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MODERN VIEW OF CREEP OF CONCRETE

Text of address to the Polish Academy of Sciences on 31st March, 1967.

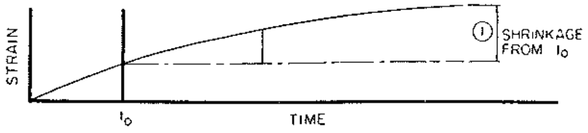
A. M. NEVILLE

My topic is creep of concrete and perhaps I ought to start by giving reasons why I feel this topic deserves your attention. Probably the simplest statement is to say that concrete is not an elastic material under any but transient loads. By this I mean that even when we design concrete structures by the so-called elastic method we are taking creep into account by using a fictitious modulus of elasticity of concrete in the design calculations. So creep is not just a refinement, not merely a topic of academic interest, not a toy of the ultimate load enthusiasts, but a necessity in the most common-garden design.

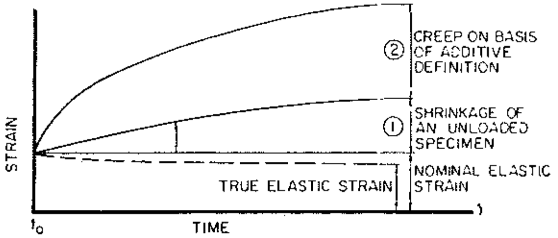
The necessity has become even greater in two more modern types of structures: prestressed concrete and highly statically indeterminate structures, or of course a combination of the two. In prestressed concrete, even in a single-span beam, the role of creep is considerable in that it induces a large loss of prestress. Indeed, it was this loss due to creep that defied early attempts at prestressing and rendered it impracticable until Freyssinet introduced high tensile steel with a large extension and therefore a relatively small loss in prestress due to creep. In indeterminate structures, the analysis depends on the modulus of elasticity (E) or perhaps we should say the strain response to stress. This response is a function of the creep properties of concrete, and therefore of age of concrete, duration of load, and some other factors. We thus have a variable E in a system of simultaneous equations. This makes the problem of satisfying the compatibility requirements rather complex, and for an accurate solution it also means that we have to know the value of E, and therefore of creep, accurately at any place and any time. One example of such structure that I can give from my experience is the supporting structure for a 500 megawatt turbo-generator. The structure is in the form of a 5 m deep beam, 50 m long on irregularly spaced and asymmetrical supports, all this being caused by the condenser and cooling gear that have to be housed underneath. Creep will introduce settlement of supports and, because of the monolithic connection between the supports and the beam, a rotation in the beam, and yet for a proper operation of the alternator a tolerance of only 0.1 mm in a 10 m length is permitted.

Another example, also from my experience, is a prestressed concrete pressure vessel for a nuclear reactor. This is a highly indeterminate structure whose analysis requires the knowledge of deformation and deformation-induced stresses at any point. Thus creep at any point is required and so an iterative approach to the problem is necessary because creep is a function of stress and temperature history. The temperature arises from the functioning of a nuclear reactor, and hence our interest in the influence of temperature on creep.

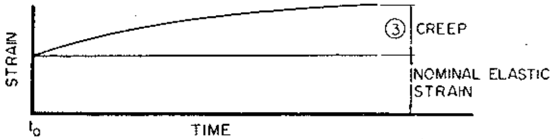
Having said so much about why we are concerned with creep, we should now define properly creep and the related phenomena. This is best done with the aid of Fig. 1.



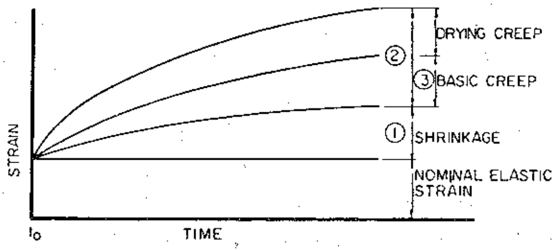
a) SHRINKAGE OF AN UNLOADED SPECIMEN



b) CHANGE IN STRAIN OF A LOADED AND DRYING SPECIMEN



c) CREEP OF A LOADED SPECIMEN IN HYGRAL EQUILIBRIUM WITH THE AMBIENT MEDIUM



d) CHANGE IN STRAIN OF A LOADED AND DRYING SPECIMEN

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

Fig. 2 illustrates the situation on removal of load, and introduces the concept of creep recovery. There are two general observations we should make: first, that creep is generally larger than elastic strain, often 3 or 4 times so. Second, the recovery is not equal to creep, so that there is a residual deformation. In other words, concrete is not even pseudoelastic because strain depends on duration of load and duration of unload so to speak, i.e. on the load history.

Let me now come to the topic which I call "creep as a function of many variables". I should make it clear that I shall not deal with the nature and mechanism of creep—

the problems of seepage, viscoelasticity and so forth. For our purposes it suffices to say that creep occurs within the cement paste, and is therefore influenced by the properties of the paste. But the contraction of the paste cannot be fully achieved when aggregate is present as it exercises a restraining effect. Thus creep of concrete is affected by many properties of concrete. In fact, at one time, studies of creep were conducted in terms of individual parameters such as aggregate size, water-cement ratio, even workability. There lies one difficulty: it is generally not possible to change in concrete one property without changing at least another one. For instance, if we decrease the maximum size of aggregate we have to increase the cement paste content, that is the richness of the mix, as otherwise the workability will become too low for full compaction. How then to study the influence on creep of the aggregate size without knowing something about the influence of the paste content?

