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Shrinkage and Creep of Concrete: Mechanisms as Described on Different Structural Levels

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ABSTRACT

In this contribution selected and relevant fundamental properties of concrete are presented and discussed. Basic mechanisms of shrinkage will be described in some detail. These mechanisms are typically described on the nano-level, the micro-level and the macro-level. Different mechanisms are first presented in a phenomenological way. It will be shown that with increasing age of concrete different mechanisms of shrinkage become activated. During the first hours after mixing, dissolution of cement is the main shrinkage mechanism. Depending on the humidity of the surrounding air capillary pressure in the pore water may cause serious damage in the first hours. After this initial loss of water, the remaining aqueous solution is retreated in the spaces between fine aggregates and first hydration products. The role of disjoining pressure is pointed out in detail. In this context it becomes clear that the influence of capillary pressure on shrinkage of hardened concrete can be neglected. At relative humidity lower than 50 % the dominating mechanism of shrinkage is the increasing surface energy of the drying gel particles.

Shrinkage of high strength concrete has a totally different time evolution. This has to be studied in detail on the macro-level. The moisture distribution in aging high strength concrete is completely different as compared to usual concrete. If high strength concrete is exposed to an environment with RH higher than 80% there will be no shrinkage at all, but swelling will be observed. These fundamental aspects of shrinkage have to be taken into consideration when long term shrinkage is to be predicted.

Creep of concrete can be described in a realistic way by means of rate theory. Elements of rate theory can be described on the micro-level. The influence of temperature and applied stress is outlined. Most important, however, is the influence of humidity content. As the humidity content of high strength concrete is comparatively low after few weeks already, creep is significantly reduced as compared to normal concrete. Prediction of creep can be significantly improved if these fundamental aspects are taken into consideration.

Keywords: Shrinkage mechanisms; Creep mechanisms; Model Codes; Structural levels.

1. INTRODUCTION

There are few properties of concrete, which have been presented and discussed in such a contradictory way as creep and shrinkage. For quite some time creep was characterized by a simple creep number that means the elastic deformation was multiplied by a factor of 2 to 3 to obtain a so-called total deformation. Shrinkage was given as a basic value, which depends on the environmental humidity and a factor, which takes the dimensions of the structural element into consideration. In the meantime the complex nature of creep and shrinkage was widely realized and more sophisticated models for prediction of creep and shrinkage in real structures were developed. In this way material properties can be described in a more realistic way and hopefully some disasters which happened in the past due to underestimation of shrinkage and creep can be avoided in the future. There are fundamentals, which are of interest for scientists exclusively and there are fundamentals, which may be helpful if not necessary for practitioners for reliable design.

In the meantime several codes for prediction of creep and shrinkage were published and they are permanently further checked and refined. Model B3, based on several precursors, was first published as a RILEM Draft Recommendation in 1995 (RILEM Draft Recommendation, 1995). Statistical aspects and the sensitivity as well as the theoretical basis were further outlined in two follow-up papers (Bazant, Z. P., and Baweja, S., 1995(1)) and (Bazant, Z. P., and Baweja, S., 1995(2)). Another code was prepared by ACI committee 209 (ACI committee 209, 1992). And a third alternative is the CEB-FIP Model Code (CEB-FIP Model Code, 1990). In fact there exist still more models all with different advantages and shortcomings. All codes are critically checked, compared, and improved on the basis of ever growing databases (see for example: Akthem Al-Manaseer, and Armando Prado, 2015). At the moment the most comprehensive database is probably the NU-ITI database (Bazant, Z.P., and G.-H. Li, 2007).

In many cases compressive strength is the only material property of concrete, which is determined regularly. Then the elastic modulus is frequently determined by means of simplistic formulae on the basis of the obtained compressive strength. As the elastic modulus of concrete depends strongly on the elastic modulus of the aggregates the same compressive strength can be measured on concrete with comparatively low or high elastic modulus. If prediction of an elastic modulus remains somewhat doubtful already we should be particularly careful if highly complex properties such as creep and shrinkage are to be predicted on this basis.

