Paper No. 1

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 (true[1] 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.

ACI member **Adam M. Neville**, chairman, Division of Engineering, University of Alberta, Calgary is a member of ACI committee 115, Research, and 214, Evaluation of Results of Strength Tests of Concrete; and is vice-chairman of ACI Committee 209, Creep and Volume Changes in Concrete. Dr. Neville, formerly dean of engineering in Nigeria, is actively engaged in research and has received the Institution of Structural Engineers Research Award and Reinforced Concrete Association Medal.

ACI member **Bernard L. Meyers**, assistant professor of civil engineering, University of Missouri, Columbia, is a member of ACI Committee 209, Creep and Volume Changes in Concrete. Professor Meyers has been actively engaged in creep research for a number of years.

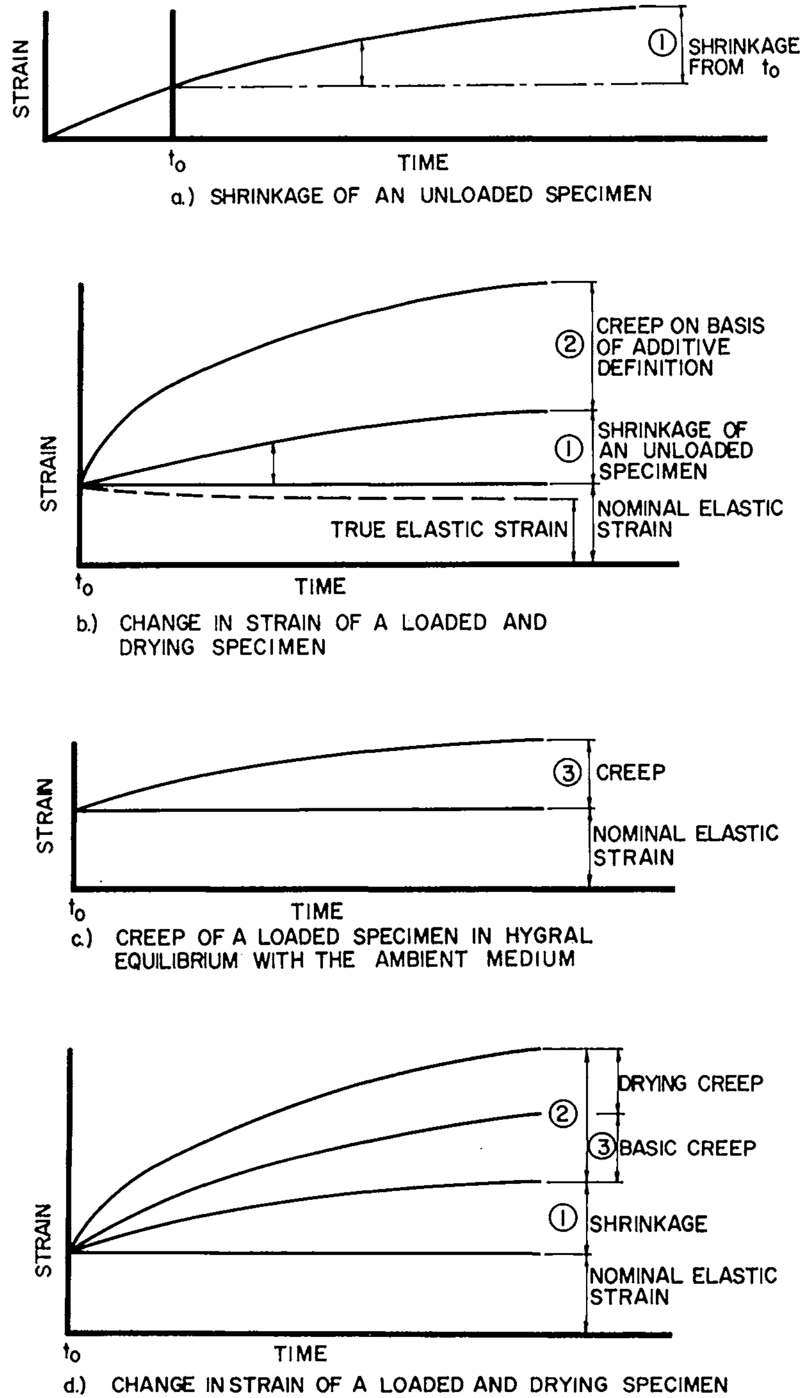

Fig. 1—Definitions of terms (t_o is the time of application of load)

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 work[6] indicates that creep of concrete, c, and the volumetric content of aggregate, g, are related by:

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

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

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

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 now[6] 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: McHenry[3] demonstrated this for a volcanic agglomerate; the Bureau of Reclamation reported creep of the Glen Canyon sandstone[4] 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 Davis[7] 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]