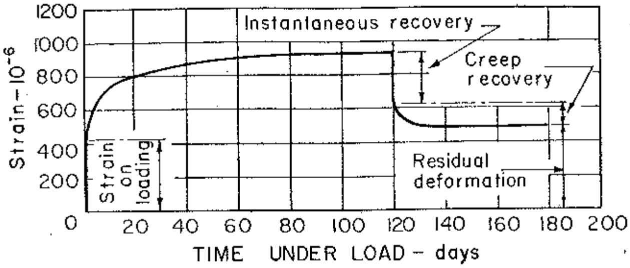


Fig. 2. Creep and recovery of a mortar specimen, stored in air at a relative humidity of 95 per cent, subjected to a stress of 151 kg/cm^2 and then unloaded

While I do not propose to present an exhaustive list of factors in creep, let me give some: aggregate content, physical properties of aggregate, type of cement, presence of admixtures, water-cement ratio, degree of compaction, age of concrete, level of stress, ambient humidity, ambient temperature, size of the concrete member, type of stress, presence of shrinkage. This is quite a number of factors and only some of them have been fully investigated. In fact, our approach, and this goes back more than 10 years, was to find a logically overriding parameter of creep and this we established to be the strength of concrete. This is a practical parameter as strength is really a mechanical reflection of the degree of hydration in relation to the space available for the products of hydration. Anyway, strength is easily measurable, and it is a meaningful parameter in concrete practice. While there are some refinements to strength with which I shall deal later, for the present purposes we can take creep as being inversely proportional to the strength of concrete at the time of application of load and directly proportional to the stress applied. We get thus the statement that creep is proportional to the stress-strength ratio. There is no lower limit to the validity of this expression as concrete creeps even at very low stresses. The upper limit is somewhat uncertain but it lies at 40 to 70% of the ultimate strength of concrete. The limit is higher in neat cement paste but decreases with an increase in the nonhomogeneity of the concrete. This is related to the advent of microcracking, and it is not surprising that once the cracking has started, the creep behaviour also changes. For practical purposes, where we are concerned with so-called working loads, we can thus assume that creep is proportional to the stress-strength ratio. This is a convenient rule but design criteria in those terms have not yet been developed. I shall therefore proceed with the conventional individual factors.

One factor, which in any case has to be considered in addition to strength, is the cement paste content of the concrete. We define as cement paste content the volume occupied by the hydrated paste inclusive of capillary as well as gel pores. Thus, ignoring entrapped air, the cement paste content is total volume of concrete less the aggregate content and less the volume of unhydrated cement. This last one is a minor factor.

We have found a linear relation between log creep and lof of inverse of the paste content, as shown in Fig. 3. The slope of the relation depends on the time

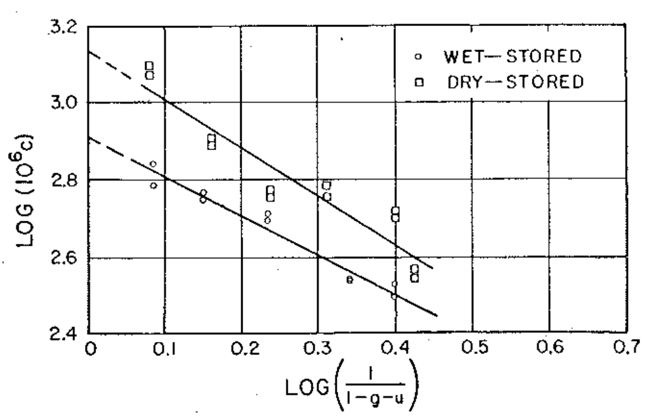


Fig. 3. Relation between logarithm of creep after 28 days under load and content of aggregate, g, and of unhydrated cement, u

under load but at any given instant the linear relation is apparent. We have derived this relation theoretically and verified it both for normal weight and lightweight aggregate. I should stress that one relation is valid only for one type of aggregate as the modulus of elasticity of aggregate determines the extent of restraint that the aggregate offers to the creep of the neat paste.

This may be an appropriate place to say some more about the physical properties of the aggregate. Its modulus of elasticity is probably the most important factor: the higher the modulus, the greater the restraint offered by the aggregate to the potential creep of the cement paste. As an illustration we can quote that sandstone has been found to lead to creep twice as large as limestone (Fig. 4). However, mineralogical or petrological description is not adequate for porosity of aggregate has also been found to influence creep. Generally, aggregate with a higher porosity or absorption has a lower modulus of elasticity (Fig. 5) so that porosity may not be an independent factor in creep. On the other hand, the porosity of aggregate, and even more so its absorption, may play a direct role in the transfer of moisture within concrete — a phenomenon involved in creep — so that porosity or absorption of aggregate affect creep. But the truth of the matter is that we do not know the exact way in which the physical properties of aggregate influence creep.

I do not propose to deal with the type of cement in any detail since we found that the type of cement influences creep only in so far as it influences the strength of concrete at the time of application of load. Thus if we prestress two beams, one made with normal cement, the other with a high early strength cement, and they both have the same strength at the time when prestress is applied, their creep is going to be approximately the same. This follows from our stress-strength ratio rule, and is quite an important observation.

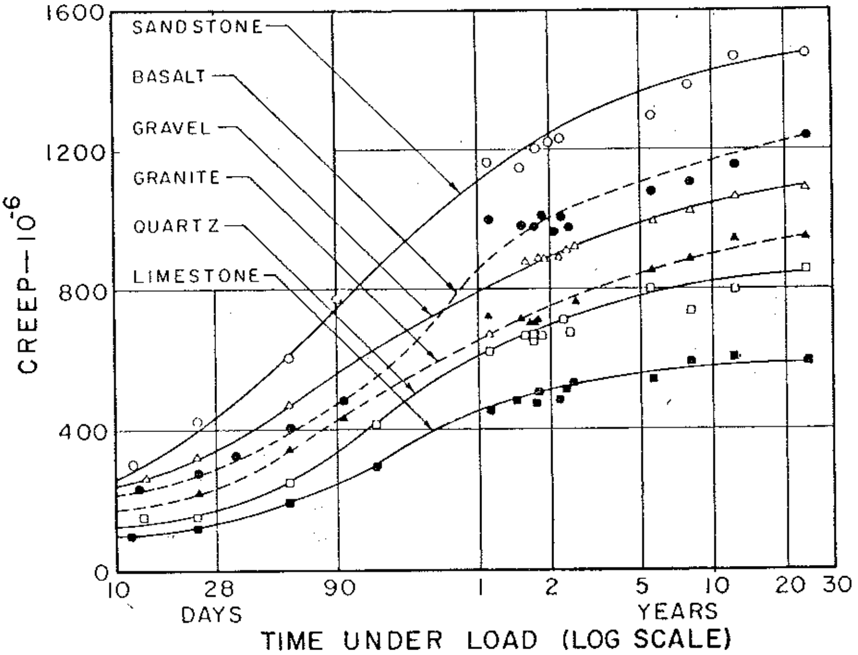


Fig. 4. Creep of concretes of fixed proportions but made with different aggregates, loaded at the age of 28 days, and stored in air at 21°C and a relative humidity of 50 per cent [26]

It is only fair to point out that the rule is an approximation as the increase in strength from the time of application of load onwards does affect creep. This is logical since if there is an increase in strength for a constant applied stress, the effective stress-strength ratio falls off. Thus there will be less creep if the concrete gains more strength, which would be the case with normal cement as compared with high early strength cement.

