voids-free structure. The reverse is represented by a high water-cement ratio body under dry conditions, resulting in an heterogeneous structure, containing partly unhydrated cement and a high proportion of voids (mainly drained capillaries).

PROPOSED THEORY FOR THE TIME-BEHAVIOR OF MORTAR

On the basis of the review and of experimental results obtained in the present work, a general theory can be formulated for the deformational time-behavior of mortar considering the structure of the material and the evolutionary processes in it. This discussion refers to the four states to which the mortar body is subjected in the course of its loading history.

Spontaneous (load-free) deformation

As proved experimentally, the appearance of spontaneous deformations (shrinkage and swelling) is governed exclusively by migration of the gel water. This water is stored in narrow gaps and thus subjected to strong van-der-Waals forces. At saturation, these forces are in equilibrium with those of solid-liquid cohesion and friction, confining the water in the voids. If a moisture gradient is formed through reduction of its external level or otherwise, equilibrium is upset, water is expelled, and the inter-solid forces tend to close the emptied voids. The result is over-all volume contraction, intensified as the expulsion process progresses.*

During the reverse process, namely when a dry body is exposed to a high moisture level, water migration is directed into the gel voids. This water, penetrating the voids and counteracting the inter-solid forces, tends to push the void walls apart and restore the situation. This swelling, as proved experimentally, is not equal in amount to the shrinkage. Even on prolonged submersion, a residual deformation is retained equal to about half the shrinkage induced during the initial drying process.

The explanation to this and other phenomena lies in the presence of two types of water in the gel. The zeolitic water in the narrow inter-layer gaps behaves like a solid, maintaining an equilibrium and resisting strong inter-solid forces. Upsetting of the equilibrium, accompanied by expulsion of the water, immediately leads to contraction of the gaps by the amount of expelled water and at the same time to an increase in the above forces, which vary, at the dimensions in question, as the fifth or sixth power of distance. On re-saturation of the body at this stage, complete recovery of the gaps is impossible because of the considerable change in the force balance compared with the original state. (Another hypothesis assumes additional secondary factors impede complete recovery: new hydrogen bonds formed between the solids on contraction, and the difficulty in forcing the water into so narrow a gap).

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*Recent evidence[22] seems to support the old theory which attributes part of shrinkage to the hydrostatic tension arising in capillary and gel water during drying.

Expulsion of the water from the amorphous gel voids also leads to void contraction, but on a smaller scale and not in direct proportion to the amount of expelled water, since the attraction forces are not strong enough to overcome the resistance of the surrounding elastic phase. (The distances involved are two to three times larger than in the case of the inter-layer gaps). The smaller relative change in gap size has a smaller effect on the inter-solid forces, so that the voids could recover their original size on re-saturation.

The prolonged swelling in a submerged body not previously dried is presumably due to continued hydration accompanied by volume changes, reflected to a small extent in increased external dimensions of the body.