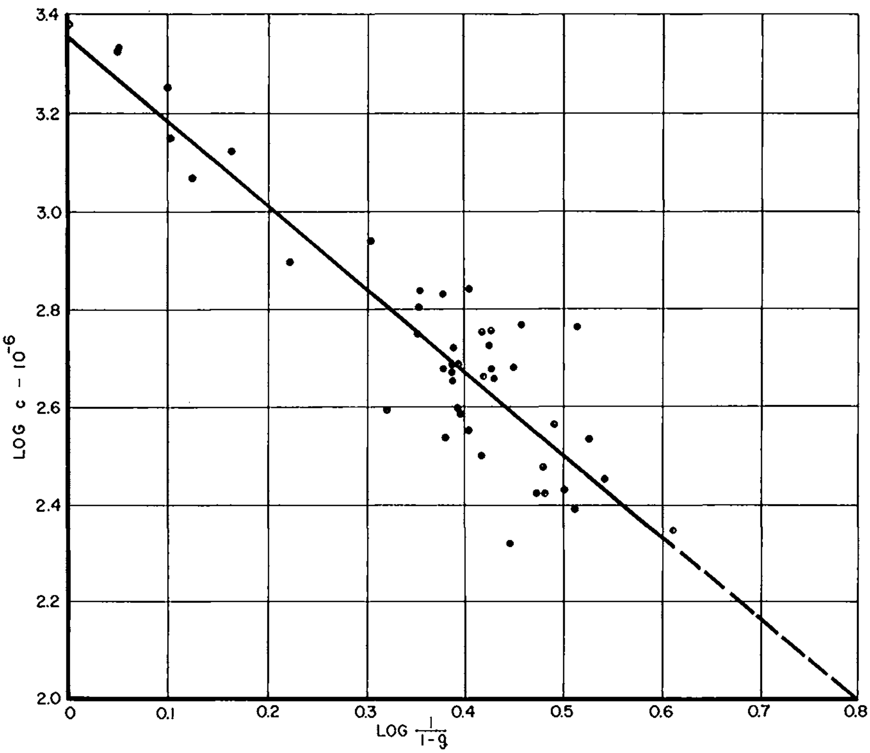

Fig. 2—Relation between creep c after 28 days under load and content of aggregate g for wet-stored specimens loaded at the age of 14 days to a stress-strength ratio of 50 percent

An even greater difference between creeps of concretes made with different aggregates was found by Rüsch, Kordina, and Hilsdorf[9] 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's[9] 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

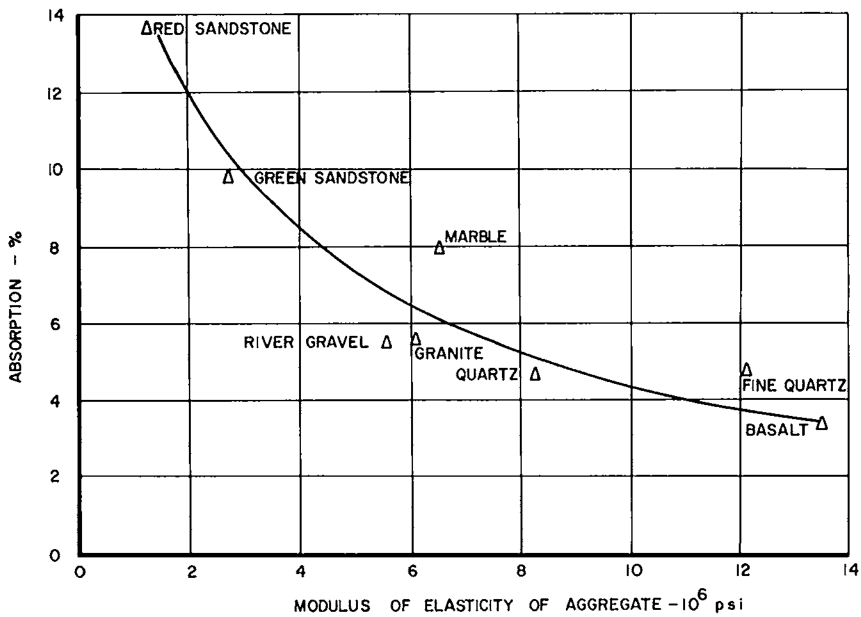

Fig. 3—Relation between absorption and modulus of elasticity of different aggregates

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 alkalies 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 Troxell[13] 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 creep[11] 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 aggegate-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