There is a further and similar complication arising from the value of the water-cement ratio. At one time we thought that the water-cement ratio per se was not a factor, that it mattered only in so far as it affected strength. But it affects not only the strength at the time of application of load but also the subsequent gain

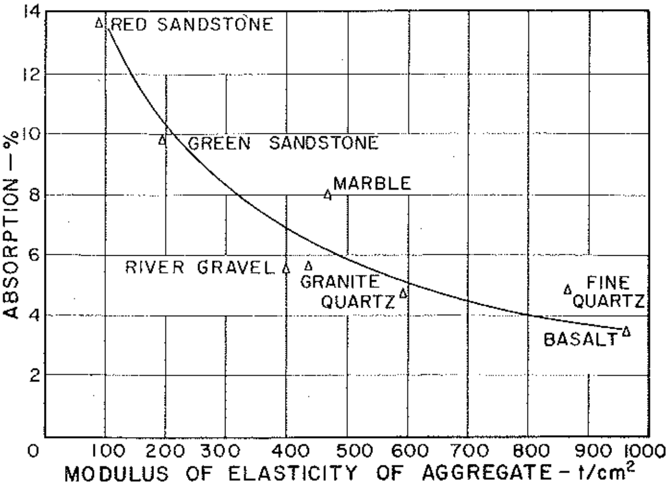


Fig. 5. Relation between absorption and modulus of elasticity of different aggregates [24]

of strength. Thus concrete with a lower water-cement ratio exhibits less late gain of strength and therefore more creep than would be expected from the stress-strength ratio rule alone. I am not saying much about this for it is not a major influence, and furthermore we do not really know enough about it. But please note that I am

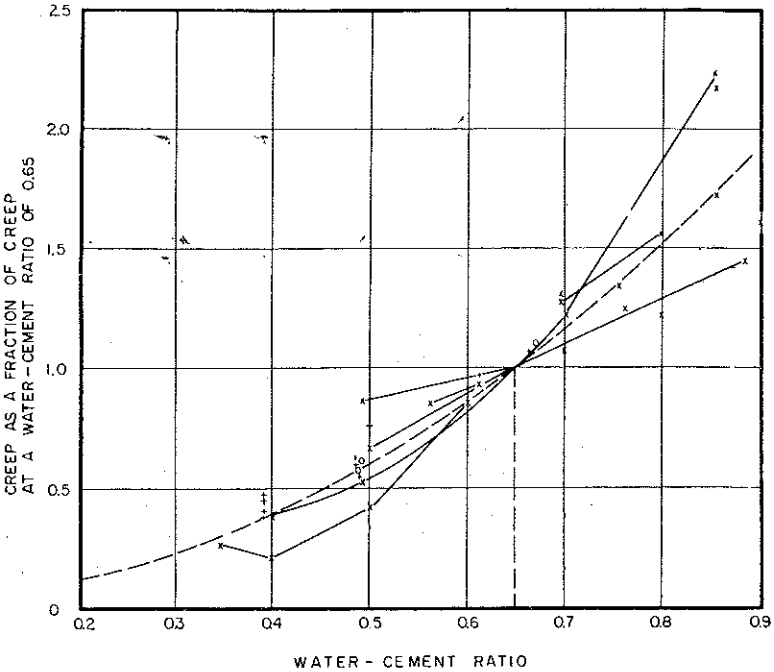


Fig. 6. Relation between specific creep and water-cement ratio [27]. All values adjusted for the cement paste content (to 20 per cent) and expressed in terms of creep at a water-cement ratio of 0.65

talking about the influence of the water-cement ratio when the stress-strength ratio at loading is the same. If it is not, i.e. if we are comparing concretes of different strengths, creep is greater the lower the strength, that is the higher the water-cement ratio. This is shown in Fig. 6, where relative creep at a given stress is shown for different water-cement ratios.

The age of concrete at loading influences creep again through the medium of strength. The older the concrete the higher its strength and therefore at a given applied stress the lower the creep. But at the same stress-strength ratio the influence of age on creep is small, and in fact older concrete exhibits more creep because it gains less strength while the load is acting. I hope I have not caused confusion by showing what happens from two different points of view: the classical one of a fixed stress, and ours of a fixed stress-strength ratio.

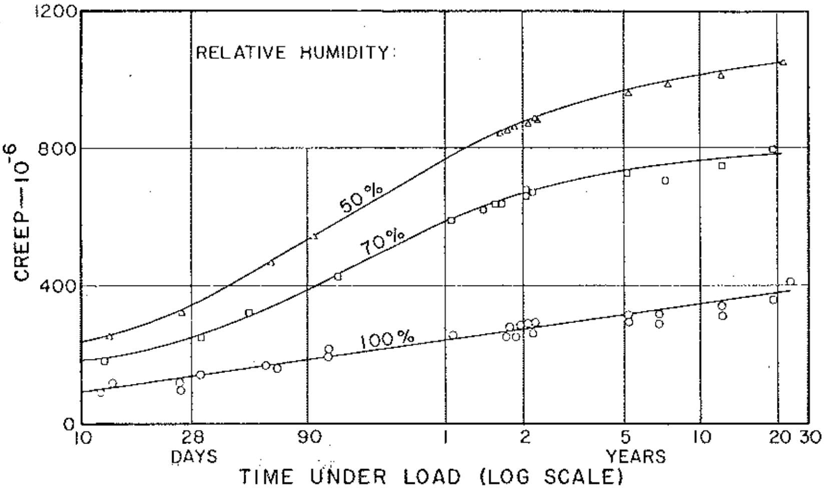


Fig. 7. Creep of concrete cured in fog for 28 days, then loaded and stored at different relative humidities [26]

Another factor, and a major one, is the influence of ambient relative humidity on creep. Creep increases with a decrease in the relative humidity of the surrounding medium. For instance, at a relative humidity of 50% creep may be 2 to 3 times greater than at 100%. This is shown in Fig. 7 but a careful qualification of our statement is necessary.

First, the ambient relative humidity affects creep if drying takes place while the specimen is under load, i.e. the drying creep. But if the concrete has reached hygral equilibrium prior to loading, the magnitude of creep is independent of the ambient humidity. It seems thus that it is not really the ambient humidity that is a factor in creep but the process of drying while the concrete is subject to creep. This is confirmed not only by tests on old concretes but also by the fact that after a period of time under load the rate of creep becomes sensibly independent of the relative humidity. This is clear from Fig. 7: once shrinkage has stopped, say after one year, the slopes of all the curves are about the same.

