, M , after periods under load of 1 to 26 weeks for tests made at the University of Missouri. The coefficient is defined as

$$M = \frac{\sqrt{(c_t - c_1)^2/n}}{c_1} \dots \dots \dots (15)$$

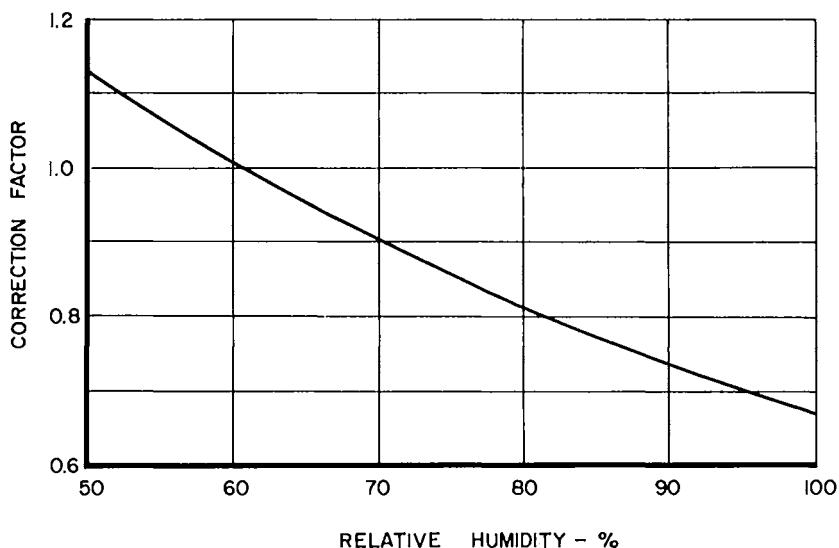


Fig. 20—Correction factor for relative humidity of storage

where c_t = creep after 1 year predicted from measured creep after time t weeks under load ($1 \leq t \leq 26$); c_1 = actual creep after 1 year under load; n = number of specimens for which creep was observed at time t . M is thus analogous to the coefficient of variation but deviation is measured from the "true" creep after 1 year. The difficulty of early prediction is apparent but if a coefficient M of about 15 percent is acceptable, creep tests need be run for about 60 days only.

There is a considerable amount of creep data available in technical literature and from this it might be possible to calculate coefficients and parameters for predicting creep of any concrete under any conditions. Two attempts have, in fact, been made.

Jones, Hirsch, and Stephenson¹² use a "standard" creep curve shown in Fig. 15. This is for a concrete containing 540 lb of cement per cu yd, with

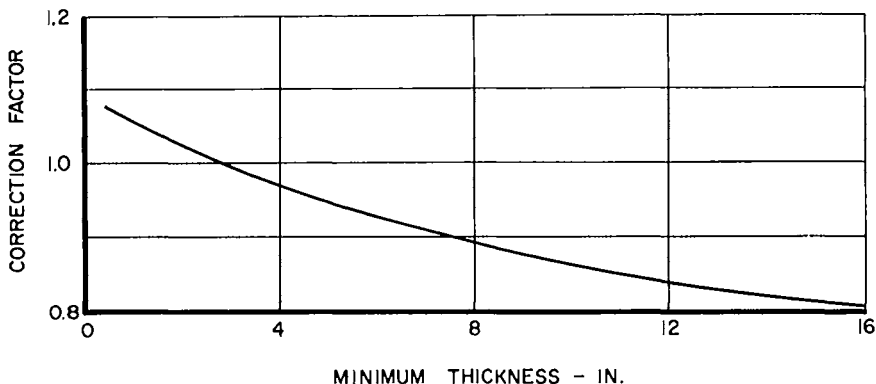
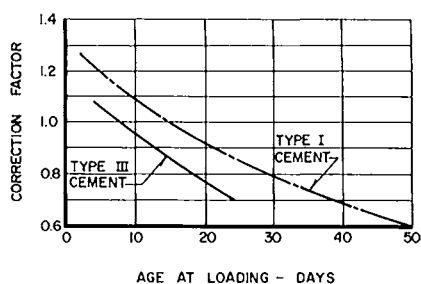


Fig. 21—Correction factor for minimum thickness of concrete

Fig. 22—Correction factor for age at loading



6 percent entrained air, and a 2-in. slump, subjected to a stress of 1420 psi at a relative humidity of 60 percent. The "standard" values of creep are then modified for the particular slump, air content, cement type and content, percent fines, relative humidity of storage, thickness of the member, and age at loading, using the correction factors shown in Fig. 16 to 22. This method was developed for lightweight concrete but appears to be valid for normal weight concrete as well. We may note that some of the factors listed (e.g., slump or fines content) are not basic factors in creep but are convenient for practical application.

A similar approach is used by Wagner.¹⁶ "Standard" values of ultimate specific creep are shown in Fig. 23; these values are then modified by coefficients given in Fig. 24 to 27. A comparison of the predicted ultimate creep using Wagner's method with 4/3 of the measured 1-year creep is shown in Table 4. In most cases the agreement is poor and it is possible that this is at least in part due to the properties of aggregate which are not considered in Wagner's curves.

Fig. 28 and 29 show creep curves derived from experimental data (for the conditions indicated) using some of the creep expressions of the preceding section. In calculating the constants creep values recorded during

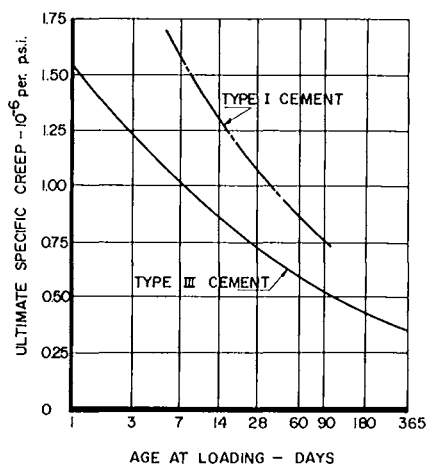
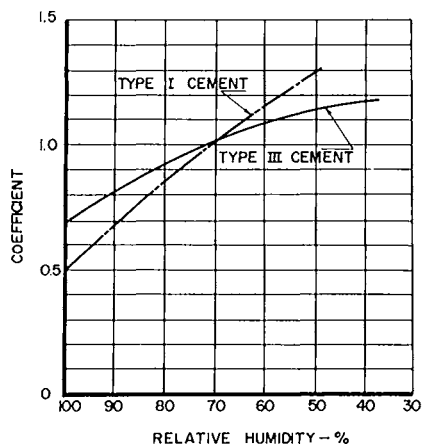
Fig. 23—"Standard" values of ultimate specific creep¹⁶