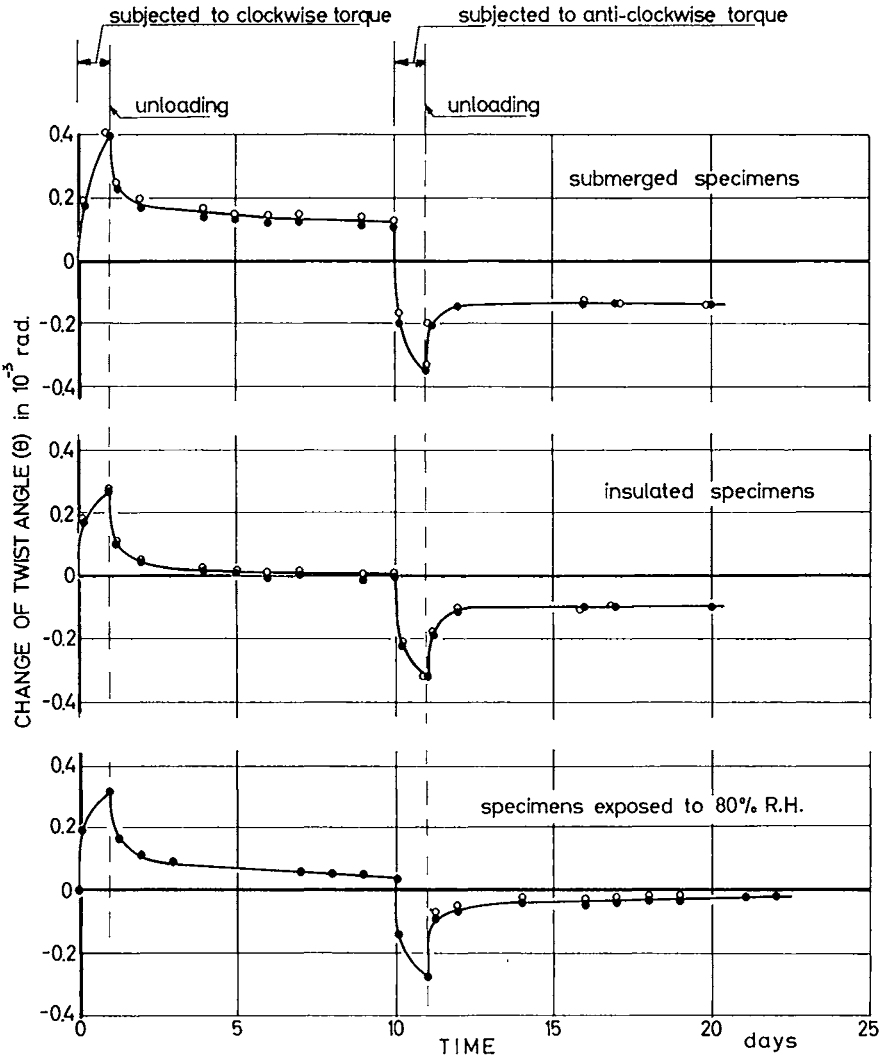

Fig. 11—Test C; Torque reversal following previous creep

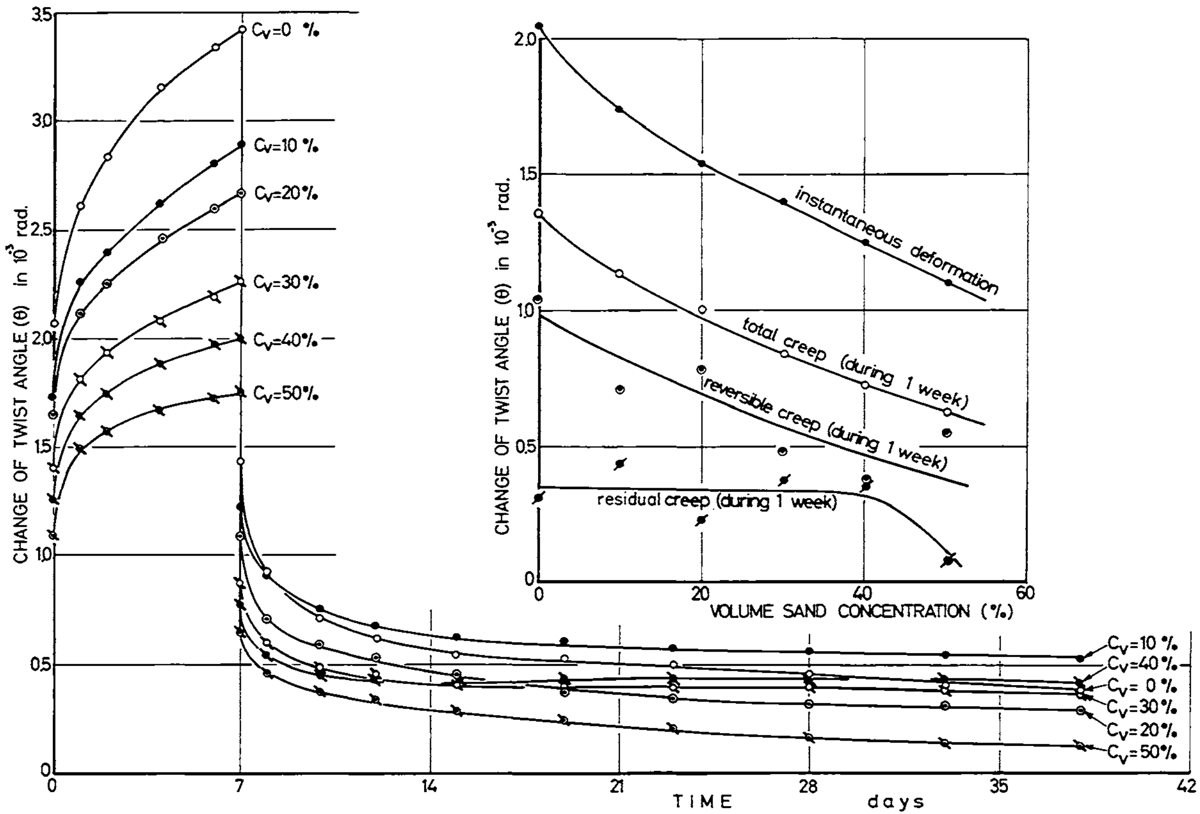

Fig. 12—(*lower left*) T... mortar specimens

Fig. 13—(*upper*) Test ... ted specimens

Deformation under load

A saturated mortar specimen can be described, at first approximation, as a porous elastic body whose numerous microscopic voids are filled with liquid. When load is applied to it at acoustic rate, the enclosed liquid behaves like rigid particles and the instantaneous deformation would equal that of an elastic body containing rigid particles at a concentration equal to that of the voids water in the mortar. When loading is sustained, oriented migration of the water occurs in the internal void system, due to the pressure differentials induced by the state of stress. This phenomenon is responsible for creep in the mortar.

Owing to the strong adsorption and friction forces between the liquid and a solid of high specific area, resulting in some sort of viscous resistance to flow (dependent on void diameters), the above migration and resulting creep are extremely slow. As the process progresses, the load is gradually transferred from the liquid to the solid phase and the creep rate decreases with time.

The general tendency of the loaded saturated body would be to undergo elastic change and attain the final state it would have assumed under instantaneous load, were its voids empty. A water-containing body would attain this final state only over a theoretically infinite period, since the process is exponential. In practice, it tends to a horizontal asymptote representing the final amount of creep.

The smaller the water content in the voids on loading, the larger the instantaneous deformation (also governed by the dry voids ratio), the smaller the final creep (governed by the actual water content).

