論文　MODELING OF SOLIDIFYING CONCRETE UNDER ONE-DIMENSIONAL LOADING

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ABSTRACT: The goal of this study is to develop a model for solidifying concrete under uniaxial compression, pullout and penetration loading, where loading rate, W/C and age at loading are the main parameters. The experimental data obtained are used for developing a Bingham-like model describing the bond resistance between steel and solidifying concrete and a model describing the behavior of the solidifying concrete subjected to uniaxial compression or penetration, both models valid up to the final setting time. The identification and expression of the material parameters for the models were simplified due to a good correlation of the experimental data obtained from the three different tests.
KEYWORDS: solidifying concrete, pullout, penetration, uniaxial compression, final setting time

1. INTRODUCTION

Since solidifying concrete undergoes a transition from a liquid state to a solid one, the modeling should follow the same tendency by describing those states in terms of the transition between respective models. If one desires to describe the evolution of concrete behavior by models at hand, then, the Bingham or Herschel-Bulkley model, or the thixotropic model, is appropriate for the period just after mixing while for the ages around the final setting time the models used for already hardened concrete are justifiable. An abrupt shift from one model to another is possible only for cases where the transient state is negligible. Attempts to describe the transient state by a special model does not eliminate the problem of the abrupt shifts between models. This effect is only reduced to some extent. A more moderate change of models can be provided by some weighted averaging of the models weighted by a respective degree of relevance. Such an analysis should be made carefully because the compatibility of models is not guaranteed. However, this is beyond the scope of this paper. In this study we concentrate on both acquiring experimental data and on modeling of solidifying concrete with the focus on overall feasibility and simplicity.

The experimental data on solidifying concrete is scarce, mainly due to the rapidly changing consistency of concrete, which hinders the applicability of experimental equipment designed for testing fresh or already solidified concrete. Despite the efforts evidenced in, e.g., [1-3] there are not enough experimental data for some more complex modeling. Therefore, three testing methods are chosen to obtain the experimental data on the strength development and the development of the bond between solidifying concrete and steel. The methods used are the penetration test, the uniaxial compression test and the pullout of a steel plate out of solidifying mortar. The experiments are conducted at constant temperature for different mixes of rapid hardening portland cement at different loading rates. Based on the experimental data a unified evolutionary function is derived for the description of the evolution of compressive strength, yield stress, bond yield stress, bond plastic viscosity, penetration resistance force, stiffening and elastic strain. Further, the range of applicability of the Bingham model and the model for already hardened concrete to solidifying concrete is investigated, where all material parameters employed in the models are based on the

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unified evolutionary function, which as an approach toward the description of solidifying concrete follows a similar concept presented by Bazant [4] in his solidification theory. However, a more general model can be obtained by physicochemical microstructure consideration.

2. EXPERIMENTS

Three experimental methods were used to obtain and verify the strength development curve and the evolution curve of the bond between a steel plate and solidifying mortar. Firstly, the standard procedure of the penetration test specified by JIS A 1147 was carried out to acquire the strength development characteristics for two kinds of design mixes. Then, the standard penetration test was repeated at different loading rates in order to find the response of the solidifying concrete to different penetration speeds. Secondly, the pullout test was conducted in order to investigate the evolutionary curve of the bond between a steel plate and solidifying mortar. Finally, the standard procedure of the uniaxial compression test was conducted in order to correlate and verify the results of the two former tests. Same as in the case of penetration test, the uniaxial compression test was conducted at different loading rates in order to investigate the response of the solidifying mortar to various loading rates. In all the testing methods the force was applied by an electric actuator. The loading force and the displacement were recorded by a loadcell and a LVDT (stroke 200mm), respectively. All experiments were performed under constant temperature 20°C.

2.1 MIX PROPORTIONS

The tests were conducted with rapid hardening portland cement (RHPC) for the target 28-day strengths of 30 and 60MPa, corresponding to W/C 0.62 and 0.37, respectively. The mix design is summarized in **Table 1**. The maximum size of fine aggregate was 2 mm.

Table 1 Mix proportions

Type	Max. size (mm)	W/C (%)	Weight per unit volume (kg/m^3)			7 day comp. strength (MPa)
			W	C	S	
RHPC 30MPa	2	62.0	168	271	764	23
RHPC 60MPa	2	36.9	185	500	590	48

2.2 PULLOUT TEST

In the pullout test, a stainless steel plate (150x20x2 mm) 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). Four steel plates were placed in a steel container (diameter=100mm, height=200mm) in a row, 20mm apart from each other and from the container wall. The embedment depth was 100mm. The plates were placed vertically in fresh mortar just after mixing and kept in the vertical position throughout the whole test.

