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Three day prediction of concrete compressive strength evolution

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0 ABSTRACT

Although there are several procedures predicting concrete compressive strength, reliable methodologies involve either extensive testing or voluminous databases. This paper presents a simple and efficient procedure to evaluate the activation energy and the rate constant of concrete. These two parameters can be used for a rapid prediction of the mechanical properties of concrete and particularly the evolution of compressive strength. They also allow separation of effects due to physical phenomena such as humidity loss. The procedure uses an experimentally-determined parameter called “hardening time” as an indicator of equivalent maturity when comparing two hardening profiles. Test results from specimens of six concrete types validate the approach.

Keywords: maturity, activation energy, degree of hydration, hardening time, separation of effect, prediction, fiber optic sensors, frequency factor, concrete strength

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1 RESEARCH SIGNIFICANCE

A maturity method is used to predict the compressive strength evolution of concrete. Values for the activation energy and the rate of reaction are necessary to implement this approach. Determination of these values usually requires either extensive tests or large databases. This has resulted in limited use of maturity methods. A simple and fast methodology to determine these values and consequently predict compressive strength evolution is presented. More timely knowledge of compressive strength evolution will lead to savings during construction and improve safety.

2 INTRODUCTION

At early age, the mechanical properties of cement-based materials are time-dependent and involve hydration. The hydration process is a thermally-activated reaction that may be described by the Arrhenius equation. This equation establishes the progression of a chemical reaction in terms of rate of reaction k [1]. The integral over time of the rate of reaction gives the degree of reaction. Two independent and parallel research areas have been generated through applying degree of reaction indices in this research. For the purposes of this paper they are called “predictions” and “separation of effects”. *Predictions* of mechanical properties of concrete are possible based on empirical relationship between the degree of reaction (hydration) and physical properties such as compressive strength, tensile strength and elastic modulus [2, 3, 4, 5 and 6]. *Separation of effects* involves decoupling the contributions to the total deformation of a physical and chemical phenomenon during hardening [7]. Unfortunately the separation of an effect cannot be done by direct comparison of deformation time-histories, measured in concrete pours that are hardening in different environments. The effects of the temperature after similar elapsed times of hydration change with the thermal expansion coefficient (TEC), and this coefficient depends on the degree of hydration [8]. In order to perform predictions and separate effects, knowledge of maturity indices is required. Maturity indices need to be determined experimentally for each concrete type. This article describes a new methodology to determine two common maturity indices. These indices lead to the *prediction* of the evolution of compressive strength in six different concretes.

2.1 Background

The Arrhenius equation states that the rate of a chemical reaction, k, increases exponentially with absolute temperature, regardless of the degree of reaction already obtained (see Eq. 1)

$$k = A \exp \frac{-E_a}{RT} \qquad \text{Eq.1}$$

A Frequency factor (s^{-1})

E_a Activation energy (KJ/mole)

k reaction rate

R Gas constant ($KJ*mole^{-1}* K^{-1}$)

T Absolute temperature (K)

The degree of reaction is calculated by integrating Eq. 1 over time. The rate of reaction k is constant when the temperature of the hydration process is constant ($T=T_r$= constant imply $k=k_r$=constant). Eq. 2 uses k_r to predict the compressive strength. This empirical equation is widely used [9].

$$S(k_r, t) = S_u \frac{k_r(t - t_0)}{1 + k_r(t - t_0)} \qquad \text{Eq. 2}$$

k_r Rate of reaction at the reference temperature T_r,

S Compressive strength at age t,

S_u Ultimate compressive strength,

t_0 Age at start of strength development (hours)

t Time (hours)

With the exception of controlled laboratory conditions, the temperature of the hydration process changes during the reaction and the Eq. 2 becomes inapplicable. To overcome this difficulty, it is sufficient to change the time-history into a degree of reaction history. This can be done using the equation of Freisleben-Hansen and Pedersen [10]. Observing that hydration of cement is a chemical reaction; the Arrhenius law is integrated to describe cement hydration through a new index, called Equivalent Age (Et) (see Eq. 3)

$$Et(t) = \int_{t_0}^{t} \left[\exp Q \left(\frac{1}{T} - \frac{1}{T_r} \right) \right] dt \qquad \text{Eq. 3}$$

