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**MECHANISM OF CREEP
OF HYDRATED PORTLAND CEMENT PASTE**

by
R. F. Feldman

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MECHANISM OF CREEP OF HYDRATED PORTLAND CEMENT PASTE

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(Communicated by F. H. Wittmann)

ABSTRACT

Understanding of the mechanism of creep requires direct measurement of the physical changes that occur in the micro-units of the solid and in the solid body itself as a result of change in exposure conditions. Results of rigidly controlled water sorption experiments are presented, giving measurements of change in length of specimen, weight, solid volume, and helium flow characteristics as a function of change in conditions of exposure. These are correlated with creep results in the literature. It is concluded that creep is a manifestation of the gradual crystallization or aging process of the layered material, resulting in further layering. Water movement, although occurring, is not a major mechanism. Other processes such as slippage and micro-cracking are also present.

SOMMAIRE

Pour comprendre le mécanisme du fluage, il faut mesurer directement les changements physiques qui se produisent dans les micro-unités du corps solide et dans ce corps lui-même par suite d'un changement des conditions d'exposition. L'auteur présente les résultats d'expériences très précises de sorption d'eau, indiquant les changements de longueur de l'échantillon, le poids, le volume à l'état solide et les caractéristiques du flux d'hélium en fonction du changement des conditions d'exposition. Ces données sont mises en corrélation avec les résultats relatifs au fluage publiés dans la littérature. L'auteur conclut que le fluage est une manifestation de la cristallisation graduelle ou du procédé de vieillissement du matériau en couches, aboutissant à une nouvelle formation de couches. Bien qu'il y ait mouvement d'eau, ce mécanisme n'est pas d'une grande importance. On trouve également d'autres procédés comme le glissement et la micro-fissuration.

Introduction

Deformation and volume change of concrete and cement paste resulting from applied stress, as a function of time (creep) and changes in exposure history, have been studied intensively for several decades (1) and many hypotheses have been advanced to explain the phenomena. Although it is almost certain that every possible mechanism has already been proposed, there are not as yet any definite conclusions. It is clear, however, that there is not necessarily a different mechanism for each set of conditions.

It has become increasingly evident that shrinkages following loss of moisture and creep are inter-related, although the motive force for creep is an externally applied pressure, as opposed to that for shrinkage (1, 2, 3). On the other hand, L'Hermite (4) emphasizes that this may be due only to the fact that the two phenomena are independently associated with some other property.

Experiments have shown (5, 6, 7) that a very low creep rate occurs in oven-dry specimens, and this in fact was used as the main evidence for the "seepage" theory. Recently (8, 9, 10, 11) it has been suggested that the latter theory is the rate-determining and structure-deforming process in which thin layers of adsorbed water are displaced from narrow spaces between particles (areas of high stress) of solid material.

Work by Feldman and Sereda (12) has emphasized the layered nature of C-S-H gel and suggested that interlayer water relocation plays an important role, although it is not necessarily the rate-determining process. Their work on compaction of bottle-hydrated cement powder has shown how bonds can be broken and remade, lending credence to "viscous flow" type theories (1). The role of adsorbed water, they postulate, is scarcely significant.

Some other authors (1, 13-18) have taken the position that several processes occur simultaneously. Most notable of these are Kesler and co-workers (16), Ruetz (15) and Neville (1). They refer to several processes such as seepage, delayed elasticity, viscous flow and aging, as well as intercrystal-

line slip and bond rupture. Some workers (1) also postulate that a shear process takes place where multi-plate crystal surfaces slide one over the other; microcracking and dislocation movement were also considered.

Three experiments (7, 17, 18) have produced pertinent results that are not well explained by current theories. They involve oven drying and rewetting of samples in different ways; the work of Wittmann (7) presents the best defined conditions of the three, and he found that the creep rate only increased significantly when dried samples were re-exposed to humidities above approximately 45% R.H. These results cannot be accounted for by the 'seepage' theory, as will be discussed. Creep measurements at different conditions of exposure, however interesting, can only provide information of significance if the changes that occur in the solid in response to changes in exposure conditions are known.

What is now needed for a more detailed and specific explanation of the mechanism of the creep process is direct experimental measurement of the physical changes that occur in the micro-units of the solid as a result of change in exposure and internal stress conditions; these changes can then be correlated with the resulting changes in creep rate, if any, when the material is placed under stress.