Fig. 24—Coefficient for relative humidity

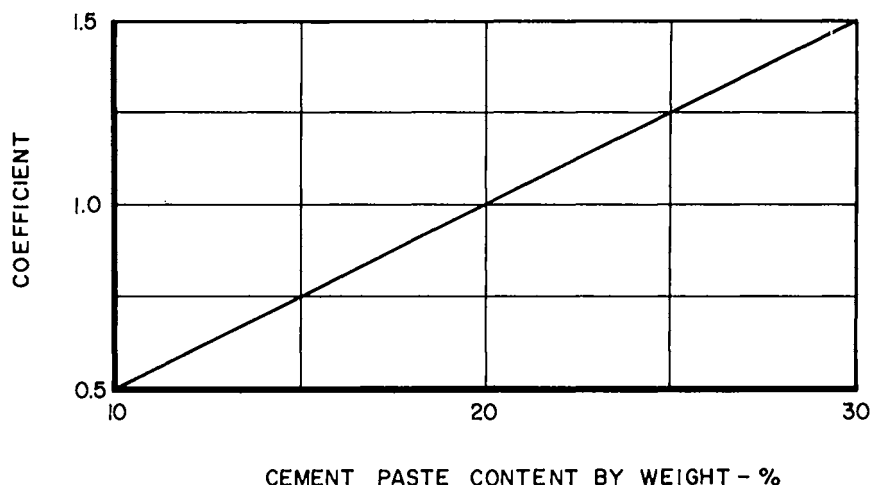


Fig. 25—Coefficient for cement content

the first 100 days under load were used. Observed creep values up to nearly 400 days under load are also plotted. The agreement between the observed and predicted values is fairly good but it must be remembered that prediction was based on measured creep up to 100 days under load, at which stage creep is equal to at least one-half of the total measured creep. All the equations were then tested using creep values recorded for periods of less than 100 days under load. For the most part the results were considered unsatisfactory (i.e., the coefficient M was more than 15 percent).

Summarizing, it seems that if it is possible to make at least a 60-day creep test, the equations of Lorman and Ross give satisfactory results. They are extremely easy to apply and have the advantage of quickly predicting the ultimate creep. If no tests can be made, the methods developed by Jones and by Wagner have to be used. These yield results which may not be sufficiently accurate when a structure is very sensitive to creep, but in the case of reinforced concrete members the predicted values are suffi-

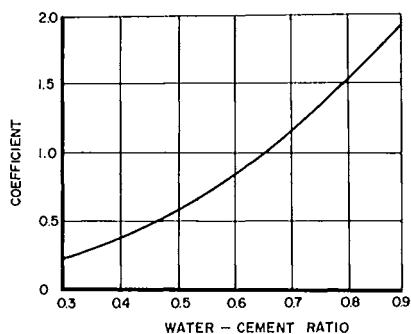


Fig. 26—Coefficient for water-cement ratio

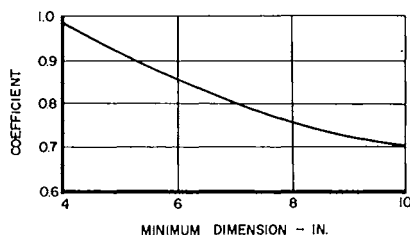


Fig. 27—Coefficient for specimen size

TABLE 4—COMPARISON OF PREDICTED AND OBSERVED CREEP

Age at loading, days	Predicted ultimate specific creep, 10^{-6} per psi (Fig. 23)	Sustained stress, psi	Predicted "standard" ultimate creep, 10^{-6}	Coefficient for relative humidity (Fig. 24)	W/C ratio	Coefficient for W/C (Fig. 25)	Cement paste content by weight	Coefficient for cement content (Fig. 26)	Predicted ultimate creep (Wagner)	Observed creep after 1 year	4/3 observed creep
31	1.05	1200	1260	1.29	0.624	0.85	0.206	1.00	1380	611	814
31	1.05	1200	1260	1.29	0.624	0.85	0.206	1.00	1380	626	835
31	1.05	1200	1260	1.29	0.624	0.85	0.206	1.00	1380	604	806
7	1.60	1200	1920	1.29	0.624	0.85	0.206	1.00	2110	1087	1450
3	2.00	1200	2400	1.29	0.624	0.85	0.206	1.00	2640	1150	1535
3	2.00	1200	2400	1.29	0.624	0.85	0.206	1.00	2640	1161	1550
2	2.30	1200	2700	1.29	0.624	0.85	0.206	1.00	3030	1080	1440

INFLUENCING FACTORS AND PREDICTION

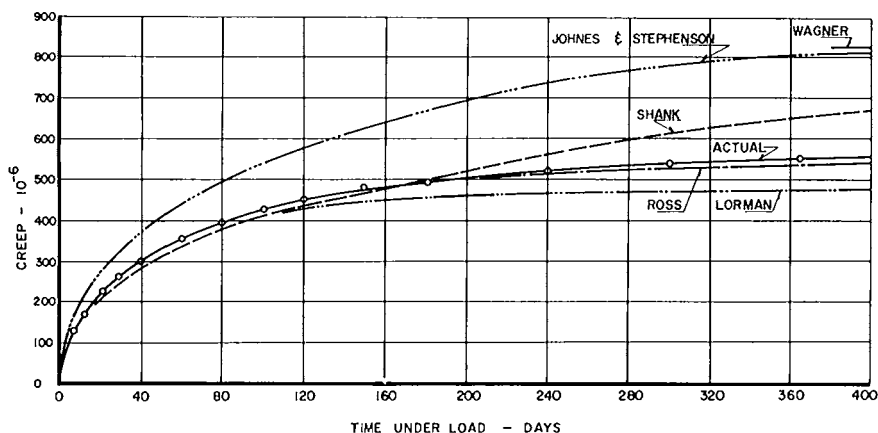


Fig. 28—Comparison of prediction methods for a 1:6.3 mix, $w/c = 0.625$, slump = 2 in., $f'_c = 5230$ psi, stress-strength ratio = 0.23, stored at 72 F, and a relative humidity of approximately 50 percent

cient for design purposes: the deflection of these members is not as sensitive to creep as has been thought in the past. This is clearly demonstrated by Pauw and Meyers in Paper No. 6 of this symposium.

CONCLUDING REMARKS

The paper has considered only the experimental-empirical approach to the prediction of creep. It must be mentioned, however, that rheological models can also describe the deformational response of concrete. They can use constants derived experimentally or from sonic properties of concrete. Kesler's³⁶ pioneer work on relating the natural frequency and logarithmic decrement to creep promises considerable success. Rheological models can be designed so that a full range of loading conditions can be studied on an analog computer. It would seem that the next logical step would be to develop models to simulate the actual behavior of a flexural member subjected to creep, and to investigate the stress redistribution under conditions of a non-linear stress-creep relation.