Et Equivalent age (hours)

Q Activation energy divided by gas constant (E_a / R)

t Time (hours)

t_0 Time at hydration start (hours)

T Temperature of concrete (K)

T_r Reference temperature (K)

Et is the integral in time of the ratio between the rates of reaction k_1 and k_r of two specimens of the same concrete types. One is a fictitious specimen and is assumed to be kept at a constant temperature T_r (generally 20 °C in Europe, 23 °C in USA).

The other specimen is real and has a temperature profile $T_1=T_1(t)$. At every time t* the real specimen has an equivalent age $Et_{,1}(t^*)$. This means that at the time t*, it has the same degree of reaction that the reference process will have after a total time $Et_{,r}(t^*)$, being cured at $T=T_r$. Where time is converted in equivalent age, the temperature of the process assumes the value T=Tr. Thus, if T=Tr=constant, Eq. 2 is applicable (see Eq. 4) for cases when temperature varies during hydration.

$$S(k_r, Et) = S_u \frac{k_r\,(Et - Et_0)}{1 + k_r\,(Et - Et_0)} \qquad \text{Eq. 4}$$

S Compressive strength at age t,

S_u Ultimate compressive strength,

k_r Rate of reaction at the reference temperature T_r,

Et Equivalent age at the time t

Et_0 Equivalent age at start of strength development

The equivalent age is of great interest for predictions and for separation of effects, since it allows direct comparisons of concrete pours (or specimens) that are hydrating at different speeds (see Fig. 1). Moreover, when used in predictions, it takes into account the so-called cross over effect of concrete [9], which affect predictions made with other degree of reaction indices [9, 11, 12,13].

The procedure explained below allows the calculation of the activation energy can be used to determine the datum temperature without modification.

2.2 The hardening time

A long gauge fiber optic deformation sensor called SOFO has recently been developed [14]. SOFO is particularly suitable for concrete, because of its robustness, temperature compensation, insensibility to magnetic fields, and a precision of 2 μm. Moreover, SOFO sensors follow the deformation of fresh concrete without disturbing the strain field of the host material [15]. The stiffness and the thermal expansion coefficient (TEC) of the SOFO sensor are influenced mainly by the characteristics of the protective tube. For instance, the axial stiffness of standard SOFO is very low because it is housed in a plastic protective tube. Glisic proposed a new sensor called SOFO “setting” sensor with a higher axial stiffness using a protective tube made of stainless steel [15, 16] (see Fig. 2). The setting sensor, once embedded in concrete together with a standard sensor of the same gauge length, leads to determination of the hardening time, see below. When concrete is placed, the standard sensor measures the swelling of concrete while the stiff sensor is not initially influenced by the deformations of the concrete matrix and therefore the difference between deformations measured by the two sensors increases.

After concrete hardens, both sensors measure only the deformation of the concrete matrix and the difference between the deformations measured by the two sensors remains constant (see Fig. 3). The hardening time is defined as the time when the derivative of the difference between the deformations measured by setting and standard sensors becomes zero.

3 EXPERIMENTAL INVESTIGATIONS

3.1 Determination of the activation energy Ea

Originally hardening time was intended to be an equivalent of setting time. Studies of the mechanism of force transmission between sensors and concrete-matrix indicate that hardening time depends on the degree of concrete hydration. This degree is unknown and will be denoted as $\alpha = \alpha^*$. Values for hardening time depend on the following factors

- Degree of reaction (types of concrete, temperature of hydration, time)
- Sensors features (thermal expansion properties, stiffness)

The strategy adopted for determining the activation energy uses two specimens of the same type of concrete. Both specimens have the same dimensions. They are monitored with a stiff and a soft sensor. Aside from their stiffness, each pair of sensors has the same features. One specimen is wrapped with glass wool. The glass wool acts as insulation and keeps the temperature of this specimen at a higher level than the temperature of the other specimen. This induces a higher rate of reaction in the insulated cylinder. The temperature is measured in both specimens (see Fig. 4). The degree of reaction, in terms of equivalent time (Et), is expressed through Eq. 3. For both specimens, at the hardening time, the degree of reaction index Et has the same value. Temperature profiles are inserted in Eq. 3 for each specimen and the integral is calculated to the hardening time. As a result two equations with two unknown values (Et and E_a) are obtained. Resolution leads to determination of the activation energy Ea (see Fig. 4).

