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# A NONLINEAR MODEL FOR PREDICTING THE EARLY AGE CREEP OF CONCRETE UNDER COMPRESSIVE LOADINGS

**Chaymaa LEJOUAD *, Jean-LUC ADIA * AND Herman KOALA†**

*EDF Lab Les Renardières
Ecuelles, FRANCE
e-mail: chaymaa.lejouad@edf.fr
e-mail: jean-luc.adia@edf.fr

† EDVANCE
Montrouge, France
e-mail: herman.koala@edvance.fr

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**Abstract.** This paper presents the development and application of a nonlinear model for predicting the creep of early age concrete under compressive loadings, a critical factor in the design and long-term performance of concrete structures in the nuclear industry. The model, inspired by previous work, incorporates an aging function to account for the decrease in creep compliance due to concrete aging, explained by the solidification theory. In this model, the non-aging viscoelastic strain is approximated using six Kelvin chains and an initial nano-porous pressure is considered for early age concrete, adjusted based on the degree of hydration. The model is calibrated using short-term creep tests performed on VeRCoRs concrete at different ages and demonstrates a good match between the experimental data and the numerical simulations. The model is further extended to predict the response of VeRCoRs concrete subjected to drying creep tests at $20^oC$ and $40^oC$. The developed model offers a comprehensive framework for predicting creep behavior in early age concrete as well as creep of mature concrete at different environment conditions.

## 1 INTRODUCTION

Concrete, as a fundamental construction material, undergoes various deformations and changes in its properties over time. Creep, the gradual deformation that occurs under sustained loading, is a critical phenomenon influencing the long-term behavior of concrete structures.

In the nuclear industry, creep due to prestressing in containment buildings concrete is a significant consideration in the design and long-term performance of these critical structures [1]. In this context, during the design phase, it is of utmost importance to get information regarding the long-term creep of mature concrete based on short-term experiments.

To achieve this objective, a nonlinear model for predicting the creep of early age concrete under compressive loadings has been developed. Based on experimental data coming from short term creep tests of early age concrete, this model has been calibrated. The so obtained model with the adjusted set of parameters has been challenged regarding its consistency with long term creep test of mature concrete.

The paper starts with a brief overview of the experimental data used in the calibration and validation of the numerical model. The subsequent section focuses on elucidating the fundamental equations of the developed model, in addition to presenting the principal outcomes.

The conclusions part emphasizes the key findings and provides some perspectives.

## 2 EXPERIMENTAL DATA

The VeRCoRs mock-up is a reduced-scale replica of the containment buildings for 1300 MW and 1450 MW power reactors in EDF's nuclear power plant fleet. With a height of approximately 30 meters and a diameter of around 16 meters, it faithfully reproduces the real structures.

The main objective of the VeRCoRs mock-up is to better understand the aging mechanisms of concrete. To achieve this, it is equipped with over 750 sensors that collect real-time data on various parameters such as strains, temperature, and moisture content of the concrete. More details about VeRCoRs mock-up can be found in [2] [3].

In addition to the work at the structural scale, the concrete used in the VeRCoRs mock-up has been extensively characterized at the material level within EDF, as well as in national and international partner laboratories. In this section, only the material-scale characterization tests used in this study will be mentioned.

### 2.1 VeRCoRs concrete

VeRCoRs concrete is a C30/37 class concrete according to the European Standard NF EN 206+A2/CN [4]. The detailed mix design of VeRCoRs concrete for a batch volume of 1 $m^3$ is reported in table 1. Table 2 summarizes the average mechanical and physical properties commonly measured for VeRCoRs concrete.

