Interaction between damage and time-dependent deformation of mortar in concrete: 3D FE study at meso-scale

S Gambarelli1 and J Ožbolt2*

1 Materials Testing Institute, University of Stuttgart, Germany
2 Institute of Construction Materials, University of Stuttgart, Germany

*E-mail: ozbolt@iwb.uni-stuttgart.de

Abstract. Creep of concrete can be partly attributed to the time-dependent deformation of cement paste and partly to the interaction between load-induced damage of mortar (hardened cement paste) and its non-elastic deformations [1]. The heterogeneity of concrete and related interaction between load-induced damage and non-elastic deformation of mortar can have significant influence on the long-term response of concrete. Some aspects of the problem have been investigated in [1] through 3D finite element (FE) analysis of a concrete cylinder at meso-scale. The concrete is treated as a bi-phase composite material, consisting of coarse aggregate and mortar matrix. The constitutive law for mortar is based on the microplane theory, while the aggregate is assumed to be linear elastic. The results obtained for basic creep and shrinkage, at different levels of applied uniaxial compressive load (both separate and combined action) are reported in [1]. This paper mainly focuses on the effect of cyclic variation of environmental temperature and its interaction with the load-induced damage, basic creep and shrinkage of mortar. It is shown that with higher loading level the increase of time deformation of concrete becomes progressive and the variation of environmental temperature strongly influences time-dependent concrete response.

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 behavior under environmental conditions is important to guarantee its durability and to prevent a critical deterioration [1].

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 [2-6], 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 [7]. 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 [8-14], where the influence of temperature is also considered. However, fewer studies [15-18] are focused on the long-term behavior of concrete under variable temperature and humidity, e.g. cyclic variation of thermal strains induced by changes in the environment temperature and humidity. This aspect is important, since many real structures are subjected to daily and seasonal temperature and humidity variations.

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. The time-dependent behaviour of concrete is numerically analysed through 3D meso-scale finite element analysis of concrete cylinder for different levels of applied uniaxial compressive load. In particular, the effect of cyclic variation of environmental temperature and its interaction with the load-induced damage, basic creep of mortar and shrinkage of mortar is investigated.

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 (see [19]). The generated meso-scale model is shown in figure 1.a, where 22% of the coarse aggregate (5 mm ≤ D ≤ 10 mm) is reproduced. The geometry of the created meso-model is imported into the 3D FE code MASA [20] used for the simulations and meshed with solid four-node finite elements (figure 1b and figure 1c).

![Figure 1. a) concrete meso-structure; b) Aggregate FE discretization; c) Mortar FE discretization.](image)

3. Constitutive law and FE discretization
In the meso-scale finite element analysis the constitutive law for mortar is based on the microplane model [21], while the aggregate is considered as linear elastic, with Young’s modulus of 90 GPa and Poisson’s number 0.18. Perfect connection between mortar and aggregate is assumed. The macroscopic mechanical properties of mortar are reported in table1.
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 [22]. The models adopted for basic creep and shrinkage of mortar are described in [1].

| Table 1. Mechanical properties of mortar at age of 28 days. |
|----------------------------------------------------------|
| Secant modulus of elasticity, $E$ [GPa] | 23.0 |
| Poisson’ ratio, $\nu$ | 0.18 |
| Uniaxial compressive strength, $f_c$ [Mpa] | 32.0 |
| Tensile strength, $f_t$ [Mpa] | 3.2 |
| Fracture energy, $G_F$ [J/m²] | 25.0 |

The influence of concrete meso-structure on the cyclic variation of thermal strains is simulated by performing a transient thermal analysis. The imposed cyclic temperature history of environment is shown in figure 2, where the maximum and minimum temperature values are related to the average daily high temperature for the warm (21°C) and cold (7°C) season in Stuttgart. These values are cyclically maintained for 30 days, for the total number of 165 cycles, which correspond to 14 years.

The thermal properties of the two concrete constituents, in terms of thermal conductivity and specific heat capacity, are evaluated based on literature data [23, 24, 25]. In [23] the temperature dependence of thermal conductivity has been studied on different rock types, for temperatures ranging from 0 to 800°C. Based on the experimental measurements, the authors calibrated several empirical equations. In this study a sedimentary rock (limestone) is assumed for the coarse aggregate (see equation. 1) with a thermal conductivity $\lambda$ (T = 0 °C) = 3.2 Wm⁻¹K⁻¹.

\[
\lambda(T) = \frac{1073}{(350+T)} + 0.13
\]  

Assuming the value of 1.15 W/mK for the thermal conductivity of mortar matrix, the Hashin-Shtrikman (H-S) bounds (see equation 2) can be applied to determine upper and lower bounds [25] for the thermal conductivity of the concrete mix assumed in this study:

Figure 2. Temperature history of the environment.

165 cycles ≈ 14 years
\begin{equation}
    k_1 = k_1 + \frac{x_2}{k_2 - k_1 + x_1} = 1.46
\end{equation}

\begin{equation}
    k_h = k_2 + \frac{x_1}{k_1 - k_2 + x_2} = 1.52
\end{equation}

where \( k_1 = 1.15 \, \text{W/m/K} \) is the thermal conductivity of mortar matrix, \( k_2 = 3.2 \, \text{W/m/K} \) is the thermal conductivity of coarse aggregate, \( x_1 = 0.78 \) is the volumetric fraction of mortar matrix, \( x_2 = 0.22 \) is the volumetric fraction of coarse aggregate. The estimated values for the upper (\( k_h \)) and lower (\( k_l \)) bounds of the thermal conductivity are in good agreement with the provisions of Eurocode 2 [26] for normal weight concrete.