3.2 Predictions of the compressive strength.

The activation energy is necessary but not sufficient for determining the rate constant k_r (see Eq. 1). The value of k_r is needed to predict mechanical properties (see Eq. 4). The value of k_r can be determined if two compressive tests using standard specimens of the same composition, humidity, boundary conditions and temperature histories, are performed at different equivalent ages Et. This allows determination of k_r through the application of Eq. 4 (see Fig. 5). Compressive tests have been carried out after 48 and 72 hours (with exception of Test 1 where test are made at 24 and 72 hours). The 24-hour test has not been found to be representative for slowly hydrating concrete.

4 COMPARISON OF PREDICTIONS AND EXPERIMENTAL RESULTS

Hardening time, activation energy and rate of reaction were evaluated and applied to six different types of concrete (see Tables 1-6) using the procedure presented above. Five were commonly used concrete types in civil engineering. They were made with different types of aggregate. Air entrainers, superplasticizers and different types of cements were used (see tables 1-6). The results shown in Figures 6-11 have been obtained within the first 72 hours. All predictions obtained were realistic and acceptable without any correction according to the criteria given in the code TEX-426-A (see Tables 7 and 8). The quality of the prediction was verified after 7, 21 and 28 days. The maximum deviation between predicted and tested values of each test is presented in Table 8. Zero equivalent age in Figures 6-11 does not always refer to the pouring time. Since poured concrete temperature is influenced by ambient temperature in the initial phases, the zero equivalent age is taken to be the point where cooling (if it occurs) slows to a variable rate. If no cooling occurs, the zero time is taken to be the batching time.

5 DISCUSSION OF THE RESULTS

The methodology presented assumes that the hardening time is an indicator of the degree of reaction. Tests support this assumption for the concrete that was studied. More mixes will be tested in order to clarify the limits of applicability. Constraints on the testing procedure (such as minimum difference in temperature profiles) could be added for a better definition of hardening time when necessary. The relationship between the hardening curve and the degree of reaction is an important issue for the extension of the methodology to the general field of hardening materials and this will be the subject of further study. The basis of the proposed methodology involves passing from mechanical properties of concrete (hardening time) to thermodynamic-chemical properties (activation energy and rate constant) and back again to mechanical properties (compressive strength). Some codified methods use similar concepts by inserting the final setting time into maturity-strength equations and performing regression analyses. A recently-developed method [17] uses a variant of the setting time to determine the equivalent age and thus helping to determine strength-maturity relationships.

Maturity methods are still rarely used in practice. This lack of acceptance is partially related to limited experience with these approaches. Confidence in the methodology presented here would be increased through performing more compressive tests during the early age of concrete. For example, using a given pair of compressive-strength values, the value of k_r and S_u are obtained, and a predictive curve can be calculated. Using other pairs, an envelope of curves is obtained. A standard apparatus for the application of this methodology is under development. Due to reusability and robustness of equipment, an inexpensive and in-situ application of the methodology is feasible.

6 SUMMARY AND CONCLUSIONS

Compressive strengths of several widely used concrete mixes have been successfully predicted using a procedure that involves early age deformation monitoring. The same procedure has been applied to a special concrete in order to study the applicability of the methodology to other types of hardening materials. This methodology allows a fast and accurate prediction of compressive strength on site. Seventy-two hours are sufficient to gather the necessary data and provide accuracy of less than 8% error. It is also an attractive procedure for the determination of the activation energy and the rate constant. Separation of various contributions to deformation (autogenous, thermal and humidity loss) is thus possible in-situ and in real time. More timely knowledge of compressive strength evolution will lead to savings during construction and improve safety.

