INTERACTION BETWEEN DAMAGE AND TIME-DEPENDENT DEFORMATION OF CONCRETE: 3D FE PARAMETRIC STUDY AT MESO-SCALE

INTERAKTION ZWISCHEN SCHÄDIGUNG UND ZEITABHÄNGIGER, NICHTELASTISCHER VERFORMUNG VON ZEMENTSTEIN: 3D-FINITE-ELEMENTE-ANALYSE (FE) AUF DER MESO-SKALA

Serena Gambarelli[1], Joško Ožbolt[2]

[1] *Materials Testing Institute (MPA), University of Stuttgart, Otto-Graf-Institute*

[2] *Institute of Construction Materials, University of Stuttgart*

SUMMARY

Heterogeneity of concrete and its interaction with load-induced damage and time-dependent non-elastic deformation of cement paste (e.g. basic creep and drying shrinkage), have strong influence on the long-term response. These effects are investigated through the 3D finite element (FE) analysis of a concrete cylinder at meso-scale. A non-linear constitutive law, based on the microplane theory, is assumed for mortar, while the aggregate is assumed to be linear elastic. The study shows that with higher loading level the increase of creep deformations of concrete becomes progressive. This is related to the interaction between the load-induced damage of mortar and its non-elastic time-dependent deformations, such as basic creep and shrinkage.

ZUSAMMENFASSUNG

Die Heterogenität des Betons und ihre Interaktion mit der lastinduzierten Schädigung und zeitabhängigen nichtelastischen Verformung von Zementstein (z. B. Schwinden) haben einen starken Einfluss auf das Langzeitverhalten. Diese Effekte sind durch die 3D-Finite-Elemente-Analyse (FE) eines Betonzylinders auf der Meso-skala untersucht. Für Mörtel wird ein nichtlineares konstitutives Gesetz angenommen, das auf der „Microplane" Theorie basiert, während die Zuschläge als linear elastisch angenommen sind. Die Untersuchung zeigt, dass mit zunehmender Belastung die Zunahme der Kriechverformungen des Betons progressiv wird. Dies hängt mit der Wechselwirkung zwischen der lastinduzierten Schädigung des Mörtels und seinen nichtelastischen zeitabhängigen Verformungen wie Grundkriechen und Schwinden.

KEYWORDS: Concrete, creep, shrinkage, FE analysis, meso-scale modeling, microplane model

1. INTRODUCTION

Research interest in time-dependent deformation of concrete, such as creep and shrinkage, has been largely increased over the years. This is due to the great number of concrete and RC structures that are sensitive to these effects in terms of structural damage and failure. Better understanding of concrete behaviour under environmental conditions is important to guarantee its durability and to prevent a critical deterioration.

Creep is manifested as slow increase of deformation under sustained load while shrinkage is defined as the strain that occurs in absence of applied load (stress-independent deformation) and is related to drying and aging of hardened cement paste. Different theories for creep of hardened cement paste exist [1-3], however, it seems that the main reason is the relative slip (micro-sliding) between Calcium-Silicate-Hydrate (C-S-H) sheets that is controlled by the amount and state of pore water [4]. Principally creep of cement paste can be divided in two parts, basic creep, which is measured at constant temperature and humidity, and drying creep, which is an additional creep associated with moisture content variation between C-S-H sheets. If the stress level is relatively low, then basic creep is approximately linear proportional to stress. However, at higher load level basic creep becomes non-linear with stress, which is a consequence of interaction between basic creep, shrinkage and damage of cement paste.

Due to inhomogeneity of concrete, creep of concrete becomes even more complex than the creep of hardened cement paste. Namely, similar to the interaction at micro structure of cement paste (e.g. basic creep, shrinkage and damage) in concrete there is a similar interaction between non-elastic deformation of cement paste (e.g. basic creep, shrinkage, temperature and humidity variation) and load-induced damage of mortar which can, in addition to the time-dependent deformation of cement paste, strongly effect time deformation of concrete. In the literature, a number of studies can be found dealing with creep and shrinkage of concrete [5-8], where the influence of temperature is also considered. From the obtained results it is clear that time-dependent strains of concrete are influenced by many factors, which can be classified as intrinsic factors, fixed once and for all components when concrete is casted, and extensive factors that can vary after casting. The former are the properties of the aggregate, e.g. the strength, Young´s modulus and its volumetric fraction in concrete, the maximum aggregate size and shape. The extensive factors (also called state variables), such as load level, temperature, degree of hydration and pore water content, strongly influence time-dependent behaviour of concrete [7]. The influence of age at loading on creep has been experimentally investigated by many researchers and in all cases it was found that creep is lower if the age at loading is higher. As shown in [5] creep is accelerated if concrete is drying simultaneously with creep, and rapid heating, as well as rapid cooling also accelerates creep.