2.3 PENETRATION TEST

A steel needle with the cross-sectional area of 100 mm^2 was indented into solidifying mortar. To obtain the initial and the final setting times and the strength development, the standard JIS procedure of penetration test was applied, that is, penetration of the needle to the maximum depth 25 mm at the speed 2.5 mm/s. To investigate the influence of the penetration speed, the needle was driven into the solidifying mortar at four different 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 diameter and the height of the container used were 165mm and 150mm, respectively. The spacing between the testing spots and between the spots and the container wall was at least 20mm.

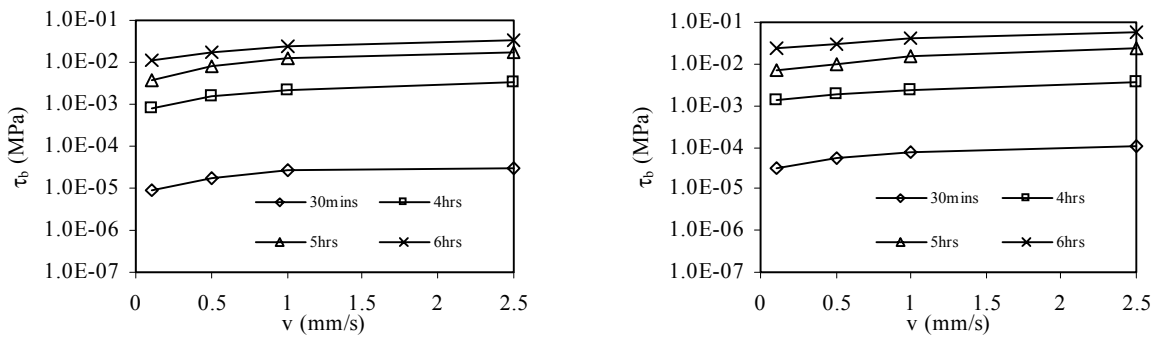
2.4 UNIAXIAL COMPRESSION TEST

The compression test at an extremely early age requires gentle manipulation with the specimen and some special equipment such as horizontal capless molds. From the preliminary tests, the earliest possible age for demolding a specimen out of a horizontal capless mold is 3 hours and 3.5 hours for RHPC 60 MPa and 30 MPa, respectively. The specimen was carefully demolded just before testing and placed on an oiled glass plate in the testing machine. The upper loading plate was equipped with a 5 mm teflon plate which was sprayed with oil to minimize the effect of friction. The specimen was loaded at four different crosshead speeds (0.1, 0.5, 1.0 and 2.5 mm/s) and at the age ranging from 3 to 7 hours after mixing cement with water.

3. EXPERIMENTAL RESULTS

3.1 PULLOUT TEST

The bond resistance stress was calculated from the pullout force-displacement curves. The bond resistance stresses, τ_b, for the four speeds, v, and ages are shown in **Fig. 1** and **Fig. 2**. The experimental data for the fresh mortar (30 minutes after mixing water with cement) correspond with the data obtained from the slipping test by Tanigawa et al. [5]. Since the bond resistance stress increases approximately proportionally to the pullout speed, it was assumed that the behavior is similar to that of a Bingham body. The same assumtion was taken for investigation of slipping resistance acting between steel board and fresh concrete by Tanigawa et al. [5]. Because of this assumption one can estimate the values of the "bond" yield stress, τ_{b0}, and the "bond" plastic viscosity, v_b, both of which have a similar tendency of increase in value over time with the strength development acquired from the penetration test and the uniaxial compression test, which were used as the material parameters in the modeling.