7 AKNOWLEDGEMENT

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Fig. 9 Compressive strength vs. equivalent age for test series 4. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.

Fig. 10 Compressive strength vs. equivalent age for test series 5. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.

Fig. 11 Compressive strength vs. equivalent age for test series 6. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.

Test 1	
Water/cement Ratio	0.45
Cement CEM II / A-LL 42.5 R	325 Kg/m3
Superplasticizer	0.9%
Air Entrainer	0.1%
Aggregate	0-32 Hüttwangen
Maximum temperature difference	5 °C

Table 1 Mix-design test 1

Test 2	
Water/cement Ratio	0.45
Cement CEM I 42.5 R	350 Kg/m3
Superplasticizer	0.8%
Air Entrainer	No
Aggregate	0-32 Sergey
Maximum temperature difference	15 °C

Table 2 Mix-design test 2

Test 3	
Water/cement Ratio	0.48
Cement CEM I 42,5 N HS	360 Kg/m3
Superplasticizer	0.8%
Air Entrainer	No
Aggregate	0-32 Sergey
Maximum temperature difference	20.2 °C

Table 3 Mix-design test 3

Test 4	
Water/cement Ratio	0.48
Cement CEM III/A 32,5 N	360 Kg/m3
Superplasticizer	0.8%
Air Entrainer	No
Aggregate	0-32 Sergey
Maximum temperature difference	14.5 °C

Table 4 Mix-design test 4

Test 5	
Water/cement Ratio	0.48
Cement CEM II/ A-LL 32.5 R	360 Kg/m3
Superplasticizer	0.8%
Air Entrainer	No
Aggregate	0-32 Sergey
Maximum temperature difference	21.6 °C

Table 5 Mix-design test 5

Test 6	
Water/cement Ratio	0.18
Cement CEM I 52,5 N	1051.1 Kg/m3
Superplasticizer	35.1 kg/m^3
Steel fiber	Not available
Air Entrainer	No
Silica fume	273.3 Kg/m^3
Aggregate	0-4 Sand of Fontainebleau
Max temp. difference	14.5 °C
*Further detail on the mix-design of this test: Katrin Habel, katrin.habel@epfl.ch	

Table 6 Mix-design test 6

Verification criteria	Adjusting procedure
s* ≤0.90 s s* ≥ 1.10 s	Develop new S-M relationship
3 consecutives within 0.90 s ≤ s* ≤ 0.95 s 1.05 s ≤ s* ≤ 1.10 s	Evaluate batching and placement adjust s-M* relationship if needed
Better correlations	S-M relationship accepted

Table 7 Verification criteria for maturity prediction; code TEX-426-A. s = predicted strength, s* = independent test results.

Test	Maximum Errors	
	Day	Maximum error %
1	7	+4.5 %
2	28	-5.1 %
3	28	+5.1 %
4	21	-7.4 %
5	28	-6.4 %
6	13	+3.7 %