Another important aspect is the influence of high stress level on concrete long-term behaviour. It is known that under stress exceeding about 40% of the uniaxial compressive short-time strength, the time-dependent strains of concrete become progressively non-linear with stress increase and this non-linearity is mainly caused by the gradual propagation of microcracks [9].

The combined effect of creep and damage of concrete under compressive loads has been investigated by many researchers [10-12]. In [10] the microplane model is coupled into a series with a linear creep model (generalized Maxwell chain model) to simulate creep-cracking interaction in concrete. Mazzotti et al. [11] used strain-based isotropic damage model and a modified version of solidification theory to simulate damage and (non-linear) creep of concrete. Moreover, the measurements on a number of structures, especially bridges [13, 14], show that the time-deformation continuously increase in time and do not converge to a certain limit.

The aim of the present study is to bring more light into the interaction between different processes related to the time-dependent deformation (creep) of concrete. Apart from the time-dependent deformation of hardened cement paste (basic creep and shrinkage), the question is how the load induced-damage and non-elastic deformations of mortar interact in concrete and how they affect the time-dependent deformation of concrete. Therefore, in the present study the time-dependent behaviour of concrete is numerically investigated through 3D meso-scale finite element analysis of concrete cylinder for different levels of applied uniaxial compressive load.

2. RANDOM AGGREGATE STRUCTURE IN CONCRETE

To randomly distribute the coarse aggregate inside the concrete cylinder (with ratio diameter/height = 100/200 mm) a simple generation procedure (implemented in Matlab R2013b) is used. The procedure is based on a minimum distance criterion, which prevents any intersection between spherical particles. Based on the information of a known concrete mix, the size distribution of the coarse aggregate is determined by using the Fuller curve and the following steps are performed [15]: (1) The centers of the aggregate particles are randomly generated avoiding any intersection between the particles; (2) Solid spheres (with a given diameter) are generated from the corresponding particle centers; (3) All the spheres are subtracted from the external solid to obtain the two distinct phases of the concrete specimen, coarse aggregates and mortar matrix. The generated meso-scale model is shown in Fig. 1a, where 22% of the coarse aggregate (5 mm ≤ D ≤ 10 mm) is reproduced. The geometry of the created meso-model is finally imported into the 3D FE code MASA [16] used for the simulations and meshed with solid four-node finite elements (Fig. 1b).

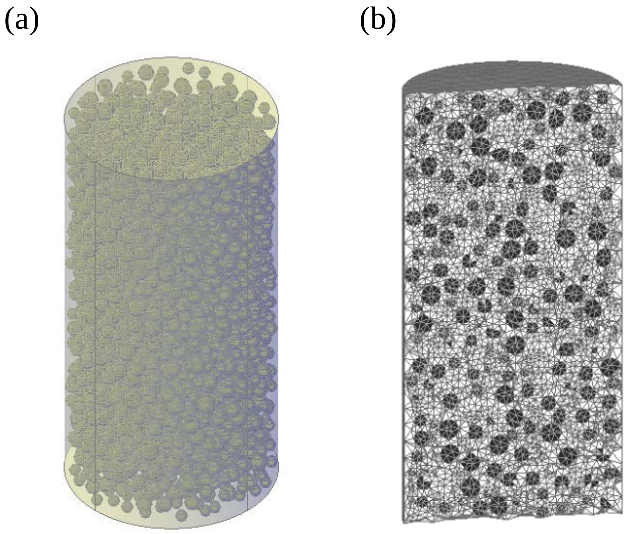

Fig. 1: Meso-scale structure of concrete: (a) geometry and (b) FE model

3. CONSTITUTIVE LAW AND FE DISCRETIZATION

In the meso-scale finite element analysis the constitutive law for mortar is based on the microplane model [17], while the aggregate is considered as linear elastic with Young's modulus of 90 GPa and Poisson's number 0.18. The macroscopic mechanical properties of mortar are reported in Table1.