The second point is really an extension of the first and lies in the fact that alternating the relative humidity between two limits results in creep that is higher than that at a constant humidity, anywhere between the given limits. Of course, with alternating humidity the concrete is subjected to drying half the time. This is an important observation because it follows that laboratory tests performed at a constant humidity underestimate the creep of concrete under practical exposure in most locations.

Why should this be so? The answer involves some knowledge of the mechanism of creep because the influence of relative humidity does not act through the medium of an additional loss of water from the concrete: there is no such loss. What happens is that the equilibrium vapour pressure of the water adsorbed on the surface of cement gel depends on its state of stress. The presence of a partly elastic skeleton and only a partial condensation of the colloidal phase permit only a small fraction of the gross externally applied stress to be transmitted to the adsorbed water. As KESLER put it, the externally applied stress to produce a given percentage of increase in the vapour pressure of the gel would thus be expected to be far higher than the corresponding increase in the potential swelling pressure due to the same increase in vapour pressure. On the other hand, adsorbed water is effective on the entire area of material and therefore the potential swelling pressure of gel is very high. Hence, the change in water content produces a high stress.

Of course, if concrete contains no evaporable water it does not creep but this can be the case in laboratory specimens only.

I did say that I was not going to discuss the mechanism of creep but, having touched upon this topic from the standpoint of the influence of concurrent shrinkage, I ought to go a little further. We believe that creep is related to internal seepage of adsorbed water. Internal seepage means that there is no loss of water to the outside — a point already made — but a movement from adsorbed gel surfaces to the voids which are always present in hydrated cement paste. In addition there is some flow of the gel and KESLER — the greatest authority in this field — considers basic creep, i.e. creep when there is no concurrent shrinkage, to be a process of molecular diffusion and shear flow of the gel and of adsorbed water under load.

This brings us to what happens at temperatures above normal, and creep at these temperatures is becoming of increasing practical importance, especially in nuclear reactor pressure vessels. Well, as temperature increases, the mobility and hence the creep of the two deforming phases — gel and adsorbed water — increases. However, at a certain temperature, the adsorbed water begins to evaporate so that the rate of creep decreases. Now, the properties of adsorbed water depend on the extent of its adsorption and also on the applied compressive stress. I understand that adsorbed water changes state at a lower temperature than free water at atmospheric pressure. It is possible that this evaporation starts in the range of 70 to 80°C, and this is where creep should begin to fall off. With a further increase in temperature, say to some 150°C, creep would decrease still further as the gel changes to microcrystalline form. This behaviour, although only up to about 120°C, is illustrated in Fig. 8: the left hand side shows our tests, performed in Saskatchewan, the right hand side, tests made by England and Ross in England. There seems to be good agreement between our theory and the experimental results. Some typical creep–time curves are shown in Fig. 9, where temperature is the variable. In our tests the stress–strength ratio was 70% and in England and Ross's tests 20%. Perhaps I should add that the concrete used was mass concrete since this is the condition of concrete in a nuclear pressure vessel.

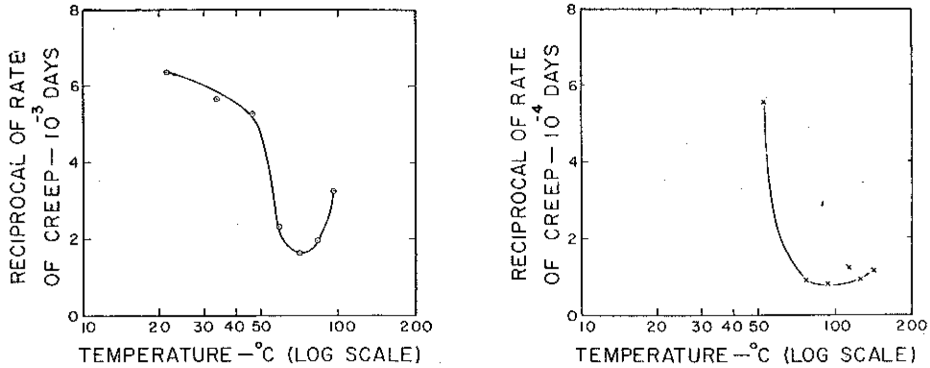


Fig. 8. Relation between reciprocal of rate of creep at 91 days after loading and temperature for Nasser and Neville's [11] (left) and England and Ross's [3] (right) data

In the tests whose results are shown in Fig. 9, the concrete was cured and stored at the specified temperature from the time of stripping the moulds at 24 hours.

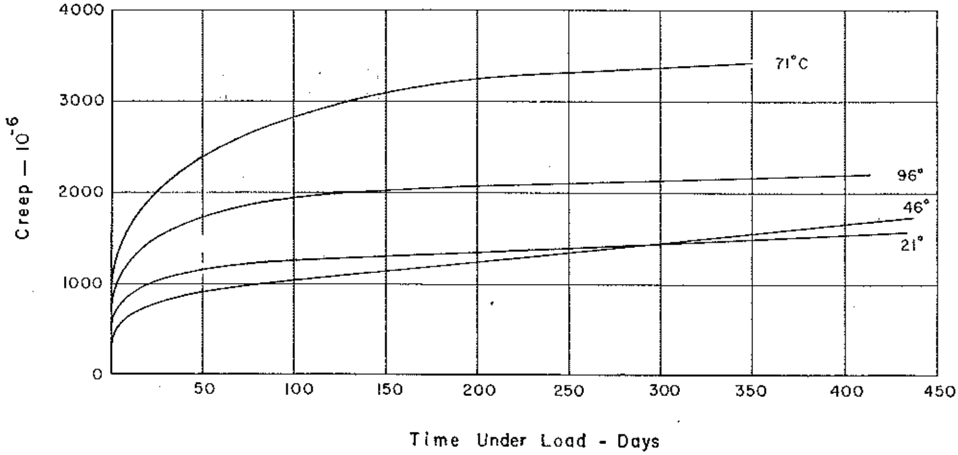


Fig. 9. Relation between creep and time under load for a stress-strength ratio of 70 per cent and different temperatures from the age of 24 hours onwards [11] (aggregate-cement ratio = 7.15, water-cement ratio = 0.6)

But in practice concrete may mature at normal temperature and be subjected to higher tempertaure at a much later age when the pressure vessel is put into operation. We did some tests on concrete under this type of condition and found higher creep than in concrete stored throughout at the elevated temperature. It is possible that prolonged moist curing at higher temperatures (in this series concrete was moist cured) increases the amount of adsorbed water which plays a role in creep. It is possible also that the change in temperature contributes to higher creep. This is analogous to the influence of the change in relative humidity, which I referred to earlier, and such an effect has been observed when temperature varies up and down.

