

Uniaxial Deformational Behavior and Its Modeling of Solidifying Concrete under Short-time and Sustained Loading

短期および持続的載荷を受ける硬化中のコンクリートの一軸変形挙動とモデル化

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The knowledge of material properties of solidifying concrete is of major importance during construction process when many subsequent damages can be prevented. In this paper an evolutionary material model which can be used during the whole period when solidifying concrete undergoes the transition from a liquid to a solid state is proposed. The evolution of the material parameters is governed by a function of water/cement ratio and elapsed time after mixing which corresponds to the degree of hydration of concrete. The model can be used for modeling uniaxial behavior of solidifying concrete including creep. The parameters for the evolutionary function were determined from three experimental methods for uniaxial loading.

Key Words: concrete, creep, penetration, pullout, solidification

1. Introduction

The long-term performance of concrete structures is greatly influenced by events which occur within few hours after concrete was mixed and placed. This period is characterized by the rapid transition of concrete from the liquid state to the solid one. The behavior of fresh concrete has been described by several researchers, e.g., Tanigawa¹⁾ and Puri²⁾. The demand for the models describing the rheological properties of fresh concrete is mainly driven by the needs identified during transport and placement of fresh concrete. The experimental methods for fresh concrete are numerous and the experimental data are easy to access. The description of material properties of hardened concrete has been targeted ever since concrete became a common building material, and, because concrete is designed to serve as a hardened solid material. The behavior of solidifying concrete began to be addressed with emerging evidence of the detrimental effects related to the rapid hydration process, mainly manifested by cracks, which subsequently calls for repairs. Another reason, also economical, is the pressure on the building industry to accelerate the construction process. Especially in the case of long span bridges or high rise buildings any reduction of the repeatedly occurring limiters in construction processes, such as first possible loading of placed concrete, results eventually in huge savings of time.

It is well known that the evolution of material properties of concrete is controlled by the hydration process. The progress in hydration can be quantified with the degree of hydration or the concept of maturity, or another concept which takes into account mix proportions of concrete, chemical composition of the constituents, the size of the concreted volume, ambient

conditions, and so on. Regarding the investigation of the progressing hydration, there are direct and nondirect testing methods available, such as the traditional penetration test or a state-of-the-art ultrasonic testing³⁾. The reason why those testing methods are employed is the impossibility of testing some material parameters used in concrete analyses directly. In the case of solidifying concrete, the standard uniaxial compression test cannot be used due to the instability of a demolded specimen to acquire the compressive strength development curve. Therefore, another method needs to be chosen to assess the compressive strength of the solidifying concrete.

In this paper, an evolutionary model for solidifying concrete under uniaxial loading is proposed. The model is defined as rate type one and the material parameters used in the model are considered non-evolutionary while the aging effect is treated separately in terms of the degree of hydration. Due to the generality of the definition of the model it can be applied both to the fresh concrete and to the hardened one, same as it can be used for the transient stage when the liquid concrete gradually becomes a solid. The model is used for the simulation of a pullout test, when a steel plate is pulled out of solidifying concrete, indentation of a steel needle into solidifying concrete, the uniaxial compression test and a creep test.

The degree of hydration was investigated by three different testing methods, i.e., the pullout, penetration and uniaxial compression tests.

The range of applicability of the proposed model in terms of time is the range from mixing until final setting time, in terms of material the model was verified for mortar and concrete using rapid hardening portland cement (RHPC) with water/ cement ratio W/C ranging from 0.37 to 0.62, assuming a linear

dependence on W/C at the constant temperature 20°C.

2. General Form of Model

In this model it is assumed that the hydrated matter is expressed by a nonaging creep law and that the aging is taken into consideration by the degree of hydration. The main advantage of such a model is the separation of the part related to hardening due to the hydration process from the part representing the time-dependent deformation. A similar approach is used for the time-dependent deformational behavior of already hardened concrete where the deformational characteristics were modeled by the solidification theory⁴⁾. The solidification theory expresses the effect of aging by the growth of two hydrated volumes of cement paste related to viscoelastic and viscous deformations which are necessary in order to express the progressing viscous deformation with long-term sustained loading. The modeling based on the solidification theory is mainly applied at the ages in orders of weeks and later when no dramatic change in the hydrated volumes occurs and when concrete represents a hard solid material.

The deformational behavior of solidifying concrete changes with the progressing hydration, such that in the nearly liquid state the deformation is purely viscous and with the age the viscoelastic deformation also becomes of importance. This change in dominance of the viscous and viscoelastic components, apparent during short-term sustained loading, is caused by the transition of the solidifying concrete from a liquid state to a solid state, which is absent in the hardened concrete, however, which needs to be accounted for.

2.1 Basic equation

The solidification effects in solidifying concrete have been investigated experimentally under short-time loading⁵⁾ and an evolutionary model has been obtained⁶⁾. In this study, the model in Ref. [6] is to be extended to include the deformational behavior under sustained loading as well. The details of the modeling are described in the following.