The temperature dependence of the aggregate specific heat is determined based on the experimental study reported in [24], while for mortar the same relationship proposed for concrete in [26] is considered. The obtained thermal properties for both, aggregate and mortar matrix, are shown in figure 3.

\section{Numerical results}

\subsection{Time-dependent analysis}

The results from the static compressive test are reported in [1]. Figure 4 shows the numerical curves obtained from the cyclic thermal analysis for different levels of the short-term strength. The predicted
curves (thin dotted lines), characterized by a cyclic variation of the strain, are depicted with the corresponding trend lines.

A markedly non-linear behavior of concrete can be observed already after 1000 days, even for relatively low level of the applied load and for a small gradient of the imposed cyclic temperature variation. The main reason for this trend is the interaction between damage induced by load and cyclic variation of thermally induced non-elastic strains of mortar and aggregate.

Concrete damage for 10% and 80% of the short-term strength after 14 years of temperature exposure is shown in figure 5, where a progressive increase of damage localization can be seen with increasing load level. The relatively strong influence of temperature variation can also be attributed to the relatively small concrete specimen and large period of time (30 days) with constant temperature, which results in the change of temperature over the entire specimen and not only close to the surface of the cylinder.

**Figure 4.** Axial average strain of concrete for: Load + Temperature.

**Figure 5.** Damage of concrete for different load levels: Load + Temperature (after 14 years).

### 4.2. Combination of creep, shrinkage and temperature

The effect of interaction between the load-induced damage, basic creep and shrinkage of mortar and temperature is shown in figure 6. Note that no interaction between basic creep, shrinkage and temperature induced strains of mortar is accounted for.
Figure 6 Axial average strain of concrete for: Load + Basic creep of mortar ($\phi_{lin}=4$) + Shrinkage of mortar ($\varepsilon_{shr}=0.002$) + Temperature.

This combination is typical for concrete exposed to load and extreme environmental conditions. For relatively high load level (80% of the short-term strength) temperature influence becomes dominant and the interaction between the load-induced damage of mortar and its non-elastic time-dependent strains results in concrete failure after 200 days.

5. Discussion of the results
The influence of basic creep, shrinkage and temperature (and their combinations) on the long-term behavior of concrete is for each level of the applied load shown in figure 7. It can be seen that with increase of the applied load level the increase of time-dependent strains of concrete becomes markedly non-linear (semi-log scale).
As shown in [1] the response of concrete under combined effect of basic creep and shrinkage of mortar is much more critical than that observed only for basic creep. This confirms strong interaction between the load-induced damage of mortar and shrinkage of mortar on creep of concrete. The influence of cyclic variation of thermal strains of concrete leads to gradual increase of time deformation of concrete with the applied load (increase of load-induced damage of mortar). Together with basic creep and shrinkage of mortar it leads to failure of concrete cylinder approximately 200 days after application of load (80% of short-term strength of concrete).

Figure 8 shows the numerically predicted relative effective creep factor of concrete \( \phi_{\text{eff}, \text{rel}} \) for all simulated cases as a function of load level, for load duration of 27 years and 14 years for temperature variation, respectively. It is calculated as:

\[
\phi_{\text{eff}, \text{rel}} = \frac{\phi_{\text{eff}}}{\phi_{\text{eff}, 10\%}} \text{ with } \phi_{\text{eff}} = \frac{\varepsilon_{\text{tot}} - \varepsilon_{\text{shr}, \text{inf}}}{\varepsilon_{\text{el}} + \varepsilon_{\text{shr}, \text{inf}}} \tag{3}
\]

in which \( \phi_{\text{eff}, 10\%} \) is effective creep factor for the lowest load level (10% of the short-term strength), \( \varepsilon_{\text{tot}} \) is total strain at the end of loading (27 years), \( \varepsilon_{\text{el}} \) and \( \varepsilon_{\text{damage}} \) are elastic and damage contributions to deformations of concrete cylinder at the application of load, respectively, and \( \varepsilon_{\text{shr}, \text{inf}} \) is shrinkage deformation of load free concrete cylinder at \( t = \infty \) (in the present study approximately 0.0008 (see [1]). The effective creep factor represents the increase of time deformation of concrete compared to the initial elastic deformation of concrete and shrinkage, if considered.

For basic creep \( \phi_{\text{eff}, \text{rel}} \) is approximately equal to the creep factor of mortar (\( \phi_{\text{lin}} = 4.0 \)). As can be seen from figure 8, for basic creep \( \phi_{\text{eff}, \text{rel}} \) is almost independent of the stress level. The relative effective creep factor for shrinkage is increasing from 1.0 (10% of load) to approximately 3.6 (80% of load). This indicates very strong interaction between the load-induced damage and shrinkage of mortar. Similar tendency can be observed for the influence of temperature as well as for the simultaneous contribution of all non-elastic strain components.
6. Conclusion
In the present study the interaction between the load-induced damage of cement paste (mortar) and its non-elastic strain deformations is investigated through the 3D FE study of the concrete cylinder at the 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) The simulation indicates that variation of environmental temperature strongly influences time-dependent concrete response. Together with the non-elastic deformations of mortar, temperature variation can lead to failure of concrete shortly after application of load; (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.

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