The general pattern of the influence of temperature on creep is the same for concrete heated later (Fig. 10) as for concrete stored at a constant elevated temperature throughout its life.

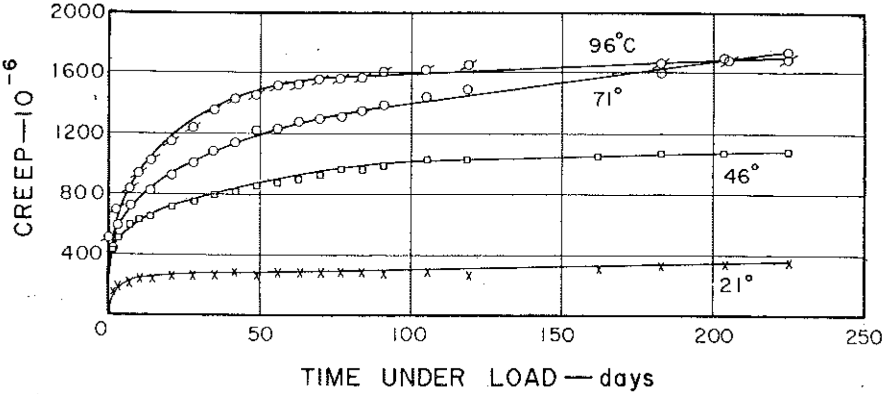


Fig. 10. Relation between creep and time under load for concrete, stored at temperatures indicated from the age of one year onwards [12] (aggregate-cement ratio = 7.15, water-cement ratio = 0.6)

We did some further tests on old concrete, some 50 years in age, obtained from a bridge pier. This concrete is still liable to creep of substantial magnitude especially at temperatures above normal (Fig. 11). The influence of temperature is still the same in that creep at 95°C is less than at 70°C. This is an interesting observation as it dispels any suggestion that temperature up to about 93°C influences creep through accelerated hydration or formation of microcrystalline products of hydration.

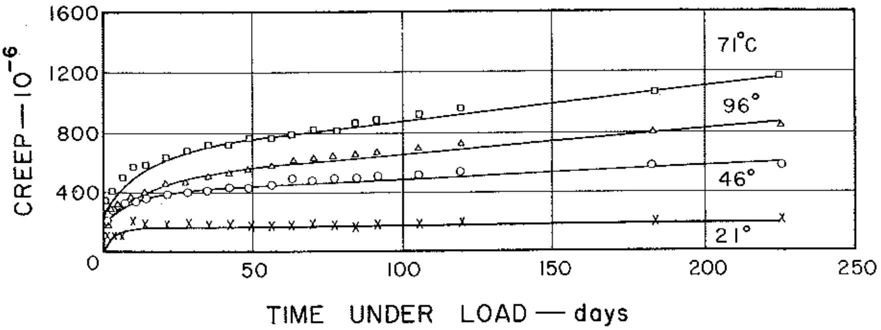


Fig. 11. Relation between creep and time under load for concrete, stored at temperatures indicated from the age of 50 years onwards [12] (stress-strength ratio = 45 per cent, estimated cement paste content = 16 per cent by volume)

Concrete stored over water for 50 years would achieve its maximum possible hydration, and temperature is likely to affect only the mobility of adsorbed water and of the gel itself. It is also reasonable to think that the mechanism of creep in old and young concretes is the same, and this finding is a significant contribution to our knowledge of creep.

I do not know to what extent admixtures are used in concrete in Poland. In North America they are very common. There is no doubt that these admixtures serve a very useful purpose as far as water reduction and set retardation are concerned. However, the matter does not end there. I have seen, for instance, the same admixtures advertised as reducing mixing time. Two graphs were shown of strength versus mixing time, one with, the other without an admixture. The one with the admixture required for the same average strength a shorter mixing time. This may well be true but is highly misleading. I presume the explanation is that with an admixture, the water requirement is reduced, therefore the potential strength of concrete is raised. If we now mix inadequately, we can achieve the specified strength without an admixture. But the concrete we have produced is not properly mixed and not adequately homogeneous so that it is not good concrete even though its average strength may have the right value.

As you can see, I am not prepared to accept uncritically the idea that admixtures are a panacea for all concrete problems. In fact, I am not happy about the present situation regarding admixtures. What bothers me is that admixtures arrived on the concrete scene not as carefully prepared chemical agents that produce a known reaction but as sort of patent medicines, or something from a medicine man, something with a secret composition and allegedly beneficial effects. As a consequence, many, so to speak, side-effects of admixtures are unknown. One of these is creep: there is hardly any literature on this subject; in fact, I only know of two papers, one more than 20 years old, the other with an experimental set-up bound to produce misleading results. If you ask the manufacturers they tell you everything is just fine: admixtures, if anything, reduce creep.

At Calgary we decided to run a couple of experimental series on creep of concrete with admixtures, one using normal aggregate, the other light-weight aggregate. We used two admixtures in the lightweight series and four with normal aggregate. Half the admixtures were of the lignosulfonic acid type, the other half a hydroxylated carboxylic acid.

The admixtures were used in amounts prescribed by the manufacturers to achieve normal water-reducing and set-retarding effect. They were supplied by the producers with their prior knowledge that these materials would be used in a creep research programme with cement from the Calgary area. Since the performance of admixtures is generally sensitive to the properties of the cement with which they are used, it may be expected that in our case the admixtures supplied would exhibit as good a creep performance as possible in their respective classes.

Figure 12 shows some of the results for creep of normal aggregate concrete with an aggregate-cement ratio of 7, and a water-cement ratio of 0.56, loaded at 28 days. When an admixture was used, the water-cement ratio was kept sensibly constant but the cement content was adjusted so as to keep a constant strength and also a constant workability.

We can see a significant increase in creep when an admixture is used, even though the reduction in cement paste content would make us expect a reduction in creep. We found the effect of admixture on creep to be greater the stronger, and in our case, also the richer the mix. However, we do not know yet whether it is the level of strength or the richness of the mix that is the real factor.