Note

ACI Committee 209 is currently preparing a bibliography on creep. The bibliography, which is annotated, starts with the earliest known papers on creep: I. H. Woolson's observations on "flow of concrete under pressure" in 1905 and W. K. Hatt's 1907 report on the increase in the deflection of reinforced concrete beams, and continues with more than 500 entries up to the present time. The bibliography will thus complement the symposium papers collected in the present volume. An earlier bibliography was prepared by Meyers.²

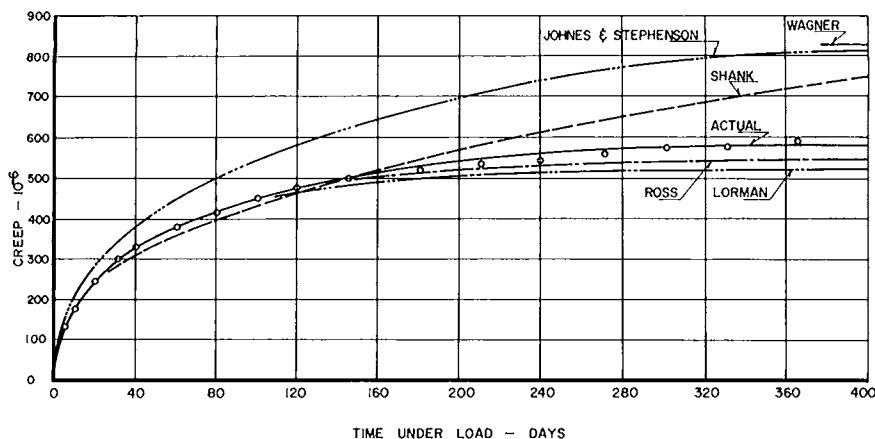


Fig. 29—Comparison of prediction methods for the same concrete as that of Fig. 28 but for different specimens

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DISCUSSION

By **C. H. Scholer***

In most studies of creep of concrete, it is assumed that concrete is a material composed of various constituents and that, under load, these constituents are forced to carry rather uniformly distributed stresses which in turn produce rather uniform deformations.

When a load is maintained uniformly for a prolonged period, it is found

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that the deformation usually increases with time, and this time-dependent deformation is considered to be creep. Shrinkage also will develop during this period and is recognized to be at least partly independent of creep.

As a matter of fact, concrete is not a material but a system of materials held together by a cement paste which bonds these particles together and causes the particular mass of concrete, called a specimen, to appear to deform much as though it were a uniform isotropic material having certain specific properties of elasticity, strength, creep, and shrinkage.

There is undoubtedly a wide variation in the way in which the discrete pieces of aggregate are loaded and in the amount and direction of yielding under these forces with time. The forces applied to the specimen are applied to the paste which has bonded to the surface of aggregate by contact. These surface forces will tend to deform these pieces of aggregate, to hold them together, and cause them to act much as though the whole mass was a homogenous, isotropic whole having certain elastic and strength characteristics.

The ability of the paste to cause the particles of matter to so perform will depend upon the strength of the paste (the water-cement ratio) and the relation between the surface which is grasped by the paste, and the volume and elastic properties of the particle. All forces must be transferred from the paste to the aggregate, and the relation between the surface area of the aggregate particle and the volume of the particle will be of great significance. The ratio of the surface area of a regular polyhedron to its volume is $6/D$, where D is the diameter of the inscribed sphere. This general relationship to the size of aggregate no doubt explains the significance of size of aggregate in relation to strength of concrete.

The elastic properties of the material in these discrete particles is one of the principal factors influencing the apparent elastic properties of the concrete. The apparent modulus of elasticity of concrete may vary from 50 to 100 percent, depending upon the aggregate and amount of aggregate in the concrete.

In a combination of paste and aggregate in a concrete specimen, the actual forces acting in the paste and mortar surrounding a large piece of aggregate are not by any means uniform. Creep which we measure in our specimen must be the result of a widely varying distribution of forces and deformations in the pieces of aggregate and layers of paste transmitting the different forces which are the result of the loading process. The natural creep under these varying stresses is an effort to redistribute the loads and deformations without causing failures. Looking at creep in this way, it is seen to be a beneficial and valuable property of concrete.

Many writers on the subject of creep have observed that the loads cause a loss of water to develop, and some have maintained that this loss is one of the major causes of creep. Usually, it is observed that this is again not strictly true, and water loss cannot be used as a definite criteria for such a purpose.

If we stop to consider that the forces acting upon the paste and mortar most certainly cannot be uniform in character at every section in a specimen, it is obvious that creep and the accompanying loss in water in the paste will not be uniform. Some of the water is merely redistributed and is not lost.

A careful elastic analysis of stress distribution in a simple specimen like a cylinder or a cube will show a wide variation in actual stress distribution.

In so far as the writer is aware, no studies have been made upon the effect of variations in the strength of concrete in which coarse aggregate is used having various known values in different specimens, and the resultant changes in creep.

Whether the forces to which concrete is subjected are caused by loads or temperature variations, and other natural external causes, it would not seem unreasonable to believe that, as these forces develop, the constituents of concrete will again attempt to creep in such a way as to prevent failure, if possible.

A study of natural rock formation, in various exposures, shows how extensive the creep has been to permit deformations to develop to prevent rupture and failure.

After all, failure in most materials is due to the deformations produced by the forces which a member is called upon to carry. If these forces develop slowly, the members of the structure try to yield without failure. Most certainly, these tendencies are present in concrete.

Can these known characteristics be utilized to design better concrete specimens which can, to a limited extent, adjust to the condition to which they are subjected?

A hypothesis for creep is presented in terms of the microstructure and properties of hydrated cement. An experimental investigation, designed to provide a quantitative basis for the hypothesis, is briefly described. Procedures are presented for estimating creep in terms of the volumetric composition of the concrete, the degree of hydration, and the observed free shrinkage characteristics.

Mechanisms of Creep in Concrete

By Iqbal Ali and Clyde E. Kesler

■ A VARIETY OF MECHANISMS, based more or less on knowledge of the macro and microstructure of concrete, has been proposed from time to time as being responsible for the phenomenon of creep in concrete. The observed creep behavior of concrete does exhibit characteristics which indicate the possible presence, to a greater or lesser degree, of most of these mechanisms. A satisfactory theory of creep cannot, however, be built by merely adding a suitable contribution from each such mechanism, as certain aspects of creep behavior just cannot be explained by any of these and some of these mechanisms preclude the possibility of certain other aspects of observed behavior.

A major aspect of creep behavior which has persistently defied explanation is the marked increase in creep under any type of load, when moisture is either lost or gained, with little or no reciprocal influence of the increased deformation on the moisture exchange. Associated with this seemingly paradoxical behavior are certain subsidiary effects which include the effect of specimen size on creep, the apparently higher creep under flexure than under axial load, and the effect on creep of the type of aggregate.

This paper represents an attempt to formulate a unified hypothesis of creep, by reinterpreting existing concepts and supplementing them where necessary, which would be capable of explaining satisfactorily the major aspects of creep behavior, specially the influence of moisture change

on creep. An experimental investigation formed a part of the study, and was designed to verify the theoretical development and to provide a quantitative basis for the proposed hypothesis.

EXISTING THEORIES OF CREEP

In the strict sense of the word there is no existing theory of creep in concrete. A number of hypotheses, based on certain possible mechanisms of deformation, are nevertheless available. None of them, however, seem capable of explaining all the major aspects of creep behavior. Some of them even involve implications contrary to observations. The various mechanisms which form, singly or in groups, the bases for existing hypotheses of creep, may be placed under six broad categories. Their plausibility, relative importance, and shortcomings, if any, are briefly discussed.