Table 8 Maximum error between predicted strength and independent test results

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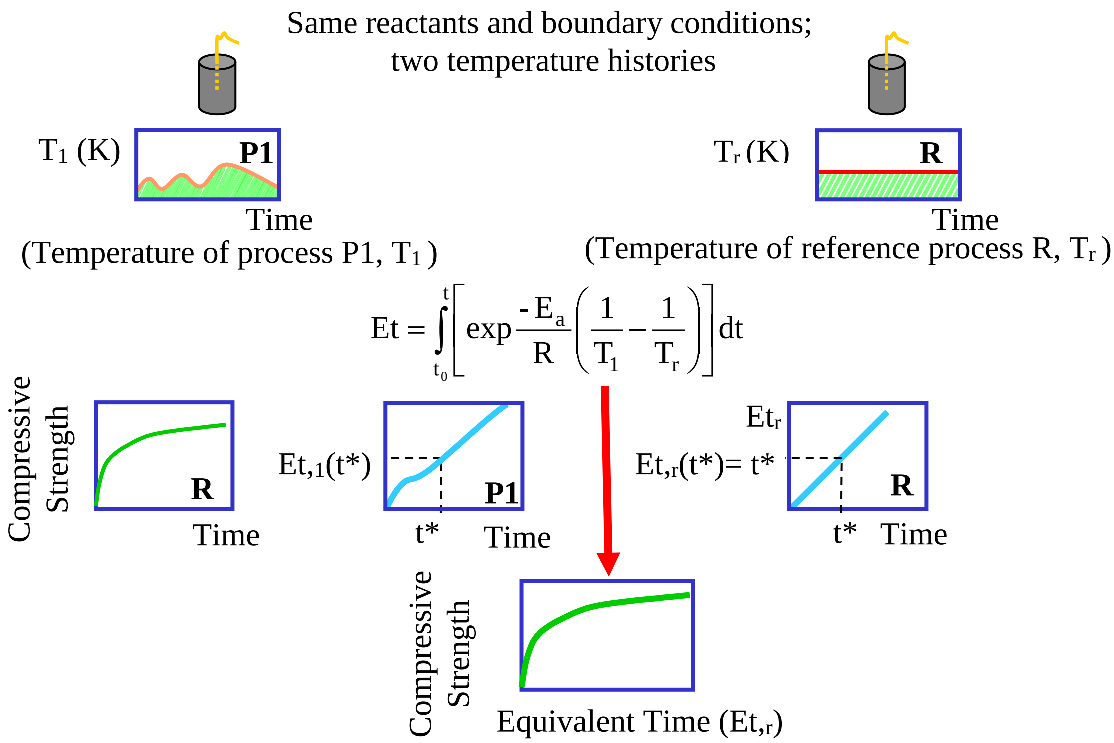


Fig. 1 The concept of equivalent age

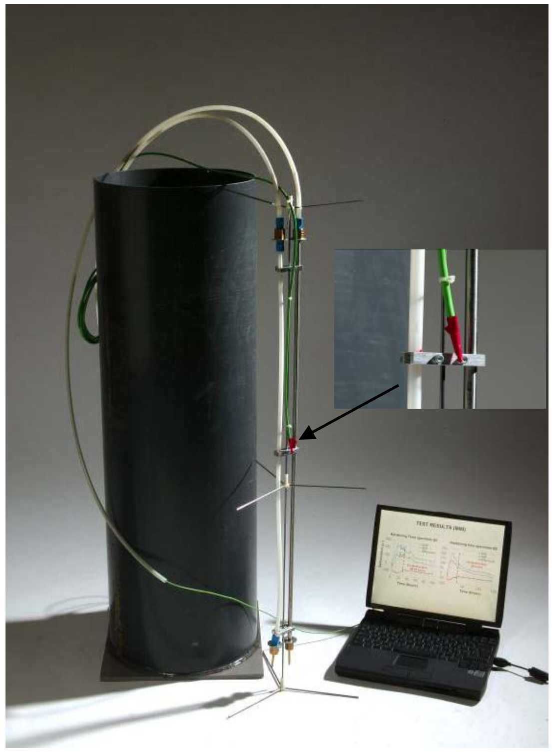


Fig. 2 The standard and stiff SOFO sensors.