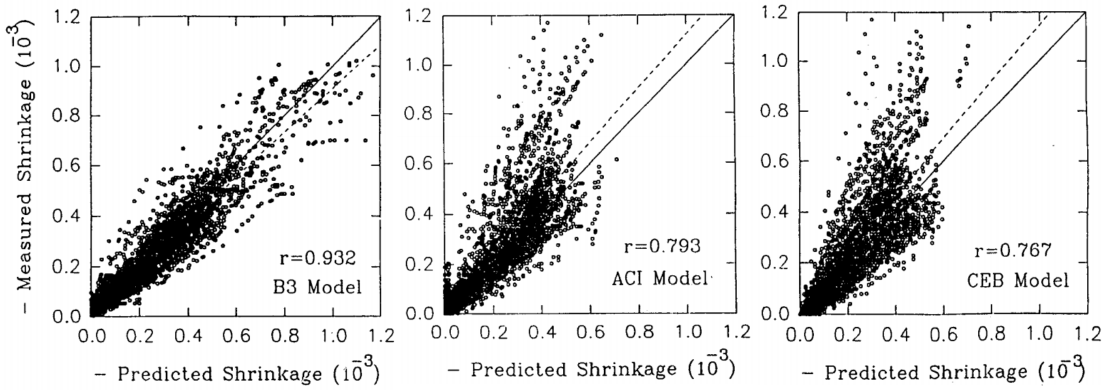

Figure 1: Scatter plots of measured versus predicted values of shrinkage of concrete, dashed lines are regression lines (Bazant Z. P., and Baweja S., 1995(1)).

In Figure 1 scatter plots of measured versus predicted values of shrinkage of concrete (Bazant Z. P., and Baveja S., 1995(1)) are shown. The dashed lines are the regression lines as obtained by fitting experimental data with three prediction models, B3 Model, ACI Model, and CEB Model. As can be seen, all three prediction models predict the average value reasonably well. In practice, however, the average value as measured on many different types of concrete is not necessarily of primary interest, as the type of concrete applied for a given construction may vary within wide limits. The type of cement, the amount of cement or the type of aggregates is not taken into consideration adequately. Modern concrete may have a low water-cement ratio, which was not achievable with the common technology as applied at the time when most prediction models were developed. If we consider for instance in Fig. 1 a predicted shrinkage value of $0.4 \cdot 10^{-3}$ the measured values may vary between 0.2 and $0.6 \cdot 10^{-3}$, depending on the properties of the specific type of concrete. Because of this enormous scatter the value for long term prediction is limited. This necessarily means that shrinkage of concrete for sensitive structures and for reliable design ought to be determined experimentally and not taken from model codes.

If, however, some characteristic properties of the material, which can be deduced from fundamental mechanisms of creep and shrinkage of concrete, are taken into consideration in addition, this will be helpful to obtain more realistic results by means of predictive models. It has already been suggested by several authors that short-time tests followed by extrapolation will be necessary to reduce the enormous scatter of data obtained from the different prediction models (see for example: Bazant, Z. P., and Li, G.-H., 2008). Results of short-time tests, however, should be evaluated carefully and interpreted on the basis of real mechanisms of creep and shrinkage. Then and then only the prediction will be based on a more realistic basis and predictions will be more reliable in future.

In this contribution dominant mechanisms of shrinkage and creep shall be briefly presented. On the basis of real mechanisms it will be possible to predict the influence of a number of parameters on creep and shrinkage. This may help to make predictions of model codes even more reliable. Because of obvious limitations of time and space a selected number of examples can be presented here only.

2. SHRINKAGE

2.1 Dissolution and capillary shrinkage

Fresh concrete behaves in the first few hours like a mixture of fine and coarse particles in water. During this early phase the volume of the mix is reduced by evaporation and in particular by dissolution of cement in water. Both evaporation of water on the surface and the dissolution shrinkage lead to an early volume reduction of the fresh mix, which in most cases leads to a vertical movement of the upper surface (Beltzung F., and Wittmann, F. H., 2001). Dissolution shrinkage may be of particular interest for the technology of steel pipes filled with concrete for instance. But it can also create problems when the fresh concrete is placed in complex formwork. Dissolution shrinkage can be at the origin of horizontal cracks for instance if the friction in high formwork hinders the downward movement of the fresh concrete.