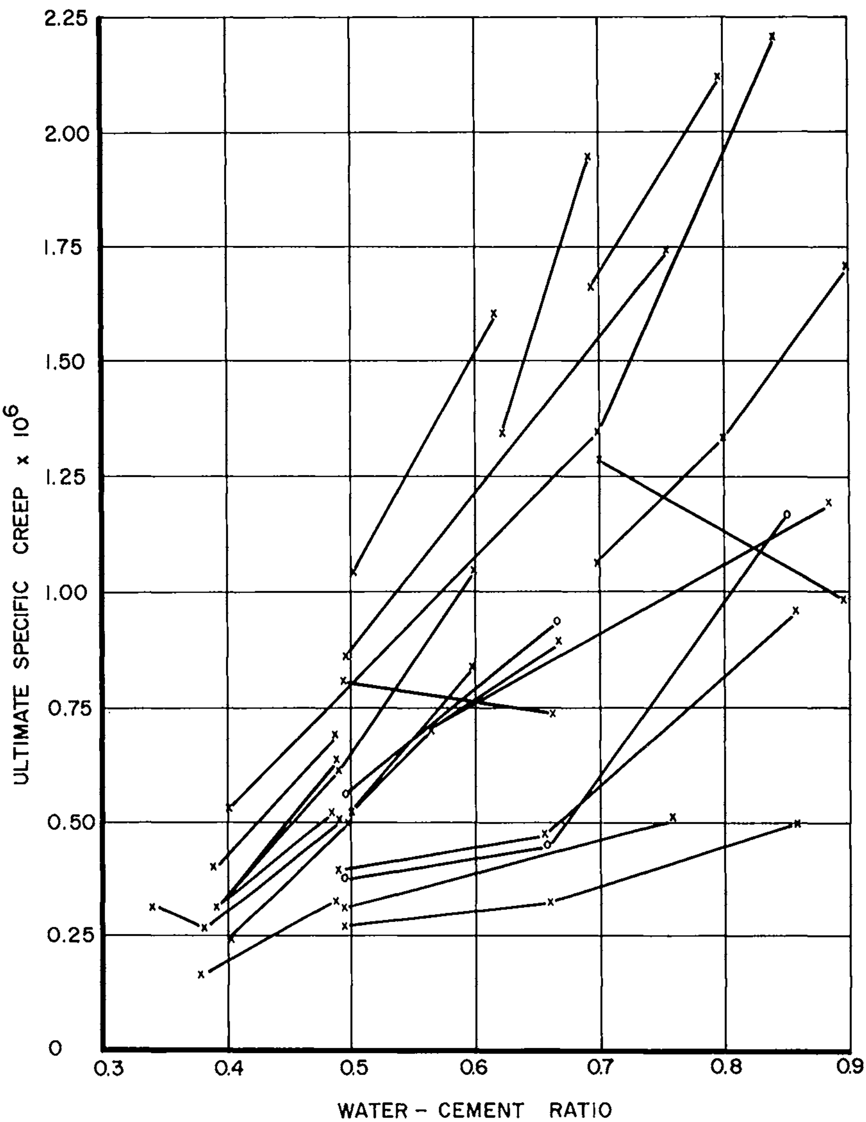

Fig. 4—Relation between specific creep and water-cement ratio in the tests of various investigators[16]

convenient and fairly reliable. As an example, Klieger's[15] 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 method[17] 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

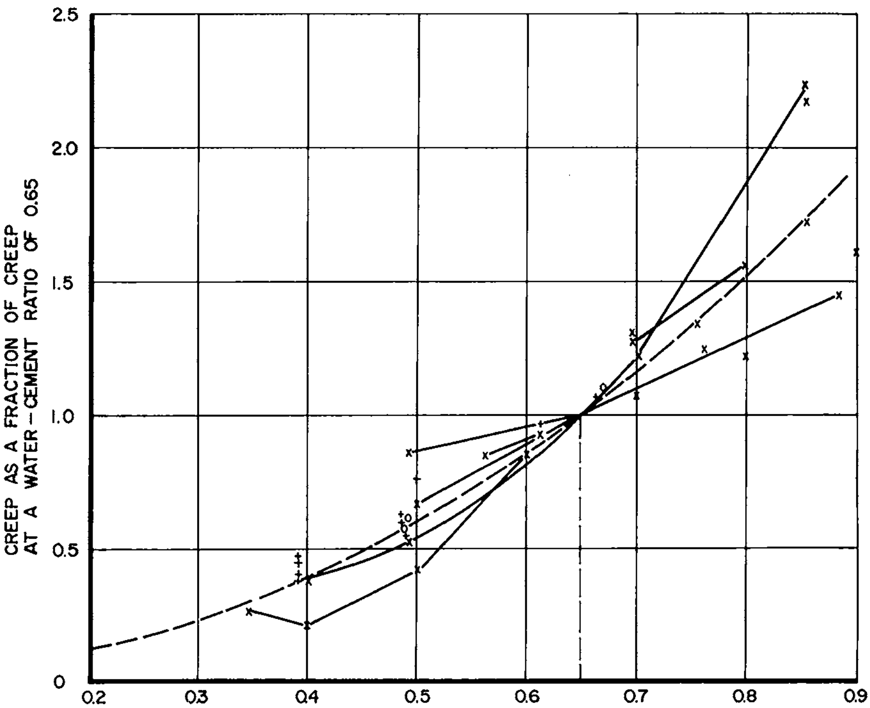

Fig. 5—Data of Fig. 4 adjusted for the content of cement paste (to a value of 20 percent) and expressed in terms of creep at a water-cement ratio of 0.65[16]