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Mathematical Modeling of Creep and Shrinkage of Concrete

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the equations and graphs in my book, warmly commended my work, and then suggested: 'Maybe you could look during your fellowship at the implications of some of our test data.' He pulled out some of his test results and compared them to a graph of my assumed creep function. I must admit the comparison was not favourable. It was on that day that the constitutive law began to worry me more than the method of structural creep analysis.

Monsieur L'Hermite, *le patron,* who was respected by everyone in his institute, was a very busy man. From time to time, at the end of one of his long days filled by meetings, Mme Glaize, his long-time secretary, called me to his spacious, elegant, wood-panelled office lined by many books. After commenting on my progress, he would point out to me some broad unexpected connections, making revealing remarks on varied subjects ranging from structural stability to reinforced polymers, from new types of tests and measuring techniques to construction methods. To come to know this great man, to be exposed to his intellect and Parisian charm, was for me an unforgettable experience. After the lapse of 20 years, let me now attempt to describe his major contributions to creep and shrinkage (L'Hermite, 1947, 1948, 1950, 1951a, b; 1952, 1953, 1955, 1959, 1960, 1961, 1972, 1973, 1977; L'Hermite and Grieu, 1952; L'Hermite and Mamillan, 1968a, b; L'Hermite *et al.*, 1949, 1963) as I see them now.

2 CREEP LAW

L'Hermite was introduced to the subject of concrete creep and shrinkage during the early 1930s when he had personal contacts with Freyssinet, the father of modern prestressed concrete who himself had conducted some of the earliest observations of concrete creep in the field and formulated one of the earliest hypotheses on the role of capillarity in shrinkage and creep. As the Director of CEBTP, L'Hermite with his co-workers experimented in his laboratory at 15 rue Brancion, since 1943. By the time of the first RILEM creep symposium in Munich in 1958, he had amassed a wealth of carefully controlled data, aided by some innovative testing devices of his own conception. In his Munich 1958 lecture (L'Hermite, 1959), he dealt in depth with the problem of the creep law. For constant uniaxial stress σ, he expressed the creep law by means of the following rate-type relation:

$$\dot{\varepsilon}_C = \sigma(\varepsilon_\infty - \varepsilon_C) f(t', t - t') \tag{1}$$

in which σ = uniaxial stress ε_C = axial creep strain; f = an empirical function of the age at loading, t', and of the load duration $t - t'$, t being the current age; and ε_C^∞ = an empirical constant interpreted as the final value

L'Hermite regarded the question of existence of a final creep value as unsettled and unlikely to be settled, he considered it convenient to assume the final value to exist. Although today many of us, including myself, prefer to treat the basic creep as unbounded, the question is unimportant as long as ε_C^∞ refers to a time that is much longer than the usual design lifetime of a structure.

Based on extensive test data, L'Hermite formulated function f in a form leading to the equation:

$$\dot{\varepsilon}_C = \sigma(\varepsilon_C^\infty - \varepsilon_C)\left(\frac{k_1}{t} + k_2\right) \tag{2}$$

in which t = current age, and k_1, k_2 = empirical constants. For constant σ, Eqs (1) and (2) are linear, and Eq. (2) can be easily integrated to yield $\varepsilon = \sigma J(t, t')$, with the compliance function

$$J(t, t') = \frac{1}{E(t')} + \varepsilon_C^\infty\left[1 - \left(\frac{t'}{t}\right)^{k_1} e^{-k_2(t - t')}\right. \tag{3}$$

in which $E(t')$ = the elastic modulus at age t'. For $k_2 = 0$, Eq. (3) is amenable through algebraic rearrangement to a linear regression plot, and for $k_2 > 0$, there is a simple deviation from a straight line. This is illustrated in Fig. 1 in which L'Hermite compared his Eq. (3) to the creep data available by 1957. These plots allow a relatively easy graphical fitting of test data, and at the same time they document excellent agreement with the data. The curves in the figures are plotted for various stress levels, and their vertical spacing indicates the effect of stress which is linear for the service stress range as indicated by Eqs (1)–(3). Furthermore, these plots, and more clearly the plot in Fig. 1 (bottom right), verify L'Hermite's finding that the final creep strain decreases roughly linearly with $\log t'$, i.e. the logarithm of the age at loading. Although today perhaps an inverse power function may be preferred since, unlike $\log t'$, it cannot yield negative creep strain values for extremely large t', L'Hermite's formulation of the age effect is simple and realistic and still remains good enough for practical purposes despite much subsequent testing.

L'Hermite's Eqs (1) or (2) was certainly much more realistic than the Dischinger (rate of creep) formulation or the Ross–Lorman hyperbola in prevalent use at that time.

For the plotting of the creep and shrinkage curves, L'Hermite was one of the few who preferred the logarithmic time-scale. I cannot agree with him more. Plots in the actual time-scale permit showing clearly only about one order of magnitude of creep durations and obscure possibly even very large discrepancies for load durations of any higher or lower orders of magnitude. Such plots are a good way to hide disagreement with test results.

When the stress σ is variable, Eqs (1) or (2) becomes non-linear. This complicates structural analysis for creep and is no doubt the main reason why L'Hermite's creep law has so far been little used by analysts. For the most part, the desire for a linear formulation has led to the use of various other creep laws, most of which, however, are quite inferior to L'Hermite's law in their description of experimental reality. Recently, however, new large sophisticated finite element codes make it quite feasible to use nonlinear constitutive laws such as Eq. (1).

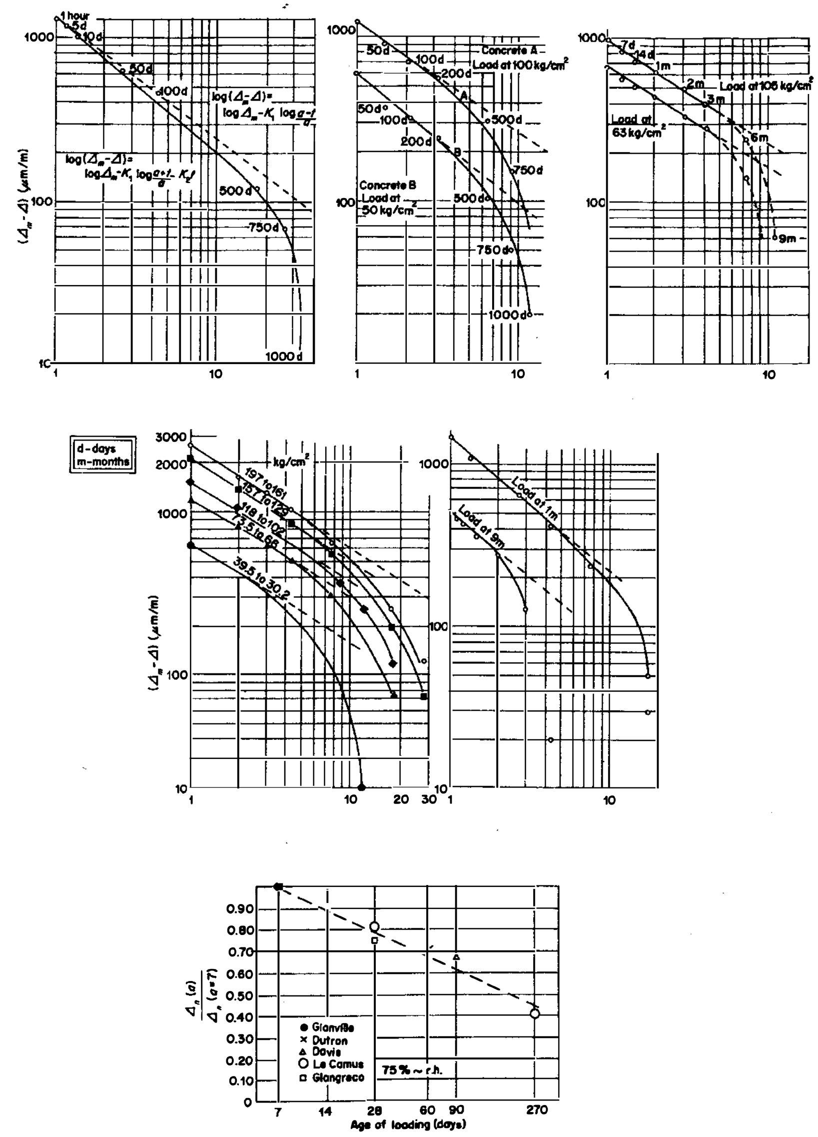

Figure 1 Comparison of creep data by Glanville, LeCamus, and others with L'Hermite's Eqs. (2) and (3); ($\log \varepsilon_C - \varepsilon_C$) versus $\log t/t'$, for various stress levels, and (at lower right) ratio of the final creep strain at any age to that at age seven days at loading, versus log-age in days (L'Hermite and Grieu, 1952)