If evaporation of water continues the initially flat water film on the surface will be replaced by menisci between the particles near the surface. As a consequence capillary pressure p_c will be created in the water under these menisci:

$$p_c = \frac{2\,\sigma\,cos\theta}{r} \tag{1}$$

σ in equ.(1) stands for the surface energy of the aqueous solution in young conctete, θ for the wetting angle and r represents the average radius of the menisci. The capillary shrinkage of fresh concrete under a drying surface is shown in Fig. 2. It can be seen that initially the capillary shrinkage follows the evolution of the capillary pressure but after few hours capillary pressure collapses and capillary shrinkage approaches a final value. At this moment the aqueous mix becomes unstable and the remaining water moves into the spaces between the particles (Wittmann, F. H., 1976). By the way, this sudden transition can be visually observed on the surface of concrete. The initially shiny surface becomes suddenly matt.

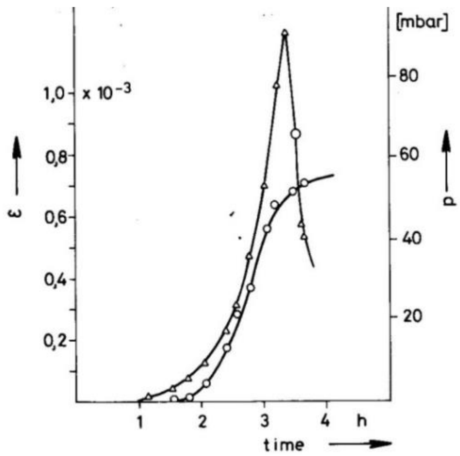

Figure 2: Evolution of capillary pressure p in fresh concrete and resulting capillary shrinkage ε as function of age of concrete (Wittmann F. H., 1976).

It is a wide spread heresy that capillary pressure is a major mechanism of shrinkage of hardened concrete (Wittmann, F. H., 2009). Wide cracks can be formed by capillary pressure in the first hours after compacting fresh concrete, but these cracks can be easily avoided by keeping the surface of fresh concrete wet, that means avoiding development of capillary under-pressure (Slowik et al. 2009). But after several hours capillary shrinkage becomes negligible.

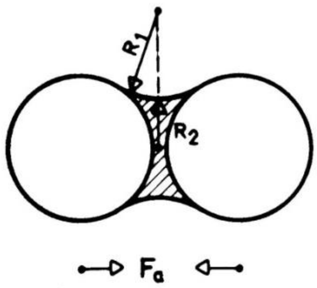

Figure 3: Water layer between two spherical particles

In Figure 3 two spherical particles are shown which are connected by a thin water layer. We may consider fresh concrete to be built up by many of these elements forming a three-dimensional network. The free water layer between the solid particles can be characterized by two radii R_1 and R_2 as shown in Fig. 3. From this geometry follows a capillary pressure P_c in the interstitial water:

$$P_c = \sigma \cos\theta \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{2}$$

If water evaporates from this system both radii R_1 and R_2 decrease and as a consequence the capillary pressure P_c increases. But it is often ignored that as capillary pressure increases the surface of contact between the liquid and the solid particles decreases. It can be shown that under these conditions the attractive force F_a between the two particles remains practically constant (Schubert H., 1972). The green strength of the young concrete also remains constant. That means other mechanisms than capillary pressure must be at the origin of drying shrinkage. We will present and discuss most important mechanisms in the following section.

2.2 Drying Shrinkage and disjoining pressure

Let us first have a look at a model experiment to observe the action of disjoining pressure. In a thin water layer between two particles a disjoining pressure is created. The energy of the system is lowered after separation by a water layer. The theoretical background of disjoining pressure has been studied in great detail (see for instance Churaev, N. V., and Derjaguin, B. V., 1985 and Deryaguin, B. V. 1933). Splittgerber has visualized the action of disjoining pressure (Splittgerber, H., 1974, and Splittgerber, H., 1976) with a comparatively simple experiment. The experimental set-up of Splittgerber is shown schematically in Fig. 4. A thin quartz plate is kept at constant distance from a polished surface of a quartz block at the right end, while the left end is free to move. In the dry state the left end is in direct contact with the quartz block by gravity and from the bending of the plate van der Waals attractive force can be determined. When the relative humidity of the surrounding air is increased above 55 % the thin glass plate is separated from the support by a thin water layer which squeezes in between the two surfaces. The increasing distance with increasing RH is shown in Fig. 5.