In reality, the above picture is oversimplified, since the mortar comprises a wide spectrum of voids of varying order, reacting differently to changes in water content. Capillary voids, in which the rate of flow is comparatively high and which undergo change only under load, can be expected to behave as described; but the gel voids, in which only slow migration is feasible, undergo additional spontaneous contraction on losing their water so that part of the total deformation is due to shrinkage before load is applied.

An approximate picture of the total creep under external load is obtained by means of a creep mechanism comprising three viscoelastic models (Kelvin bodies) in series (Fig. 14). In the first model, representing capillary water migration, the arresting viscosity will be much lower than in those representing the various types of gel water. That of the zeolitic water model will thus be highest. (To give an idea of the proportions of the various viscosities it should be borne in mind that the average capillary diameter is 100 times that of the gel voids).

In addition to the viscoelastic mechanism described above, responsible for continuous creep, loading induces erratic deformation through rupture of weak fibers and formation of microcracks. This process, governed by the state of stress, is prolonged due to delay in transferring part of the

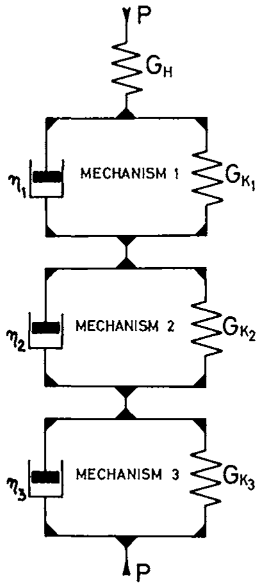

Fig. 14—Composite rheological model representing total creep in mortar body

load from the liquid to the solid phase. A relatively fresh mortar body contains fibers and lattices of varying degrees of strength, according to their age. On application of the load, with only partial transfer to the solid, bonds below the transmitted stress level are ruptured. The proportion of the load applied to the solid phase increases at the early stage of loading, and cracking proceeds accordingly.

In aged concretes, as well as after prolonged loading, it can be assumed that this cracking would be arrested simultaneously with strengthening of the solid and slowing down of the load transfer process.

Internal processes under load

The two parallel nonreversible processes in the specimen must be separated. The first takes place in the capillaries at early stages of loading and the second (slower) in the inter-layer gaps, as long as there is creep.