The total uniaxial strain rate is defined as a sum of strain rate components, which is a common method used in, e.g., Ref. [7], and is expressed by the following equation

$$\dot{\varepsilon}(t) = \dot{\varepsilon}^e(t) + \dot{\varepsilon}^v(t) + \dot{\varepsilon}^f(t) + \dot{\varepsilon}^0(t) \quad (1)$$

where ε^e is the elastic or instantaneous strain, ε^v is the reversible viscoelastic strain, ε^f is the irreversible viscous (flow) strain, and ε^0 is the strain produced by the hydration process such as thermal strain, autogeneous shrinkage and cracking strain. The superposed dot indicates the differentiation with respect to time t . In the modeling, the first three components of Eq. 1 are considered. The last term, ε^0 , is neglected due to the difficulties with measuring it experimentally.

2.2 Elastic strain

The elastic strain rate is given by

$$\dot{\varepsilon}^e(t) = \frac{\dot{\sigma}(t)}{E_0 f_0(t)} \quad (2)$$

where E_0 is the initial elastic modulus and $f_0(t)$ is the function expressing the evolution of microstructure. The elastic deformation comprises the deformation of aggregate, the deformation of already hardened cement paste and the not yet hydrated cement grains. Same as in the solidification theory⁴⁾ those particles are considered nonaging, which is also consistent from the physicochemical point of view.

2.3 Viscoelastic strain

The viscoelastic strain rate is expressed as follows

$$\dot{\varepsilon}^v(t) = \frac{F_1[\sigma(t)]}{\alpha f_1(t)} \int_0^t \dot{\Phi}^v(t-t') d\sigma(t') \quad (3)$$

where $\Phi^v(t)$ is the creep function related to the viscoelastic strain component, $f_1(t)$ is the function expressing the evolution of the microstructure of solidifying concrete and α is an empirical constant. The function $F_1[\sigma(t)]$ is to express the effect of large stress because it is known that the deformational characteristics become nonlinear when the stress approaches the ultimate strength.

2.4 Viscous strain

The viscous strain rate is expressed as follows

$$\dot{\varepsilon}^f(t) = \frac{F_2[\sigma(t)]}{\beta f_2(t)} \int_0^t \dot{\Phi}^f(t-t') d\sigma(t') \quad (4)$$

where $\Phi^f(t)$ is the creep function related to the viscous component, $f_2(t)$ is the function expressing the evolution of microstructure related to the viscoelastic component and β is an empirical constant. Same as in the case of the viscoelastic strain, the function $F_2[\sigma(t)]$ expresses the effect of large stresses.

When $\dot{\Phi}^f = 1/\eta_{f0}$, the viscous strain becomes

$$\dot{\varepsilon}^f(t) = \frac{F_2[\sigma(t)]}{\eta(t)} \sigma(t) \quad (5)$$

$$\eta(t) = f_2(t) \eta_{f0} \quad (6)$$

where η_{f0} is an empirical material constant and $f_2(t)$ is the function expressing the evolution of microstructure related to the viscous component.

3. Evolutionary Change during Solidification

The evolution of the microstructure of solidifying concrete is a physicochemical process which depends on many factors of varying importance. Eliminating the outdoor factors, such as climatic conditions, by maintaining constant ambient temperature and humidity or establishing fully adiabatic conditions, the effect of the intrinsic factors can be observed. The chemical reaction at the microscopic level depends mainly

on the chemical composition and amounts of the concrete constituents, such as W/C and the type and fineness of cement. In order to introduce the effects connected with internal material changes to the proposed model it is necessary to choose a suitable internal variable. The degree of hydration is an internal variable whose concept is commonly accepted and which implicitly involves the physicochemical considerations. While the concept of degree of hydration, as the amount of chemically bound water or the amount of liberated heat, is known, a general expression or a model of the degree of hydration for solidifying concrete is not at hand, partially due to difficulties with quantifying it by some feasible measuring method. The methods which can effectively exhibit the microstructural evolutions are, e.g., pullout and penetration tests which can be used continuously during the whole period when concrete undergoes the transition from the liquid to solid state.

The evolutionary change during solidification includes the transition from a liquid state to a solid state which affects the deformational behavior of solidifying concrete. While the deformation of concrete in the liquid state is viscous, with the age the instantaneous elastic deformation and the viscoelastic deformation also become apparent. Partially, this effect is reflected by the evolutionary functions, $f_i(t)$, present in Eqs. 2-6. However, for the general use of the model, as it is conceived to describe the deformational behavior of concrete at the fresh, transient and solidified states, three parameters should be added to Eq. 1 in order to select only appropriate components for a certain age such that

$$\dot{\epsilon}(t) = c_1(t)\dot{\epsilon}^e(t) + c_2(t)\dot{\epsilon}^v(t) + c_3(t)\dot{\epsilon}^f(t) \quad (7)$$

The coefficient $c_i(t)$ in Eq. 7, whose value ranges from 0 to 1, represents the distribution function which expresses the degree of contribution of each deformational component for a given age, t . The coefficient $c_i(t)$ is set in such a way that, for example, for concrete in the fresh state the instantaneous and viscoelastic components are not included by setting $c_1 = 0$, $c_2 = 0$ and $c_3 = 1$.