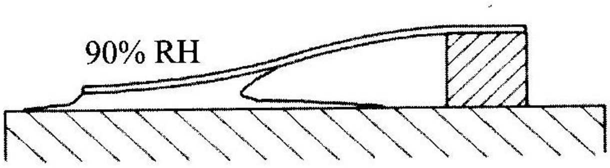

Figure 4: Thin glass plate separated from the polished quartz support by disjoining pressure of water

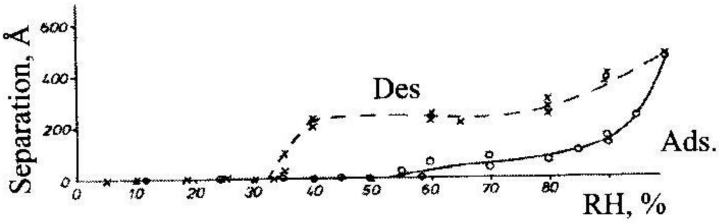

Figure 5: Distance between the free end of the thin glass plate and the support as function of RH. Both the adsorption and desorption branches are shown.

In Fig. 5 a pronounced hysteresis between the adsorption and desorption branch can be seen. This observation explains the origin of the hysteresis of sorption isotherms as measured on hardened cement paste or concrete. Based on this information we have to subdivide the influence of RH on properties of cement-based materials into two regions: Below 40 % RH adsorbed water reduces the surface energy of gel particles. This leads to expansion of all particles. At higher RH the disjoining pressure modifies the nano-structure of the material by separating existing gaps. This change of the system is also reflected in the change of strength of the material. The strength of dry concrete is a maximum and it decreases with increasing RH as the surface energy decreases.

In Fig. 6 hygral length change is shown as function of RH. The observed length change can be subdivided into two parts. At low RH adsorbed water reduces surface energy of the gel particles. All particles expand until RH reaches a value around 50%. At higher RH additional length change is due to the action of disjoining pressure (dashed zone in Fig. 6).

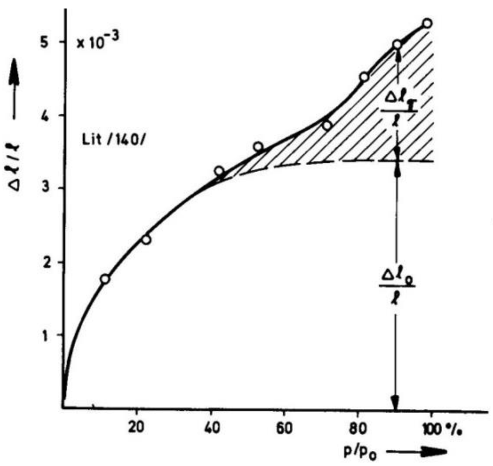

Figure 6: Hygral length change of hardened cement paste as function of RH.

It is well-known that disjoining pressure can be modified by ions dissolved in the pore water. If disjoining pressure increases swelling and shrinkage will increase. In Fig. 7 the total shrinkage of a given type of concrete is plotted as function of the alkali content. The final shrinkage increases approximately linearly with increasing alkali content. Obviously this observation cannot be explained by the action of capillary pressure. Taking the influence of disjoining pressure into consideration shrinkage can be modified and reduced within limits by choosing cement, which contains a small amount of alkali only. If this relation is taken into consideration it will also help to make shrinkage predictions more realistic.

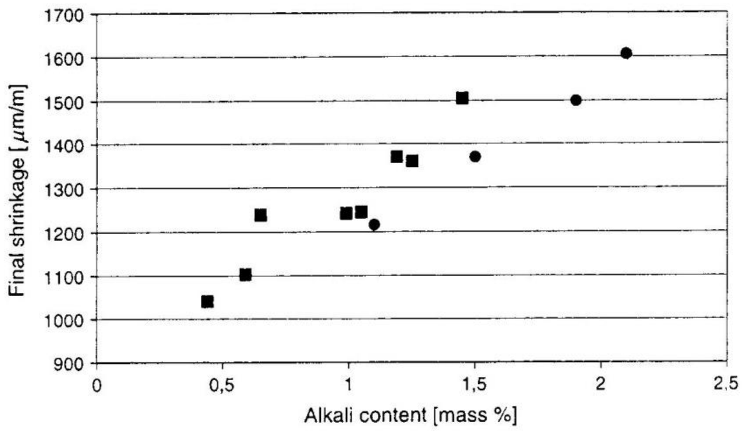

Figure 7: Final shrinkage of concrete as function of the alkali content
(■ Na_2O and ● K_2O), (F. Beltzung et al., 2001).