There is, nevertheless, one significant limitation of a creep law of the type of Eq. (1), as L'Hermite was well aware. Equations (1) or (2) implies the hypothesis of strain-hardening, which has been widely used for creep of metals and means that the creep rate decreases as a function of the creep strain accumulated up to the current time. This hypothesis can be justified physically, for metals as well as concrete, by a gradual exhaustion of the creep sites during the creep process, and may be brought, as recently shown, in a direct simple relation to an activation energy description of creep mechanism. The limitation of Eqs (1) or (2), and of the strain-hardening creep laws in general, is that they significantly underestimate the additional creep due to the stress changes (positive or negative) which take place long after the application of the first stress (see Figs 2.26 and 2.27). This limitation is of interest to one current debate of a new creep formulation with a certain equivalent time, which is mathematically equivalent to a strain-hardening creep law. No doubt cognizant of this limitation, L'Hermite and Mamillan in 1968 pointed out that certain aspects of creep at strongly variable stress need to be described according to the principle of superposition. This viewpoint was in fact implemented much later in our Center for Concrete and Geomaterials by Bažant, Tsubaki and Celep (1983). It transpired that a combination of strain-hardening with the principle of superposition can describe essentially all the known features of the history dependence of creep in the service stress range. To sum up, L'Hermite's formulation of the creep law was well ahead of the state of the art and we only now see its full implications and application potential.

For a multiaxial formulation, the creep Poisson ratio, ν_C, is the central question. L'Hermite studied it experimentally and in his 1958 Munich lecture (L'Hermite, 1959) he concluded, in disagreement with some earlier authors, that ν_C is much below 0.5—the value typical of metal creep or plasticity, which is strictly deviatoric. Thus he asserted that concrete creep is predominantly volumetric, although again in disagreement with some other researchers at that time, he did not believe it to be exclusively volumetric. His early experiments (L'Hermite, 1947) led him to suggest that the value of ν_C may be approximately 0 and in any case much less than the elastic Poisson ratio ν, which lies between 0.15 and 0.20 (L'Hermite and Mamillan, 1968b). Today it is generally accepted that $\nu_C = \nu$, and the reason for finding too low a value in 1958 was the superimposed effect of drying with the inherent microcracking (strain-softening). After further extensive testing, which included sealed and water-immersed specimens, L'Hermite himself in 1968 (L'Hermite and Mamillan, 1968b) concluded that, for basic creep, ν_C lies between 0.15 and 0.20, and is thus about the same as the elastic Poisson ratio, as far as the inevitable statistical errors permit us to detect.

The fact that $\nu_C = \nu$ means that concrete creep has also a significant deviatoric component. This was demonstrated in the 1960s by tests of torsional creep, and serves as one argument against the early capillary and consolidation hypotheses of creep mechanism.

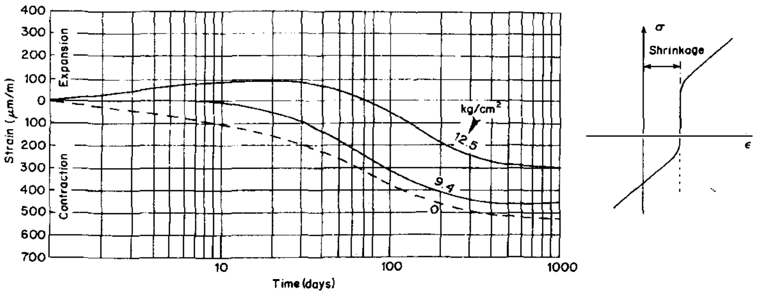

Figure 2 Tests of creep in tension (L'Hermite, 1959); strain versus $\log(t-t')$ at various stress levels, and (at right) dependence of total long-time strain on stress

These and other early concepts of creep mechanism regard creep as a strictly compression phenomenon. As typical of him, L'Hermite questioned such speculations, and successfully overcame in his laboratory the difficulties of applying tensile load to concrete in a direct tension test. His approach, namely epoxy-gluing of straight (unflared) cylinders to the loading platens, is now the prevalent approach. The results of L'Hermite's tensile creep tests, reproduced in Fig. 2 (L'Hermite, 1959), showed that the creep in tension is significant and, per unit stress, is about as large as the compression creep.

In view of structural loads, as well as from the viewpoint of creep mechanism, creep under cyclic loading is of interest. L'Hermite was one of the first to study it, and his typical experimental results for compression cyclic creep are reproduced in Fig. 3 (L'Hermite 1959). He demonstrated the hysteretic energy loss in the subsequent hysteretic loops, the gradual straightening of the loops, and the fact that the elastic modulus for the loop stabilizes at a value roughly equal to the initial elastic modulus, E. This stabilization, characteristic for the service stress range, means that the microstructure does not undergo any significant changes (today called damage).

An ingenious idea of L'Hermite was to test the cyclic creep also on a specimen which previously underwent large creep under a constant stress. This test revealed no significant cyclic creep in the preloaded specimen (L'Hermite, 1959). This result implies that the cyclic creep is not additive to the static creep (creep at constant stress) but should be regarded as an accelerated creep, a view which was later confirmed by other tests, e.g. by Neville, Brooks, and Hirst, and is now generally accepted.

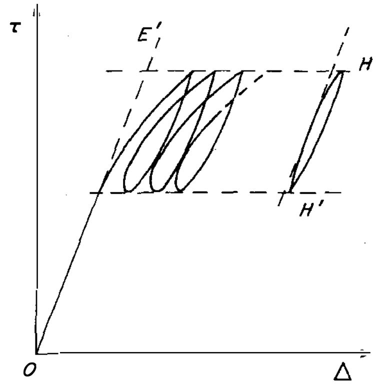

Figure 3 Typical measured force–deformation diagram at repeated loading (L'Hermite, 1959)

3 EFFECT OF HUMIDITY ON CREEP

The hygro-mechanical behavior of concrete is no doubt the most complex problem of creep and shrinkage theory which has been studied continuously for 60 years. One of the early hypotheses was that concrete creep is like clay consolidation, i.e. is a consequence of water being squeezed out of the pores due to compression loads. This speculation was put to rest by L'Hermite's tests of water loss of loaded and load-free specimens which were otherwise identical and exposed to the same environmental history (L'Hermite and Mamillan, 1968b). From the fact that the difference between the curves in Fig. 4 is statistically negligible, L'Hermite concluded: 'Concrete does not behave like a sponge which loses its water when compressed' (L'Hermite and Mamillan, 1968b).

Together with his co-workers, L'Hermite assembled perhaps the most extensive and systematic experimental information on creep at drying and without drying, at various stress levels, various ages at loading and various relative humidities h_e of the environment. These results (as replotted and theoretically fitted by Bažant and Wu, 1974) are summarized in Figs 5 and 6. They have subsequently proven invaluable to many investigators, including myself, in their formulation of constitutive law. The basic trends which transpire from these results are further reproduced in Fig. 7 (L'Hermite *et al.*, 1965; L'Hermite and Mamillan, 1968a), which shows the effect of environmental humidity on the final creep strain for various ages t' at loading, as well as the dependence of the final creep strain on $\log t'$ at various environmental humidities h_e. From Fig. 7 (left) as well as Figs 5 and 6, we clearly see the large additional creep produced by drying environment, called the drying creep. L'Hermite with his co-workers have made a major contribution to its understanding and quantification.