Plastic deformations

Plastic deformations include intracrystalline slips and local rupture of the hardened cement paste, and possibly the aggregate. Such deformations would, presumably, be irrecoverable, nonlinear with the applied stress and occur only after a limiting stress is exceeded. Creep of concrete does have an irrecoverable part, but there is no apparent threshold of stress below which there is no creep.¹ Again, strain at any instant is practically in linear proportion to the sustained stress up to stress levels as high as 50 percent of the ultimate. The great sensitivity of creep to moisture and moisture movement cannot be explained in terms of the plastic deformation mechanisms. Such deformations might contribute significantly only at stress levels near the ultimate.

Viscous flow

Many investigators notably Thomas,² Glanville,³ Reiner,⁴ and Freudenthal,⁵ have considered hardened cement paste as a viscous fluid, sur-

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rounding the loose and relatively rigid aggregate particles. The concept offers plausible explanations for the linearity of creep strain with stress, the absence of a limiting stress for creep to occur, stress relaxation at a constant deformation, and the sensitivity of creep to temperature. It cannot, however, explain either wholly or partially certain observed characteristics of creep. These include creep recovery on removal of the applied stress, change of volume during creep, the progressive reduction of the creep rate with time and the marked sensitivity of creep to moisture exchange.

Seepage of gel water

Hardened cement paste has been considered as a limited swelling gel, whose equilibrium with its solid skeleton and external load is determined by the vapor pressure of the gel water.⁶ The seepage theory⁷⁻¹¹ envisages a disturbance of such equilibrium under applied load and its gradual re-establishment by exchange of moisture with the environment. The volume change accompanying the resulting moisture movement is identified with creep. Of the many suggested creep mechanisms, this appears to be the most promising. Although at first sight it seems capable of explaining many aspects of creep, including the marked increase in creep under compression with simultaneous drying, a closer look discloses certain serious difficulties. If creep were indeed the direct result of the change in the gel moisture content, one would expect a specimen under sustained compression to suffer an additional gel moisture loss over an unloaded control specimen, roughly in proportion to the corresponding creep and shrinkage deformations. On the contrary, several carefully conducted tests¹²⁻¹⁴ indicate little or no effect of applied load on the moisture lost by a drying specimen. Moreover exchange of moisture results in increased creep irrespective of the direction of such exchange of the applied stress.¹⁵ These observations greatly weaken the conventional seepage hypothesis. Again, significant creep is observed even in the absence of moisture exchange.

Delayed elasticity

The morphology of hydrated cement indicates the presence of both crystalline and noncrystalline components of colloidal size with associated absorbed moisture. Under load, the gel could presumably behave as a composite body consisting of more or less elastic and viscous phases which could interact, resulting in delayed elastic behavior. Creep of concrete does exhibit such behavior, but to a rather limited extent. This mechanism cannot offer a convincing explanation of the observed influence of moisture exchange on creep.

Another delayed elastic mechanism has been proposed by Freyssinet¹⁶ to explain creep deformation in terms of the changes in the surface tension forces arising in the capillary pores of hardened cement paste. The

application of the conventional relationships between meniscular curvature and capillary tension, to pores of this size, has been questioned.^{17,6} In addition, creep deformation of concrete with practically empty capillaries is not significantly lower than that for saturated concrete.

Nonuniform shrinkage

The presence of differential shrinkage stresses due to nonuniform drying, has occasionally been considered partly¹⁸ or wholly¹² responsible for the phenomenon of creep in concrete. The validity of the assumptions involved in the concept that creep is entirely the result of restrained shrinkage has been seriously challenged. Only a small part of the increase in creep with simultaneous drying, specially at high stresses, may be explained on this basis.¹⁵

Intercrystalline deformations

Imperfectly formed crystal lattices are known to suffer viscous deformation under sustained stress.¹⁹ Such disordered zones are likely to exist not only where the crystalline components of cement gel grow into each other, but also at the gel-aggregate interface.¹⁵ Although such deformations would be expected to progress very slowly, the almost constant rate of flow could result in sizeable deformations after a sufficiently long time.

PROPOSED HYPOTHESIS

It may be observed that although some of the mechanisms discussed above do offer plausible explanations for certain aspects of observed creep behavior, none of them appear capable of providing a convincing explanation for the great sensitivity of creep to moisture exchange. The seepage mechanism does show considerable promise in this direction. In its conventional form however, as shown earlier, it appears to have several serious shortcomings. The suggested hypothesis is the result of a re-examination and reinterpretation of this mechanism and its integration with the viscoelastic behavior of the cement gel. Creep deformation is explained partly in terms of the modification, by the applied stress, of the shrinkage or swelling resulting from changes in moisture content, and partly in terms of the viscoelastic deformation of the structural elements of the gel. In the form presented, the hypothesis is applicable to creep of concrete under moderate stress levels. It may, however, be readily supplemented with other mechanisms to take into account plastic deformations under high stresses and other special effects.

Structure of cement gel

The characteristics of hydrated cement have been studied both by means of water-fixation and adsorption techniques⁶ as well as by crystallographic

and electron microscope observations.^{20,21} The microstructure that emerges is that of a colloidal mass or gel, with a partly crystalline and partly amorphous structure. It has a characteristic porosity of about 28 percent and an enormous specific surface estimated at over 200 sq m per g. The equivalent pore width is of the order of 15 to 20 Å or about five times the effective size of a water molecule. Much larger continuous and discontinuous voids or capillary pores are also present which vary with the water-cement ratio and degree of hydration. Large noncolloidal crystalline inclusions are also interspersed through the gel.