On application of a load to mortar undergoing hydration, an oriented change takes place in the setting process, hitherto homogeneous and isotropic. In a fresh body, the state of stress induces ion migration and causes changes in their concentration in certain directions, so that hydration is accelerated in some zones and slowed in others. As noted, the strength and rate of formation of bonds is governed by: type and size of the stress, duration of its action, hygrometric conditions, and temperature. Since the first three vary with the state of stress, bond formation is obviously governed and controlled by the external load. These bonds, mainly formed in the capillaries, result from the growth of rod-shaped crystals oriented towards the interior of the void. These crystals, growing at a faster rate than the amorphous mass, freeze the void walls in their deformed state under the load, and resist their recovery on unloading. Similar setting takes place between the micro-cracks, as in healing. These processes, known as oriented hydration and responsible for part of the residual deformation, are especially intensive during early stages of loading (particularly in fresh concretes), but their rate drops steeply with time, together with that of hydration.

The second process, slow, prolonged, and responsible for the main part of the residual creep, is due to migration of zeolitic water whose effect is similar to that of the residual part or drying shrinkage.

In addition to the above two processes, which are liable to take place under almost any hygrometric conditions, there is a third nonreversible process observed only in bodies subjected to drying.[3] Expulsion of water from a wet zone into the atmosphere, into dry zones, or its comsumption in the hydration process, due to stress action or to a moisture gradient, results in reduced vapor pressure in the voids and in meniscus formation at the capillary openings. These menisci, capable of resisting tensile stresses, have an effect similar to that of the crystal bonds in the capillary described above.

Deformation on unloading

Immediately on unloading, part of the elastic deformation is recovered, with the enclosed water behaving like rigid particles. This deformation would be smaller than its counterpart on loading, owing to the general hardening of the mortar under load. This is followed by a reverse viscoelastic process. The stressed elastic phase surrounding the saturated voids tends to return to its initial state against the high viscous resistance of the adsorbed water, leading to slow liquid migration in the direction of the recovery forces. These forces decrease gradually through transfer to the liquid, and the rate of flow decreases accordingly with time. This process, also exponential, tends to restore the body to its original state over a theoretically infinite period. In practice, identical behavior cannot be expected because mortar is not an ideal viscoelastic solid but consists of lattices subject to chemical and physical time-evolution. The reversible deformation behaves as described above and tends to a horizontal asymptote, but even long after unloading a considerable residual deformation is retained, due to the following causes:

1. As long as the oriented hydration bonds in the capillaries or crack gaps are strong enough, the deformed state is retained on unloading. Weak bonds, on the other hand, are liable to rupture on transfer of an increasing proportion of the load from the elastic phase to the void zone, thus permitting additional recovery. This is illustrated by the structural model in Fig. 16.

2. The changes taking place in the inter-layer force pattern during loading permit only partial recovery of the zeolitic water, which is smaller the longer the original loading period. In general it can be concluded

that residual deformation due to changes in the inter-layer gap is an integral part of the creep under load which causes these changes and is promoted by the same inter-layer water migration. Hence, similar behavior can be expected in both cases.

3. Water loss and meniscus formation at the capillary openings also preclude recovery in this phase in bodies subjected to external or internal drying.

Since the processes responsible for residual creep take place in capillaries and inter-layer voids, it can be concluded that water migration in the amorphous gel voids is totally reversible. Even if part of this water is lost through drying, the hygroscopic gel is capable, as long as there is water in the capillaries, of re-absorbing it up to saturation. In addition, new hydration bonds cannot form inside the gel voids, owing to their smallness.

For these reasons, the reversible creep should mainly be attributed to water migration in the amorphous gel.

CREEP MODELS BASED ON THE PROPOSED THEORY

The complex character of the time-behavior of mortar, comprising physico-chemical processes, precludes complete and accurate representation by means of a single model.

In addition to this model (Fig. 14), used for quantitative description of viscoelastic creep, an attempt is made to illustrate the various stages contributing to the assorted deformations by means of a qualitative description of the structure and of the general time-behavior of the mortar.*

Parameters and rheological equations

According to the proposed theory, total creep results from water migration in voids of three orders of magnitude. Hence, the proposed general rheological model will comprise a combination of three Kelvin elements and one Hookean element in series (Fig. 14). The general rheological equation of such a model will be

$$\gamma = \frac{P}{G_H} + \frac{P}{G_{K_1}}(1 - e^{-t/T_1}) + \frac{P}{G_{K_2}}(1 - e^{-t/T_2}) + \frac{P}{G_{K_3}}(1 - e^{-t/T_3}) \quad . \; . \; . \; . \quad (1)$$

where γ = angular deformation per unit height of cylinder, radians; P = τ = maximum torsional shear stress, psi; G_H, G_K = rigidity modulus of Hookean and Kelvin elements; $T = \eta/G_K$ = retardation time of Kelvin element; η = coefficient of viscosity Kelvin element; and t = loading duration, days.