Table 1: Mechanical properties of mortar at age of 28 days

Secant modulus of elasticity, E [GPa]	23.0
Poisson' ratio, v	0.18
Uniaxial compressive strength, f_c [Mpa]	32.0
Tensile strength, f_t [Mpa]	3.2
Fracture energy, G_F [J/m^2]	25.0

Note that these properties were assumed to be constant in the transient finite element analysis, i.e. the increase of mechanical properties due to the further hydration of cement was not accounted for in the mechanical part of the model (microplane model), however, it was accounted in the computation of basic creep of mortar (Maxwell chain model). Basic creep of mortar matrix is simulated based on the linear rate-type creep law (generalized Maxwell chain model) with eight age-dependent units [10]. It is coupled into a series with the microplane model (see Fig. 2).

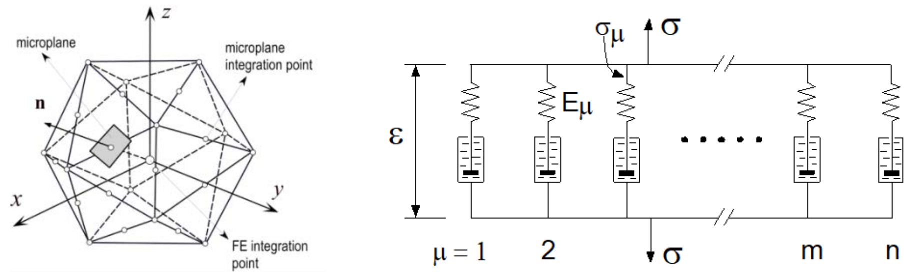

Fig. 2: Serial coupling of microplane model (left) and generalized Maxwell chain model (right)

The total strain tensor is decomposed into elastic (ε_{el}) and damage (ε_{dam}) strains (microplane) and time-dependent non-elastic components (basic creep (ε_{bcr}), shrinkage (ε_{sh})):

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_{dam} + \varepsilon_{bcr} + \varepsilon_{sh} \quad (1)$$

Creep strain from the Maxwell chain model is assumed to be linear proportional to stress. For concrete this is approximately valid if the stress level is relatively low compared to strength. However, at higher stress levels there is interaction between non-elastic strains and damage, which leads to progressive creep deformations (non-linear creep). In this study, meso-scale FE analysis is performed to check whether the model is able to naturally reproduce non-linear creep effects through the material heterogeneity and interaction between damage and non-elastic strains of mortar. The linear creep factor (φ_{lin}) for mortar is set equal to 4, which is relatively high compared with those typically assumed for concrete [7]. This assumption is justified by the presence of coarse aggregate, which does not creep appreciably and has a restraining effect on creep of concrete.

Shrinkage of mortar matrix is modelled by an algebraic formula (Eq. 2) that indicates the mean shrinkage of the cross section of a test specimen:

$$\varepsilon_{sh}(t, t_0) = \varepsilon_{sh\infty} k_h S_t \quad (2a)$$

$$S(t) = [t/(\tau_{sh} + t)]^{1/2} \quad (2b)$$

$$k_h = 1 - 0.95h^3 - 0.25h^{200} \tag{2c}$$

where t_0 is the curing time (in days), t is duration of drying (in days), $\varepsilon_{sh\infty}$ is the ultimate shrinkage (humidity 0%), k_h is the humidity coefficient, h is the environmental relative humidity, $S(t)$ is a function of t giving the shape of the shrinkage curve and τ_{sh} is the shrinkage square half time. In this study, the ultimate shrinkage of mortar ($\varepsilon_{sh\infty}$) is assumed equal to 0.002. This parameter has been calibrated through shrinkage analysis of the concrete cylinder, to reproduce a realistic shrinkage value for concrete that is approximately equal 0.0008 [7]. The environmental relative humidity (h) is set equal to zero (perfectly dry environment), with consequent unit value for the humidity coefficient (k_h). The shrinkage square half time (τ_{sh} = 200) has been calibrated in order to approach the final asymptotic value for shrinkage ($\varepsilon_{sh\infty}$) after 5 years.