However, at the ages up to the final setting time it is difficult to identify the instantaneous and viscoelastic components because of their small magnitude. Therefore, in the present modeling of the response of solidifying concrete under pullout, penetration and short-time uniaxial loading only the viscous component was considered, which corresponds to setting $c_1 = 0$, $c_2 = 0$ and $c_3 = 1$ in Eq. 7.

Since all experimental data in this paper were obtained with relatively small specimens under constant ambient temperature using only one type of cement, the degree of hydration in the present examples is assumed to be a function of mix proportions, namely W/C.

4. Deformational Behavior under Short-time Loading

The experimental work was focused on the acquisition of the data used in the modeling. The applied experimental methods were the pullout, the penetration and the uniaxial compression tests for obtaining the time evolution function, $f(t)$, and the creep test for obtaining the data on creep of solidifying concrete. Two types of mix proportions of concrete using rapid hardening portland cement (RHPC) were chosen for the creep

test. The mix proportions are shown in Table 1. For the pullout, penetration and uniaxial compression tests, two types of mixes of mortar using RHPC, which correspond to the mix proportions of concrete with the same target slump, were used as shown in Table 2.

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 28 day strength = 30 MPa (C-1)
60 MPa (C-2)

Target slump = 8 cm

Target air content = 2 %

Table 2 Mix proportions of mortar

Type	Weight per unit volume (kg/m ³)		
	W	C	S
M-1	300	483	1363
M-2	330	892	1052

[Note] Target 28 day strength = 30 MPa (M-1)
60 MPa (M-2)

Target slump = 8 cm

The initial and the final setting times for Type-1 and Type-2 following the testing method of JIS A 1147 were 4hr 35min and 7hr 15min, and 4hr 5min and 6hr 10min, respectively.

4.1 Pullout test

The objective of this test is to obtain the normalized evolutionary function $f_b(t)$ describing the development of microstructure of solidifying concrete in terms of the development of bond resistance stress. In this test, a stainless steel plate (150x20x2mm) was pulled out of solidifying mortar. This was done for four different pullout speeds (0.1, 0.5, 1.0 and 2.5 mm/s) and at four different ages (30 minutes, 4, 5 and 6 hours after mixing cement with water). The detailed procedure of the pullout test is described in Ref. [5].

Regarding the linearity in the experimental data for the steady part of the pullout test⁵⁾, the Bingham-like model was chosen to describe the bond resistance stress. The model is expressed by Eq. 8

$$\dot{u}_b^f(t) = \frac{1}{\eta_b}(\tau_b - \tau_{b0}) \quad (8)$$

corresponding to Eq. 5 where the viscous strain rate is expressed as the pullout velocity and $F_2[\alpha(t)] = 1.0$. In Eq. 8, τ_b is the bond resistance stress (in MPa), τ_{b0} is the bond yield stress (in MPa), η_b is the bond plastic viscosity (in MPa s/mm) and $\dot{u}_b^f$ is the pullout displacement (in mm). The bond plastic viscosity, η_b , as an evolving quantity can be expressed by Eq. 9

$$\eta_b(t) = f_b(t)\eta_{b0} \quad (9)$$

where $\eta_{b0} = 0.030 \text{ MPa s/mm}$ was identified from experiment⁵⁾. The bond yield stress, τ_{b0} , can be assumed to evolve in the same manner

$$\tau_{b0}(t) = f_b(t) \tau_b \quad (10)$$

where $\tau_b = 0.025 \text{ MPa}$ was also identified from experiment⁵⁾. The normalized evolutionary function $f_b(t)$ includes the effect of different mix proportions. The results of the model are compared with the experimental data⁵⁾ in Fig. 1. The evolution of the bond resistance stress is shown in Fig. 2 for Type M-1 and Type M-2 under different pullout speed.

4.2 Penetration test

The penetration test was conducted in order to obtain the normalized evolutionary function, $f_p(t)$, describing the evolution of microstructure of solidifying concrete in terms of the penetration resistance force. The penetration test represents