A striking example of the role of disjoining pressure in the complex process of shrinkage can be observed in the so-called Chichibu GRC Cement. This cement is composed in such a way that the portlandite, which is formed during hydration of C_3S and C_2S is progressively consumed by secondary pozzolanic reactions and formation of ettringite. Concrete and mortar fabricated with this special cement has extremely low shrinkage. If, however, $Ca(OH)_2$ is added to the mix, the usual shrinkage deformation is observed. Surface tension of pore water is not changed by Chichibu GRC Cement, nor is it changed by the addition of $Ca(OH)_2$. Shrinkage can be changed within wide borders just by the influence of Ca ion concentration on disjoining pressure.

So far we have considered dissolution shrinkage, capillary shrinkage and drying shrinkage. In looking into the different mechanisms we can find ways to modify, under given circumstances, the prediction of model codes and come to more realistic design. With the advent of high strength concrete another aspect became apparent. In high strength concrete a considerable amount of the mixing water is consumed by hydration of cement. In normal concrete the relative humidity in the pore space may be reduced to 95 % at most. Under these conditions the influence on shrinkage exists but it remains modest. In high strength concrete, however, the relative humidity in the pore space may be reduced to values below 80 % at an early age. Under these conditions self-desiccation and autogenous shrinkage can be observed.

2.3 Shrinkage of normal and high performance concrete

In Fig. 8 results of Miyazawa S. and Tazawa E., 2001, are shown. It can be seen that shrinkage of high strength concrete differs fundamentally from shrinkage of normal concrete. Due to hydration of cement a considerable amount of mixing water is consumed after seven days already. The result is considerable shrinkage at very early age. After seven days high strength concrete has reached shrinkage deformation, which can be observed on normal concrete after several years only. If a concrete like this is exposed to an environment with RH of about 80 % no shrinkage can be observed at all, but in contrast the material absorbs humidity from the environment and swells. It will swell even more if placed in an environment with RH of 90 %. Obviously in this case predictions of most model codes are far from the observed behavior.

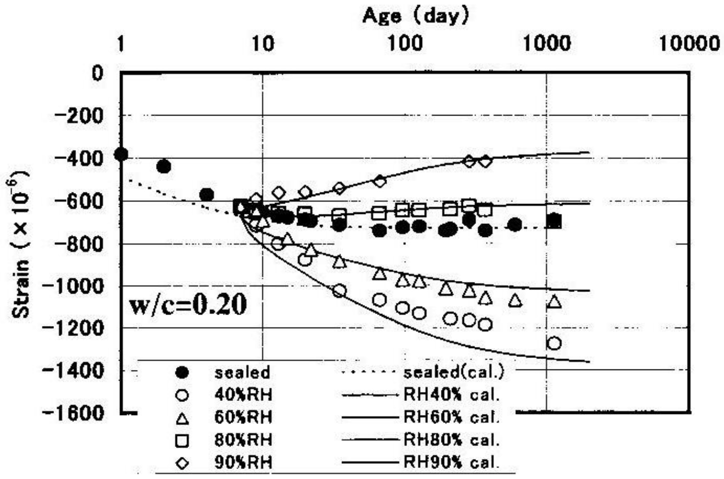

Figure 8: Self-desiccation and autogenous shrinkage of high strength concrete,
(S. Miyazawa and E. Tazawa, 2001)

To understand the fundamental differences of shrinkage of normal and high strength concrete it helps to have a look into the moisture distributions as function of time. In Fig. 9 the distributions of relative humidity of normal strength and high strength concrete are shown for the first five years after casting (Alvaredo, A. M., and Wittmann, F. H., 1995). In this case the concrete is supposed to be exposed to an environment with an average relative humidity of 50 %. The concrete sample is supposed to have a thickness of 500 mm. The quick self-desiccation of high strength concrete leads to a decrease of RH to approximately 80 % after two weeks over the entire cross section and finally a value of slightly more than 70 % is reached after six months. The RH will not decrease further in the center because the hydration of cement is practically stopped at this low relative humidity. The remaining pore water is not sufficient for further hydration of cement. The slow loss of water by drying continues of course for many years and finally equilibrium with 50 % RH will be reached.