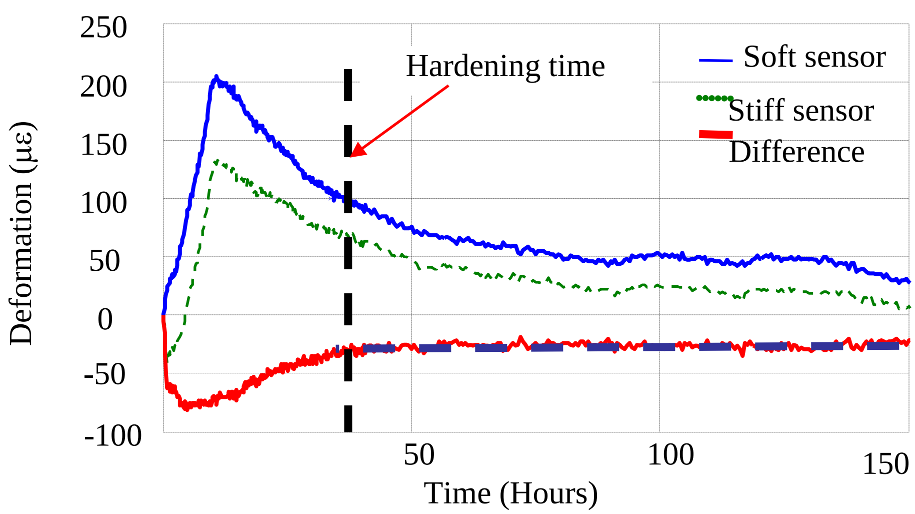
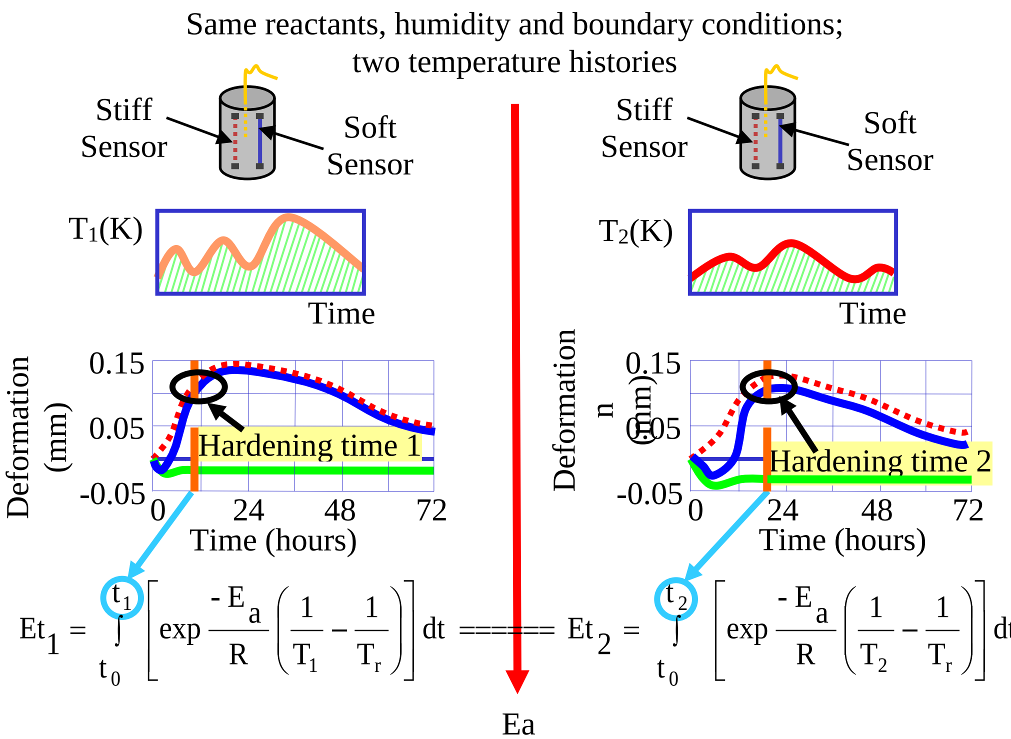


Fig. 3 The hardening time



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338 **Fig. 4 Determination of the activation energy Ea**