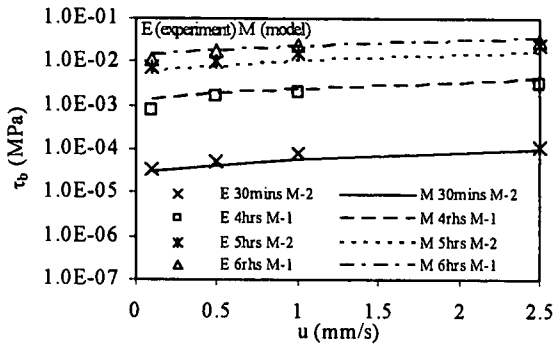


Fig. 1 Relationship between bond yield stress and pullout velocity

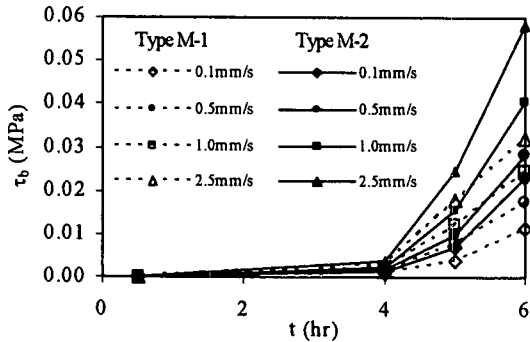


Fig. 2 Evolution of bond resistance stress

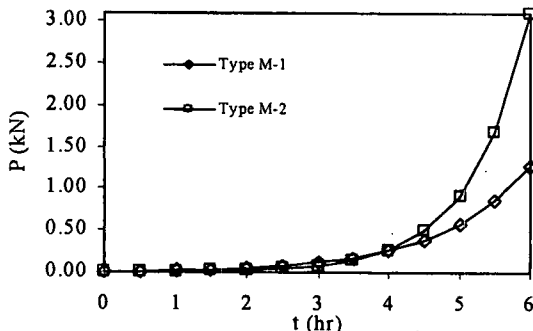


Fig. 3 Evolution of penetration resistance force

a complex mechanism which requires some comprehensive multi-dimensional analysis. Nevertheless, a simple method which can simulate the penetration test with incorporating the effect of rapidly changing microstructure based on the proposed model was also investigated.

In the penetration test a steel needle with the cross-sectional area of 100 mm^2 was indented into solidifying mortar. The test was conducted continuously for four different penetration speeds (0.1, 0.5, 1.0 and 2.5 mm/s) in the time range from 30 minutes after mixing up to the final setting time with an emphasis on the values at 4, 5 and 6 hours. A detailed description of the procedures of the penetration test can be found in Ref [5]. The evolution of the penetration resistance is shown in Fig. 3. The evolution of the relationship between the averaged penetration resistance force and the penetration depth at the averaged penetration speed is shown in Fig. 4.

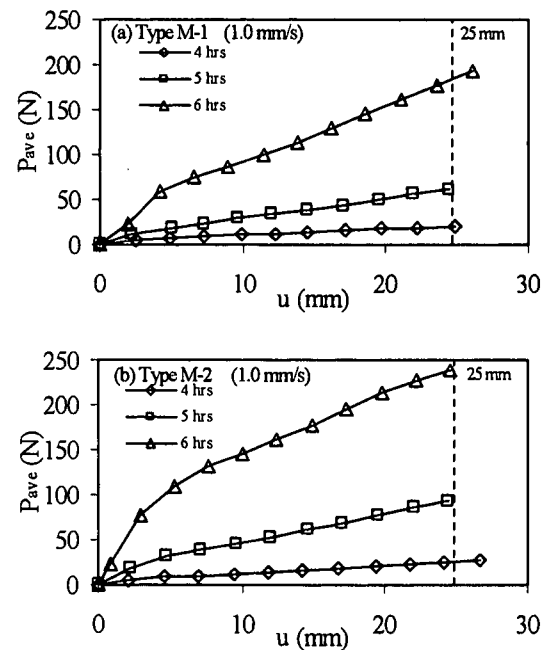


Fig. 4 Relationship between average penetration resistance force and penetration depth

From the curves in Fig. 4 one can observe two distinct phenomena. The first one is the breaking point of the curve approximately at the depth of 4 mm representing the yield stress level caused by the actual pricking of the upper layers of the solidifying mortar. The force, P_0 , under which the mortar yields can be described as a product of a non-evolutionary material parameter, P_I , and the normalized evolutionary function, $f_p(t)$, as shown in Eq. 11.

$$P_0(t) = f_p(t) P_I \quad (11)$$

The second phenomenon is the proportionality between the penetration resistance force and the increasing plastic deformation represented by the penetration depth. The deformation of the solidifying mortar after reaching the yield force, P_0 , can be described by Eq. 12 where u'_p is the plastic displacement rate, $S(t)$ is the mean penetration force acting on the tip of the needle after reaching the yield force, P_0 , and η is

the mean viscous plasticity obtained from the averaged penetration resistance force and the averaged penetration speed.

$$\dot{u}_p^f(t) = \frac{S(t)}{\eta(t)} \quad (12)$$

Eq. 12 is formally identical with Eq. 5 and follows same reasoning. The integration of Eq. 12 leads to a relation Eq. 13, where u_{p0}^f is the displacement at which the mortar yields.

$$u_p^f = u_{p0}^f + \frac{P - P_0}{\eta_p(t)} \quad \text{for } P \geq P_0 \quad (13)$$

The plastic viscosity, $\eta_p(t)$, can be expressed by Eq. 14 where η_{p0} is a non-evolutionary material parameter and $f_p(t)$ is the normalized evolutionary function.