**Table 1**: Mix design of VeRCoRs concrete

| Component | Mass (kg) |
|---|---|
| Cement CEM I 52.5 N | 320 |
| Aggregate G1 (0 – 4 mm) | 830 |
| Aggregate G2 (4 – 11 mm) | 445 |
| Aggregate G3 (8 – 16 mm) | 550 |
| Admixture SIKAPLAST | 2.4 |
| Added water | 195.53 |

**Table 2**: VeRCoRs concrete properties at 90 days

| | |
|---|---|
| Compressive strength | 48 MPa |
| Tensile strength | 4.3 MPa |
| Young's Modulus | 37 GPa |
| Porosity | 14% |

### 2.2 Basic creep tests

For this study, the experimental data obtained in the framework of a Ph.D Thesis carried out at EDF R&D is used [5] [6]. In this experimental campaign, cylindrical specimens of 8 × 30 cm dimensions were manufactured with VeRCoRs concrete. These specimens were subjected to basic creep tests at different ages : 2 days, 7 days, 28 days and 90 days.

The tests are conducted in the lab's creep room, where both temperature and relative humidity are maintained at 20°C and 50%, respectively. The endogenous condition was maintained by sealing the samples with aluminum foil and applying X60 glue around the openings where the instrumentation supports were anchored.

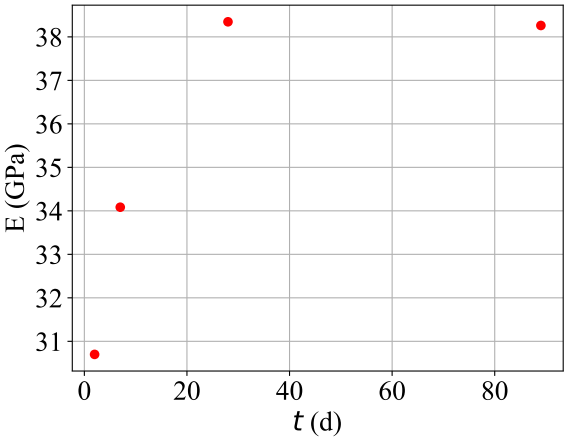

Figure 1: Young's modulus measured at 2, 7, 28 and 90 days.

The force applied during loading at every age is determined based on compressive strength testing conducted on supplementary samples. For each specimen, not more than 30% of the measured compressive strength was applied in order to remain in the linear creep regime. Figure 1 presents the Young's modulus measured on these additional VeRCoRs specimens at different ages.

For each test, the strain is measured by the means of 3 LVDT sensors placed at 0°, 120°, and 240° around the cylinder axis. It is important to mention that apart from the creep measurements taken during the loading phase, recovery is also tracked following the unloading process for a short period of time. Figure 2 depicts the obtained creep measurements at different loading ages.

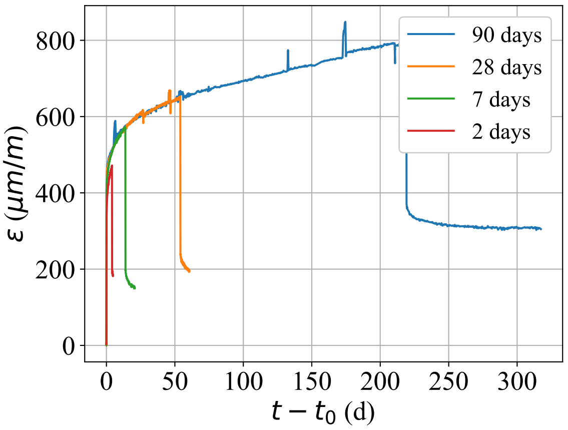

Figure 2: Basic creep for VeRCoRs concrete loaded after 2, 7, 28 and 90 days.

In addition to the short-term tests ($<$ 6 months duration) mentioned above, a basic creep test carried out for about 5 years duration is used. This test was performed on cylindrical specimens of $16 \times 100$ cm casted with VeRCoRs concrete mix. The specimen was sealed with aluminum foil and subjected to a compressive force equal to 30 % of the compressive strength. The applied stress and resulting creep strains are tracked over time. In figure 3, the measured strain is plotted as a function of time.