(a) RHPC 30 MPa (b) RHPC 60 MPa

Fig. 1 Relationship between bond resistance stress and pullout velocity

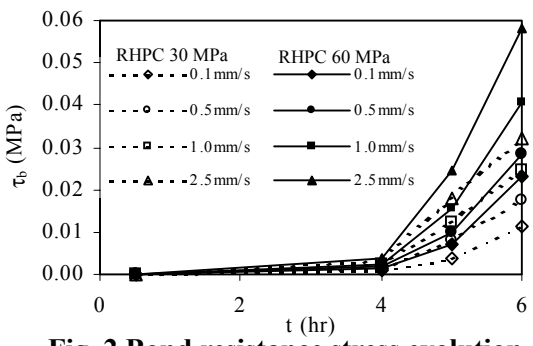


Fig. 2 Bond resistance stress evolution

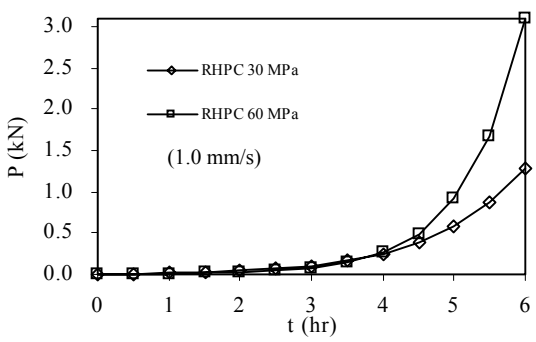
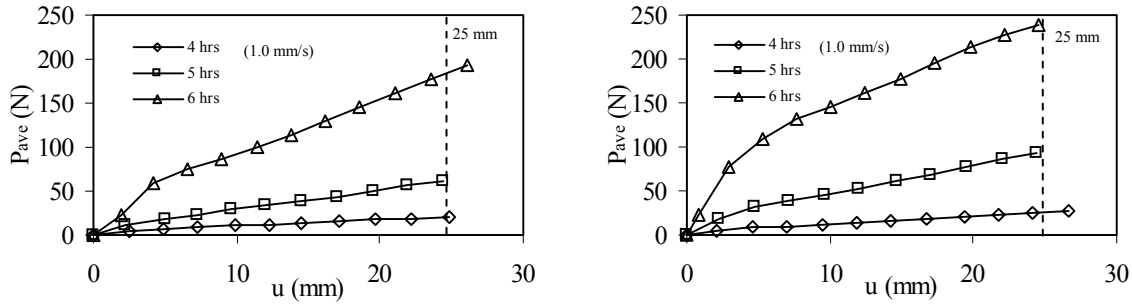


Fig. 3 Penetration resistance evolution

3.2 PENETRATION TEST

The standard penetration test was conducted in order to assess the strength development and the initial and final setting times for the two mix proportions. The initial and the final setting times for the RHPC 30

MPa and RHPC 60 MPa were 4hr 35min and 7hr 15min, and 4hr 5min and 6hr 10min, respectively. The penetration resistance, or strength development, can be seen in **Fig. 3**. It was observed that the change of speed did not have any significant effect on the final value at the depth 25 mm. Only the path in the resistance force-depth curve differed slightly. The relationship between the averaged resistance force, P_{ave}, and the penetration depth, u, is shown in **Fig. 4**, where the yield point can be identified. It was also observed that the effect of the cross-sectional area of the tip of the needle was dominant and the effect of friction on the side of the needle for such a shallow penetration depth was negligible. This was noticed during reverse loading after the depth 25mm was reached.