The spatial 3D finite element discretization of the two concrete phases is shown in Fig. 3. Fixed boundary conditions are imposed at the top and at the bottom of the specimen. The vertical load is applied at the top of the cylinder, either through displacement control (instantaneous loading) or through load control (sustained load). To assure results independent of the element size the regularization technique based on the simple crack band approach is used [18].

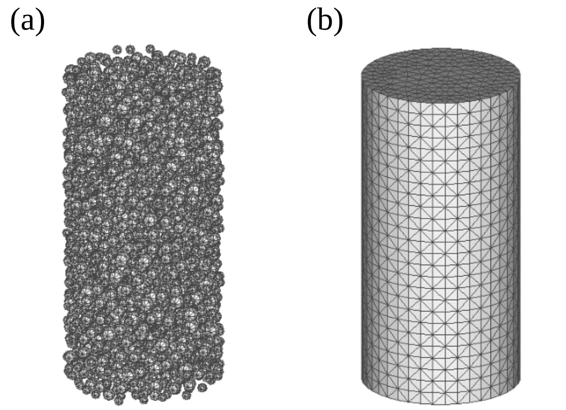

Fig. 3: FE model: (a) coarse aggregate and (b) mortar matrix

4. NUMERICAL RESULTS AND DISCUSSION

4.1 UNIAXIAL COMPRESSIVE TEST

As a first step of the study, a uniaxial compressive test has been performed on the concrete cylinder to evaluate the maximum compressive load and to check whether the model predicts a realistic material response. The obtained results, in terms of axial stress-strain curve and concrete failure mode, are shown in Fig. 4. It is possible to infer from Fig. 4 that the meso-scale model is able to correctly reproduce the typical compressive curve of normal strength concrete (f_c = 28 MPa, ε_c = 0.002, E_c = 27 GPa), in both pre and post-peak regions (Fig. 4a). Concrete failure mode is shown in Fig. 4b in terms of maximum principal strains. The red zones correspond to a crack opening of 0.12 mm. As can be seen damage localizes in the central part of the specimen with several vertical and inclined cracks. To show the internal damage distribution the specimen is cut at mid-section.

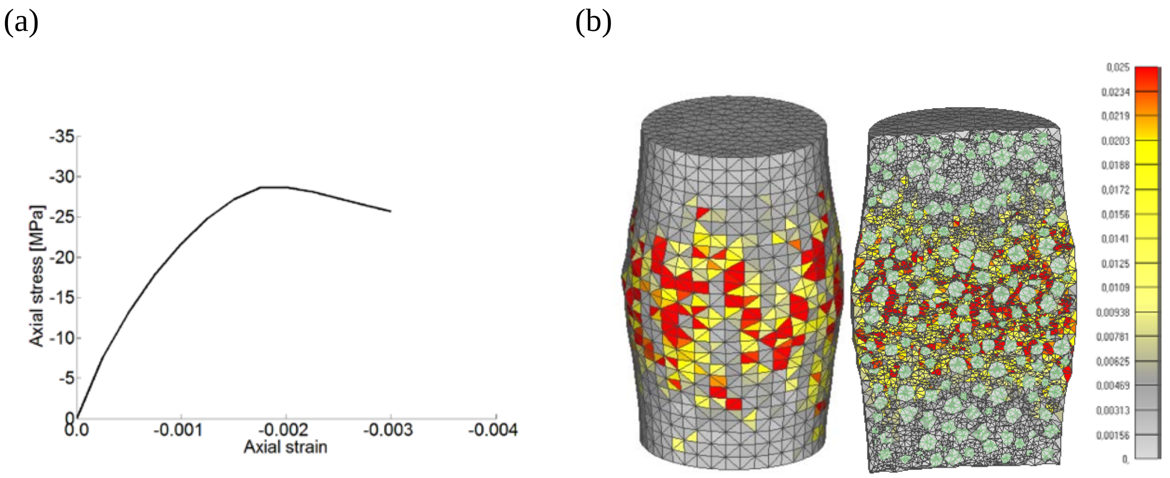

Fig. 4: Uniaxial compressive test: (a) stress-strain curve and (b) concrete failure mode

4.2 TIME-DEPENDENT ANALYSIS

For different levels of the applied uniaxial compressive load (10%, 40%, 60%, 80% of the short-term strength), the influence of the following parameters has been investigated: (i) basic creep of mortar and (ii) shrinkage of mortar. Finally, to account for the interaction between these variables, the effect of their combination has been also studied.