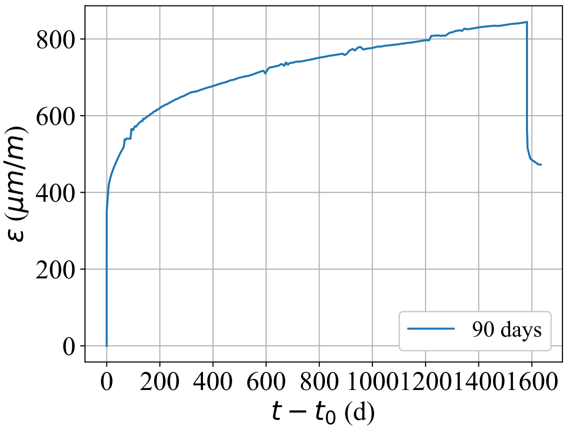

Figure 3: Long-term basic creep test performed on $16 \times 100$ cm cylindrical specimen.

### 2.3 Drying creep tests

Drying creep tests are used to validate numerical creep models in the case of a variable water field. In this study two tests are used :

- the first one consists of a drying creep test applied on a cylindrical specimen of $16 \times 100$ cm dimensions casted with VeRCoRs concrete and cured for up to 90 days in autogenous conditions. The test is performed at an imposed temperature of 20° C and 50 % relative humidity. The Measured strains are plotted in figure 4.

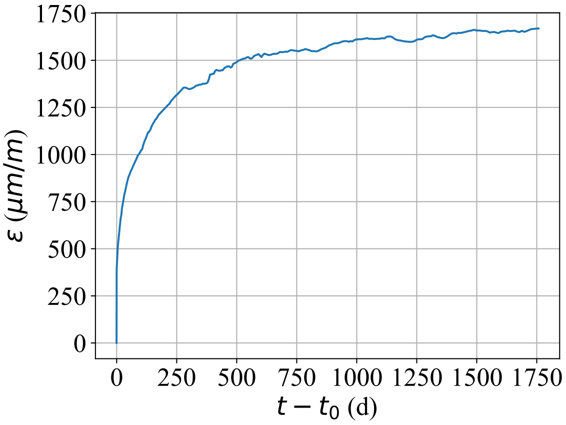

Figure 4: Drying creep performed at a temperature of $20°C$ and a relative humidity of 50%.

- the second test was performed at the LMDC Lab. A cylindrical specimens of $11 \times 22$ cm dimensions was subjected to a drying creep test under a temperature of $40°C$ and a relative humidity of $50\,\%$. The specimen was at first loaded at ambient temperature of $20°C$ before raising the temperature up to $40°C$. At the end of the loading phase, the specimen was unloaded before lowering the temperature from $40°C$ to $20°C$. The strains measured at the different phases are represented in figure 5.

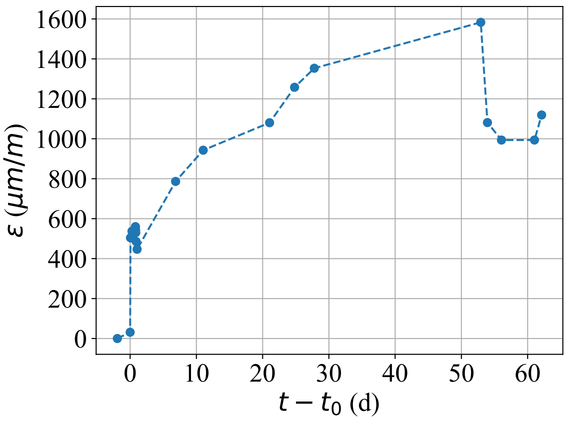

Figure 5: Drying creep performed at a temperature of $40°C$ and a relative humidity of $50\%$.

## 3 NUMERICAL MODELING

### 3.1 Model formation

The model developed in this study is inspired by the one developed in [7] and [8]. As shown in equation 1 and figure 6, the total strain increment $\varepsilon^t$ is the sum of the elastic $\varepsilon^{el}$ , thermal $\varepsilon^{th}$ and delayed strain increments. Delayed deformations are modeled by a consolidating Maxwell element for permanent creep $\varepsilon^m$ and a Kelvin element for reversible creep $\varepsilon^{kv}$. Finally, an additional Maxwell element is added in series to model non-consolidating permanent creep $\varepsilon^{dt}$.