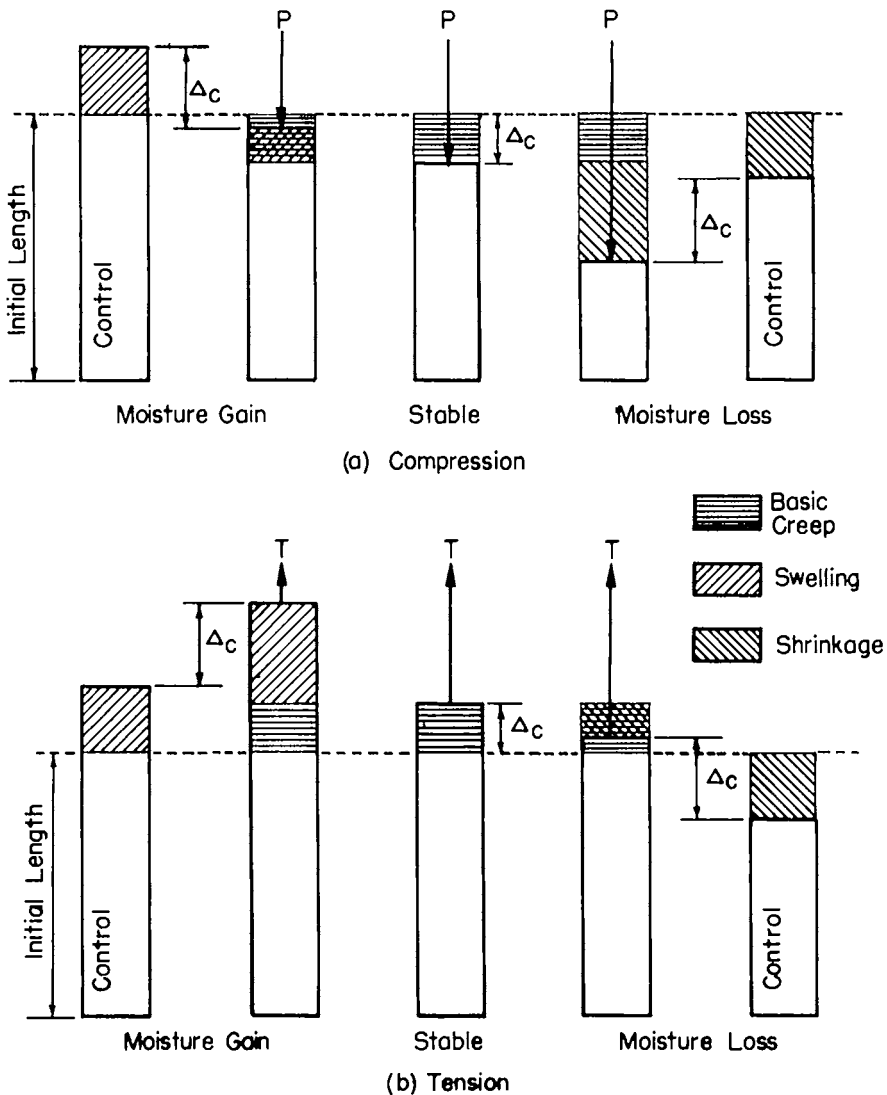


Fig. 1—Schematic representation of creep with and without moisture exchange

Adsorbed moisture and volume change

It has been estimated⁶ that the moisture content of saturated gel is equivalent to a layer of water two molecules thick over the entire gel surface. A monomolecular layer would correspond roughly to about 16 percent of the over-all gel volume. The actual volume change suffered by fully hydrated neat cement paste, which is practically all gel, does not however exceed about 2 percent even after complete desiccation, which is smaller than the volume of moisture withdrawn. Only a small fraction of the possible shrinkage is thus realized when such volume change occurs in the absence of externally applied load. The simultaneous application of load may however modify the volume change associated with the withdrawal of a given quantity of gel moisture. The action may be envisaged as that involved in a servo-mechanism, where the relatively small applied stress controls or orients the much larger surface forces, which in turn are responsible for volume change. Depending on the relative directions of the applied stress and moisture exchange, the volume change attained may be greater or smaller than that possible in the absence of such stress.

Applied stress and moisture equilibrium

A problem closely related to the one discussed above is the influence of applied stress on the hygrometric equilibrium of the gel moisture. It has been estimated that, under constant volume conditions, an increase of only 5 percent in the vapor pressure of the gel moisture would result in a swelling pressure of over 1000 psi.⁶ No quantitative solution is available for the reciprocal problem, i.e., the change in vapor pressure caused by a given applied stress. In view of the partial condensation of the gel structure in the wake of withdrawing moisture, as discussed earlier, it may nevertheless be anticipated that much larger applied stresses, than those indicated by the estimates of swelling pressures due to a given increment of vapor pressure, would be required to change the vapor pressure by a given extent. Applied stresses of usual magnitudes may thus be expected to disturb the internal hygrometric equilibrium to a relatively insignificant extent.

Effect of moisture exchange on creep

The part of the proposed hypothesis dealing with the influence of moisture exchange on creep, is based on the above discussed volume change behavior due to variation of the adsorbed moisture in the presence of applied load. For the purpose of this discussion, the terms shrinkage and swelling will be employed to denote volume changes due to egress and ingress respectively of the adsorbed moisture with or without applied load. Such volume changes in the absence of applied load will be termed free shrinkage and free swelling.

With the above definitions in mind, the anticipated behavior under

TABLE 1—SIGNIFICANT FACTORS AFFECTING CREEP OF CONCRETE UNDER MODERATE STRESS

Significant factors affecting creep	Influence on basic creep		Influence on drying creep
	Delayed elastic action, partly recoverable on removal of stress	Viscous flow, irrecoverable on removal of stress	Stress-modified shrinkage, partly recoverable on restoration of moisture
Mix proportions	Primary	Primary	Primary
Degree of hydration	Primary	Primary	Primary
Moisture content	Secondary		Secondary
Moisture exchange			Primary
Temperature	Primary	Primary	Secondary
Aggregate properties			
1. rheology	Secondary	Secondary	Secondary
2. permeability			Primary
3. surface texture			Secondary
4. shrinkage, swelling			Secondary
Stress magnitude	Primary	Primary	Primary
Stress distribution			Primary
Specimen size			Primary

various conditions of moisture exchange and applied load may be expressed as follows:

1. Free shrinkage is less than shrinkage under compression and more than shrinkage under tension.
2. Free swelling is more than swelling under compression and less than swelling under tension.

Conventionally, creep is defined as the difference between the time-dependent deformations of the loaded specimen and an unloaded control. In accordance with this definition and the influence of applied load on shrinkage and swelling, creep would be expected to increase with moisture exchange, irrespective of the mutual directions of the load and the moisture movement. The behavior is depicted schematically in Fig. 1. Again, as discussed earlier, such increase in creep would entail no significant change in the moisture movement in relation to the unloaded control specimen.

Creep without moisture exchange

Although relatively large creep deformations take place under conditions of concurrent moisture loss, significant creep does occur in the absence of any moisture exchange. Obviously such creep would be the result

TABLE 2—PARTICULARS OF CONCRETE AND MORTAR USED

Mix	Proportion by weight					28-day compressive strength, psi	Volumetric parameters at 95 percent hydration	
	Cement	Fine sand	Coarse sand	Gravel	Water		β	γ
A	1.00	0.50	3.00	. . .	0.55	5050	0.579	3.45
B	1.00	0.78	4.22	. . .	0.75	3200	0.657	4.63
C	1.00	. . .	2.77	3.13	0.53	5100	0.375	4.69
D	1.00	. . .	4.26	5.00	0.83	3250	0.462	6.99

of mechanisms other than the stress-modification of shrinkage or swelling, which would presumably operate irrespective of moisture exchange. Among the various mechanisms of creep, delayed elastic action and intercrystalline deformations, which may be described by the general term viscoelasticity, seem to best account for creep in the absence of moisture exchange. As mentioned earlier, the interaction of the crystalline and amorphous phases of the cement gel and the adsorbed moisture could interact to exhibit a partly recoverable and partly nonrecoverable response under sustained load. The adsorbed moisture may be visualized as deforming in shear and hence without volume change. The porous structure of the gel would insure the presence of microshearing action irrespective of the type of external load. This porosity would also make it possible for the gel to suffer over-all volume change under such shearing deformation of its structural components.