Results of controlled water sorption experiments under high vacuum conditions are now presented, giving measurements of change in length of specimen, weight, solid volume and helium flow characteristics as a function of change in conditions of exposure. Finally, a more detailed mechanism for the creep phenomenon is postulated.

Experimental

Three series of experiments were conducted:

(1) D-Dried samples of hydrated portland cement were re-exposed to water vapour in increments of relative humidity up to a certain value and in increments back down to the d-dry conditions. Both length and weight were measured at each humidity. Several runs were performed, highest humidities of exposure for each being, consecutively, 97%, 16.8%, 75% (partial

pressure of methanol); 1.47%, 53.3%, 71.8%, 85.0% and 100%. At the conclusion of each run, on the return to the dry position, the length of the specimen was compared with its length at the previous d-dry condition at the commencement of the run. There was net shrinkage on each occasion.

(2) The "solid volume" of the sample of hydrated portland cement was measured with a helium pycnometer as a function of water content, commencing with the 11% R.H. condition on the first drying cycle; solid volume was measured at moisture content increments down to the d-dry condition. This sample was then re-exposed to relative humidities of 11, 42, 66 and 100%, consecutively. After exposure to each humidity it was returned to 11% R.H. for a considerable period in order to attain equilibrium before the solid volume was measured again and recorded as a function of weight. The sample was then dried in several steps back to the d-dry condition, the solid volume being measured at each step.

(3) Helium inflow measurements were made on the above sample at the following conditions:

- the 11% R.H. condition on the first drying stage;
- the d-dry state;
- the 11% R.H. condition attained after rewetting of the d-dry sample to 100% R.H.

Materials

Five samples were used in the first experiment; three were compacts of a bottle hydrated type I cement, hydrated for a period of 4 months at a water cement ratio of 5. Degree of hydration was over 90%. The other two samples were paste hydrated for one year at a water-cement ratio of 0.5. The bottle-hydrated cement was stored and conditioned in desiccators to 10 to 15% R.H. using a concentrated NaOH solution. Degree of carbonation of samples was 1.0% by weight. The cast paste cylinders were sliced into discs 0.05 in. (1.27 mm) thick, approximately 3.175 cm in diameter, and were stored as above. Compacts were formed at 8,200 psi (pore volume approximately equivalent to that of a 0.8 w/c paste) in a mold 1.25 in. (3.175 cm) in diameter from the bottle-hydrated cement. The procedure

for making the compacts and the samples has been described (19).

The methanol used in this work was purified by making a magnesium iodine Grignard complex by refluxing magnesium turnings and iodine in a large excess of 99% pure methanol. After several distillations, the methanol was distilled directly into the high-vacuum apparatus.

In the second and third experiments representative paste discs from cylinders 3.2 cm in diameter and hydrated at water-cement ratios of 0.4, 0.6, 0.8, and 1.0 for 2.5 years were used but only the results for the 0.8 water-cement ratio paste are now presented. They are considered to be representative. Discs were cut 1.25 mm thick and stored at 11% R.H. in a desiccator.

Apparatus

(1) High vacuum sorption apparatus

This apparatus, described previously (20), was used to obtain length change versus weight change relations while samples in the first experiment were exposed to various humidities. The apparatus was designed to expose 12 samples, simultaneously and for long periods, to the same vapor pressure conditions, with air excluded. Six of the samples were mounted in individual tubes on quartz spirals of the McBain-Bakr type and gave values of weight change to a sensitivity of 3.0×10^{-5} gm. The remaining six samples were mounted on modified Tuckerman optical extensometers and placed in individual cells. This determined dimensional changes to a sensitivity of 4×10^{-6} in./in.

(2) Helium comparison pycnometer

This apparatus has been described in a previous paper (21). "Solid volume" measurements are made immediately after helium has been compressed to two atmospheres in the apparatus and helium flow measurements are subsequently made as a function of time, with the pressure maintained at two atmospheres.

Procedure

(1) Length and weight change

Two samples of each, measuring 3 by 1 by 0.127 cm, were cut from discs of both paste and compacts and mounted, one section on the extensometer and the other on the quartz spiral. Samples were degassed by evacuating simultaneously through a manifold. The samples were heated during evacuation at 95°C for 4 hours. For subsequent cycles the samples were heated for longer periods at 97°C to achieve the same weight loss. The relation between this treatment and conventional d-drying has been discussed (20).