$$\dot{\varepsilon}^t = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{th} + \dot{\varepsilon}^m + \dot{\varepsilon}^{dt} + \dot{\varepsilon}^{kv} \tag{1}$$

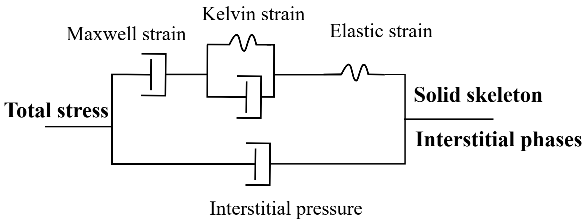

Figure 6: Rheological scheme for poro-mechanical creep model [7] [8].

It is experimentally demonstrated that the concrete aging induces a decrease in the creep compliance $J(t, t_0)$. This decrease is explained by the solidification theory. It corresponds to the filling of the pores by growing volume fraction of a non-aging constituent, the cement gel, or C-S-H (calcium silicate hydrate) [9] [10]. In the actual developed model, this effect is taken into account by multiplying the sum of the viscoelastic and elastic strains by an aging function [10] as shown in equation 2.

$$\dot{\varepsilon}^{ve}(t) = (\dot{\varepsilon}^{el} + \dot{\varepsilon}^{kv}) \times \frac{1}{v(t)}$$

$$\frac{1}{v(t)} = \left(\frac{\lambda_0}{t}\right)^m + \alpha \tag{2}$$

In equation 2, $\lambda_0 = 1\,\text{day}$, whereas $\alpha$ and $m$ are two parameters determined by a fitting of the function on the experimental data related to the young's modulus measured for VeRCoRs concrete at different ages (see. figure 1). The obtained fitting is showed below.

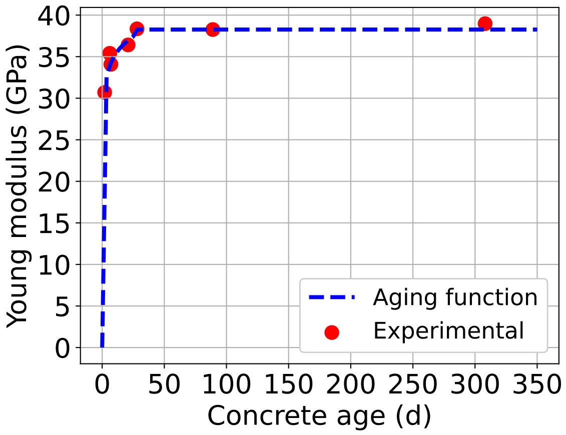

Figure 7: Experimental data and fitting of the aging function.

As suggested in [9], the non-aging creep compliance function of the solidified material $\Phi(t - t')$ is approximated by a generalized Kelvin chain. This approximation is based on the discretized retardation spectrum method [11] [12], so that in practice it is possible to pass from the empirical form of this creep function to the associated generalized Kelvin chain, as shown in figure 8.

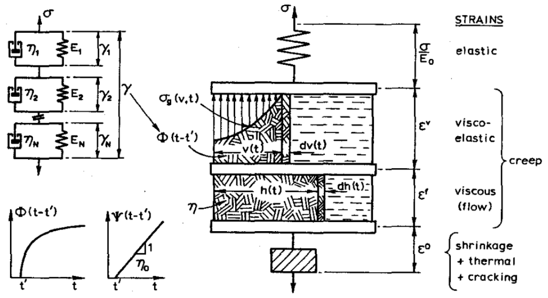

**Figure 8**: Rheological model MPS [9].

In the present model, only 6 Kelvin chains are considered to approximate the non-aging viscoelastic strain. The evolution of the viscoelastic deformation associated with the kelvin chains is specified in equation 3.

$$\dot{\varepsilon}^{kv} = \sum_{i=1}^{n} \dot{\varepsilon}^{kvi} = \sum_{i=1}^{n} \frac{1}{\tau_{kvi}} \left( \frac{\varepsilon^{el}}{\Psi_{ki}} - \varepsilon^{kvi} \right) \quad (3)$$