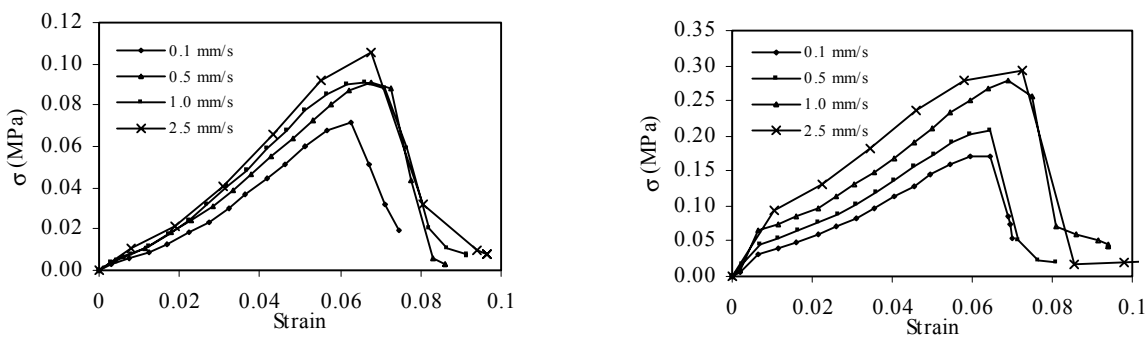


(a) RHPC 30 MPa (b) RHPC 60 MPa

Fig. 4 Relationship between averaged resistance force and penetration depth

3.3 UNIAXIAL COMPRESSION TEST

The uniaxial compression test results revealed some similarity with the results obtained by the penetration test. Unlike in the case of the penetration test, the volume which was subjected to loading in the compression test was known. The experimental data showed that during the first half of the period between mixing and the final setting time the point at which the concrete yielded could not be clearly identified in the stress-strain diagrams, whereas during the latter half of the period the stress level at which the concrete yielded grew exponentially. During the latter half the growth of the elastic component of the total strain followed approximately at the same rate. It was observed that during the solidification the loading rate influenced the ultimate compressive strength of the solidifying mortar and the path towards the peak in the stress-strain diagram with decreasing tendency with progressing solidification. Examples of the stress-strain diagrams are shown in **Fig. 5** for the RHPC 30 MPa and RHPC 60 MPa, respectively, where at higher ages the point at which mortar yielded can be clearly identified. After this point the deformation is governed by viscous plasticity. After reaching the ultimate strength, σ_u, the specimen exhibited bulging with vertical cracks. The compressive strength development can be seen in **Fig. 6**. Moreover, the lateral deformation was recorded simultaneously so that some data on the volumetric response was also obtained as shown in **Fig. 7**. The lateral deformation was measured from the digital image data.



(a) RHPC 30 MPa (b) RHPC 60 MPa

Fig. 5 Stress-strain diagram at 5 hours after mixing

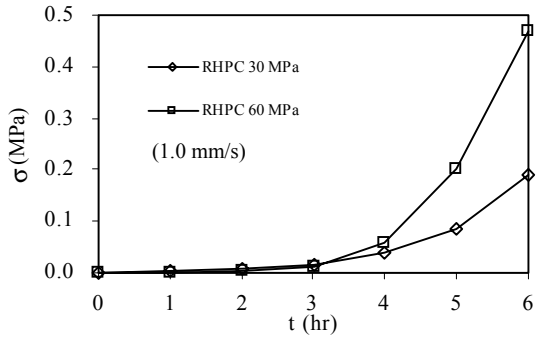


Fig. 6 Evolution of compressive strength

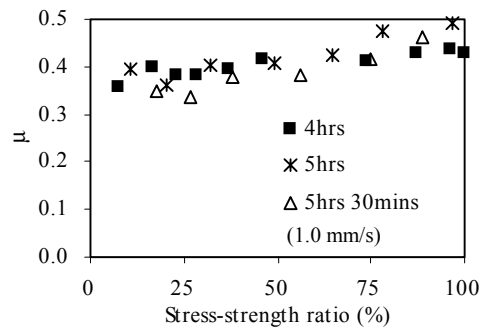


Fig. 7 Poisson's ratio of RHPC 60 MPa

4. COMPARISON BETWEEN TEST RESULTS

Through the correlation between the experimental data, where the age was normalized with the respective final setting time and the values were normalized with the respective value at the final setting time, a normalized evolutionary function, $f_{hn}(t_n)$, for all investigated material parameters was identified by Eq. 1, 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, ν_b, yield stress, σ_0, strength, σ_u, parameter of stiffening, E_{st}. The function $f_{hn}(t_n)$ multiplied by a scale approximated the experimental data satisfactorily. The values of the correlation coefficient among the tests were 0.989 and 0.998 for RHPC 30 MPa and 60 MPa, respectively. The regression functions for the bond resistance, f_b, penetration resistance, f_p, the strength development, f_c, from uniaxial compression test and $f_{hn}(t_n)$ can be seen in **Fig. 8**.

$$f_{hn}(t_n) = \frac{32W/C - 3.78}{10000} \cdot \exp\left(t_n\,(3.31 + 9.08W/C)\right)^{1.31-0.74W/C} \tag{1}$$

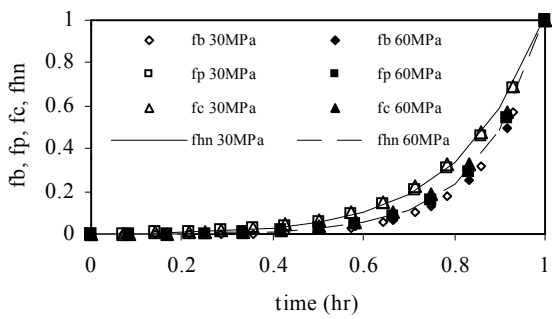


Fig. 8 Correlation of pullout, penetration and uniaxial compression tests

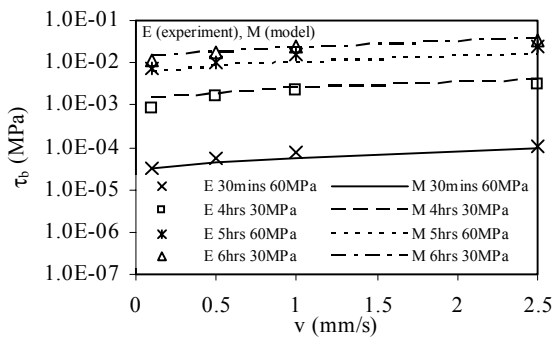


Fig. 9 Bond resistance stress vs. pullout velocity (τ_{b0}=0.025MPa, ν_b=0.030MPa s/mm)

