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EXPERIMENTAL ANALYSIS AND MODELING OF HARDENING CONCRETE UNDER UNIAXIAL LOADING

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Summary: *The uniaxial compression is a kind of loading which occurs in concrete structures frequently. In the case of solidifying concrete the uniaxial compression without any lateral constraint, which can be the surrounding concrete mass, does not exist. However, after about the initial setting time the microstructure development progressed long enough so that concrete can support itself and it does not slump under its self weight. Another possible application of uniaxial compression can be seen during erecting walls of reasonable thickness uniformly loaded by self weight. In those cases the effect of self weight on the evolution of the concrete microstructure should not be neglected. The accidental overloading, which can happen as an erroneous placement of another lift or fallen objects on the surface of hardening concrete, especially in the cases when removal of the affected concrete is no longer feasible, and its consequences have to be assessed by some reasonable modeling. In this paper, an experimental analysis is shown and a model of hardening concrete under short-time and sustained uniaxial loading is proposed.*

1. Introduction

The available models for concrete can be divided into two groups. The first group is intended for fresh concrete and the models are usually applied for simulation of mixing of concrete, flow of concrete in tubes during pumping, flow during placement in order to investigate the effect of reinforcing bars, or for a direct simulation of the flow and slump tests. The second group is huge and comprises a majority of all models ever developed, which are used for simulation of already hardened concrete. Those models differ conceptually, in the number of parameters involved, in their complexity, and in other ways depending on the classification. For both these groups it holds that the assumption of constant material parameters will not impose significant error to their results. This is the cardinal difference from the models for solidifying and hardening concrete where the rapidly progressing hydration is the ruling phenomenon which cannot be neglected by assuming it constant and which constitutes the main difficulty for which, probably, the models are few. Moreover, most of the models which can be classified as those for solidifying and hardening concrete are mere extensions of the models for hardened concrete with addition of some parameters referring to the rapid hydration.

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In the case of solidifying and hardening concrete it is also important to choose upon which way the real time will be treated in the modeling. Unlike in the case of fresh and hardened concrete where the change in ambient conditions does not affect the response of concrete over a reasonable time span considerably and time can be used as the scaling parameter, the response of solidifying and hardening concrete alters significantly for different ambient conditions and therefore for the same time but different ambient conditions the responses will not be identical. This effect has been taken into account in preceding modeling in different ways. For example, the effect of progressing hydration was tackled with the help of the maturity concept where the age of concrete is defined as the sum of time intervals multiplied by averaged temperature during that time interval or in the concept of the degree of hydration where the progressing hydration is quantified in terms of a ratio of, for example, the heat generated till the instant of interest to the ultimate amount of heat which can be generated. Another concept which was originally developed for expressing the material change in metals is the internal variable called intrinsic time which was defined in the so-called endochronic theory.

In this paper, a general framework for modeling the evolution of hardening concrete under sustained uniaxial loading is proposed. The model is based on the on the identification of an evolutionary function and is conceived to be used throughout the whole life of concrete, which suggests its application to the three evolutionary stages when concrete is in the fresh, solidifying and hardened states An uniaxial compression test based on image processing was pursued to supply the experiment data on the deformation behavior of hardening concrete under sustained uniaxial loading.

2. Experimental analysis of hardening concrete under uniaxial loading

The uniaxial compression test was used for the investigation of the response of solidifying and hardening concrete to both short-time and sustained loading. For this purpose a loading system which was able to maintain a constant load was developed and successfully applied.

2.1. Description of loading system

The loading system, which was used for the uniaxial compression test, consisted of a data logger, a load cell, an electric actuator and a personal computer, as shown in Figure 1. An online fuzzy controller was programmed in the personal computer. This controller made decisions which were based on the online load-cell readings conveyed through the data logger. The decisions regarding the loading action were communicated to the actuator's controlling unit. The accuracy of the loading system was –2%. The minus sign means that the actual load level was always under the desired load level in order to avoid overshooting which would impose a plastic deformation to the solidifying or hardening concrete. This would in turn damage experimental data on the creep deformation.

2.2. Measuring technique

For measuring lateral deformation, an optical method where the image of the specimen is captured with a high resolution CMOS camera and then processed by a computer program was used. The shutter of the camera was correlated in terms of time with a PC collected data on longitudinal displacement measured by linear displacement sensor SM50 (for precisely admeasured length 50 mm) and loading force measured by a load cell. The loading force was imposed by an electric actuator with an online fuzzy controller. See [2], [3] for detailed test configuration and image processing.