To describe the drying creep, a cross effect between shrinkage and creep which, as we now know, is observed in other materials such as wood and fibre-reinforced polymers, L'Hermite (1960) proposed the ingeniously simple relation

$$\varepsilon_C = \sigma\varepsilon_C^0(1 + Q_0\varepsilon_{sh}) \tag{4}$$

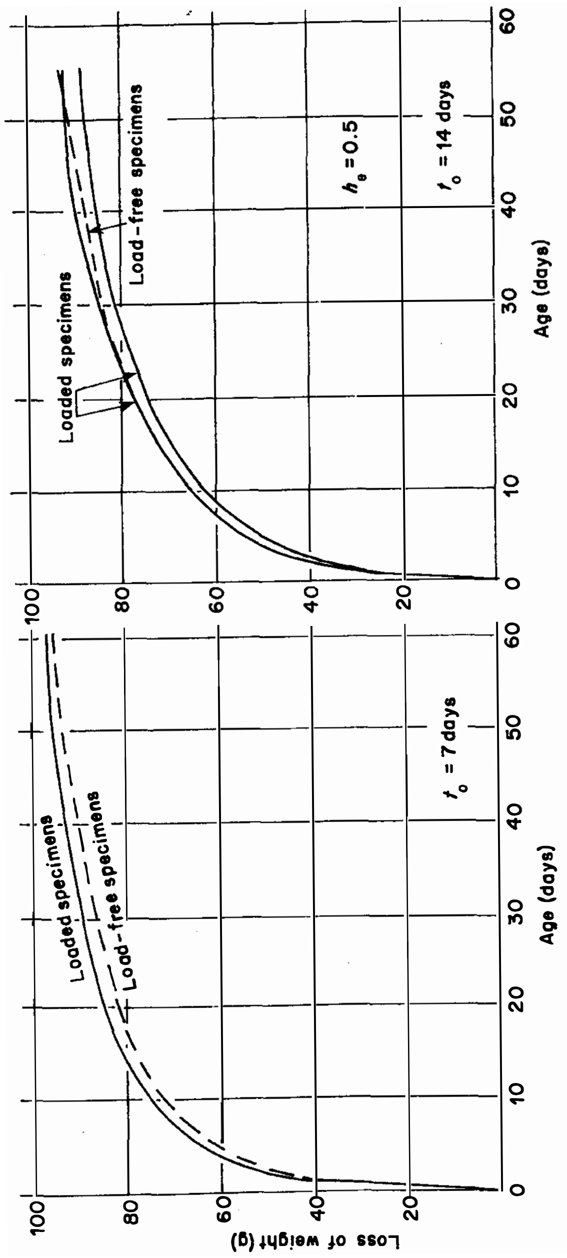

Figure 4 Weight loss versus drying time (L'Hermite and Mamillan, 1968b) of loaded specimens (———) and identical load-free specimens (– – –) (L'Hermite and Mamillan, 1968b)

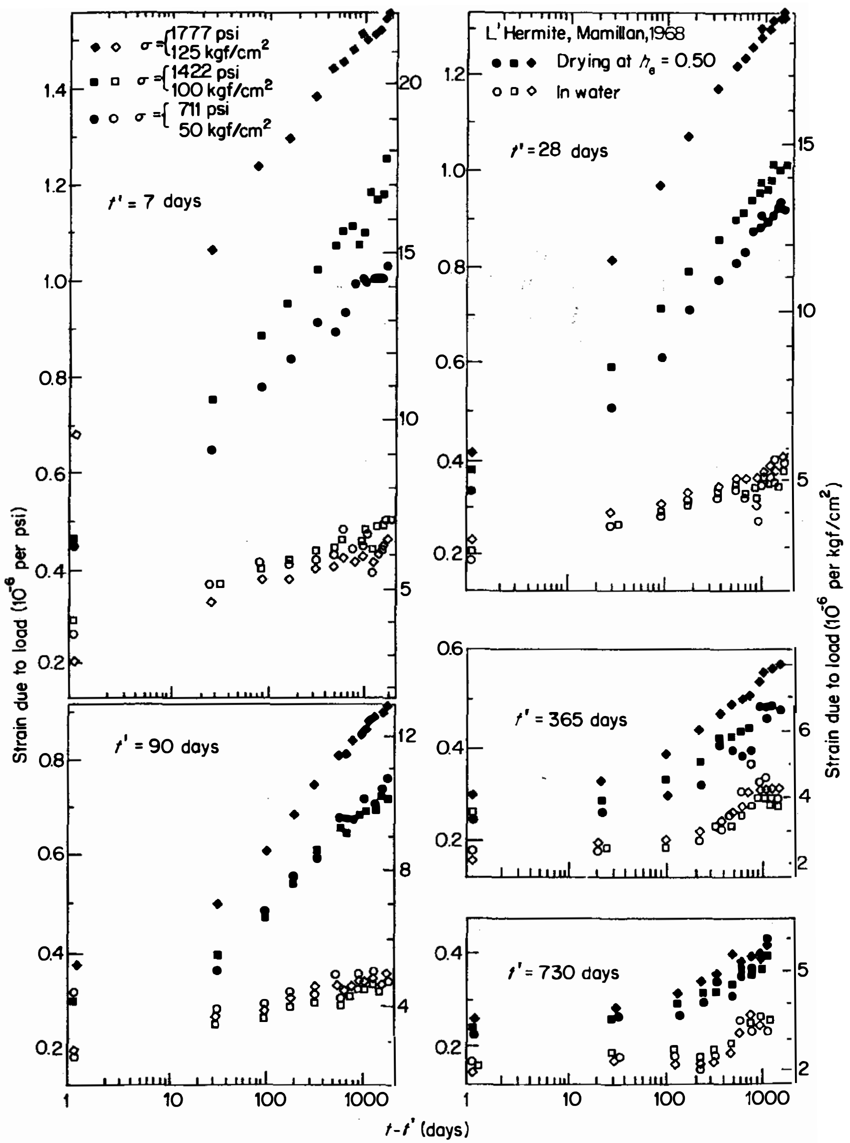

Figure 5 Compliance versus load duration (log scale) for various ages t' at loading, various stress levels, at environmental humidity 50 per cent and in water (as replotted from L'Hermite, 1955 by Bažant and Wu, 1974)

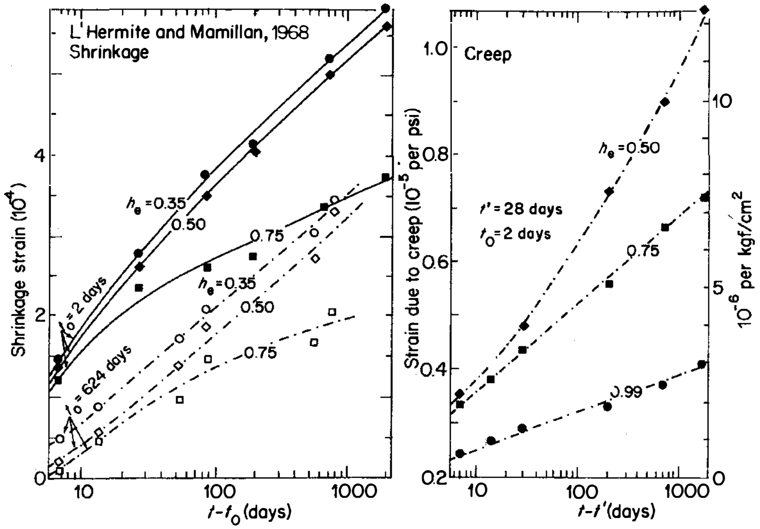

Figure 6 Shrinkage strain (left) and creep strain (right) versus the logarithm of drying duration or load duration at various environmental humidities h_e, various ages t_0 at drying start (as replotted from L'Hermite, 1955 by Bažant and Wu, 1974)

in which ε_C^0 and Q_0 = empirical constants, ε_C^0 representing the basic creep (creep in absence of moisture exchange with the environment), and the term $\sigma\varepsilon_C^0 Q_0 \varepsilon_{sh}$ represents the drying creep.