*For simplicity, the proposed models refer to behavior in compression, but the relevant formulae are also valid for shear, as confirmed in the experimental part of the study.

The general creep equation requires six rheological parameters and one for the instantaneous deformation: G_H, G_{K_1}, G_{K_2}, G_{K_3}, ν_1, ν_2, and ν_3.

For this purpose, the curves obtained for submerged specimens (Fig. 8)* were analyzed on the following assumptions:

1. The rheological equation of a single Kelvin model is

$$\gamma_t - \gamma_{t\infty}(1 - e^{-t/T}) \quad \ldots \ldots \ldots \ldots \ldots \quad (2)$$

where γ_t = time-dependent angular deformation and $\gamma_{t\infty}$ = asymptotic angular deformation.

2. Differentiation of Eq. (2) with respect to time and suitable substitution yields

$$\gamma_t = \gamma_{t\infty} - T\dot{\gamma}_t \quad \ldots \ldots \ldots \ldots \ldots \quad (3)$$

3. This linear relationship yields, in turn, the asymptotic value $\gamma_t = \gamma_{t\infty}$ for $\dot{\gamma}_t = 0$, obtainable graphically.

4. A general curve can be resolved into its components by semi-logarithmic transformation

$$\log(\gamma_{t\infty} - \gamma_t) = \log \gamma_{t\infty} - \frac{t}{T}\log e \quad \ldots \ldots \ldots \ldots \quad (4)$$

Eq. (4) gives a straight line whose ordinate intercept give the asymptotic creep value, its slope representing the retardation time T of the model.

The $\gamma_{t\infty} - \gamma_t$ values based on Fig. 8 and determined graphically from the asymptotic value of the total creep are plotted against time in semi-logarithmic coordinates (Fig. 15).† The result was a dropping curve straightening off after about 60 days, which means that at this stage the creep process obeys Eq. (2) and is purely exponential. This will be referred to as Mechanism 1. With this component isolated from the total creep and the remainder re-plotted in semi-logarithmic coordinates, another straight line is obtained, representing the second mechanism setting in after 10 days. The third mechanism, similarly obtained, is another straight line terminating at the origin.

These three line segments gave the six parameters for the three Kelvin elements (Fig. 14). They are given in Table 2, together with their counterpart for the Hookean element.

The residual creep curve of Fig. 8 is similarly transformed into a straight line beginning 12 days after loading, whereas prior to that the curve is nonexponential. The parameters thus obtained for the residual creep (Table 2) are close to those obtained for Mechanism 1 of the total creep.

*In this case behavior is closest to the theoretical assumption, since the voids are saturated throughout the process, in contrast to the other hygrometric states in which the internal moisture content varies with time.

†The angular deformation in Eq. (1) to (4) and the twist angle θ in the experimental curves are directly proportional: $\gamma = d\theta/2h$ where d = cylinder diameter and h = elevation of indicator arm.

Analysis of the experimental creep curves indicates that three exponential processes, attributed by the proposed theory to water migration in the voids, comprise total creep: Mechanism 1—slow ultra-high-viscosity migration, sustained during action of the load (attributable to zeolitic water); Mechanism 2—lower-viscosity migration, terminating in practice after about 2 months (attributable to amorphous gel water); and Mechanism 3—much lower viscosity compared with the other two, terminating after 10 days (attributable to capillary water). The character of the residual creep during the first days, with its marked resemblance to Mechanism 1 subsequently favors the hypothesis that zeolitic water migration is mainly responsible for the residual deformation setting in after the early creep period.