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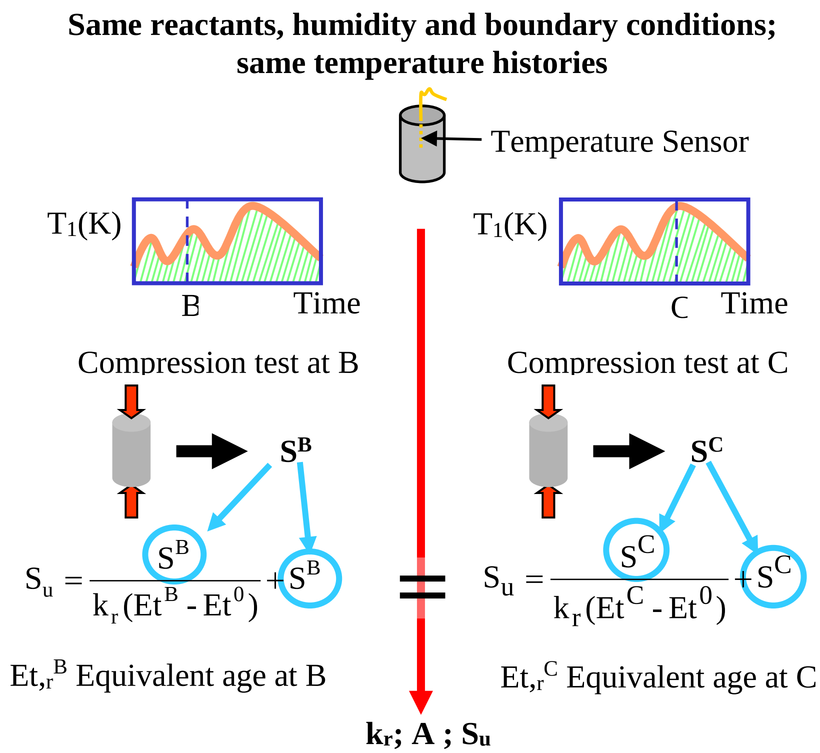

Fig. 5 Determination of the rate of reaction kr, the frequency factor A and the ultimate compressive strength Su

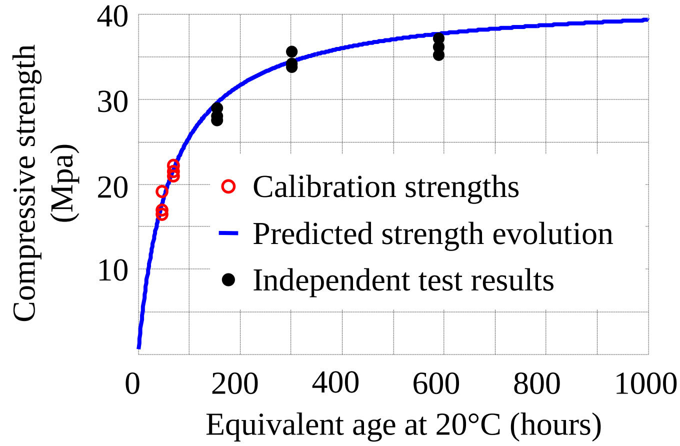

Fig. 6 Compressive strength vs. equivalent age for test series 1. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.

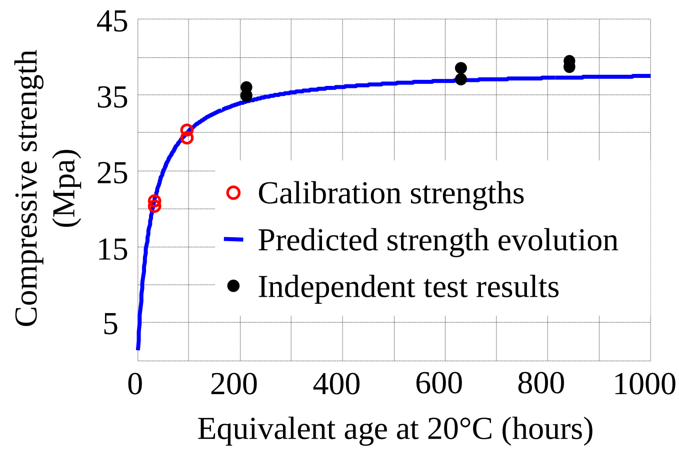

Fig. 7 Compressive strength vs. equivalent age for test series 2. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.

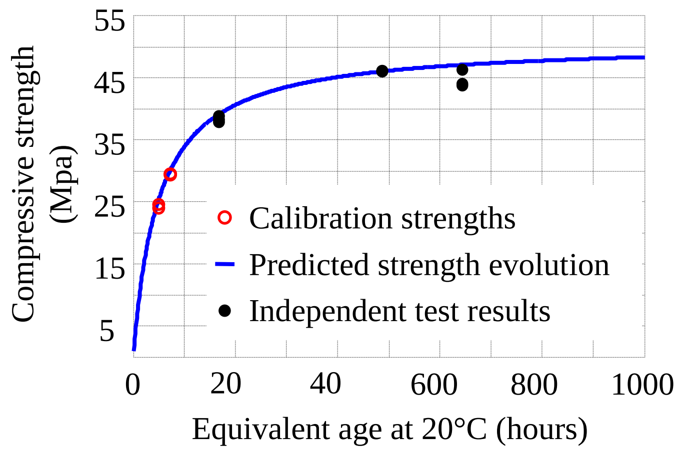

Fig. 8 Compressive strength vs. equivalent age for test series 3. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.