The consequence of this relation for the stress dependence of creep at drying is illustrated by the curves in Fig. 8. The coordinate is the total strain, i.e. the creep plus elastic strain, plus shrinkage, and the ordinate is the uniaxial stress (L'Hermite, 1959). The variability of shrinkage strain ε_{sh} causes the dependence of the creep strain ε_C on the applied stress σ to be significantly non-linear, which is well verified by L'Hermite's measurements.

Equation (4) represented a major contribution which is still of interest to the current research. Through Eq. (4), L'Hermite rejected the previous hypothesis, enunciated e.g. by Pickett (1956), that creep is just an acceleration of shrinkage. Equation (4) means that creep and shrinkage are related through the drying creep term, representing what in mechanics might be called a cross effect, while the basic creep is an independent phenomenon. After much further research, Eq. (4) still remains approximately valid at present, although it may be limited to conditions of constant uniaxial stress σ. With this formula, L'Hermite was well ahead of the front of research. To my knowledge, he did not attempt generalizing Eq. (4) to variable stress, which requires a differential equation. This problem has in fact been the subject of research during the last few years, made possible by many further test data which became available after the first symposium in

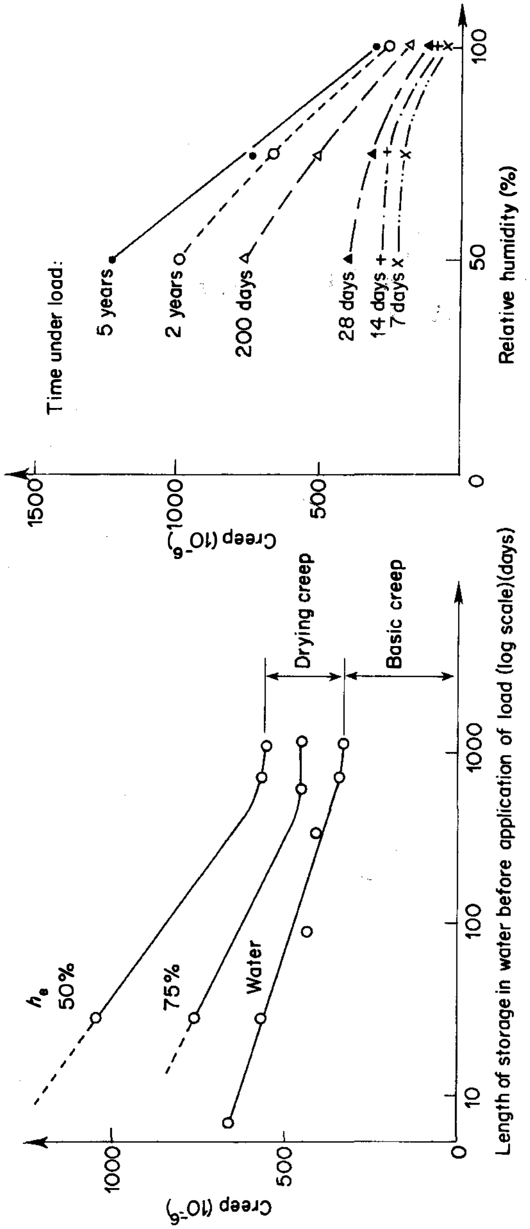

Figure 7 Creep strain versus age at loading with curing in water prior to loading (left, L'Hermite *et al.*, 1965), and creep strain versus environmental humidity h_e for various durations of loading (right, L'Hermite and Mamillan, 1968b)

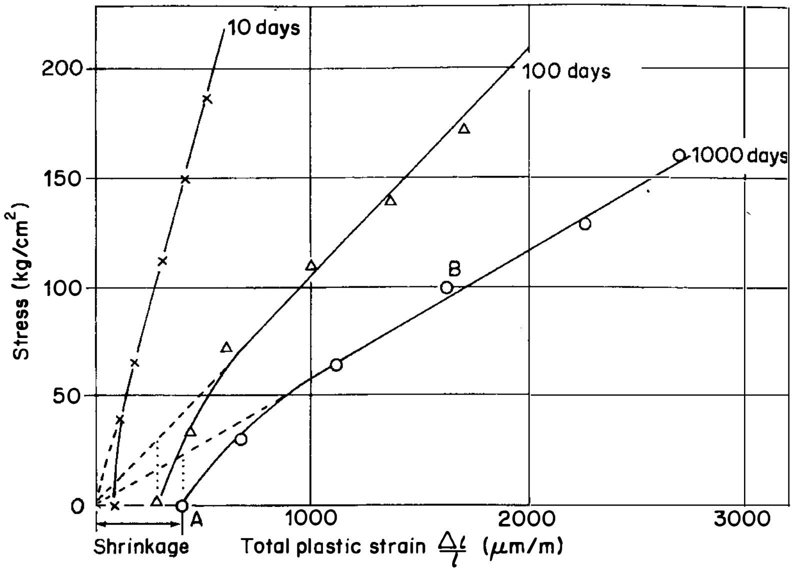

Figure 8 Stress versus total strain (elastic plus creep plus shrinkage) for various load durations (L'Hermite, 1959)

Munich. One recently proposed differential equation for creep at drying involves a term which may be called the stress-induced shrinkage, consisting of a product of stress and pore humidity rate, which is analogous to the product $\sigma\varepsilon_{sh}$ and can be obtained from Eq. (4) through differentiation at constant σ. We are still benefiting from L'Hermite's insight.

Understanding of creep recovery is basic to the formulation of a constitutive equation as well as the physical mechanism of creep. L'Hermite was one of the early researchers to test the phenomenon and establish its existence (L'Hermite, 1959). This led him to conclude that a viscoelastic creep governed by some sort of superposition principle must be part of the creep formulation, aside from Eq. (1) which describes no recovery (L'Hermite and Mamillan, 1968b).

Furthermore, L'Hermite was first to discover one peculiar, initially quite surprising, property of creep recovery: when creep recovery is observed on specimens exposed to a lower environmental humidity, and the specimen is submerged in water at a certain time during the recovery, a large additional creep recovery is seen; see Fig. 9 (left) (L'Hermite, 1959). The recovery as plotted represents, like the preceding creep, the difference between a loaded specimen and a load-free companion specimen exposed to the same environmental history. L'Hermite (1959, 1960) also showed that the same kind of behavior is observed for both compression (Fig. 9) and tension. This test, perhaps more than any other,