$$\eta_p(t) = f_p(t) \eta_{p0} \quad (14)$$

With regard to the experimental data, Eq. 13 can be readily converted into a well-known bilinear model, Eqs. 15 and 16, which describes the behavior of solidifying mortar under penetration loading at the ages ranging from initial setting time to the final setting.

$$u_p^f = \frac{P}{\eta_p(t) K_{pl}} \quad \text{for } P < P_0 \quad (15)$$

$$u_p^f = \frac{P_0}{\eta_p(t) K_{pl}} + \frac{P - P_0}{\eta_p(t)} \quad \text{for } P \geq P_0 \quad (16)$$

Indeed, the bilinear model defined by Eqs. 15 and 16 is capable of an approximation which takes into account the effect

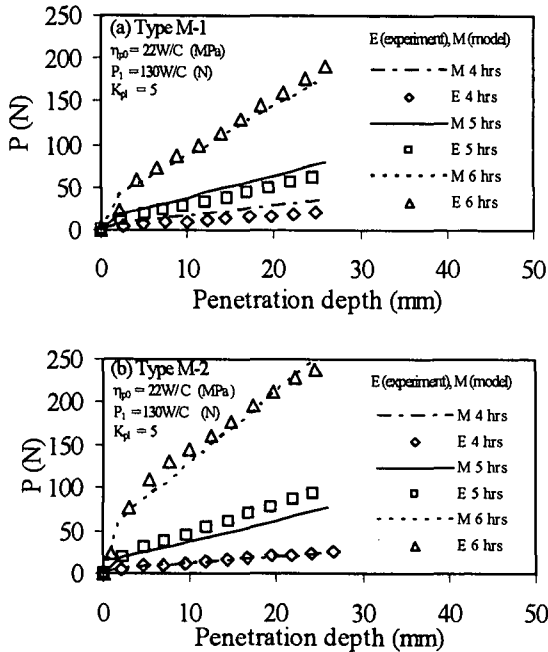


Fig. 5 Modeling for penetration resistance force – penetration depth relationship

of rapidly changing microstructure of solidifying concrete as shown in Fig. 5 where the approximation curves are compared to the experimental data. The parameter K_{pl} was identified as a non-evolutionary constant from the experimental data.

4.3 Uniaxial compression test

The uniaxial compression test, which is primarily designed for testing on hardened concrete, can be applied to testing on solidifying concrete only after a demolded specimen supports itself. This is a limiting factor which allows the use of this testing method from ages around the initial setting time, which was identified from preceding experiments as 4hr 35min and 4hr 5min for Type-1 and Type-2, respectively. However, in our case the first possible age when the specimen were demolded was 2hr 30min and 2 hours for Type-1 and Type-2. It is also required to used some special equipment for placement and manipulation with the specimens at such extremely early ages, such as, horizontal molds and teflon plates.

The uniaxial compression test was conducted with standard specimens (height=200mm, diameter=100mm) made of solidifying mortar. The loading rates were displacement controlled with the speeds 0.1, 0.5, 1.0 and 2.5 mm/s, identical with those applied to the pullout and penetration tests. The ages ranged from 3 hours to the respective final setting times with an emphasis on the ages of 4, 5 and 6 hours for both types of mixes. The loading rate influenced the ultimate compressive strength and the stress level at which the mortar yielded. On the other hand, the loading rate did not affect the rate of viscous deformation. Similar tendencies were observed in the case of the penetration test. Representative experimental results for the age 5 hours are shown in Figs. 6 and 7.

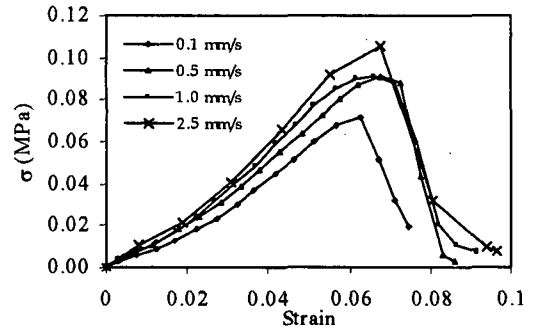


Fig. 6 Stress-strain diagram at 5 hours after mixing (type M-1)

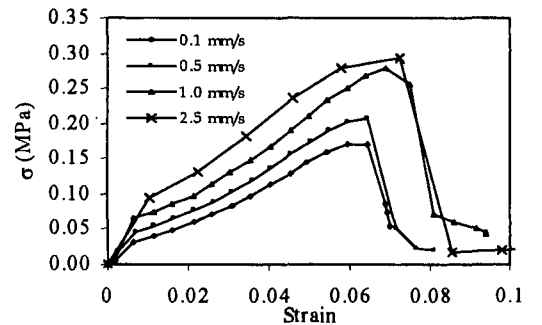


Fig. 7 Stress-strain diagram at 5 hours after mixing (type M-2)

In order to obtain the evolutionary function in terms of the compression strength development, the peak values were averaged for all loading speeds. This was possible due to the good correlation among the strength development curves obtained for mortar and concrete at different loading speeds where the coefficient of correlation between the test data and regression values was 0.997 for the types M-1 and C-1 and 0.988 for the types M-2 and C-2. The compressive strength evolution is plotted in Fig. 8.