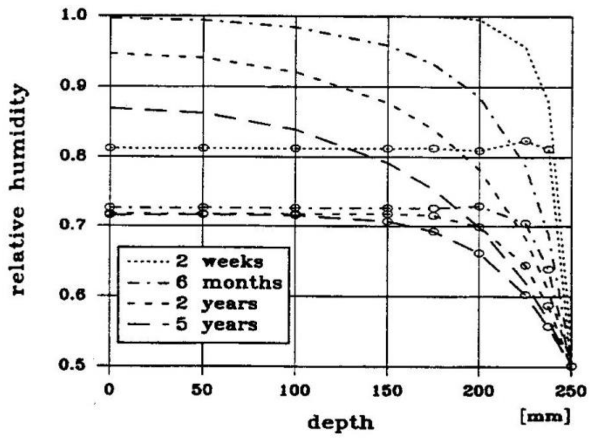

Figure 9: Moisture distribution in normal and high strength concrete (curves plotted with circles) in the first five years

Based on the time-dependent moisture distributions shown in Fig. 9 shrinkage of specimens made with the two types of concrete can be numerically determined. Typical results are shown for the first 5 years in Fig.10. It is obvious that the time-dependence of shrinkage is totally different. Shrinkage of normal concrete develops comparatively slowly over the five years while shrinkage of high performance (strength) concrete reaches extremely high values after one month already. From these results follows that it is not realistic to assume a common shrinkage law for concrete with significantly different water-cement ratios. If these characteristic differences are not taken into consideration in design and values from model codes are used instead, serious damage may occur at an early stage.

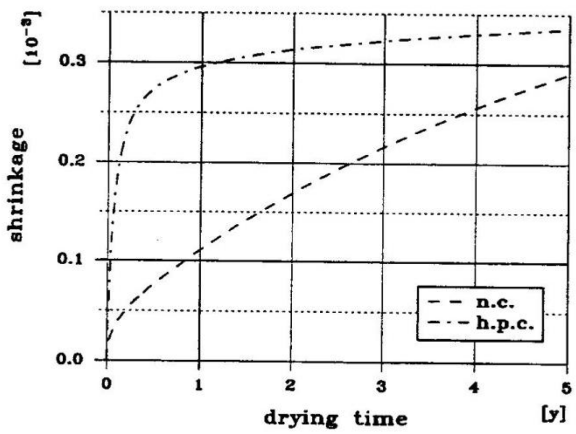

Figure 10: Evolution of shrinkage of normal (n.c.) and of high performance concrete (h.p.c.) as determined along the axis of the specimens

If the drying specimens of normal and high strength concrete are fixed at both ends a time-dependent restraint reaction can be observed. Results of numerical predictions are shown in Fig. 11. As can be expected from results shown in Fig. 10, normal strength concrete will fail under tension after 500 days of drying. The high strength concrete, in contrast, will fail after 13 days already because of the quick endogenous drying process. It should also be taken into consideration, that shrinkage of normal strength concrete depends strongly on the size of the structural element, while autogenous shrinkage of high strength concrete is hardly influenced by size.

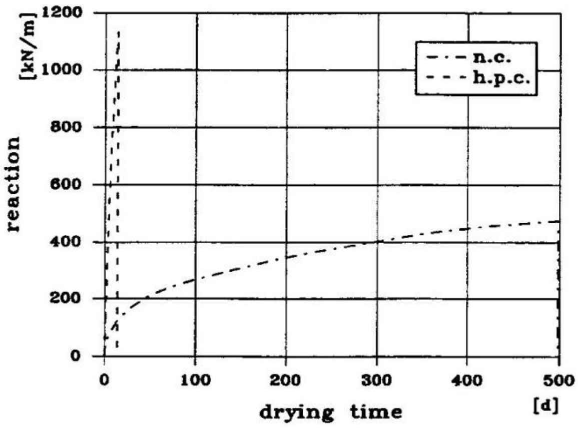

Figure 11: Evolution of restraint reaction of fully restraint members of normal (n.c.) and of high performance concrete (h.p.c.)