Many closely spaced equilibrium points were taken at different relative humidity values; generally, three days per point were allowed for equilibrium. Figure 1 presents the results of the $\Delta l/l$ and $\Delta w/w$ measurements for one sample compact. Each cycle is numbered according to the total number of dryings the sample has experienced up to the end of the cycle. Cycle II consists of 59 experimental points in a total time of 10 months; cycle III, of 15 points in 23 days; cycle IIIa for methanol, of 13 points in 23 days; cycle IV, of 7 points in 8 days; cycle V, of 34 points in 5 months; cycle VI, of 29 points in 4 months; cycle VII, of 32 points in 10 months; and cycle VIII, of 12 points in one year. At completion of the experiments the degree of carbonation was the same as at the beginning of the experiments.

(2) Solid volume and helium flow measurements

In the first drying from the 11% R.H. condition the sample was heated under vacuum in a separate vacuum vessel to remove an increment of water. The sample was in the form of several discs (previously described), the total weight being about 13 gm. After each increment of weight change, the solid volume was measured by means of a helium pycnometer; following the final stage of drying the samples were stored in vacuum desiccators over the appropriate salt solution for the desired humidity (22). After exposure in excess of 40 days at each humidity the samples were maintained at 11% R.H. for 5 months. Solid volume measurements were made each

FIG. 1

Length versus weight change for hydrated cement
compact-cycles II to VIII

time the samples were at 11% R.H. Helium flow measurements were made at three conditions, as mentioned above.

Results

(1) $\Delta l/l$ vs $\Delta W/W$ relations

These are presented on Fig. 1 for one of the compacted bottle hydrated cement samples. The results are typical of the compacts and paste samples.

The general features of the curves, for example curve II, have been discussed previously. First drying, not shown here, produced a shrinkage from the 11% R.H. condition to d-dry of 0.80%; back to 11% on the desorption part of the cycle via 100% R.H. yielded a re-expansion of 0.41%, a total irreversible shrinkage of 0.39%. The consecutive cycles measured on

the one sample are plotted so that the final value for $\Delta l/l$ on every cycle is always negative, i. e. a net shrinkage with respect to zero at the commencement of that cycle and an increase in over-all net irreversible shrinkage commencing with cycles I and II. The slope of the linear portion of the adsorption part of the cycle does not increase significantly from curves II to VII, and to only a moderate extent for curve VIII. After 5% weight gain, however, curves V to VIII show a significant increase in $\Delta l/l$ in relation to curve II in going from approximately 45 to 100% R. H. (for example, 0.336, 0.380, 0.394, 0.420 and 0.406% length change for curves II, VI, VII and VIII, respectively). This trend continues for higher weight gains; after 8% weight gain, 0.432, 0.474, 0.516 and 0.560% length change for curves II, VI, VII and VIII, respectively. In addition, curve II shows a total length change of 0.528% compared with 0.768% for curve VIII. The extra weight gain in cycle VIII over that of cycle II does not cause much length change and is probably only due to a greater degree of condensation in the large pores at 100% R. H. The additional expansion, however, only partially reflects the irreversible shrinkage accumulated between curves II and VII. This amounts to 1.026%, while the increase in expansion between curves II and VIII is only 0.24%. The total irreversible shrinkage for the eight cycles, including first d-drying, is 1.906%; this would probably be increased by further cycles.

Observations from these results also include:

- (a) Expansion up to 50% R. H. on the adsorption curve of cycles II and VIII is 65 to 70% of the total expansion at 100% R. H. The 50% and 10% R. H. 's are marked with arrows (on Fig. 1) on adsorption and desorption curves of all the cycles where these humidities were attained.
- (b) In all cases hysteresis between the adsorption and desorption curves at both 50% and 10% R. H. is large.
- (c) Shrinkage between approximately 100% R. H. and 50% R. H. on desorption is 0.104% and 0.049% for curves VIII and II, respectively, and between 50% and 10%, 0.128 and 0.071, respectively.
- (d) Shrinkage for each cycle beyond its original zero, termed "irreversible shrinkage," is plotted as a function of its maximum relative humidity of

FIG. 2

Irreversible shrinkage versus re-exposure relative humidity for hydrated cement compacts.