4.2.1 Basic creep

The results obtained for basic creep, considering linear creep factor for mortar (φ_{lin}) equal to 4, are shown in Fig. 5. The average axial strain, measured along the specimen height, is plotted against time (in semi log-scale). It can be seen that increasing the applied uniaxial compressive load there is a progressive increase of non-elastic (creep) strains. However, the interaction between damage and basic creep is not so strong, even for relatively high load level (80% of the short-term strength). It follows that basic creep alone is not responsible for the markedly non-linear behaviour of concrete. In fact, as confirmed by experimental studies [5], creep becomes more critical when concrete is drying simultaneously with creep (drying creep effect).

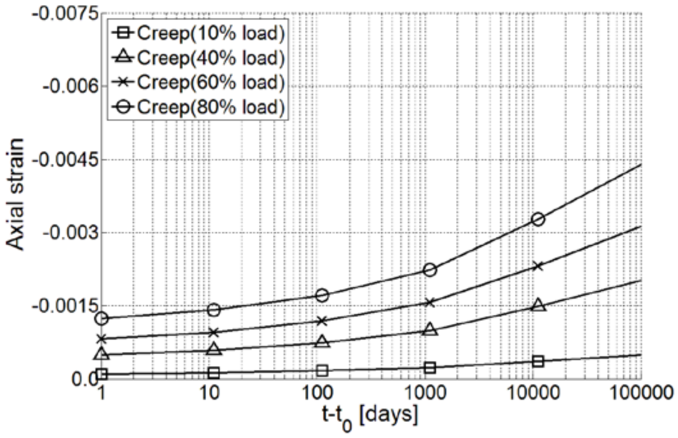

Fig. 5: Axial average strain of concrete for: Load + Basic creep of mortar (φ_{lin} = 4)

4.2.2 Shrinkage

Shrinkage analysis of the concrete specimen (without load) was performed to clarify the influence of shrinkage of mortar (maximum assumed to be 0.002) on the time-dependent behaviour of concrete. The predicted shrinkage curve of concrete is shown in Fig. 6a. The final shrinkage value obtained for concrete (0.0008) is evaluated considering a perfectly dried environment ($h = 0$), which is an extreme case, but still it is in agreement with typical values for concrete [7]. It is worth noticing that the final shrinkage of concrete (0.0008) is relatively low with respect to the final value assumed for mortar (0.002). This result is justified by the presence of the coarse aggregate, which restraints the specimen volume changes, due to their rigidity. The final shrinkage value obtained for concrete (0.0008) is evaluated considering a perfectly dried environment ($h = 0$), which is an extreme case, but still it is in agreement with typical values for concrete [7].

(a) (b)

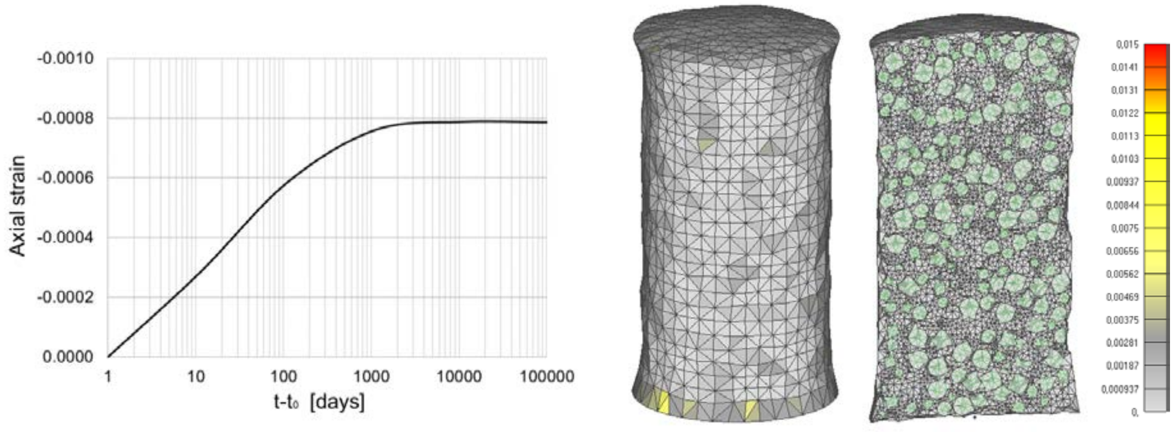

Fig. 6: (a) Shrinkage strain of concrete ($\varepsilon_{sh\infty}$ = 0.002); (b) Damage of concrete due to shrinkage of mortar (27 years of drying)