Where:

$\varepsilon^{kv}$ is the viscoelastic strain of the generalized Kelvin chain

$\varepsilon^{kvi}$ is the viscoelastic strain of the Kelvin chain number i

$\varepsilon^{el}$ is the elastic strain

$\tau_{kvi} = 10^{i-1}\tau_1; \tau_{kv0} = \frac{\tau_1}{\sqrt{10}}; \tau_1 = 10^{-4}$jour

$\Psi_{ki} = \frac{1}{Eq_2A_i}$ , $q_2$ is a empirical material parameter

the $A_i$ values are given in the table below

Table 3: $A_i$ values obtained with the discretized retardation spectrum method.

| | |
|---|---|
| A0 | 0.27166222 |
| A1 | 0.06513008 |
| A2 | 0.07815955 |
| A3 | 0.0925178 |
| A4 | 0.10789128 |
| A5 | 0.1238521 |
| A6 | 0.13990094 |
| A7 | 0.15552763 |
| A8 | 0.17027456 |
| A9 | 0.1837866 |
| A10 | 0.19583709 |

In [8] and [13], the kinetics of water pressure evolution in nanopores is related to capillary pressure by the relation :

$$\frac{\partial P^n}{\partial t} = \frac{P^w - P^n}{\tau^n} \quad (4)$$

In order to keep the characteristic time $\tau^n$ sufficiently high (12 days), it was necessary to change this equation for the present model, the new evolution equation is shown below. The coefficient $C_0$ is taken equal to 1 Pa. Furthermore, an initial nano-porous pressure $P_0^n$ for the case of early age concrete has been considered. This value is adjusted in relation to the degree of hydration $\xi$. We assume that $\xi$ value is the ratio between the Young modulus measured at the age $t_0$ on the Young modulus of mature concrete (90 days after casting). Figure 9 depicts the evolution of the hydration degree $\xi$ as a function of concrete age and figure 10 presents the initial nano-porous pressure as a function of hydration degree.