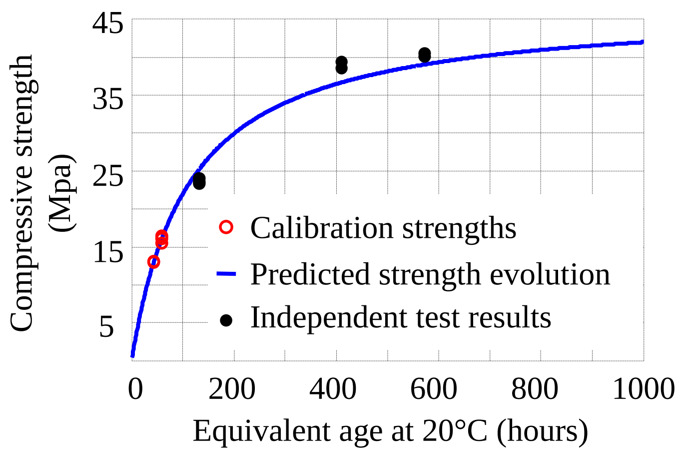

Fig. 9 Compressive strength vs. equivalent age for test series 4. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.

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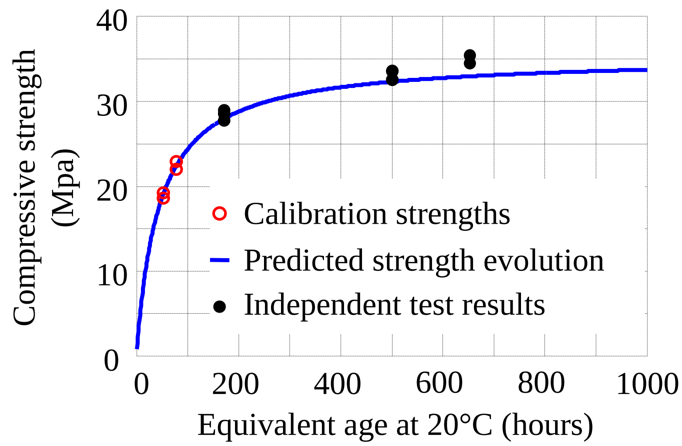

Fig. 10 Compressive strength vs. equivalent age for test series 5. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.

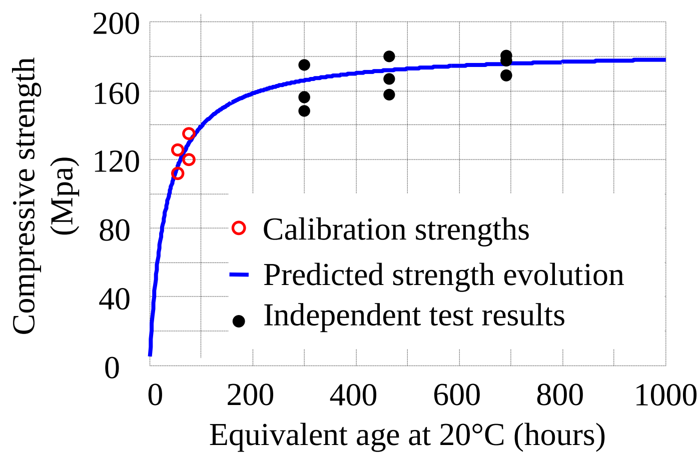

Fig. 11 Compressive strength vs. equivalent age for test series 6. Calibration strengths of young concrete are used to predict strength evolution and this prediction is verified by independent test results using cylinders containing more mature concrete.