FIG. 3

Irreversible shrinkage versus re-exposure relative humidity for cement paste.

exposure. These plots are presented on Figs. 2 and 3 for the three compacts and two paste samples, respectively. The subscripts on the points at 100% R. H. represent cycles II and VIII. Cycle II was measured on a third sample of paste.

As may be observed, irreversible shrinkage increases abruptly beyond 50% R. H. after a relatively constant, low value between 10 and 50% R. H. This is analogous to the results of Wittmann (7) of the creep rate versus relative humidity of exposure. The point at 100% R. H. for cycle VIII is anomalous in that the values between the pastes and the compacts are not similar although all other points are. The reason is not fully understood, but it may be related to the fact that the compact is pressure formed.

(e) Although the order of relation of shrinkage of samples between 50 and 10% R. H. versus the maximum relative humidity of exposure is similar to that of the irreversible shrinkage obtained after completion of a cycle, the former shrinkage is only a minor proportion of the total shrinkage. In addition, the irreversible shrinkage during the 100 to 10% R. H. drying period is only a relatively small proportion of the total irreversible shrinkage.

CREEP, STABILITY, HELIUM FLOW, CEMENT PASTE

FIG. 4

Weight change versus volume change for cement paste during drying and re-exposure to various humidities.

(2) Solid volume and helium flow measurements

The variation of "solid volume" with weight for different humidity conditions and treatments is presented on Fig. 4. The first drying curve, from 11% R.H. to d-dry, shows an almost linear decrease in solid volume with weight until an increase in rate over the final 2.5% weight loss. On rewetting, the sample was exposed at four points, 11, 42, 66 and 100% R.H. For all these points, however, the sample was returned to 11% R.H. for lengthy periods before measurement. The increase in weight and volume is due to interlayer water re-entry, as has been discussed in several papers (12, 19-21). Following exposure to 42% R.H. the re-wetting curve commences to cross over the first drying curve, and after exposure to both 66 and 100% R.H. the solid volume is greater than the original sample during first drying at the same weight. Following exposure to 100% R.H., the sample at 11% R.H. (C) is about 2.5% greater in solid volume than the sample at 11% R.H. (B) on first drying. The second drying leads to a decrease in solid volume similar to that of first drying, but there is a net increase in solid volume at the d-dry position (D) over the first d-dry position (A) of about 3.7%. Thus, the wetting and drying procedure, which produces an irreversible (see cycle II, Fig. 1) externally-measured shrinkage of the specimen of 0.42%, results in an increase of solid volume. This also means that there must be a decrease in porosity of the specimen and a decrease in absolute density.

The three conditions at which helium flow rates were measured are marked A, B, and C on Figs. 4 and 5. The helium that flowed into the re-exposed (100% R.H.) sample is significantly greater (curve C) than the original (curve B) at the same water content and relative humidity (11%).

FIG. 5

Helium inflow versus time for cement paste at different conditions.

The interlayer space has increased as a result of drying and re-exposure and this can account for the increased solid volume. This will be discussed later.

As has been shown in a previous paper (21), the type of flow curve exhibited by curves B and C appears when helium flows rapidly into partially (dehydrated) vacated but open entrances to interlayer spaces. The increase in solid volume and helium flow of the type observed, together with irreversible shrinkage, strongly suggests a partial movement together of sheets or layers of silicate in the region of the entrances to interlayer spaces; or the formation of new interlayer space when sheets, formerly remote, move together.

Curve A, Fig. 5, represents the helium flow rate at the d-dry condition when the entrances to interlayer spaces have collapsed. Figure 6, (a) and (e), illustrates a d-dried collapsed interlayer into which helium flows very slowly (see curve A, Fig. 5). Figure 6, (a) to (d), illustrates how interlayer water re-entry and stress or subsequent drying extend the interlayer region by bringing surfaces closer together at the entrances; the helium flow curves B and C (Fig. 5) also show this.

Comparison of (a) and (e) and (c) and (d), Fig. 6, illustrates how the increase of solid volume occurs. Measurement of solid volume by helium pycnometry (21) includes the interlayer space as such; in the fully hydrated state this is occupied by water.