Structural model

The rheological model represents a mechanism actuated by external loading. The accompanying nonreversible time-dependent processes re-

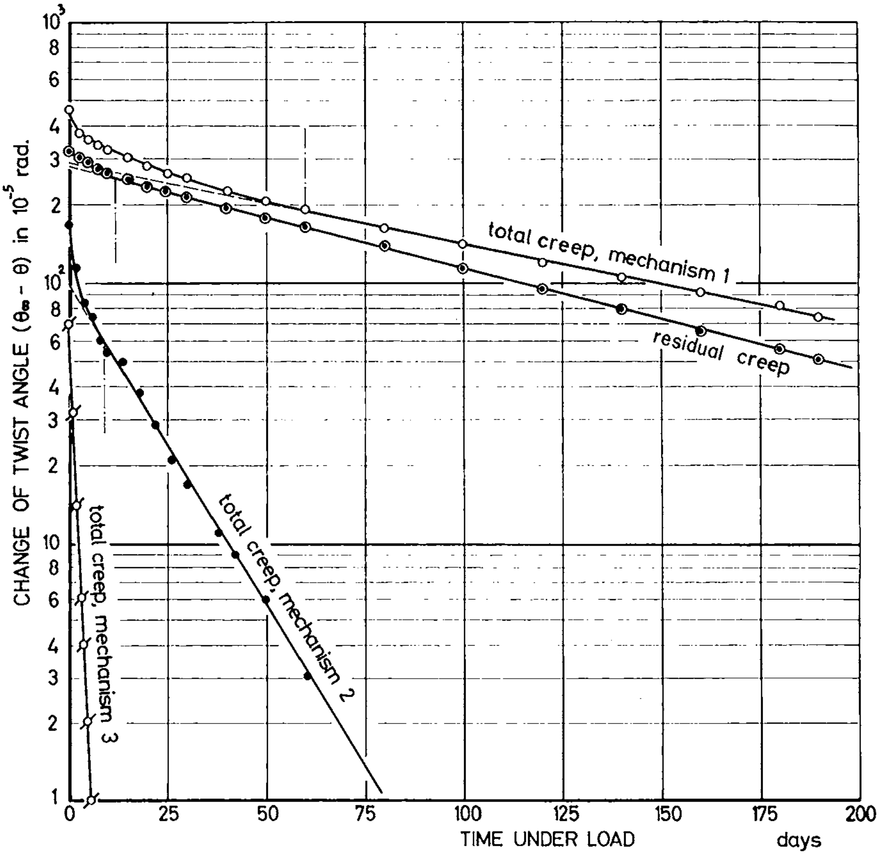

Fig. 15—Resolution of creep curves for submerged specimens

TABLE 2—PARAMETERS OF GENERAL RHEOLOGICAL MODEL

Components	Time-dependent modulus of rigidity G_K, psi	Instantaneous modulus of rigidity G_H, psi	Coefficient of viscousity, η, poise	Retardation time, T, days
Total creep Mechanism 1	1.05×10^6	. . . .	8.89×10^{17}	140.0
Total creep Mechanism 2	3.05×10^6	. . . .	3.21×10^{17}	17.4
Total creep Mechanism 3	4.35×10^6	. . . .	3.39×10^{16}	1.29
Residual creep	1.09×10^6	. . . .	8.5×10^{17}	112.00
Instantaneous deformation	. . . . . .	1.92×10^6	. . . .	. . . .

quire a different approach, and in this case only a qualitative model can be constructed. It consists of a continuous mass comprising uniformly spherical liquid-filled voids with chemical and physical changes represented by means of bonds between void walls.

Such a model can represent the motion of an elastic solid comprising any of the three types of voids separately, and the bonds would represent: bonding in the capillaries due to hydration, the increase in inter-solid forces due to inter-layer gap contraction, and meniscus formation on drying.

The behavior of this model is characterized by five distinct stages (Fig. 16). Stage 1 describes the initial state of the solid in question. The moment the load is applied in Stage 2, the spherical voids behave like rigid spheres and are displaced through deformation of the surrounding elastic phase.

At Stage 3, after the load has been allowed to act for time t_1, outward liquid migration sets in and the spherical voids become elliptical. This stage is characterized by simultaneous formation of intra-void bonds, with orientation and strength dictated by size, direction and duration of the stress. On unloading (Stage 4), only the elastic phase undergoes recovery, with the liquid in the voids behaving rigidly as before.

At Stage 5, taking place after unloading, the time-deformed part of the elastic phase tends to return to its initial state, resulting in tensile stresses on the bonds resisting recovery. Part of the bonds, still below adequate strength, are gradually ruptured, permitting increase of the reversible deformation ϵ_{tr}, but on formation of stronger bonds overcoming the recovery