It is worth noticing that the final shrinkage of concrete (0.0008) is relatively low with respect to the final value assumed for mortar (0.002). This result is justified by the presence of the coarse aggregate, which restraints the specimen volume changes, due to their rigidity. The corresponding concrete damage due to shrinkage of mortar is shown in Fig. 6b in terms of maximum principal strains. Maximum crack width due to shrinkage at the concrete surface far from boundaries is approximately equal to 0.05 mm.

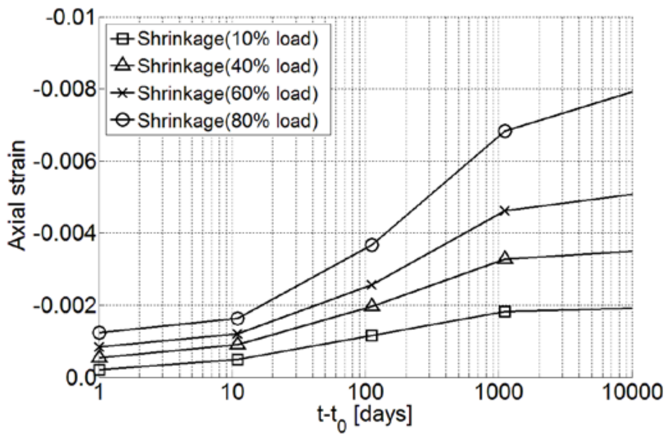

Fig. 7: Axial average strain of concrete for: Load + Shrinkage of mortar ($\varepsilon_{sh\infty}$ = 0.002)