FIG. 6

Simplified illustration of ordering effect due to interlayer re-entry and d-drying or stress application

Discussion

The foregoing presentation of results establishes the correlation between irreversible shrinkage (on d-drying) and relative humidity of re-exposure, as well as the correlation between this irreversible shrinkage and solid volume increase and helium flow increase. It leads to the conclusion that each time the solid is exposed to more than 50% R.H. it is altered in some way so that it possesses the potential for irreversible shrinkage when d-dried. It is noted that even after relative humidity has been lowered to 10% this potential still exists. It is logical to expect these changes to alter the response of the material to both internal and external stress. Thus, it is not surprising that the results for irreversible shrinkage correspond to those of Wittmann (7) on creep rate; both phenomena behave similarly with the changes in relative humidity and increase only when the samples are exposed to relative humidities above approximately 50% (above 42% R.H. in Wittman's experiments). It is concluded that change in the potential for creep and the potential for irreversible shrinkage are manifestations of the same change that has occurred in the solid.

It is inferred, then, that the creep process results in an increase of solid volume and interlayer space. In other words, the creep process is associated with a moving together of sheets or layers of silicate in the specific region of the entrance to the interlayer spaces or of the movement of sheets apart to form new interlayer space. Some water movement must therefore occur from the entrances of the interlayer spaces. It is thought that this further layering or crystallization of the silicate is the main physical change that may be detected by surface area measurements made by N_2 adsorption (23, 24). The solid material is unstable (i. e., not inert) and will move towards a lower free-energy position and surface area. This process is also known as aging (23). In this concept of creep the rigidly held interlayer water is not affected by stress, nor is the separation of the majority of interlayer positions affected; only the limited region of the entrances to the interlayer spaces are affected (Fig. 6). This process may be partly reversible, depending on how close the layers have moved towards each other.

In contrast, the seepage concept of reversible creep is illustrated on Fig. 7, (a) to (d). In this case the whole interparticle separation is altered by drying or stress and recovered by rewetting; interlayer water is not considered in this mechanism, but each particle in itself would be layered and contain interlayer water.

Several points remain to be proved or justified in the light of other hypotheses.

FIG. 7
Illustration of reversible creep
from seepage hypothesis

(1) At 50% R.H. about two molecular layers of adsorbed water are present on a hydrated portland cement surface, about four layers across a pore. In addition, the present work shows that 65 to 70% of the total expansion on adsorption has taken place at 50% R.H., although the creep rate of re-exposed samples only starts to increase at this humidity. At 42% R.H. it is low (7). This is taken as evidence that single layers of strongly held interlayer water are not responsible for creep, since 50% of the interlayer water has re-entered at 50% R.H. (20, 25). Also, as pores up to about 14 Å in diameter will have been filled and the expansion is about 65 to 70% of the maximum, "hindered adsorption" and "disjoining pressure" related to physically adsorbed water clearly do not play a role either.

(2) Above 50% R.H. larger pores become filled with water; by 100% R.H. interlayer positions are completely filled. Wittmann's results (7) show an increase in creep rate in this range to a maximum at 100% R.H. As a result, Wittmann concluded that some change occurs in the solid structure during exposure. This change is not reversible since, on desorption, there is hysteresis in the creep rate versus relative humidity curve (7). This is more clearly indicated in the shrinkage data where, on desorption, little of the potential irreversible shrinkage has yet occurred at 10% R.H. These facts again indicate that hindered adsorption or disjoining pressure are not connected to the creep process.

(3) Further evidence that creep is not merely the reverse of interlayer re-entry, i. e. squeezing out of interlayer water that has re-entered between 50 and 100% R.H., may be taken from the results. The manner in which additional and irreversible shrinkage can be generated by exposure indicates that the mechanism is not simple.

(4) In describing the Munich model, Wittmann (7, 26) ascribes the altered condition of the sample to a weakened structure resulting from disjoining pressure above 50% R.H. There is considerable experimental evidence, however, that the structure is not weakened. Measurements of Young's modulus versus relative humidity (19) show a large increase in Young's modulus from 50 to 100% R.H., and flexural strength measurements (19) show little or no loss from 15 to 100% R.H. and no change on drying

back to 20% R.H. Expansion on adsorption above 50% R.H. is only about 30% of the total.