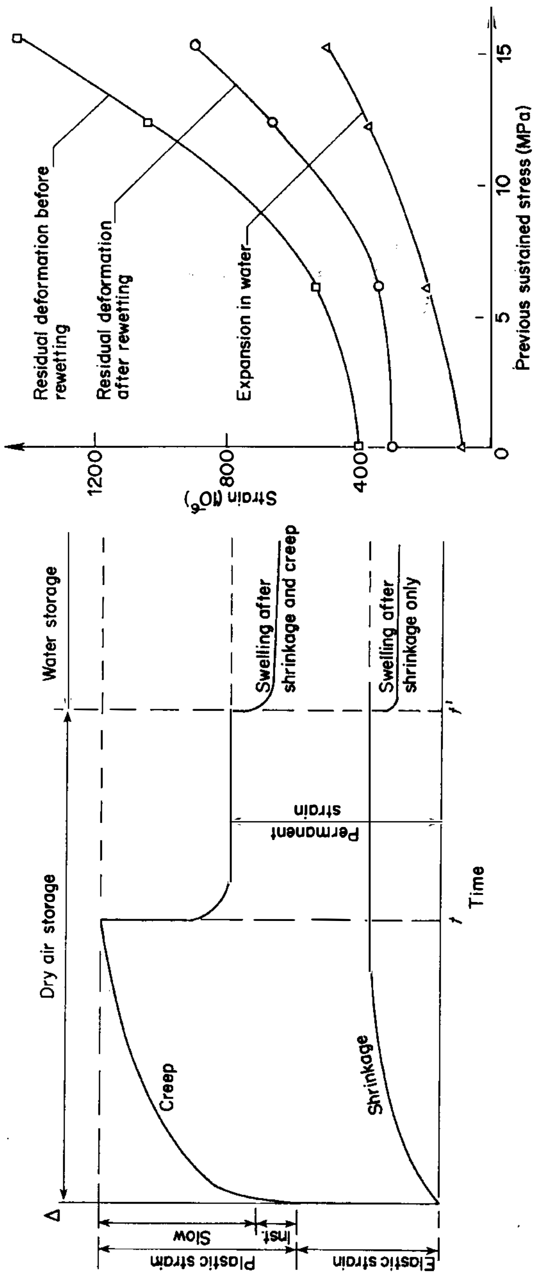

Figure 9 Creep recovery accelerated by immersion in water (left, L'Hermite, 1960), and creep recovery strain versus previous constant stress for various humidity regimes (right, L'Hermite, 1959)

establishes that water does play a significant role in the mechanism of creep. L'Hermite considered the additional recovery caused by a humidity increase to represent an increase of swelling due to load. This viewpoint has recently found its mathematical formulation in the differential equation for stress-induced shrinkage or swelling (depending on the sign), whose development has been a recent effort in our Center at Northwestern. The cross effect between stress and humidity now appears to be just a different manifestation of the same phenomenon, as described by L'Hermite's Eq. (4) and illustrated in Fig. 8.

4 SHRINKAGE AND HYGROTHERMAL BEHAVIOR

Due to the ubiquitous problems with shrinkage cracking, prediction of shrinkage interested L'Hermite since the beginning of his career. Noting that the dependence of shrinkage strain ε_{sh} on environmental humidity h_e is more involved than on specific water content w, he verified the simple relation

$$\Delta\varepsilon_{sh} = \rho(D)\Delta w \tag{5}$$

in which ρ = an empirical coefficient depending on the characteristic dimension d of the specimen or structure. This linear relationship, which was also established by others (e.g. T. C. Powers), approximately applies through the entire range for hardened cement pastes, while for concrete it is only true after a certain initial water loss (L'Hermite, 1960). The direct relationship of shrinkage strain and water loss is still accepted at present as a somewhat crude but still very useful approximate description of the phenomenon, having its merit mainly in its simplicity. The dependence of coefficient ρ on size D, which was introduced by L'Hermite, is understood today as chiefly a correction for the different effects of shrinkage on microcracking in small and large specimens, as well as for the differences in the aging effect, which is stronger in larger specimens because they retain their moisture for a longer time and thus reach a higher degree of hydration. To take the effect of size approximately into account in a simple manner, L'Hermite proposed (L'Hermite and Grieu, 1952) the use of the volume–surface ratio:

$$D = V/S \tag{6}$$

which is still used in the current design recommendations, including the BP model developed in our Center at Northwestern.

Although L'Hermite noted that the calculation of water content and shrinkage should ideally be based on the diffusion theory (Fourier differential equation), he proposed that, for the sake of simplicity, the practical calculations may be conducted on the basis of the ordinary differential equation in time:

$$\dot{w} = w_1 f_1(h_e)(w_\infty - w) \tag{7}$$

in which w_1 = the initial specific water content before the start of drying, f_1 is an empirical function of environmental relative humidity h_e, assumed to be constant in time, and w_∞ is the final specific water content corresponding to thermodynamic equilibrium at h_e. While Eq. (2.7) is not in good agreement with the diffusion theory for the initial drying period, it may be shown that it describes quite well the later stage of drying and is asymptotically exact for the final stage of drying. In comparison with his numerous measurements of water loss and shrinkage (L'Hermite and Grieu, 1952; L'Hermite, 1960), L'Hermite noted that the final value is approached systematically slower than the exponential solution of Eq. (7) indicates. He then observed that the time derivative (denoted by a superimposed dot in Eq. 2.7) should be taken with regard to some reduced time $\eta(t)$ rather than the actual time, in which case the solution of Eq. (7) may be adapted as

$$w - w_\infty = (w_1 - w_\infty)(1 - e^{-\eta(t)}) \tag{8}$$

For the reduced time $\eta(t)$ he considered various formulas, e.g.

$$\eta(t) = (\alpha t^{-1/3} + \beta)(t - t_0)^{1/2}$$

in which α, β = constants and t_0 = age at the start of drying. Coefficients α and β were considered by L'Hermite to depend on size D, which is a necessary consequence of diffusion theory. However, the fact that the water loss as well as shrinkage should be a function of $(t - t_0)/D^2$, which is an essential part of the latest prediction formulae, was not introduced by L'Hermite. No doubt this was for the reason that the size-square dependence of shrinkage times is partially obscured by several other effects, especially irreversible strain-softening or microcracking, and ageing, which were not clearly recognized at that time.

The extensive measurements in L'Hermite's laboratory led to a wealth of fundamental information on shrinkage, the essentials of which are illustrated in Figs 10 and 11 (L'Hermite *et al.*, 1965, L'Hermite and Mamillan, 1968a, b). Figure 10 shows the dependence of the shrinkage strain at various times on the environmental relative humidity, for the start of drying at $t_0 = 2$ days (left) and 624 days (right) (L'Hermite *et al.*, 1965). Figure 11 shows the famous results (L'Hermite and Mamillan, 1968b) on the curves of shrinkage versus logarithm of the duration of exposure $(t - t_0)$ for various sizes and shapes of specimens ranging up to the largest specimens apparently ever tested in a laboratory (100 × 100 × 400 cm); these tests were carried out in L'Hermite's new laboratory in Saint-Rémy-les-Chevreuses, a suburb of Paris. The curves in Fig. 10 can be approximately described as $1 - h_e^3$, and in this form are used in the present design recommendations (e.g. the BP model).

As for the dependence on size D, approximately described as a dependence on V/S, L'Hermite noted that the times to reach the same shrinkage value are, for long times, approximately proportional to $(V/S)^n$, where $n = 1.5$ to 2. According to the diffusion theory the exponent should be exactly $n = 2$, however only if the spoiling effects of aging, microcracking (strain-softening), and initial heating due to hydration are ignored. It was because of these spoiling effects on the size-square dependence that L'Hermite found values of n that were not exactly 2.

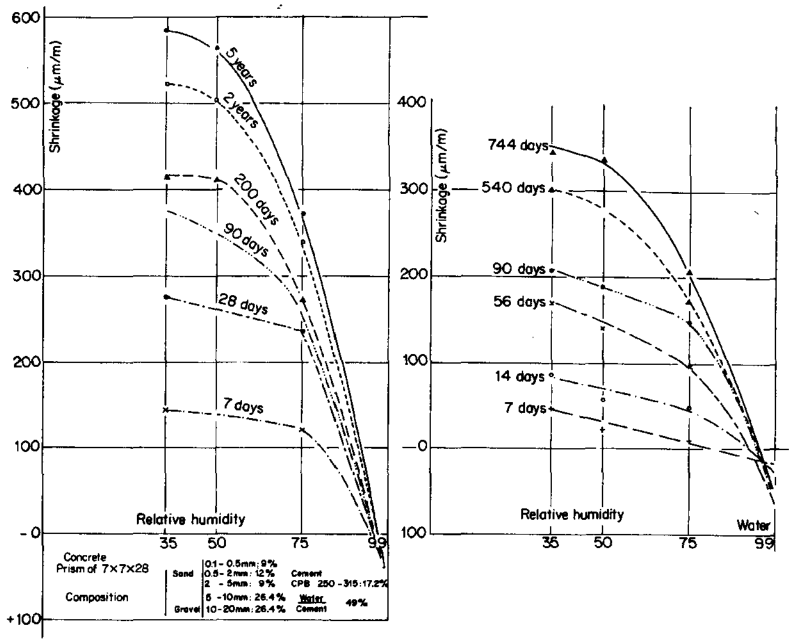

Figure 10 Shrinkage strain versus environmental humidity for various durations of drying exposure beginning at age 2 days (left) and 624 days (right, L'Hermite and Mamillan, 1968a)