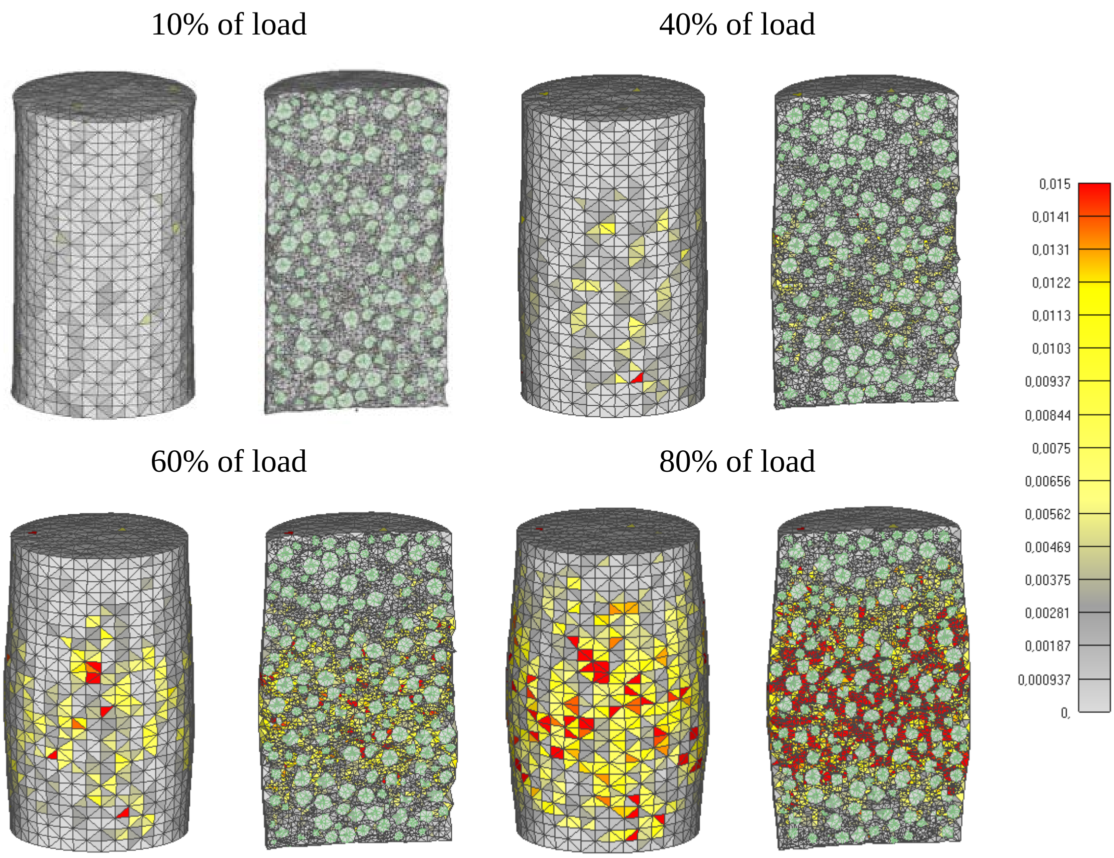

Fig. 8: Damage of concrete for different load levels: Load + Shrinkage of mortar (after 27 years)

The results obtained from the shrinkage analysis at different load levels are shown in Fig. 7. It can be seen that with increasing the applied load there is significant increase of non-elastic strains of concrete, i.e. there is a strong interaction between shrinkage strain of mortar and damage induced by load. Concrete damage is shown in Fig. 8, where a fully damaged specimen can be observed for load level of 80%.

4.2.3 Combination of creep and shrinkage

The combined effect of basic creep and shrinkage of mortar has been numerically simulated to investigate the interaction between load-induced damage and basic creep and shrinkage of mortar. Note that here no interaction between basic creep and shrinkage of mortar is accounted for. In the model, creep and shrinkage of mortar are activated after the application of load (28 days). The numerical results at different load levels are shown in Fig. 9. The curves obtained by simultaneous action of basic creep and shrinkage (continuous lines) are depicted together with those obtained by superimposing the separate contributions (dotted lines). The interaction between the load-induced damage and time-dependent non-elastic strains of mortar (basic creep + shrinkage) leads to strong non-linear response of concrete. As can be seen, the total deformation after 27 years is slightly smaller than that obtained by simple superposition of deformations due to separate action of basic creep and shrinkage. This suggests that there is no strong interaction between basic creep and shrinkage on the total deformation of concrete.

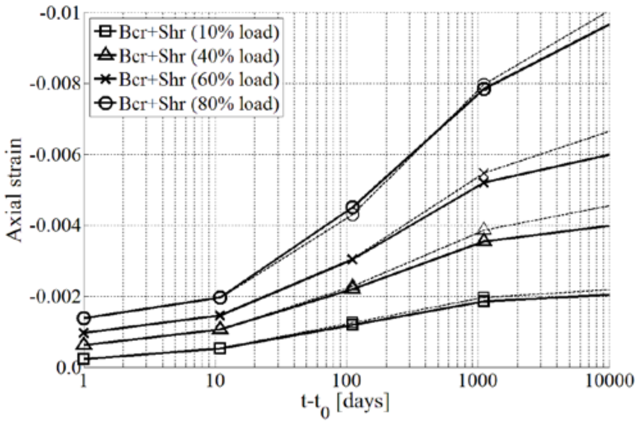

Fig. 9: Axial average strain of concrete for:
Load + Basic creep of mortar (ϕ_{lin} = 4) + Shrinkage of mortar ($\varepsilon_{sh\infty}$ = 0.002)

5. CONCLUSIONS

Creep of concrete consists of two contributions: (i) The contribution of creep of hardened cement paste and (ii) The contribution that is a consequence of the interaction between the load-induced damage of hardened cement paste (mortar) and its non-elastic strain deformations. In the present study some aspects related to the second contribution are addressed and investigated through the 3D FE study of the concrete cylinder at meso-scale. From the obtained numerical results, the following can be concluded: (1) Increase of the applied load level leads to the increase of non-elastic strains (creep) of concrete. This is related to the interaction between the load-induced damage of mortar and its non-elastic time-dependent deformations; (2) Results for the influence of basic creep of mortar show that its effect alone cannot reproduce the markedly non-linear creep of concrete at high stress level. However, the response becomes critical when basic creep of mortar is combined with shrinkage of mortar; (3) The results suggest that the mechanical interaction between the load-induce damage of mortar and its non-elastic time-dependent deformations strongly influence time-dependent response of concrete. This contribution to the creep of concrete can be larger than the contribution of time deformation of hardened cement paste. It can be attributed to the heterogeneity of concrete with the consequence that in practice the time-deformation of concrete (creep) constantly increases and do not converge to certain limit.

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