(5) It is clear that for further ordering of layers to occur by drying or stress application, the layers or openings of the interlayer space must change their orientation or position during rewetting between 50 and 100% R.H. so that both factors can cause collapse of the entrances of interlayer spaces. This is illustrated in Fig. 6, (a) to (d), with re-entrance of interlayer water. With surfaces drawn closer together, surface-to-surface forces become greater and may help to strengthen the effect. Although the interlayer water must be clearly load-bearing, it is not clear whether one or two layers beyond the surface layer can be regarded as such; neither does it appear important. As only relatively small shrinkage occurs on drying from 100 to 10% R.H. (where approximately one monolayer of adsorbed water is present), it appears that the water beyond the surface layer is not largely load-bearing. This and the conclusion that the water involved is to be found at the entrances indicate that adsorbed water movement does not contribute very much to the long-term time dependent feature of creep.

Thus, a structural change occurs at the entrance to the interlayer spaces, these being extended in length. The surfaces of layers are brought closer together into a zone where the load applied, the water between the surfaces, and the surface-to-surface forces are balanced, any change in one leading to a closer approach of the layers. This reasoning should also apply where an increase in the number of layers (i. e. a thickening of a crystallite) occurs.

Over-all mechanism of creep

The surface-to-surface approach occurs only in some regions and not at all interlayer positions, so that even when creep strains measured externally are small, the surface-to-surface movement at entrances and points of contact can be relatively quite large. In local areas significant shear or even tensional stress may be set up. Many of the processes involving slipping, microcracking, bond breaking and reforming may then

act as the rate determining process. The possibilities with regard to bond breaking and reforming have already been demonstrated.

It is postulated that the time dependent deformation, creep, is a combination of several factors which may be divided into (1) rate determining processes, and (2) activating processes.

(1) Adsorbed water seepage from the entrances of interlayer spaces and areas of close proximity of two sheets controls the initial rapid creep rate but is not directly involved in longer-term creep. Investigation (1, 13-18) has indicated that several or all of the processes involving shear slippage, microcracking, bond breaking and reforming are operative.

(2) The moving together of adjacent surfaces of large entrances of interlayer spaces, brought on by compressive stress or drying, creates specific regions of increased shear or even tensional stresses. These stresses lead to greatly increased creep rates through the mechanisms referred to as rate determining processes. Water movement and layer collapse are thus associated with creep but are the rate determining process only in the early stages.

When a sample is d-dried or oven dried, changes occur in addition to the mere removal of physically adsorbed water. Hydrate and interlayer water are removed, causing collapse of the interlayer spaces and increase in the solid interlayer volume. This results in a large irreversible, permanent shrinkage, as discussed previously. Subsequent creep experiments from 0 to 42% R.H. by Wittmann (7) and shrinkage experiments now reported show that in all regions where the potential for collapse of layers exists, collapse has already occurred at the d-dried state. New regions, however, can be generated by subsequent wetting above 50% R.H. This explains the work of Hannant (16), who found that creep resumed when oven-dried samples were rewetted while still under load. Hannant concluded that where water re-entered under load, it could not be ejected by the same load. The regeneration of new regions requires the re-entrance of over 50% of the interlayer water, at which stage new surfaces at the entrances of interlayer spaces are brought to within a critical distance of each other (Fig. 6). It

is from these new positions, which do not exist when re-entry of interlayer water first commences, that water movement tends to occur. Further evidence that interlayer re-entry is required for regeneration of these sites may be obtained from the adsorption and desorption of methanol (Fig. 1 cycle IIIa) where only a small irreversible shrinkage was obtained; this shrinkage occurred probably because the cycle commenced with 0.4% water present, water which was subsequently lost on drying.

It is clear that the solid material is very unstable and that rewetting can regenerate a situation leading to repeated instability. This seems to refute the hypothesis of absolute creep and shrinkage potential (6). It appears that first drying shrinkage is also a process of layer collapse and alignment and condensation of adjacent sheets into larger groups; conditions that create high first drying shrinkage and high surface area (such as high water-cement ratio and high dosages of some admixtures (27)) would also create conditions of high creep rate.

A thermodynamic approach to the creep process is very complex, involving several terms in the fundamental equation not included by others (8), i. e. those involving the change of concentration of water on the surface, the relative movement of surfaces of layers and the creation of shear stress within the solid. Equations based on the dislocation mobility concept involving the transition state theory (28, 29) may be applicable to the process. This approach results in exponential type expressions.

Conclusions

Creep is a manifestation of gradual crystallization or aging in a poorly crystallized material, accelerated by drying or stress. Water transport from entrances of interlayer spaces occurs and probably controls creep rates at early stages. The process may activate the rate determining processes at later stages, however, including crystal slippage, micro-cracking, and bond breaking and reforming.

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