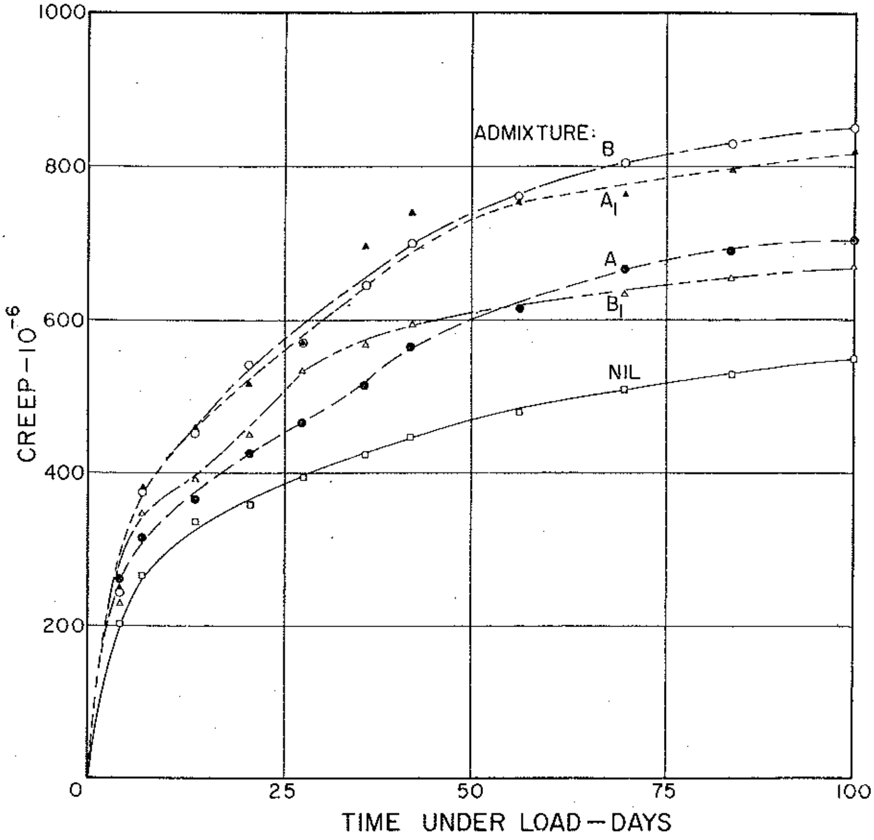


Fig. 12. Creep of concrete loaded at the age of 28 days [6] (aggregate-cement ratio = 7.0, water-cement ratio = 0.56; admixtures A and A1 are hydroxylated carboxylic acid, B and B1 lignosulfonic acid)

Our findings concerning increased creep in concrete with an admixture are of interest in design where deflections are of importance and also in prestressed concrete. The question of deflections is particularly important since the American Concrete Institute Building Code 318–63 specifies a maximum ratio of non-elastic to elastic strain on loading as 2. In our tests, the ratio of *creep* to elastic strain ranges between 1.3 and 2.5. If we add shrinkage, the A.C.I. recommendation may not be sufficiently conservative when admixtures are used. In other words, the long-term deflections may be excessive, and we all know that with the modern more slender construction the deflection often controls the design.

The deflection problem does not arise with lightweight aggregate even though the use of admixtures increases creep. This is so because the admixture increases the elastic strain on loading, too. Thus the ratio of the non-elastic to elastic strain does not become excessive. Let me explain this apparent anomaly in the case of lightweight aggregate concrete. When we use an admixture and keep the strength of concrete the same, we reduce the cement content of the mix, and therefore the paste content, too. Because of the low modulus of elasticity of the lightweight aggregate, an increase in its content reduces the modulus of elasticity of concrete. Hence, the elastic strain on loading increases and, even though creep with admixture is higher, the ratio of creep to elastic strain does not exceed the value specified by A.C.I. On the other hand, with normal aggregate, an increase in its content increases the modulus of elasticity of the concrete, and hence decreases the elastic strain. Thus when creep increases due to the use of an admixture, the ratio of creep to elastic strain increases.

We did not find any pattern in creep of the two types of admixtures: lignosulfonic acid and hydroxylated carboxylic acid. Careful qualification of our results is therefore necessary: they apply only to the admixtures used, and only to the mixes and cements used. There is no doubt that the composition of cement affects the performance of an admixture, and, without going into details, we have reason to believe that the C_3A content is significant in this respect.

This inability to generalize about the performance of admixtures is something I find regrettable but it is inevitable since the composition and properties of admixtures are not divulged by their manufacturers so that we are compelled to deal with a black box about whose mechanism we know nothing.

I have spent a great deal of time on various factors in creep and I would now like to move to the practical problem of predicting creep. Several attempts at this have been made but the best prediction from tables and charts without any measurement can be obtained by using the method of Jones and his co-workers. They use a, so to speak, "standard" creep curve, shown in Fig. 13. This is for a concrete containing 320 kg of cement per m^3, with 6% entrained air, and a 5 cm slump, subjected to a stress of 70 kg/cm^2 at a relative humidity of 60%. Such a stress represents a stress-strength ratio of about 30%. The "standard" values of creep are then modified for the particular slump (as a measure of water content), air content, cement type and content, percentage of fines, relative humidity of storage, thickness of the member, and age at loading, using the correction factors shown in Fig. 13. The accuracy of the prediction is of course not too good, maybe ±50%, but then we have done no experimental work to help ourselves. A particular failing of the method is that it does not explicitly allow for the type of aggregate used. I believe direct testing of this property is necessary.

If this is done and if we are prepared to and able to do some laboratory creep measurements, we can use a method of predicting creep developed at Calgary.