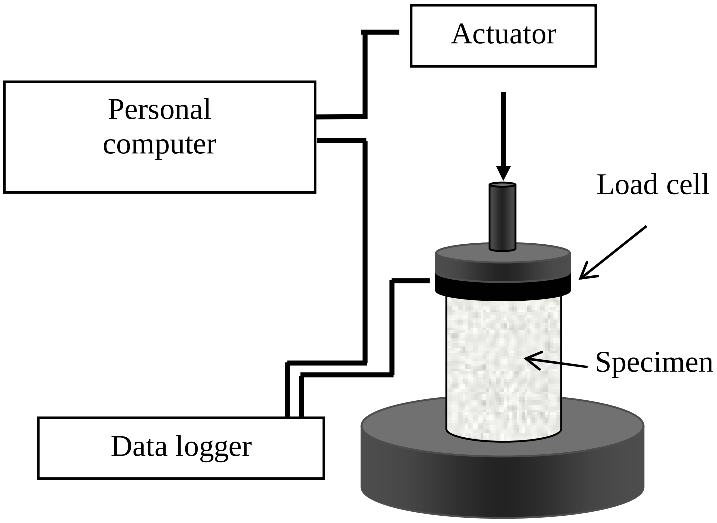

Figure 1. Loading System for Uniaxial Compression Test

The standard specimens (ϕ=100mm and height=200mm) were used. The mix designs are shown in Table 1.

Table 1. Mix Proportions of Concrete

Type	Weight per unit volume (kg/m^3)			
	W	C	S	G
C-1	168	271	767	1136
C-2	181	490	598.5	1093

[Note] Target 28days strength = 30 MPa (C-1)
60 MPa (C-2)

Target slump = 8 cm

Target air content = 2 %

3. Modeling of creep of hardening concrete under uniaxial

The response of hardening concrete subjected to the sustained uniaxial compression loading is dominated by the irreversible viscous deformation same as the response to the short-time loading. The development of the creep deformation which was obtained from the experimental data of the creep test on hardening concrete resembles in an accelerated form the creep of the already hardened concrete and the shape resembles especially the so-called viscoelastic part of the deformation. However, in the case of the hardening concrete the deformation is mostly irreversible which was observed in the experimental data for the short-time cyclic loading under uniaxial loading. Even though the experiment of the reversible creep was not conducted, it is assumed that the time-dependent deformation of the hardening concrete under sustained loading is also irreversibly viscous, nevertheless, it is described by the reversible viscous component of the general model. This is for the sake of consistency when it is safe to assume that this part of the deformation will later become the reversible viscous deformation, known as the viscoelastic deformation.

The time-dependent deformation of hardening concrete is significantly influenced by the rapidly progressing hydration, which prohibits the assumption of a non-aging material. For that reason the basic equation of the time-dependent response should include the effect of aging, which once treated separately eases the numerical evaluation of the time-dependent response. The irreversible viscous strain vector is given in a rate-type form by

$$\dot{\varepsilon}_v(t) = \frac{F[\sigma(t)]}{\alpha f(t)} \int_0^t \dot{J}^v(t-t')d\sigma(t') \qquad (1)$$

where t is time, t' is time at the instant of loading, f(t) is a function expressing the effect of aging, α is a scaling parameter, σ is the vector of stresses at the instant of loading and F[σ(t)] is the effect of load level. $\dot{J}^v(t-t') = J^v(t-t')T$, where $J^v(t-t')$ the uniaxial creep function and T is the transformation matrix. Based on the knowledge acquired from the experimental data the creep function was identified as

$$J^v(t-t') = \frac{(t-t')^\gamma}{t_0 + (t-t')^\gamma} \qquad (2)$$

where t is time (in sec), t' is the instant when the load was applied (in sec) and $\gamma = 1$ and t_0=30 sec. The scale parameter α was identified from the experimental data as

$$\alpha = 2193 - 3360W/C \qquad (3)$$

The function of the evolution of microstructure, which expresses the aging, was identified from experiments on the evolution of penetration resistance, pullout resistance and compressive strength and is given by