Creep components and factors affecting them

Almost all the observed characteristics of creep in concrete, under moderate stress levels, may be explained in terms of the stress-modification of shrinkage or swelling due to variation of gel moisture, and the viscoelastic deformation of the gel and its associated moisture. Broadly speaking, creep of concrete may be considered as composed of two practically independent components, caused by distinctly different groups of mechanisms:

1. Basic creep, or that part of creep that can occur independently of the moisture exchange, is a manifestation of the viscoelastic behavior of the gel. Presumably, it would depend only on the volumetric composition of the concrete, its degree of hydration and the ambient temperature, except perhaps for low moisture contents, at which it might vary with the actual relative humidity in the interior.

2. Drying or wetting creep is defined as the additional creep over the basic, which occurs as a result of simultaneous moisture exchange with the environment. It is the result of the modification of shrinkage or swelling by the applied stress. It would therefore be sensitive to all the

organismic and environmental factors which affect free shrinkage or free swelling.

Fig. 1 schematically depicts the concept and Table 1 lists the characteristics of the various components of creep and the factors which would influence them.

EXPERIMENTAL INVESTIGATION

An experimental investigation was carried out to verify and to provide a quantitative basis for the proposed hypothesis. Creep tests were conducted under sustained compression, flexure, and torsion. Test conditions included creep with and without moisture exchange with the environment. All specimens were cured to a high degree of hydration before being loaded, to facilitate interpretation of the test data.

Scope of the tests

Mix proportions.—Two each of mortar and concrete mixes, with nominal 28-day strengths of 3000 and 6000 psi, made from Type I portland cement, river gravel, and river sand, were used. The mixes were arbitrarily designated as A, B, C, and D. Table 2 gives details of the mix

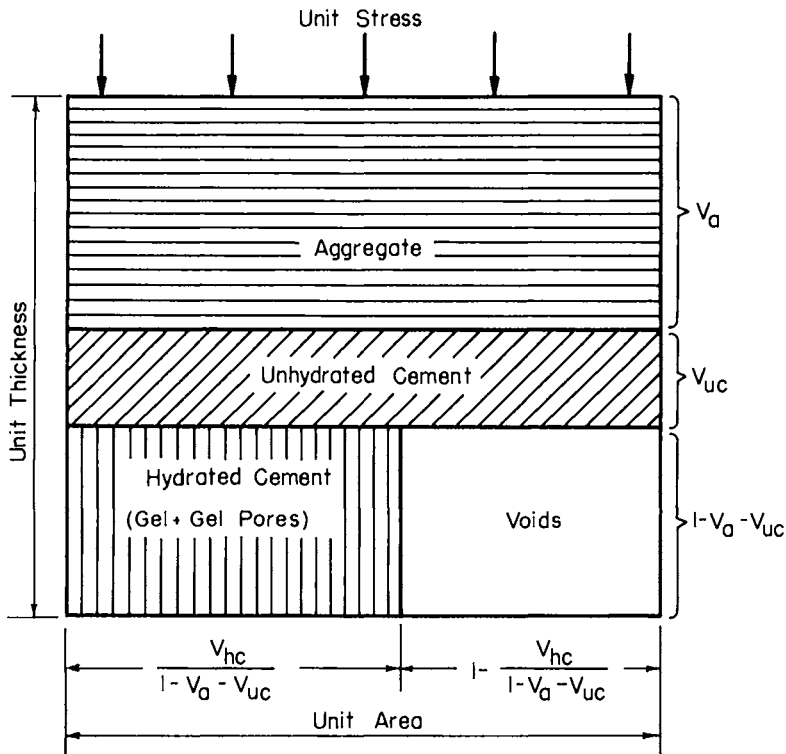


Fig. 2—Concrete as a composite material

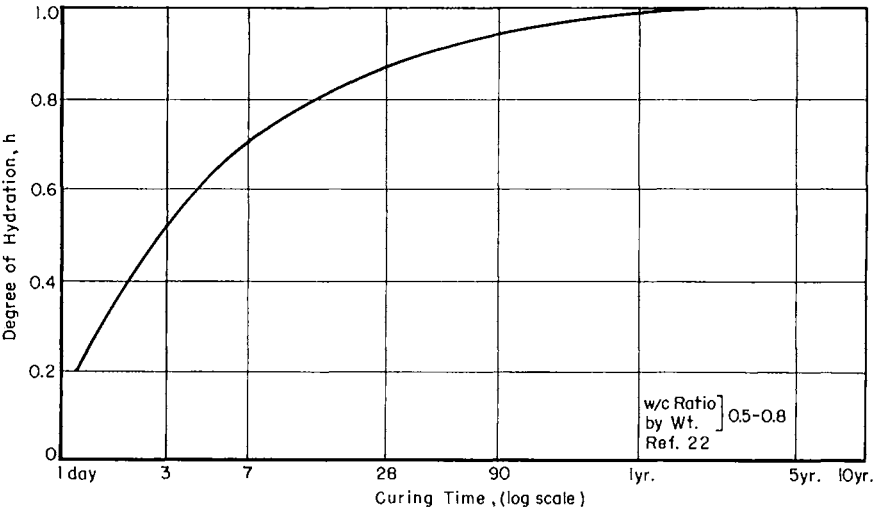


Fig. 3—Variation of the degree of hydration with curing time

proportions. Both concrete and mortar were used for compression tests, while flexure and torsion tests were carried out on mortar specimens only.

Environmental conditions.—Basic creep tests were carried out with the specimens stabilized at relative humidities of 50 and 100 percent. Creep tests involving simultaneous moisture loss, were carried with initially saturated specimens drying out in an atmosphere maintained at 50 percent relative humidity. A temperature of about 70 F was maintained throughout all tests.