$$\frac{\partial P^n}{\partial t} = \frac{(P^w - P^n)^2}{\tau^n C_0} \quad (5)$$

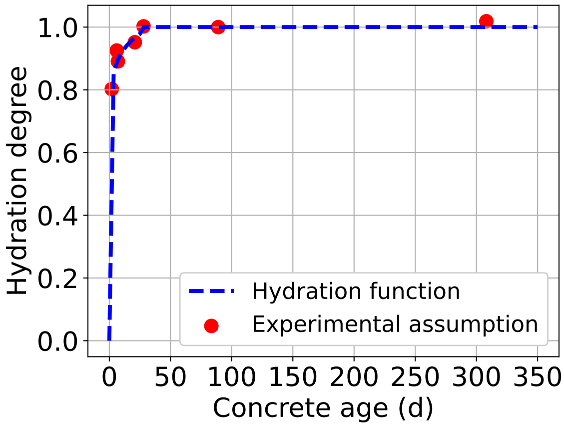

**Figure 9**: Evolution of hydration degree.

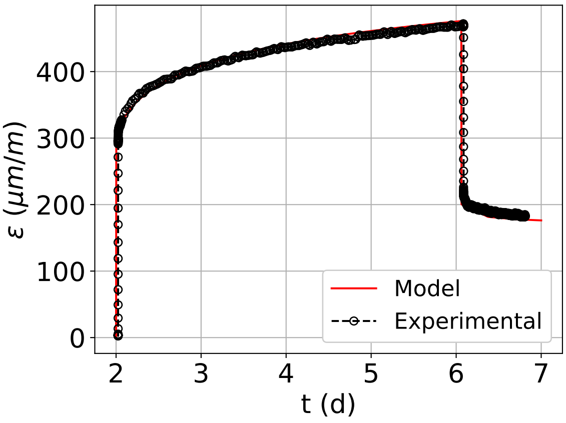

**Figure 11**: Basic creep $t_0 = 2$ days.

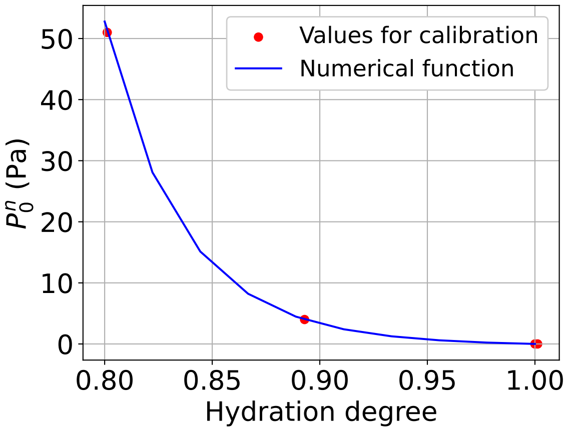

Figure 10: Evolution of $P_0^n$ as a function of hydration degree.

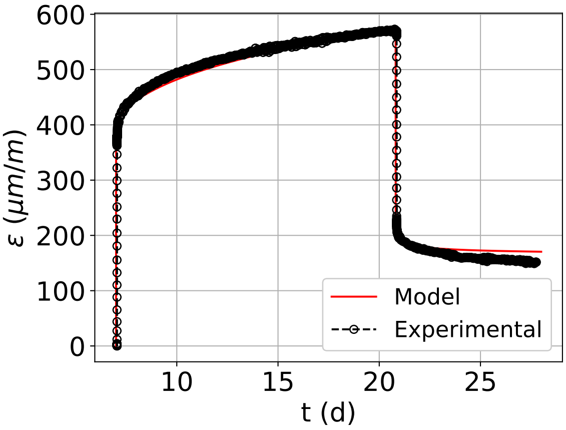

**Figure 12**: Basic creep $t_0 = 7$ days.

### 3.1.1 Results and discussion

Using the model described in paragraph 3.1, the first step was to calibrate the model using only the experimental data coming from the short-term basic creep tests performed on VeRCoRs concrete at different ages (paragraph 2.2). The figures 11, 12, 13 and 14 shows in the same graph the experimental results and the numerical simulations obtained in term of strains over time. The origin of the x-axis is taken as the time of the concrete casting. Based on these figures, we observe a good match between the experimental data and the numerical simulations.

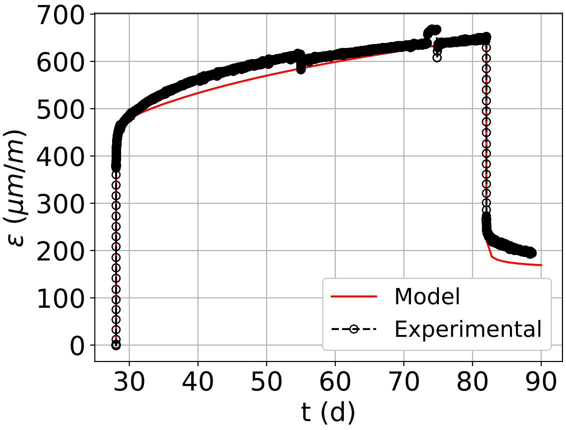

**Figure 13**: Basic creep $t_0 = 28$ days.

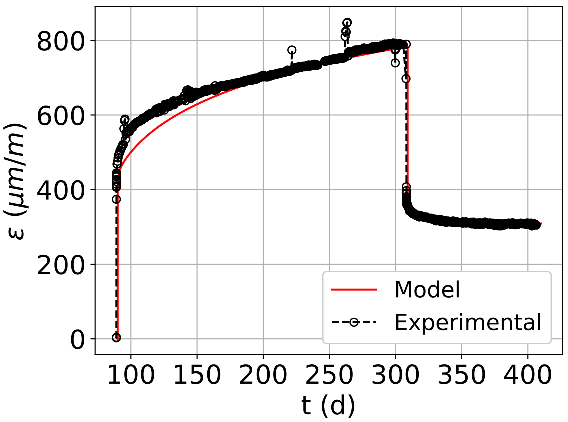

**Figure 14**: Basic creep $t_0 = 90$ days.

Using the same parameters as in the previous simulations, we could check the relevance of this model to predict long-term basic creep test ($> 5$ years) introduced in paragraph 2.2 (figure 15).