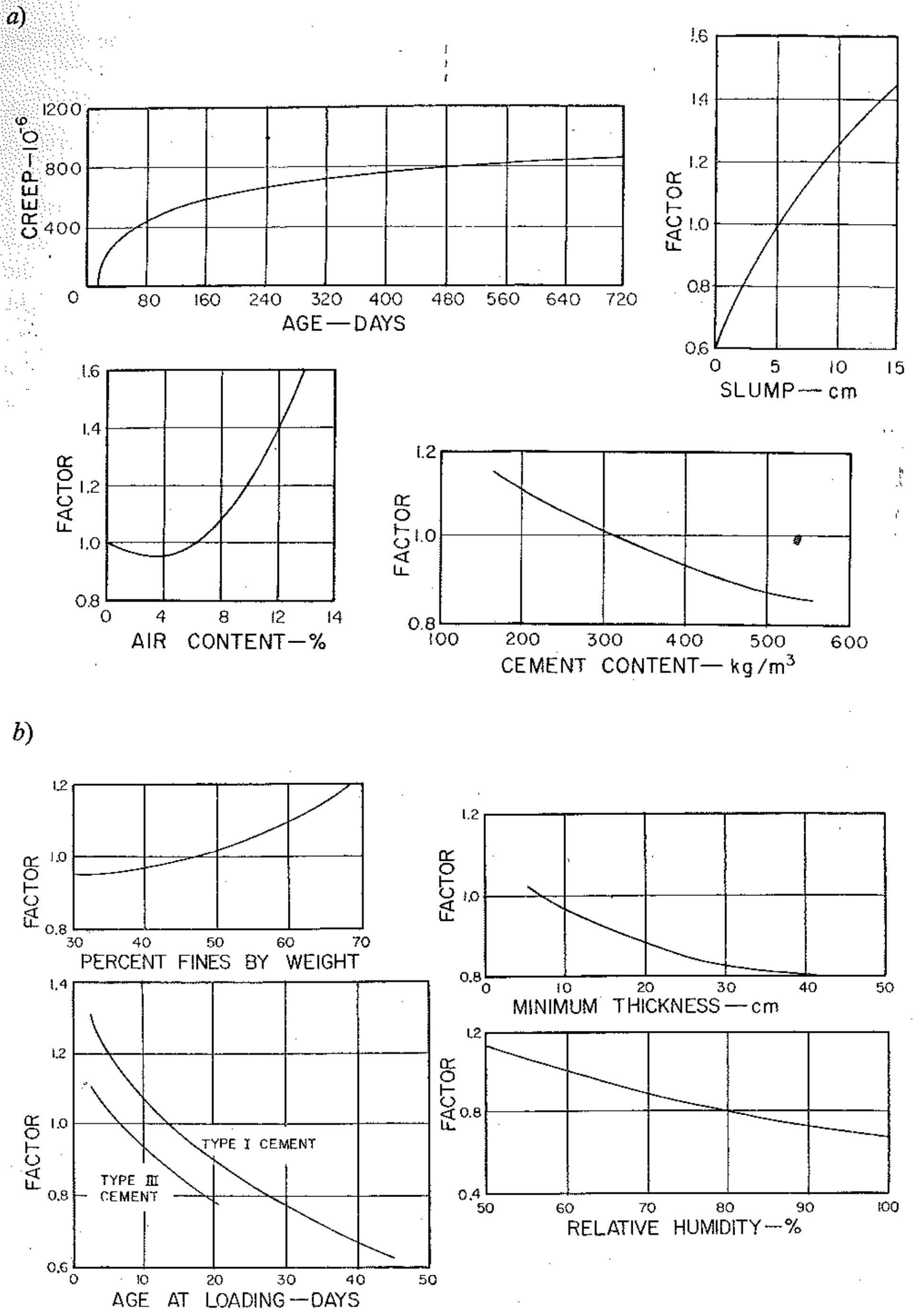


Fig. 13. Jones, Hirsch and Stephenson's [9] "standard" creep curve for concrete containing 320 kg of cement per m³, with 6 per cent entrained air, and a 5 cm slump, subjected to a stress of 70 kg/cm² at a relative humidity of 60 per cent, and various correction factors

As I said earlier, in our studies we started with the question of influence of the cement paste content of the mix on creep. We established that there is a simple logarithmic relation between these two quantities so that the higher the paste content the higher the creep, other properties of the mix, such as strength, remaining the same. This is interesting as the idea that using a richer mix, for instance in precast prestressed units, cannot but be conducive to safety is erroneous. Of course we know that a richer mix exhibits higher shrinkage, too, so that the dilution of the cement paste by aggregate is a good thing from the technical standpoint and not just an economic expedient of making the cement go further. This is worth remembering and indeed we should look upon concrete as stone connected by cement paste into a cohesive whole; i.e. as a sort of mini-masonry. As a corollary, we must not regard aggregate as an inert filler. For instance, as I have just said, the quantity of aggregate, as well as its elastic properties, affects creep. The expression developed by us is:

$$\log\frac{c_p}{c} = a\log\left|\frac{1}{1-g-u}\right|, \tag{1}$$

where c_p is creep of neat cement paste, c creep of concrete, g volume of aggregate in a unit volume of concrete, u volume of unhydrated cement in a unit volume of concrete, and

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

where μ denoted Poisson's ratio of surrounding material (concrete), μ_a Poisson's ratio of aggregate, E modulus of elasticity of surrounding material (concrete), E_a modulus of elasticity of aggregate.

Some experimental results are shown in Fig. 3. We confirmed the validity of this expression for normal weight aggregate, lightweight aggregate, and also for lightweight coarse and normal sand.

Our expression for the influence of paste content, or aggregate content, the two being almost complementary, has led us to develop a general expression for prediction of creep. This assumes a hyperbolic creep-time relation and a logarithmic creep-cement paste content relation, as follows:

$$c = \frac{T}{a+bT}(1-g-u)^{\frac{T}{s+pT}} \tag{2}$$

where c is creep of concrete, g volume of aggregate in a unit volume of concrete, u volume of unhydrated cement in a unit volume of concrete, T time under load, a, b, s, p are constants.

To use this expression some tests are necessary but their number is small. The constants a and b can be obtained from a creep-time curve of neat cement paste assumed to be in the form $c_p=T/(a+bT)$, or alternatively from intercepts of regression lines of logarithm of creep, c, on logarithm of $1/(1-g-u)$ for mixes with different aggregate contents, each intercept being obtained for a different value of time under load, T. The relation between T/c_p and T is linear, and hence a and b are easily obtained. We can note that a and b are independent of the properties of aggregate, and therefore the values, once obtained, can be used for concretes made with different aggregates. On the other hand, the coefficients s and p are functions of the modulus of elasticity and Poisson's ratio of the aggregate and have to be determined from tests on concrete containing the given aggregate. The relation between $s+pT$ and T is linear and hence s and p are obtained. These data apply only to the given age at loading as both c_p and $T/s+pT$ depend on this age.

We have used this method and compared the predicted and observed results. The agreement is good as shown in Fig. 14.