5. MODELING

Regarding the linearity in the experimental data for the pullout test shown in **Fig. 1**, the Bingham model was chosen to describe the bond resistance. The model is expressed by Eq. 2, where τ_b is the bond resistance stress (in MPa), τ_{b0} is the bond yield stress (in MPa), ν_b is the bond plastic viscosity (in MPa s/mm) and v is the pullout velocity (in mm/s). The results of the model are compared with the experimental data in **Fig. 9**.

$$\tau_b = \tau_{b0} + \nu_b \cdot v \tag{2}$$

A bilinear model was selected to describe the behavior of solidifying mortar under penetration and uniaxial compression loading at the age about the final setting time and subsequently its applicability toward the initial setting time, and possibly beyond, was verified. The model is expressed by Eq. 3, where σ_0 is the

yield stress, E_{st} is considered a parameter of stiffening identified as the tangent of the stress-strain curve up to the yield stress, E^*_{st} ($E^*_{st} = E_{st}/K_{pl}$) is E_{st} reduced by the parameter K_{pl} reflecting the increase of the viscous plasticity after reaching the yield stress.

$$\varepsilon = \frac{\sigma}{E_{ST}} \quad \text{for} \quad \sigma < \sigma_0 ; \qquad \varepsilon = \frac{\sigma_0}{E_{ST}} + \frac{\sigma - \sigma_0}{E^*_{ST}} \quad \text{for} \quad \sigma \geq \sigma_0 \tag{3}$$

The results of the model are compared with the experimental data in **Fig. 10** and **Fig. 11**. The parameters σ_0 and E_{st} are expressed by the evolutionary function, f_{hn}, multiplied by a respective scale identified from the experimental data. The parameter K_{pl} was identified as a non-evolutionary constant.

6. CONCLUSIONS

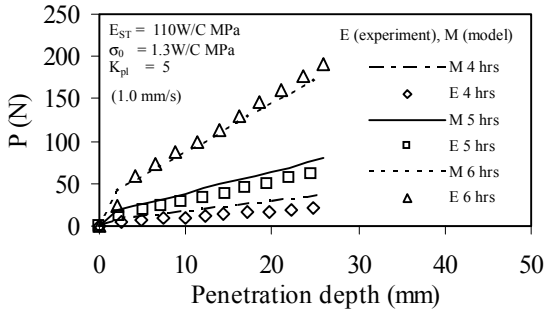
Three experimental methods were used to investigate the mechanical properties of solidifying concrete. A good correlation among these methods offered the possibility to use pullout and penetration tests to extrapolate the uniaxial compression test to very early ages.

(1) All the material parameters evolve exponentially and are expressed by using the same evolutionary function expressing the degree of hydration. Its parameters are the water/cement ratio and the elapsed time after mixing.

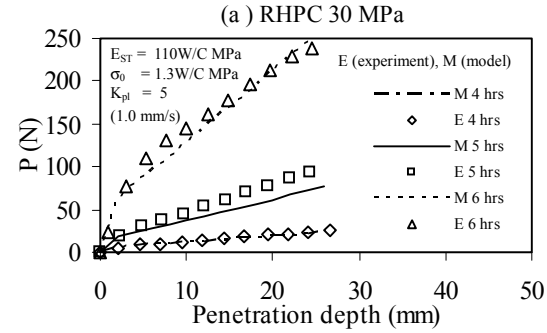
(2) The bond between steel and solidifying mortar is expressed by a Bingham-like model.

(3) The behavior of solidifying mortar under penetration and uniaxial compression up to the peak is expressed by the bilinear model up to the final setting time.

(4) The range of the Poisson's ratio of solidifying mortar is between 0.35 and 0.5.



(a) RHPC 30 MPa



(b) RHPC 60 MPa

Fig. 10 Resistance force vs. penetration depth

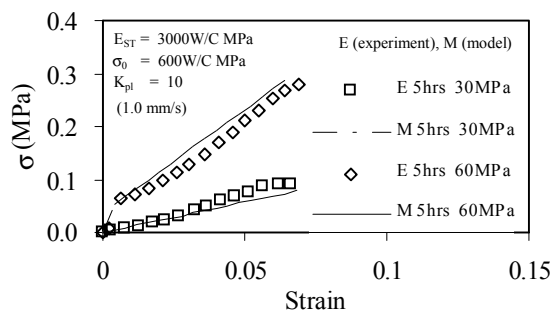


Fig. 11 Stress-strain diagram

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