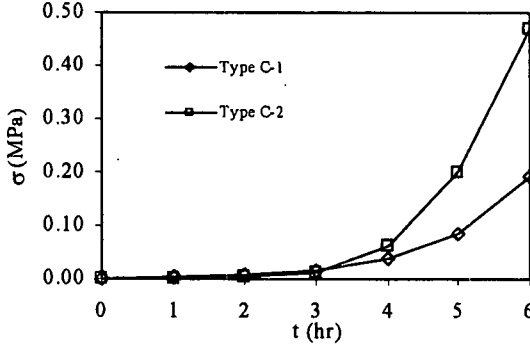


Fig.8 Evolution of compressive strength

The experimental data of the uniaxial compression test reveal some similarity with the experimental data acquired from the penetration test. The distinctive breaking point in the stress-strain curve this time indicates the yield stress, σ_0 , and it is described by Eq. 17.

$$\sigma_0(t) = f_c(t) \sigma_i \quad (17)$$

where σ_i is a non-evolutionary material parameter and $f_c(t)$ is the normalized evolutionary function. Following the same reasoning as in the modeling of the penetration test, the averaged viscous strain, ϵ^f , can be expressed by Eq. 18

$$\dot{\epsilon}^f(t) = \frac{\sigma}{\eta} \quad (18)$$

where $\sigma(t)$ is the mean loading stress sustained by mortar after reaching the yield stress, σ_0 , and η is the mean plastic viscosity obtained by averaging the data for all loading speeds. The integration of Eq. 18 leads to Eq. 19

$$\epsilon^f = \epsilon_0^f + \frac{\sigma - \sigma_0}{\eta(t)} \quad \text{for } \sigma \geq \sigma_0 \quad (19)$$

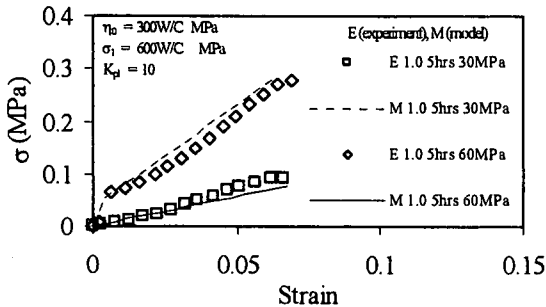


Fig. 9 Modeling for stress – strain relationship under uniaxial compression

The mean plastic viscosity is defined by Eq. 20

$$\eta(t) = f_c(t) \eta_0 \quad (20)$$

where η_0 is a non-evolutionary material parameter and $f_c(t)$ is the normalized evolutionary function. The model is compared with the experimental data in Fig. 9

4.4 Comparison between test results

In order to correlate the experimental data obtained from the pullout, penetration and uniaxial compression tests, the age at which the data were acquired was normalized with the respective final setting time and the values were normalized with the respective value at the final setting time. The data in Figs. 2, 3 and 8 were approximated by respective regression functions, f_b for the bond resistance in the pullout test, f_p for the penetration resistance in the penetration test and f_c for the strength development from uniaxial compression test. The values of the correlation coefficient among the tests were 0.989 for the types M-1 and C-1 and 0.998 for the types M-2 and C-2.

An evolutionary function normalized with respect to its value at respective final setting time, $f_{hm}(t_n)$, for all investigated material parameters was identified as

$$f_{hm}(t_n) = a \cdot \exp(t_n b)^c \quad (21)$$

$$a = \frac{32W/C - 3.78}{10000};$$

$$b = 3.31 + 9.08W/C;$$

$$c = 1.31 - 0.74W/C \quad (22)$$

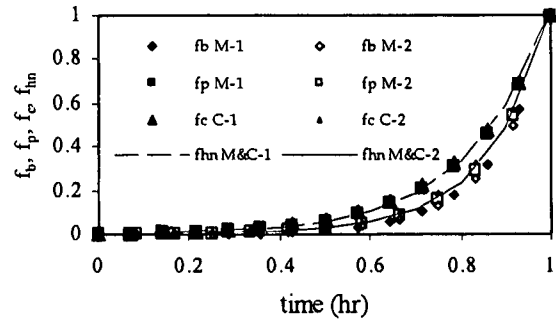


Fig.10 Correlation of pullout, penetration and uniaxial compression tests on time evolution

where W/C is the water/cement ratio (in decimal) and t_n is the normalized time (0 at mixing, 1 at the final setting time). The material parameters were: bond yield stress, τ_{b0} , bond plastic viscosity, η_b , the penetration force at which the mortar yielded, P_0 , compressive strength, σ_{a0} , and the mean plastic viscosity, η . The function $f_{hm}(t_n)$ multiplied by a scale approximated the experimental data satisfactorily. The regression functions $f_b(t_n)$, $f_p(t_n)$, $f_c(t_n)$ and $f_{hm}(t_n)$ can be seen in Fig. 10. $f_1(t)$ and $f_2(t)$ in Eqs. 3 and 4 are replaced by $f_{hm}(t)$.