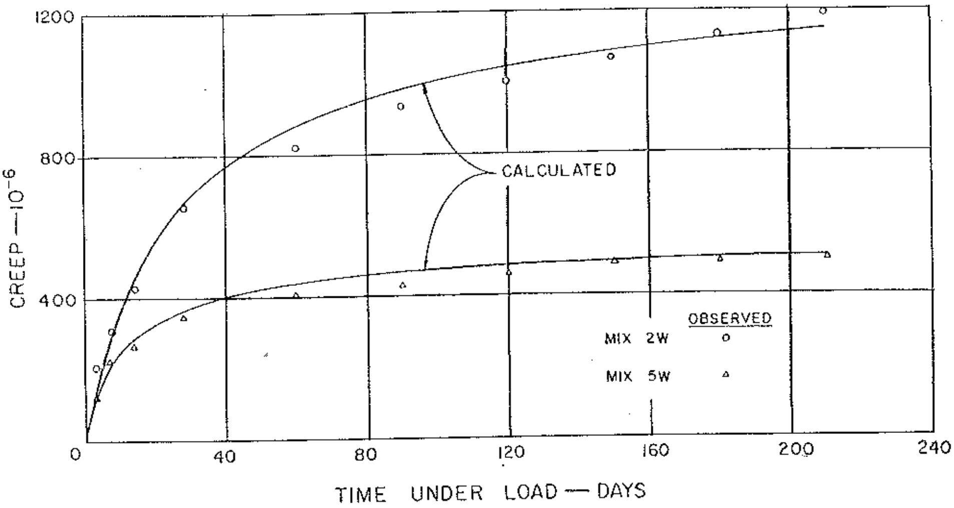


Fig. 14. Relation between creep and time under load. Comparison of observed and calculated data using Eq. (2)

My time is rapidly running out, and I can only deal briefly with two items First, the situation regarding recovery of creep. It has been suggested that creep recovery at any time is equal to negative creep for a load applied at the same time (Fig. 15). This is the so-called principle of superposition. We have found over a number of years that the principle is not very accurate, and an analysis of recovery data over the last few years leads us to a somewhat different point of view. The recovery is governed to a large extent by the rigidity of the hardened paste skeleton, and this is why the recovery is essentially the same under wet and dry conditions. The rigidity, and therefore the recovery depend, however, on the type and volume concentration of aggregate and on the degree of hydration at any time.

Finally, I would like to come to the problem of creep vis-a-vis structural behaviour of concrete. How do we use our creep knowledge in design? Three alternatives are open to the design engineer depending on the requirements and tolerances of the project. First, for exacting and critical conditions, as in the case of the generator mentioned earlier, an iteration solution can be set up for a computer which takes into consideration the time-dependent relation of stress and deformation of concrete. This procedure was proposed by BRESLER and others but the accuracy of the results will depend on the formulation of the basic relation between stress, strain, creep, time, and environment. Second, for less demanding requirements, a semi-graphical solution as proposed by PAUW and MEYERS is suitable for use in most engineering offices where the slide rule is still the king. The procedure takes into consideration the effects of shrinkage and creep on stresses and deflections of prestressed and ordinary reinforced beams. The accuracy of the results is again dependent on the establishment of the relation between stress, strain, creep, time, and environment. Third, for the average type of structure, concrete responds to reasonable design and construction deficiencies by redistribution of stresses and strains and hence the recommendations of the building codes are satisfactory. As you can see, our state of knowledge in this area is still limited and much work is needed yet before further recommendations may be advanced.

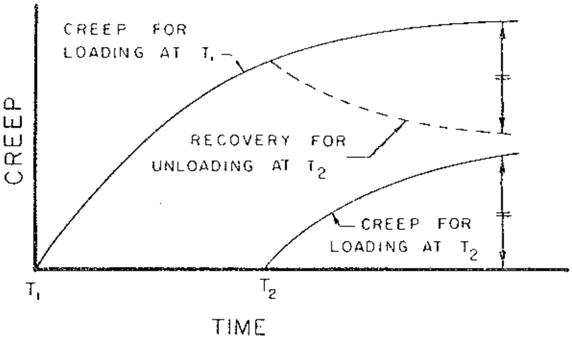


Fig. 15. Creep recovery according to the principle of superposition

As a last remark let me say that creep is a valuable property of concrete. True enough, it complicates design and it is disadvantageous in prestressed concrete and in many situations where deflection governs design. But creep enables concrete to behave in a ductile manner, it enables it to accommodate large local or unexpected stresses, especially concentrations of stress in statically indeterminate structures. Creep permits the development of rotations necessary for a moment redistribution and this is really vital from the ultimate load standpoint.

Thus creep is not only a good thing for the professors who make a living studying it. Without creep, concrete would not have reached its ubiquity as a most successful structural material.

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Streszczenie

AKTUALNY PRZEGLĄD ZAGADNIEŃ ZWIĄZANYCH Z PEŁZANIEM BETONU

Tematem pracy jest analiza wpływu na pełzanie betonu różnych czynników, związanych z warunkami zewnętrznymi, obciążeniem i składem betonu. Autor przeanalizował kolejno te czynniki, zwracając uwagę na ich wzajemną zależność oraz uwzględniając również takie, które rzadko uwzględniane są w związku z pełzaniem betonu, np. temperatura otoczenia. Następnie autor przedstawił metodę przewidywania wielkości pełzania betonu, opracowaną przez siebie w Calgary; wiele innych wiadomości zawartych w pracy również pochodzi z własnych badań i prac autora. Rozważania o znaczeniu pełzania w konstrukcjach betonowych kończą przedstawioną pracę.

Резюме

СОВРЕМЕННЫЙ ОБЗОР ВОПРОСОВ, СВЯЗАННЫХ С ПОЛЗУЧЕСТЬЮ БЕТОНА

Темой работы является анализ влияния на ползучесть бетона различных факторов, связанных внешними условиями, нагрузкой и составом бетона. Автор провел последовательно анализ этих факторов, обращая внимание на их взаимозависимость, учитывая при этом, такие которые редко принимаются во внимание в связи с ползучестью бетона, как напр. температура окружающей среды. Затем, автор представил, разработанный им в Кальгари, метод определения предусматриваемых величин ползучести бетона; много других сведений, заключенных в работе, также проводились автором.

В заключение даются рассуждения, касающееся значения ползучести в бетонных конструкциях.

DEAN OF FACULTY OF ENGINEERING,
UNIVERSITY OF CALGARY, CANADA

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