Another curious but doubtless correct property of the size effect in Fig. 11 (left) is the large swelling observed for large specimens. Initially L'Hermite with Mamillan suspected it might be due to thermal expansion caused by hydration heat, which leads to higher temperatures in larger specimens. Therefore, he carefully measured (L'Hermite and Mamillan, 1968b) the temperature histories in specimens of various sizes. He found, however, that the temperatures returned to normal long before the end of the swelling segment of the curves in Fig. 11. This led him to conclude, certainly correctly, that hydration heat can yield at best only a partial explanation of the initial swelling. He conjectured that his concrete exhibited some sort of autogeneous volume change due to chemical reactions. This explanation seems to me unlikely, though, since swelling in normal concretes is observed only at water immersion. In view of various recent finite element analyses of the stress and strain fields in drying specimens, I think that the main cause for the long duration of the observed swelling (Fig. 11) was the fact that hydration heat probably produced microcracking (strain-softening) which is largely irreversible and, therefore, makes the swelling persist for a much longer time until it is finally overcome by shrinkage from the final drying. Strain-softening and its irreversibility (established, e.g. by Reinhardt and Cornelissen,

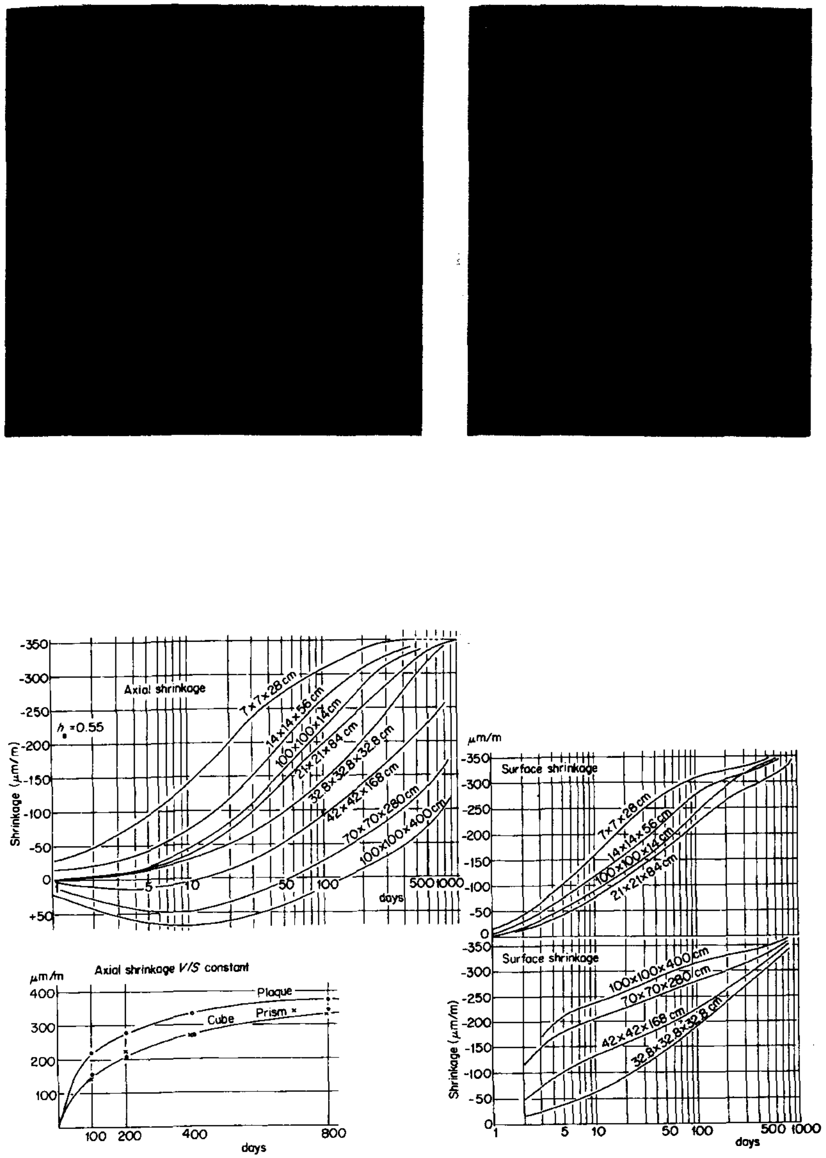

Figure 11 Photos of large shrinkage specimens and deformation measurement (top), shrinkage strain versus logarithm of drying duration for various sizes and dimensions of specimens, measured at specimen axis (left) and at specimen surface at midlength (right), and shrinkage strain versus the logarithm of drying time for slabs, cubes, and prisms (bottom left), L'Hermite *et al.*, 1965

1984) was, of course, unknown at the time of L'Hermite's work.

In Fig. 11 (bottom left) results are shown (L'Hermite and Mamillan, 1968b) which document the effect of geometrical shape on shrinkage. The curves are for slabs, cubes, and prisms of the same volume-to-surface ratio.

Another important result which we owe to L'Hermite was his detection of a very significant difference between the shrinkage measured on the specimen axis and on its surface at midlength, as shown at left and right of Fig. 2.11. For an infinitely long prism or cylinder, both shrinkage strains must of course be exactly equal, however the length of typical laboratory specimens is too small in this regard. Obviously, for typical structural members which are usually quite long, the axial shrinkage is more relevant, whereas up to L'Hermite's discovery most of the shrinkage measurements had been taken on the specimen surface. Recently, two- and three-dimensional finite element analyses have clearly confirmed these results theoretically. In this respect I wish to call attention especially to the work of Wittmann and Roelfstra (1983) who calculated the deformation field of typical shrinkage specimens, taking into account moisture diffusion (according to a nonlinear diffusion equation), creep, aging, and cracking, and particularly documented the out-of-plane warping of the end surfaces of shrinkage specimens.

By means of Fig. 2.11 (right) L'Hermite also documented how misleading the surface measurements of shrinkage on insufficiently long specimens can be. Note the reversal of the size effect for specimens thicker than about 30 cm, which is doubtless a consequence of the great difference in the spread of microcracking between small and large specimens.

To check relevance to real structures which are exposed to fluctuating rather than constant environmental humidity, L'Hermite tested identical specimens in the laboratory (at relative humidity 50 per cent) and in the field where the mean environmental humidity was roughly the same (L'Hermite and Mamillan, 1968b). The results are reproduced in Fig. 12 (L'Hermite and Mamillan, 1968b). They reveal that the differences are not terribly large and that laboratory specimens can be used as a crude indicator of shrinkage outdoors. It may be noted that the differences between the shrinkage of laboratory specimens and actual structures can be much larger, but most of these differences are probably caused by differences in structural shapes and dimensions, which can greatly alter the effects of microcracking from residual stresses.

Note in this regard that shrinkage does not respond to fluctuating humidity the same way as creep. L'Hermite with Mamillan (L'Hermite *et al.*, 1965; L'Hermite and Mamillan, 1968a) conducted extensive laboratory investigations of creep at cyclic humidity changes, and detected an appreciable increase of the drying creep, which was later confirmed by other investigators. These laboratory measurements at cyclic humidity changes yielded valuable data on irreversibility of shrinkage (hysteresis of sorption isotherms) also studied by many other investigators.