$$
\begin{aligned}
&f(t_n) = a_5\left(\frac{a_3 t_n^{a_2}}{a_1 + a_3 t_n^{a_2}}\right)^{a_4}\\
&a_1 = 10;\\
&a_2 = 9.164 - 7.2W/C;\\
&a_3 = 0.72;\\
&a_4 = 1;\\
&a_5 = 15
\end{aligned}
\tag{4}
$$

where t_n is a normalized time with respect to the final setting time (here 6hr00 and 7hr15 for type 30MPa and 60MPa, respectively), W/C is water-cement ratio (in decimal) and a_1, a_2, a_3, a_4 and a_5 are empirical parameters. The value of the function f is normalized so that it becomes unity at the final setting time.

When compared with Bažant's function of nonlinearity (in [4]), in the case of hardening concrete the function of nonlinearity needs to reflect the effect of water-cement ratio as it was learned from the experimental data. The function is defined by

$$
F_2[\sigma(t), W/C] = \frac{\exp\left((2 - 1.6W/C)S\right)^3}{1 - S^{10}} \tag{5}
$$

$$
S = \frac{\sigma(t)}{f_c} \tag{6}
$$

where W/C is the water-cement ratio (in decimal). The denominator is introduced to ensure the growth of the strain beyond all limits with reaching the ultimate compressive strength.

For a multidimensional analysis, which in the case of concrete at the ages ranging from initial to final setting times can involve mainly compressive loading conditions, the Poisson's ratio, μ, is expressed by

$$
\begin{aligned}
&\mu(S) = 0.25 && && S \in \left\langle 0; 0.3\right)\\
&\mu(S) = 0.25 + 0.5(S - 0.3) && \mathit{for} && S \in \left\langle 0.3; 0.8\right)\\
&\mu(S) = 0.5 && && S \in \left\langle 0.8; 1\right)
\end{aligned}
\tag{7}
$$

where S is given by Eq. 6.

4. Discussion of results

The response of the hardening concrete to the sustained uniaxial compressive loading was model with the used of the reversible viscous component formulation. The main reason for this decision was the actual shape of the creep curves represented by the specific creep which resembled the shape known for the already hardened concrete. The estimation what portion of the creep deformation is reversible was not considered in this modeling. However, it can be reflected by adding a coefficient similar to the coefficients of appropriateness. The results of the creep test and the modeling are compared in Figures . 2 to 7 (see more in [5]).

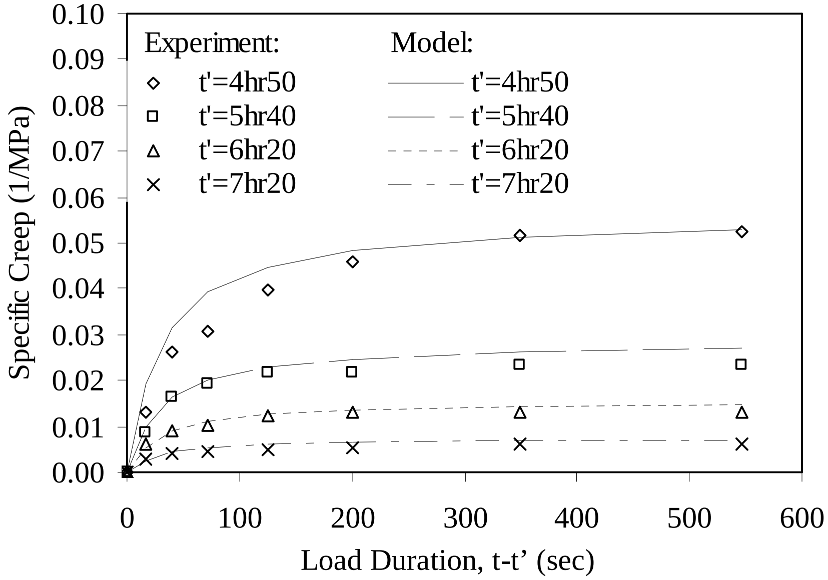

Figure 2. Comparison between Model and Experimental Data for Type C-1 and Load Level 30%