Although the function is derived for rapid hardening portland cement, a good correlation was observed for normalized data by Byfors⁸⁾ for compressive strength evolution of Swedish standard cement and data by Okamoto⁹⁾ on

rheological constants used in a four element creep model applied to ordinary portland cement at the age ranging from 2 to 7 hours. Comparison of the data with Eq. 21 is shown in Fig. 11. The correlation coefficient was 0.998.

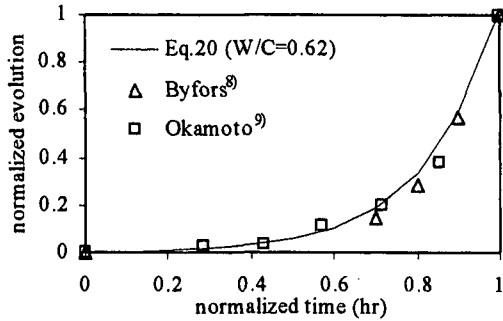


Fig.11 Comparison between normalized evolutionary function and experimental data

5. Deformational Behavior under Sustained Loading

The model was applied to experimental data obtained with a creep test. In this test specimens were loaded at the loading levels of 30%, 50% and 70% in order to investigate the possible nonlinearity at high stress levels. The load was applied by an electric actuator with an online fuzzy controller. The tests were conducted at the ages ranging from 3 hours to 8 hours. Due to the rapid changes of the material parameters, the load was maintained for only 10 minutes. The results of the creep test and the modeling are compared in Figs. 12 to 17.

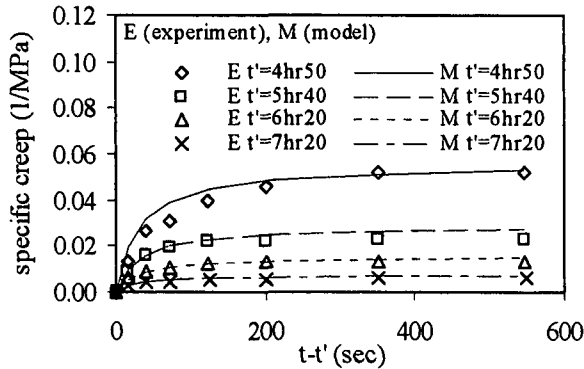


Fig.12 Comparison between model and experimental data for type C-1 and load level 30%

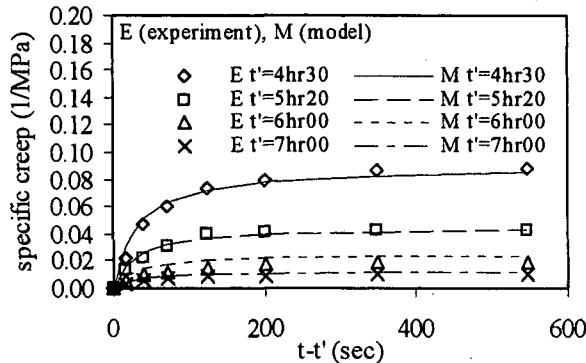


Fig.13 Comparison between model and experimental data for type C-1 and load level 50%

5.1 Viscoelastic component

The creep function $\Phi'(t)$ used in Eq. 3 was identified from the experimental data as

$$\Phi^v(t-t') = \frac{(t-t')^\gamma}{t_0 + (t-t')^\gamma} \quad (23)$$

where t is the age and t' the age when the load was applied (in seconds), $\gamma = 1.0$ and $t_0 = 30$ sec. The scale parameter α for $f_m(t)$ is

$$\alpha = 2193 - 3360W/C \quad (24)$$

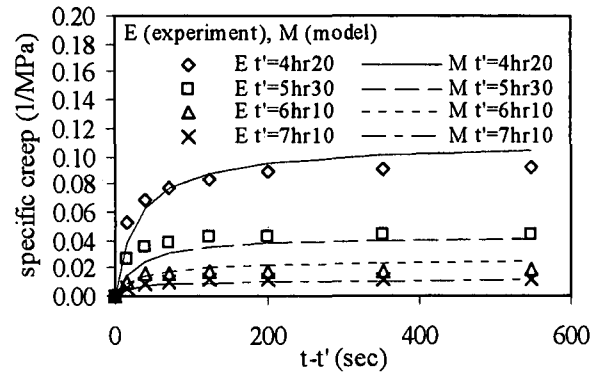


Fig.14 Comparison between model and experimental data for type C-1 and load level 70%