An important aspect of shrinkage and creep, frustrating from the theoretical viewpoint, is the dependence on composition. We owe to L'Hermite one simple

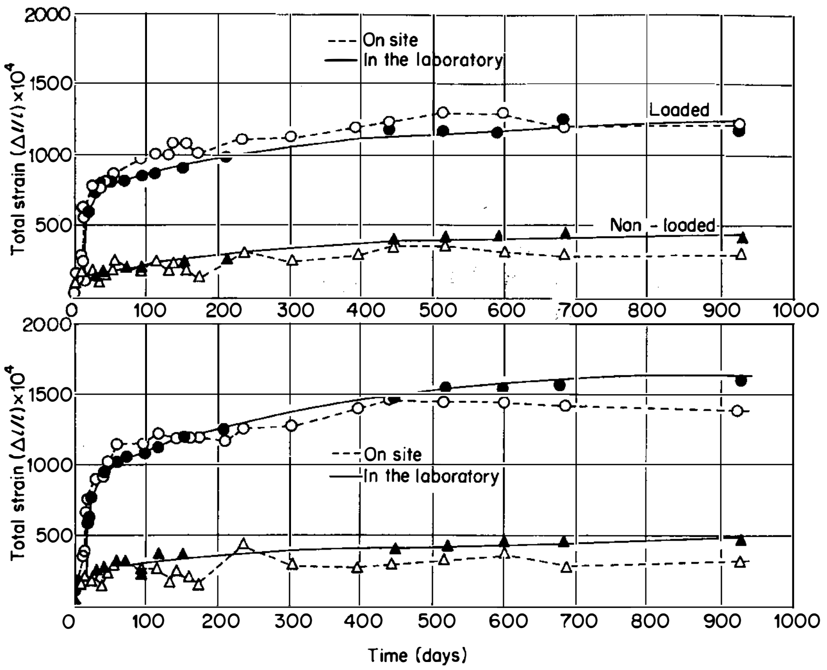

Figure 12 Total strain versus time for identical loaded and load-free specimens in the laboratory (——, constant environment relative humidity 50 per cent) and outdoors (L'Hermite and Mamillan, 1968b)

semi-empirical formula which gives relatively good results:

$$\varepsilon_{sh} = \varepsilon_{sh}^{cp} \frac{v_c}{v_c + \mu_{ca} v_{ag}} \tag{9}$$

in which ε_{sh}^{cp} = shrinkage of hardened cement paste, v_c and v_{ag} = volume fractions of cement and aggregate in the concrete mix, and μ_{ca} = an empirical coefficient which seems to depend on the water–cement ratio (L'Hermite, 1959).

Related to shrinkage are the hygrothermal effects. L'Hermite (1960) was one of the first to observe that the coefficient of thermal expansion of concrete, α, is not a constant but strongly depends on the environmental humidity h_e with which the specimen is initially in equilibrium; see Fig. 13 (L'Hermite, 1960). Later several researchers including myself theorized to explain this phenomenon. No doubt heating or cooling causes a change of the relative humidity in the pores of concrete. Therefore, at least a part of the apparent change in the thermal expansion coefficient in Fig. 13 is attributable to shrinkage or swelling induced by temperature change (and described, e.g. by the hygrothermal coefficient κ).

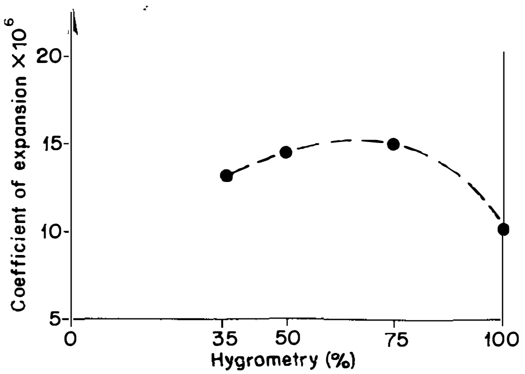

Figure 13 Thermal expansion coefficient at various environmental humidities (L'Hermite and Mamillan, 1968b)

5 STRENGTH, DEFORMATION, AND OTHER ASPECTS RELEVANT TO CREEP

The most deleterious consequence of shrinkage and creep in structures is cracking. L'Hermite studied experimentally various influences which affect the appearance of shrinkage cracks. In 1952 (L'Hermite and Grieu, 1952) he made an observation which apparently did not arouse much interest at that time but which appears to me remarkable in the context of our present—day research. He noted that the value of the shrinkage strain that is necessary to produce the first cracks is much larger for small specimens than for large ones. The size of the specimen is of course related to the gradient of strain, $\partial\varepsilon/\partial x$, and so he concluded that the greater the strain gradient, the greater must be the shrinkage strain to produce the first cracking. This means that the critical strain at which the first cracks appear may be expressed as (L'Hermite and Grieu, 1952)

$$\varepsilon_{\text{crit}} = k_{\text{cr}} \frac{\partial \varepsilon}{\partial x} \tag{10}$$

in which k_{cr} = an empirical constant. With this relation L'Hermite leaped well ahead of the research front. Within the context of bending theory based on the assumption of plane cross-sections, the dependence of failure strain or strength on the stress or strain gradient was discovered and intensely studied during the 1960s (e.g. by Karsan and Jirsa, 1969), and in the general context of continuum mechanics we started to tackle these problems only in the 1980s, in the more general context of non-local continuum.

As we now know, a salient characteristic of brittle heterogeneous materials such as concrete is that their failure condition can be described locally (pointwise) neither by means of fracture mechanics (fracture energy) nor by strength criteria or failure surfaces expressed in terms of stresses or strains. Rather, the failure condition requires a non-local formulation which in some suitable manner averages the strains or stresses, damage, or cracking from a statistically representative volume of the heterogeneous material. If the non-local formulation is ignored, the theory predicts physically meaningless results; e.g. in a continuum theory it invariably predicts the failure zone to localize into a vanishing volume and the structure to fail at zero energy dissipation, which is impossible. The key to correct modeling is to mathematically formulate the so-called localization limiters which reflect in one or way another the non-local character of the smoothing continuum for a statistically heterogeneous medium. One device which achieves this in a simple manner is to consider that the strength parameters depend on the strain or stress gradient, as recently introduced by Floegl and Mang (1981) and Schreyer and Chen (1986). This is obviously the same as proposed for shrinkage cracking more than 30 years ago by L'Hermite (L'Hermite and Grieu, 1952).

The stresses produced by shrinkage or creep must be compared to the long-time strength. L'Hermite was one of the early researchers occupied with the determination of long-time strength, and showed that for uniaxial compressive stress the long-time strength is approximately 80 per cent of the short-time strength f'_t, a fact which was established roughly at the same time in several laboratories. L'Hermite extended his inquiry also to tensile loading and was probably the first to find that a similar strength reduction occurs in tension (L'Hermite and Mamillan, 1968b).

A large study in L'Hermite's laboratory, motivated by the French development programme for nuclear prestressed concrete pressure vessels, was conducted to elucidate the effect of temperature on concrete creep as well as strength. In 1968, he reported with Mamillan (L'Hermite and Mamillan, 1968b) test results on strength reduction at high temperatures, showing a 50 per cent reduction at 400° C. Major results on the effect of very high temperatures on concrete creep were later obtained in L'Hermite's laboratory by Maréchal.

Another interesting experimental result by L'Hermite on cracking deals with the difference in load-deflection diagrams between plain concrete and reinforced concrete in tension. He made the differences conspicuous by his measurements (Fig. 14) of tensile response of plain concrete cylinders and cylinders cast within a steel tube and bonded to it (the tube was threaded to prevent bond slip). The stress plotted in Fig. 14 he deduced from the load after subtracting the known force in the tube.