3. CREEP OF CMENT-BASED MATERIALS

Creep of different materials such as metals, ceramics, and polymers can be described in a realistic way by rate theory. This very general approach can also be applied to cement-based materials (Wittmann, F. H., 1977, Klug, P. and Wittmann, F. H., 1974, Wittmann, F. H. and Lukas J., 1974). On this basis creep strain ε as function of time t and as function of applied stress σ can be expressed by the following equation:

$$\varepsilon = a t^n \exp\left(-\frac{Q}{RT}\right) \sinh\left(\frac{V}{RT}\,\sigma\right) \tag{3}$$

Q stands for the activation energy and V for the activation volume of the material. The activation energy of concrete is in most cases approximately 4.5 kcal/Mol. The activation volume varies with water-cement ratio and with humidity content. An average value of 10^{-17} mm^3 has been determined for hardened cement paste (Klug, P. and Wittmann, F. H., 1974).

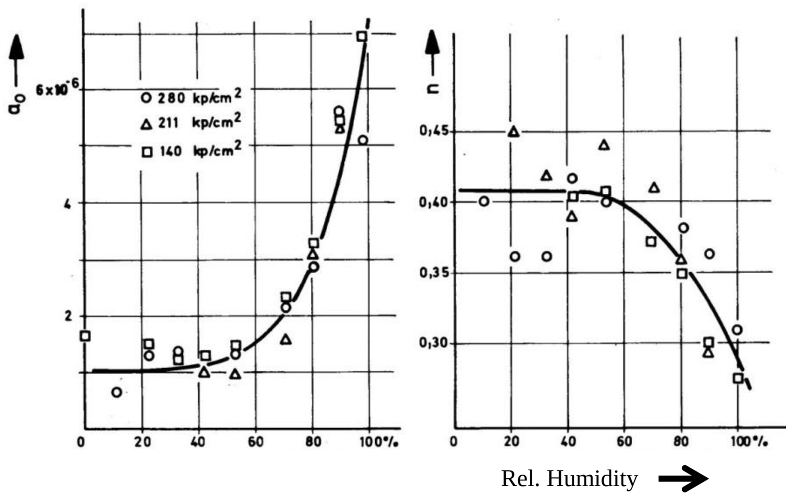

Figure 9: *a_0* and *n* of Eq. (4) as function of relative humidity

If creep at constant temperature T and at moderate applied stress σ is to be described, Eq. (3) can be simplified:

$$\varepsilon = a_0\, t^n\, \sigma \tag{4}$$

Under constant moisture content creep follows a simple power law. But the moisture content has a significant influence on the activation volume. The lower the moisture content, the lower will be the creep strain. Measured values for a_0 and n of Eq. (4) are plotted in Fig.

9. As expected, creep of saturated specimens is at maximum. In high strength concrete the equilibrium humidity in the mass may be reduced after one week already to values around 80 %. According to Fig. 9 creep of high strength concrete will then be reduced to one third of the value at saturation. This relation ought to be taken into consideration if materials properties are to be introduced in a realistic way.

4. CONCLUSIONS

Shrinkage of porous materials such as concrete is a complex process based on a number of different mechanisms. The most important mechanisms at an early stage are dissolution shrinkage and capillary shrinkage. In the hardened state of concrete shrinkage is essentially due to loss of water in the pore space. Water can get lost by drying to the environment and by internal drying by continuing hydration (self-desiccation). Disjoining pressure in concrete depends strongly on the amount and type of ions dissolved in the pore water. When all these mechanisms are taken into consideration prediction of shrinkage by model codes can be significantly improved. For high strength concrete and for concrete produced with blended cements existing model codes are applicable with certain limits only. If the interaction between water and the hydration products of cement are taken into consideration, model codes can be modified. For given applications and for special types of concrete predictions of model codes can be made more realistic.

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