Compression tests.—Solid 6-in. diameter cylinders or 6-in. outside di-

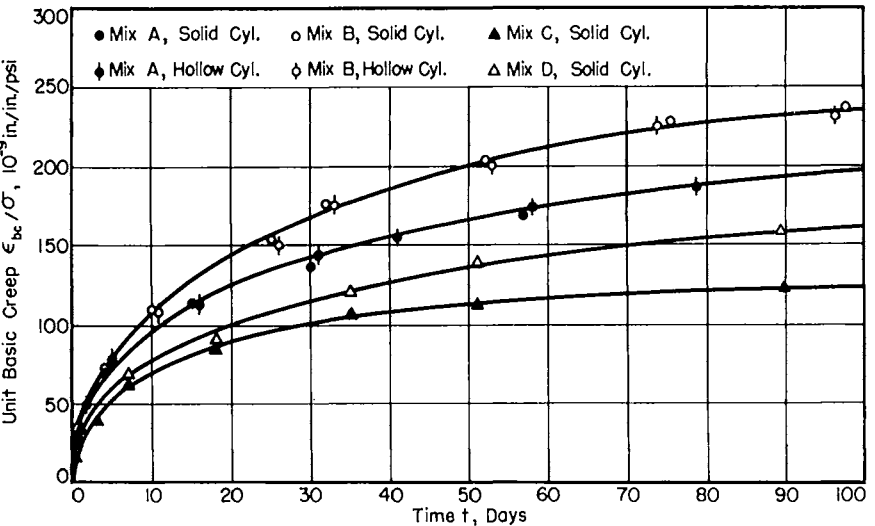


Fig. 4—Unit basic creep under compression at 100 percent relative humidity

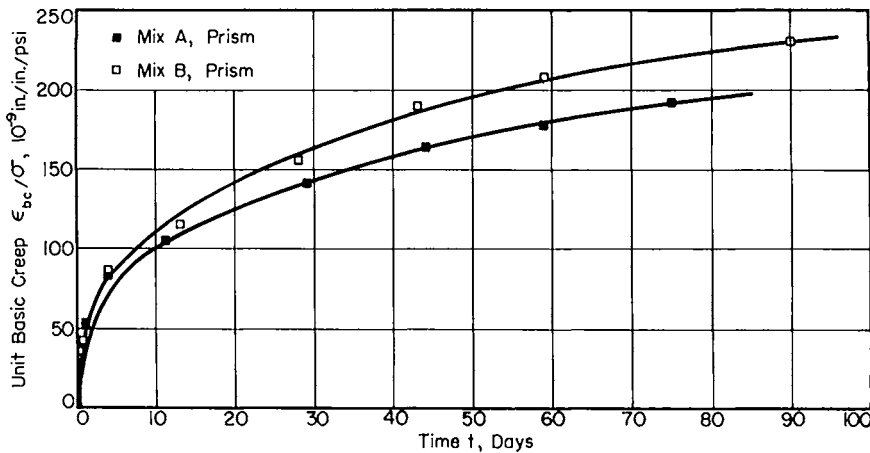


Fig. 5—Unit basic creep under flexure at 100 percent relative humidity

ameter, 4-in. inside diameter hollow cylinders 6 in. or 12 in. long were used for creep tests under compression. Hollow mortar specimens were used for basic creep tests at 50 percent relative humidity, solid concrete and both solid and hollow mortar specimens for basic creep tests at 100 percent relative humidity, while tests with concurrent drying were carried out on solid concrete and mortar specimens. Both hydraulic and spring

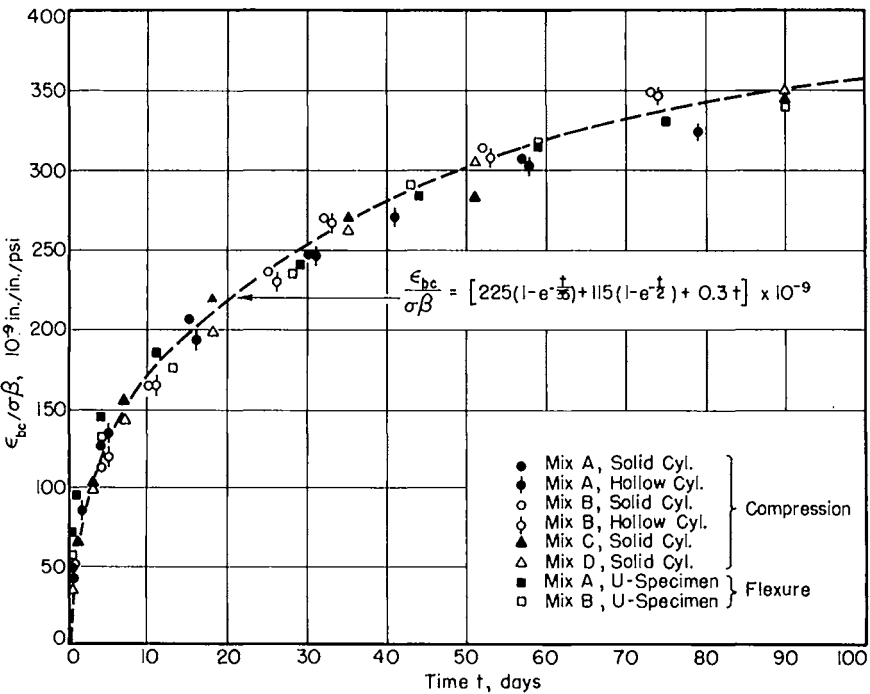


Fig. 6—Normalized unit basic creep at 100 percent relative humidity

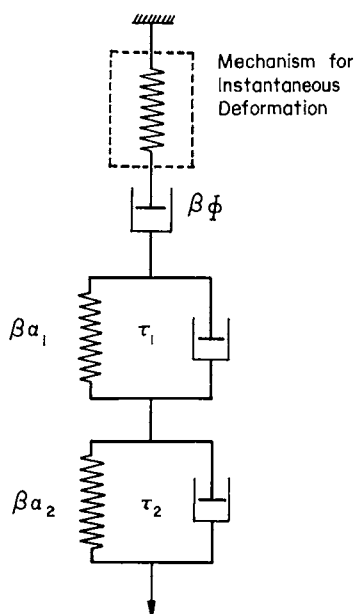


Fig. 7—Proposed rheological model for basic creep of concrete

loaded racks were used. A Whittemore gage or dial gage extensometers were used for measurement of creep and free shrinkage strains.

Flexure tests.—U-shaped mortar specimens with 1 x 1 x 10-in. arms were used for flexure tests. Only basic creep tests at 50 and 100 percent relative humidity were carried out. Dead weights were used for loading and deflections were observed directly with a measuring microscope.

Torsion tests.—Only a few pilot tests were conducted in torsion. The specimens used were 1 x 1 x 11 and $\frac{3}{4}$ in. mortar prisms. Basic creep at 50 and 100 percent relative humidity and creep while drying were studied. Dead weights were used for loading. A telescope and mirror arrangement was used for measuring deformations.

Stress levels.—In order to ensure linear relationship between sustained stress and isochronous creep strain, stress levels were not permitted to exceed about 40 percent of the ultimate strength.

Duration of tests.—The data presented correspond to maximum creep time of about 100 days.