The difference in response after initial cracking between these two specimens, as apparent from Fig. 14, is truly remarkable. To my knowledge we do not yet have a general material model which would correctly described this behaviour, although we understand that the phenomenon is due to the fact that bonding to the reinforcement (a tube in this case) forces the cracks to be distributed more densely and have a smaller opening width. Cracks of small widths are known to

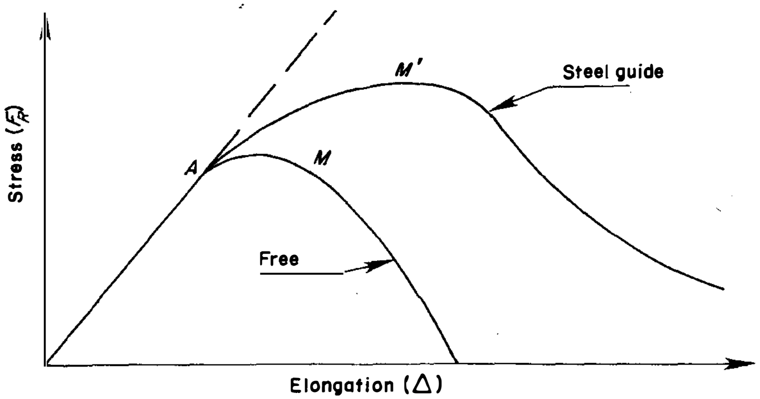

Figure 14 Tensile stress–strain diagram for plain concrete specimen (free) and for a specimen cast into a threaded steel tube (the force in the tube excluded) (L'Hermite, 1960)

be discontinuous and are capable of transmitting large tensile stresses. Hence must come the large increase of the tensile carrying capacity of bonded concrete, demonstrated in Fig. 14.

L'Hermite was a pioneer in the development of sonic non-destructive methods for concrete. He measured sound velocity as well as sound emissions at various stages of the uniaxial compression test; see Fig. 15 (L'Hermite, 1960). The results presented a coherent picture: the increase of sound emissions due to cracking, which begins at roughly 60 per cent of the strength, coincided with the beginning of the decrease of sound velocity, as well as with the beginning of the increase in Poisson ratio caused by inelastic volume expansion whose source is microcracking (Fig. 15).

The sound velocity studies led L'Hermite to conduct tests to determine the relation of the dynamic modulus to the conventional static elastic modulus (L'Hermite and Mamillan, 1968a). He concluded that the dynamic modulus is apparently very close to the initial tangent modulus of the static stress–strain curve, as required if the initial rapid creep is governed by linear viscoelasticity. He showed the effect of various rates of loading on the stress–strain curve (L'Hermite *et al.*, 1965).

In connection with these studies L'Hermite recognized that for a complete description of creep he must add to the expression for long-time creep the rapid initial creep ε_i, e.g. in his Eq. (3). Some of us may prefer today to describe the initial creep and the long-time creep by one and the same expression, since it now seems there is no clear-cut distinction between them, both in terms of a time limit and in terms of physical mechanism. Nevertheless, from the practical viewpoint there can be no dispute with L'Hermite's separation of both components since they can describe the test results quite well.

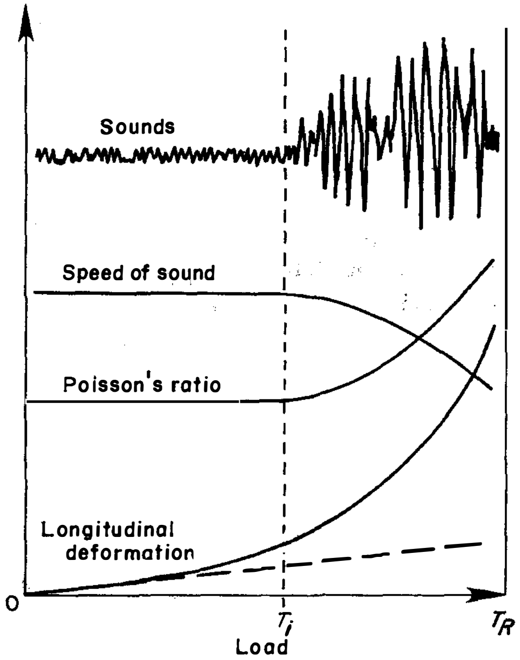

Figure 15 Sound emissions, sound velocity, and Poisson ratio as a function of load in a uniaxial compression test (L'Hermite, 1960)

Finally, I would like to mention that we are indebted to L'Hermite for a widely used empirical conversion formula between the strengths of cylinders and cubes (L'Hermite, 1955) (given in psi):

$$f'_{\mathrm{cyl}} = 0.76 + 0.2 \log \frac{f_{\mathrm{cube}}}{2840} \tag{11}$$

6 TEST EQUIPMENT

In his heart, L'Hermite was primarily a man of the laboratory. He kept inventing testing methods and was ingenious in devising improved test equipment. He developed the L'Hermite–Lepetit dynamometer, the electrical resistance fleximeter, a permeability measurement device, etc.

For creep testing, his innovation was the hydraulic loading frame which was both less costly and easier to use than the previous spring-loading devices. L'Hermite's creep-loading device, illustrated in Fig. 16 (L'Hermite, 1959), makes hydraulic long-time loading possible by perfectly eliminating leakage of the fluid.

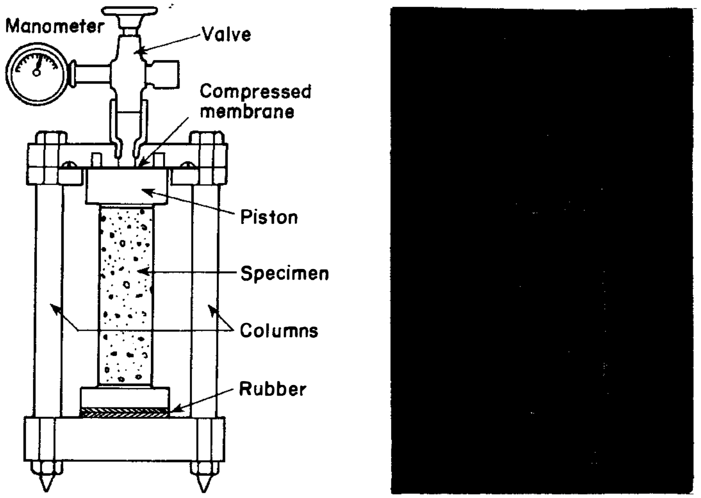

Figure 16 L'Hermite's hydraulic creep loading device (L'Hermite, 1959)

This is achieved by the use of a rubber membrane (an idea previously introduced by Rüsch), which is made possible by the fact that the displacements are extremely small.

7 CONCLUDING THOUGHTS AND REMINISCENCES

Despite the limited scope of my account, I hope to have demonstrated what an original thinker and prolific researcher L'Hermite was. As a society president and chairman of various committees and boards, he had to be a man of compromise. Yet he was a man of uncompromising principles. This I realized, for example, at the 1975 RILEM meeting in Edinburgh where as I know he resisted compromise in a matter of a politically motivated challenge having to do with the conferral of the RILEM Medal.

Having shared his table at the Edinburgh banquet, I still recall as he shifted the conversation, after his presentation of the RILEM Medal (now known as L'Hermite Medal), to his thoughts about science, the role of theory and attitudes of theorists. He had previously (1959) put some of his thoughts on paper, and let me end by quoting them (L'Hermite, 1959, p. 41):

> In the present state of knowledge, is it expedient to ... establish a theory of creep? The proposition will seem unnecessary to some, presumptuous to others. My opinion is that a theory is always necessary, in experimental studies, even if it be false. Let me explain. ... A theory must first of all satisfy the curious mind that wants to know why things happen. The experimenter, on the other hand, needs psychological support, for he does not like to work in the dark. A theory is meant to verify correct hypotheses or to invalidate erroneous hypotheses. It is meant to be abandoned for another, more satisfying one, or to be perfected when knowledge is improved. A theory must always be such that it can be abandoned, even if this is painful to the author, but only in favor of another.

In the case of L'Hermite, however, none of his basic contributions to the creep theory have had to be abandoned so far, and I hope my review demonstrated that sufficiently.

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