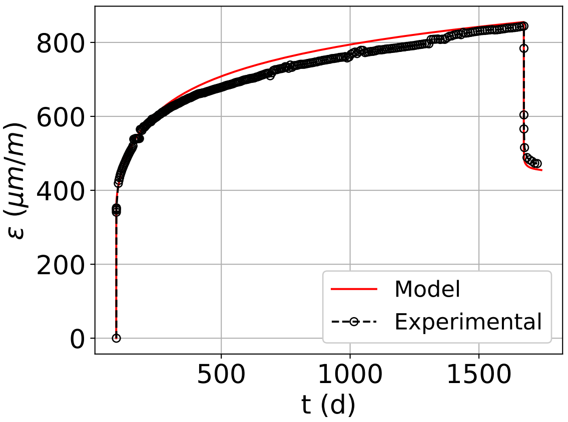

**Figure 15**: Long-term basic creep for mature concrete.

The use of the model has been extended to predict the response in terms of strains of the VeRCoRs concrete subjected to drying creep test at $20°C$ and $40°C$ temperature as described in paragraph 2.3. The same parameters as determined before has been used combined with a calibration of parameters that governs the creep behavior at drying conditions (eg. the activation energies). Based on figures 16 and 17 , we can appreciate the ability of the model to reproduce drying creep tests.

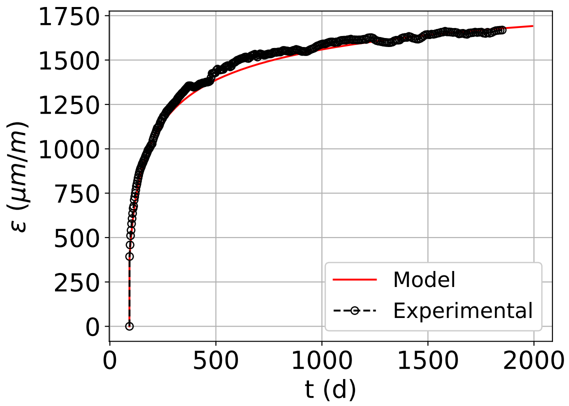

Figure 16: Drying creep for mature concrete $20°C/50\%$.

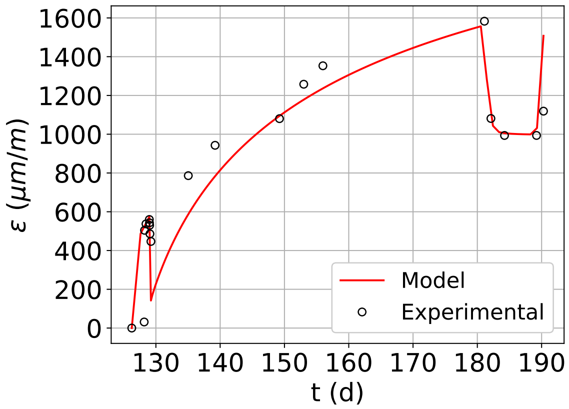

Figure 17: Drying creep for mature concrete $40°C/50\%$.

## 4 CONCLUSIONS

In conclusion, this paper presents a comprehensive nonlinear model for predicting the creep behavior of early age concrete under compressive loadings. The model incorporates elastic, thermal, and delayed strain increments, taking into account the effects of aging and drying conditions. Calibration of the model using short-term creep tests on VeRCoRs concrete at different ages demonstrates its ability to accurately reproduce the experimental data. Furthermore, the model is successfully extended to predict the drying creep response of mature VeRCoRs concrete at different environment conditions .

Future research can focus on further refining the model parameters and expanding its application to different types of concrete (eg. high performance concrete) and environmental conditions. Additionally, the model can be used in the optimization of concrete mix designs and in the assessment of the long-term performance of concrete structures based only on short-term creep tests performed on early age concrete.

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