Tests results and analysis.—For concrete made with commonly used relatively rigid aggregates, all time-dependent deformation may be assumed to originate almost entirely in the cement gel. Fig. 2 shows the corresponding composite body. It can be shown that under a given stress on the gross cross-section, the compliance or strain per unit stress contributed by the gel is directly proportional to the gel compliance factor, β , which may be expressed as

$$\beta = \frac{(1 - V_a - V_{uc})^2}{V_{hc}}$$

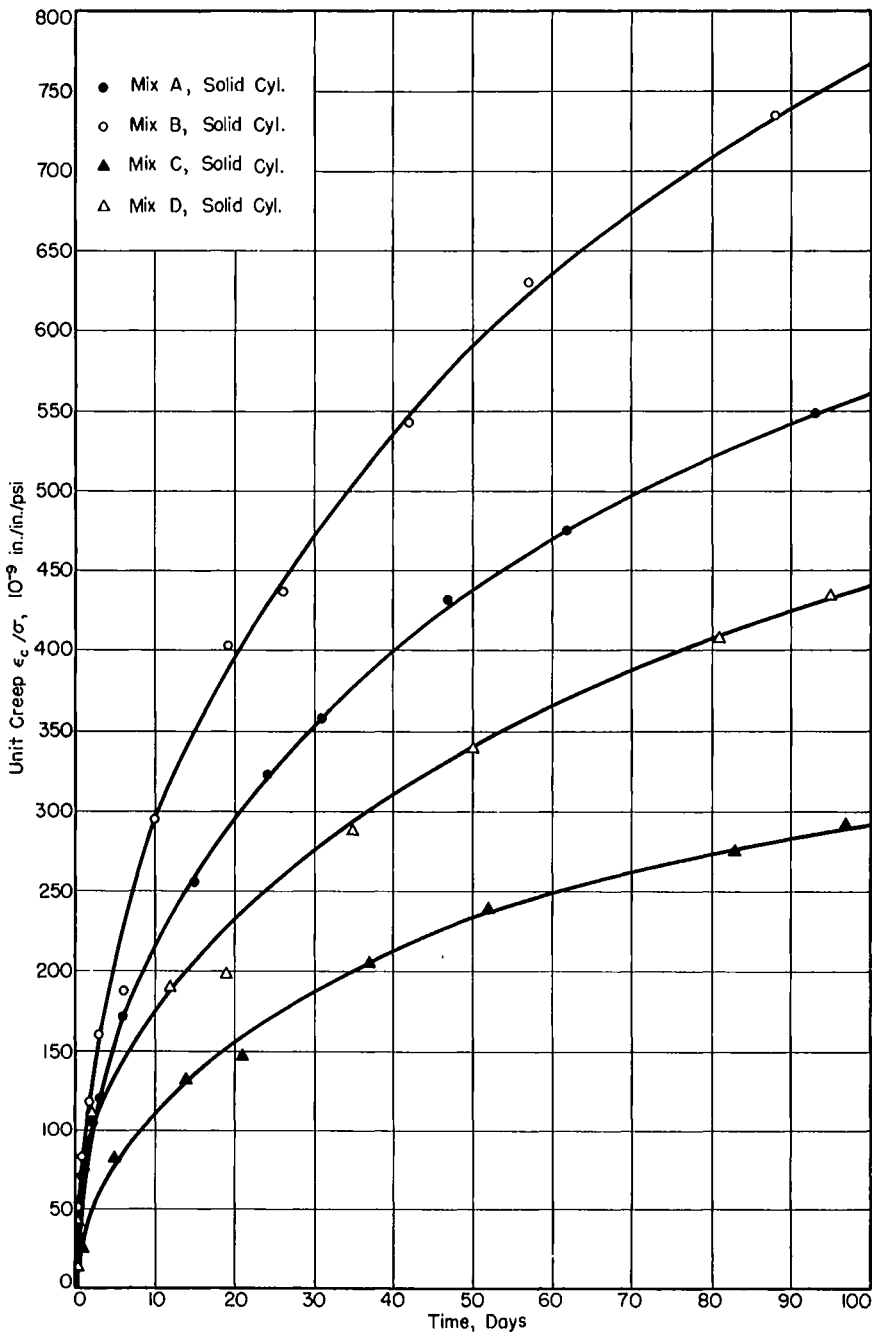


Fig. 8—Unit creep in compression while drying at 50 percent relative humidity

where V_a = volume concentration of aggregate; V_{hc} = volume concentration of hydrated cement, including gel pores; and V_{uc} = volume concentration of unhydrated cement.

Given the original mix proportion, the volumetric composition and hence the corresponding gel compliance factor β can be easily calculated. The actual degree of hydration, α , attained after a given curing period may be estimated from Fig. 3 which is based on heat of hydration studies,²² for ASTM Type I portland cement pastes cured at 100 percent relative humidity and 70F temperature.

The reciprocal, γ , of the volume concentration V_{hc} of hydrated cement is another convenient factor which can be used for converting the observed free shrinkage of concrete to the free shrinkage of its gel content.

Basic creep.—Fig. 4 and 5 show the results of basic creep tests under sustained compression and flexure respectively, at 100 percent relative

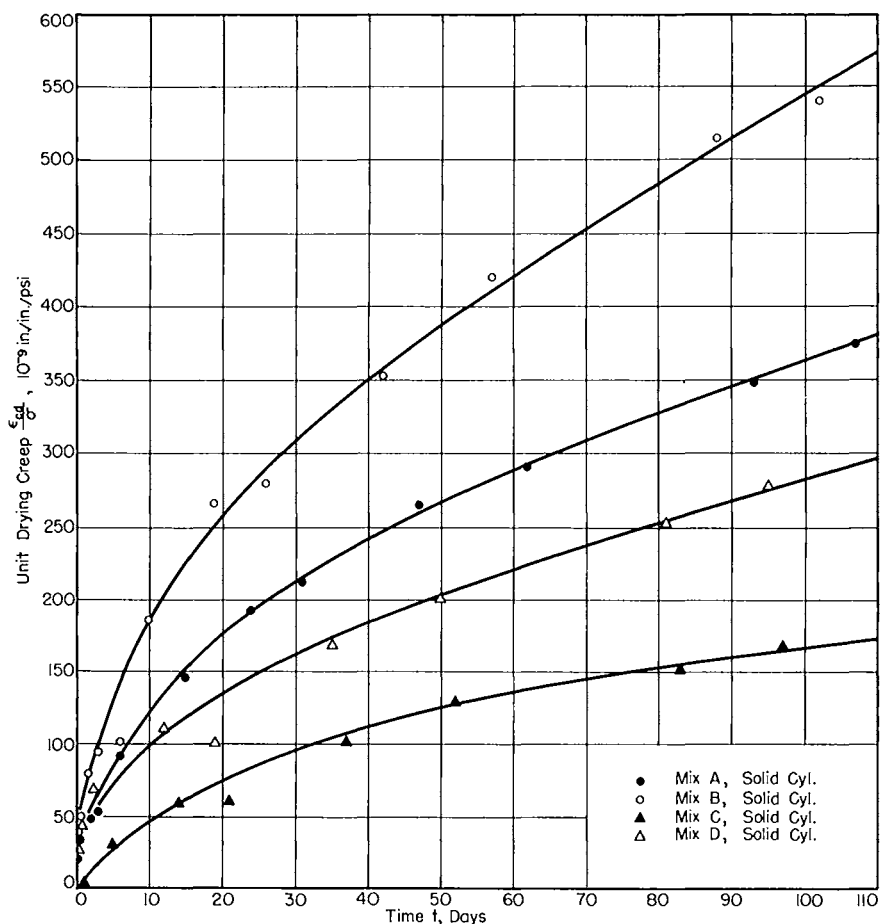


Fig. 9—Unit drying creep in compression, at 50 percent relative humidity