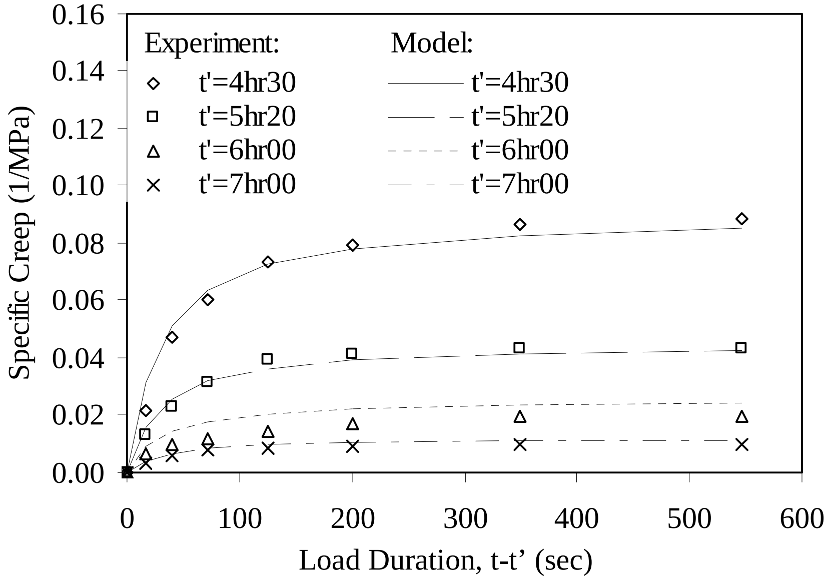

Figure 3. Comparison between Model and Experimental Data for Type C-1 and Load Level 50%

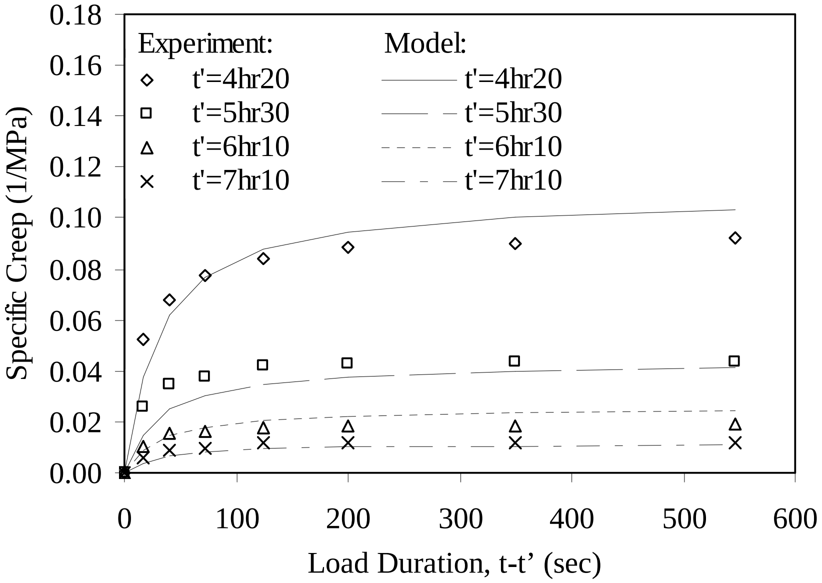

Figure 4. Comparison between Model and Experimental Data for Type C-1 and Load Level 70%

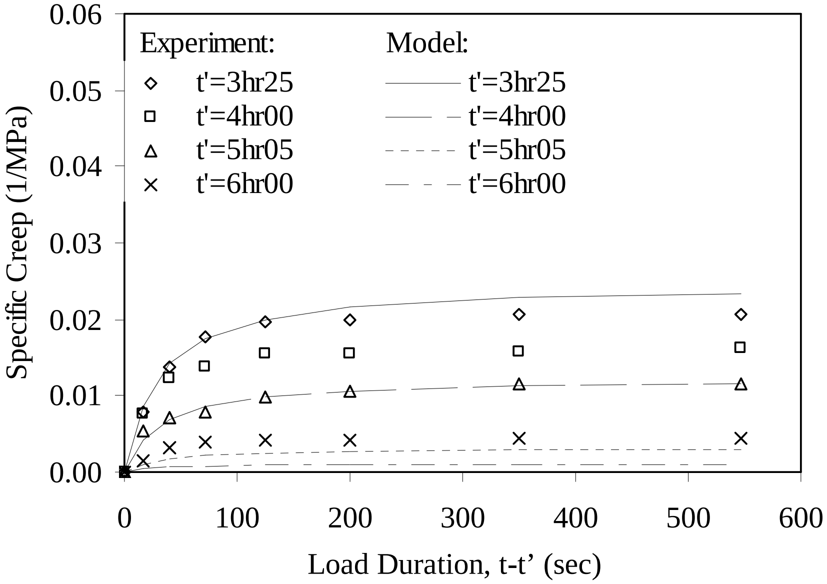

Figure 5. Comparison between Model and Experimental Data for Type C-2 and Load Level 30%