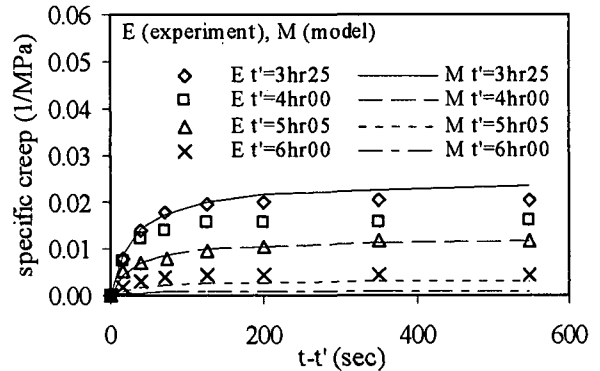


Fig.15 Comparison between model and experimental data for type C-2 and load level 30%

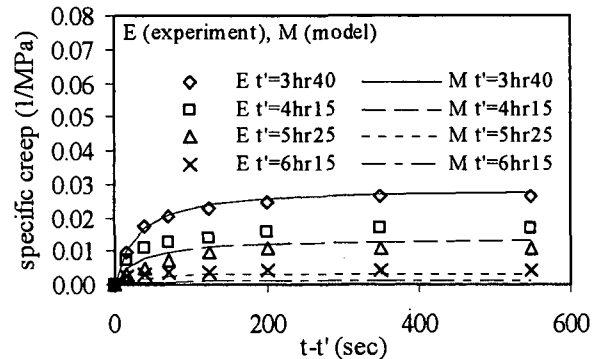


Fig.16 Comparison between model and experimental data for type C-2 and load level 50%

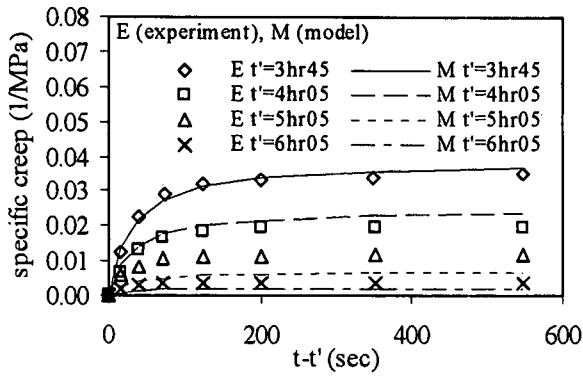


Fig.17 Comparison between model and experimental data for type C-2 and load level 70%

5.2 Nonlinearity due to higher stress level

Compared with Bažant's function of nonlinearity⁴⁾, for solidifying concrete the function of nonlinearity needs to reflect the effect of W/C. The function is defined by Eq. 25

$$F_1[\sigma(t), W/C] = \frac{\exp((2 - 1.6W/C)S)^3}{1 - S^{10}} \quad (25)$$

$$S = \frac{\sigma(t)}{f_c} \quad (26)$$

where W/C is the water/cement ratio (in decimal) and f_c is the compressive strength at the time of loading. The denominator is introduced to ensure the growth of the strain beyond all limits with reaching the compressive strength, f_c .

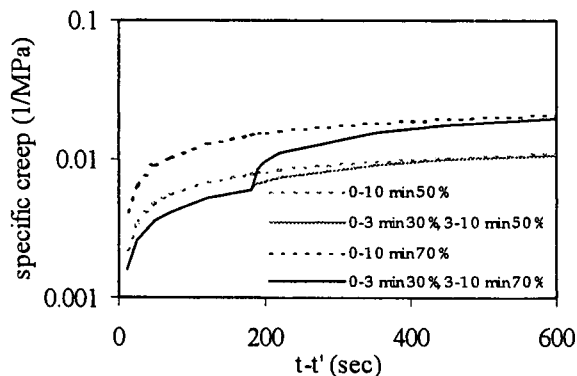


Fig.18 Creep under various stress levels

5.3 Effect of Rapid Hydration on Creep Behavior

The simulation in Fig. 18 shows the effect of rapidly changing microstructure where four loading patterns were used. The first two loading patterns represent constant loading under the load level 50 and 70 % applied for 10 minutes. At the other two loading patterns the initial load level was set at 30% and kept constant for 3 minutes, then it was increased to the respective load level of 50 and 70%.

It is observed that the specific creep under constant load is larger than the one subjected to lower load level at the beginning. From this example, it is confirmed that the hydration effect is properly represented by the function $f_1(t)$ in Eq. 3.

6. Conclusions

An evolutionary model for solidifying concrete under short-time loading and sustained loading was proposed in the present study. The model can be used for fresh, transient or solidifying and hardened concrete and mortar with the limitation up to the compressive strength at the age of testing. The model was verified for mortar and concrete using rapid hardening portland cement (RHPC) with the water/cement ratio of 0.37 and 0.62.

For the deformational behavior under short-time loading, an evolutionary function representing the degree of hydration was determined by three simple testing methods, the pullout, penetration and uniaxial compression tests. This evolutionary function is used in modeling to express the evolution of the material parameters.

For the deformational behavior under sustained loading an evolutionary uniaxial stress-strain model was also determined. In the model, the effects of the age at loading and the stress level were taken into account.

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