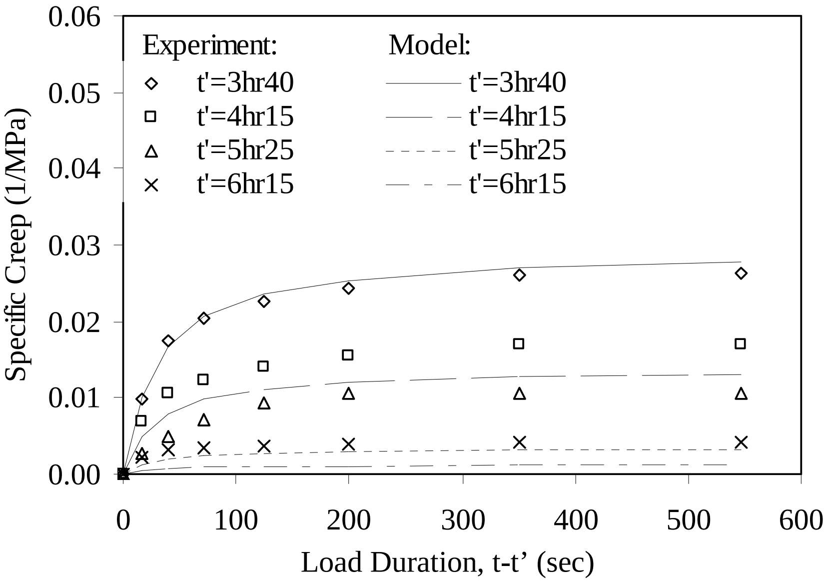

Figure 6. Comparison between Model and Experimental Data for Type C-2 and Load Level 50%

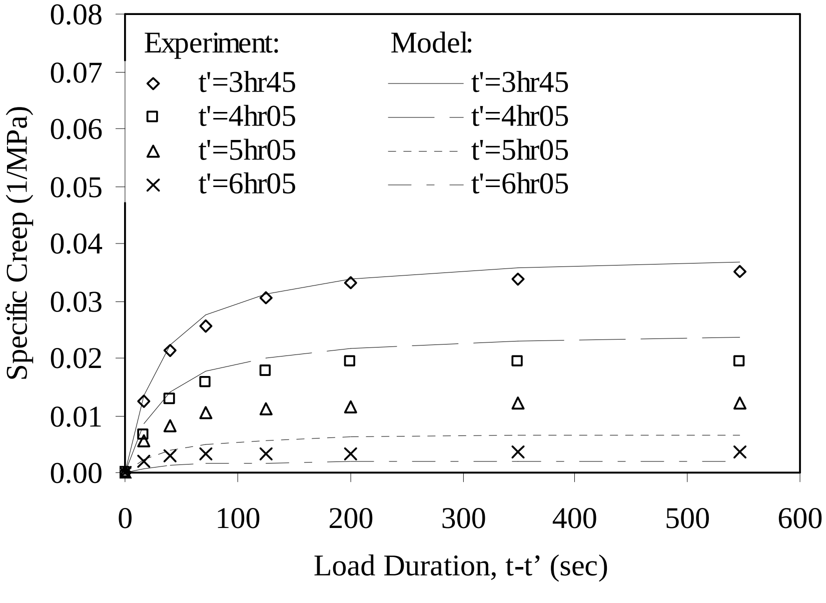

Figure 7. Comparison between Model and Experimental Data for Type C-2 and Load Level 70%

5. Conclusions

This paper focused on experiments with hardening concrete and modeling of hardening concrete under sustained uniaxial loading. A model of time-dependent response of hardening concrete, which includes the effect of rapidly progressing hydration and the effect of excessive loading was proposed. Experiments data on creep, Poisson's ratio of hardening concrete under sustained uniaxial loading were obtained and then compared with the results from the model.

6. Acknowledgement

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7. References

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