Model for Concrete Strength Development Including Strength Reduction at Elevated Temperatures

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ABSTRACT

When casting concrete structures, one of the most important properties is the concrete strength development. The need of actions on site is different at various stages of hardening, from the fresh concrete to the hardened concrete. The paper defines a model analysing maturity and associated strength growth within three important time periods. The model can be applied separately within each of these periods depending on test data available.

It is shown in the paper that the temperature plays an important role on the strength development of concrete structures. The hydration rate increases with increased temperatures, which can be described by maturity functions. If the concrete temperature remains high, strength reduction at later ages usually occurs compared to hardening at lower temperature, which may be denoted strength reduction at elevated temperatures or cross over effects. Both these phenomena have been implemented in the model for strength growth presented in the paper. The functionality of the model is demonstrated by evaluation of laboratory tests for five concrete mixes and two types of cement.

Key words: Concrete hardening, Maturity function, Strength development, Construction stages, Strength reduction, Cross over effects.

1. INTRODUCTION

The range of commercial cements in Sweden has been relatively small. For each type of cement the variation in properties is very small, both in time and between cement plants. One consequence is that the so called tendency strength curves from the cement producers in practice are considered as “true” strength development. Therefore, strength controls on construction sites in Sweden are very rare.

The present situation will probably change with respect to the general demands of lowering the environmental impact of concretes. There is reason to believe that cements with lowered CO_2 loading will show larger variation both in cement properties and concrete compositions, as new non-reactive fillers as well as different kinds of SCMs (supplementary cementitious materials) will be introduced to lower the environmental impact. Besides, since Sweden entered the European Union about 10 years ago, the import of cement has increased gradually, and today the import of cement is about 18%. Thus, there will probably be an increased need to test and evaluate new compositions in the future. Resulting parameters can be applied both in the planning stage of a concrete casting as well as in the follow up procedure at construction site.

In order to model strength development, it is common to describe the strength growth at a reference concrete temperature together with the maturity function for the concrete in question.

There are two situations where it is important to estimate concrete strength development

1) Pre-calculations of temperature and strength development prior the casting of concrete.

2) Follow-up an in situ casting to translate measured concrete temperatures to estimated strength development.

For both situations the maturity function and strength development have to be known. In addition, to be able to calculate the concrete temperature, the first situation needs information concerning heat of hydration.

Application in situation 1) means pre-calculation of temperature and strength development in any specific point in a construction. This is essential during the planning stage to analyse choice of materials and measures to be able to fulfil demands concerning strength. Such analyses may comprise variation of concrete mix, casting sequence, framework stripping, insulation, cooling, heating etc.

Another application of situation 1) is when something unexpected has happened, where calculation with known boundary conditions may be a helpful tool to analyse consequences on site.

In situation 2) above, the temperature inside the concrete construction has to be measured. The application means estimation of strength based on known strength development and maturity function for the concrete in use.

The paper presented deals with a model for strength development based on laboratory tests at variable curing temperature for five concrete mixes and two types of cement.

2. AIMS AND PURPOSES

The aims and purposes in this paper are

- To define and motivate time periods concerning strength growth in concrete with respect to rational information on site affecting production behaviour.

- To analyse and develop a model for strength development in concrete including early age behaviour as well as strength reduction at elevated curing temperatures.

3. A BRIEF HISTORY OF THE MATURITY CONCEPT

It has been generally known since long that the temperature and moisture state in concrete plays an important role for the hardening process, and therefore also for the strength growth. A rational way to take into account variable temperature effects on strength growth is presented by diagrams for practical use in [1], although no models where established. During the planning stage of the Hoover dam [2] a more complex role of temperature on concrete hardening was observed. Higher strength growth at higher temperatures was confirmed at early ages, but for long-term strength a strength reduction at higher temperatures was seen in some of the tests. The latter phenomenon is today known as a cross over effect.

The temperature is fairly easy to measure and calculate, while moisture is hard to measure and calculate. A consequence is that the application for use in practice prefers to use only temperature as base for strength prediction. The first model analysing the single influence of the concrete temperature was presented in [3]. The author used a basic age index, defined as the cumulative area below the temperature-time curve down to a datum temperature as the fundamental parameter related to the strength growth. This opened a door for an inviting way of taking temperature and time into consideration analysing strength development at variable temperature. Tests on strength rate using steam curing [4] showed that initially steam cured cement paste showed accelerated strength growth for early ages, but also a drop in 28 day strength compared with air cured specimens. These observations confirmed the findings in [2]. In [5] it was stated that for early age concrete a datum temperature of –10°C worked sufficiently enough for curing at normal temperature variations, and this was established as the well-known Nurse-Saul maturity function formulated by

$$M = \sum_{0}^{t} \left(T - T_0 \right) \cdot \Delta t \qquad (1)$$

where M = maturity at time t; T = concrete temperature; T_0 = datum temperature; t = time after mixing.

The Nurse-Saul maturity function was quickly adopted in the Scandinavian countries as a technique to estimate the concrete maturity and associated strength when casting in cold climate conditions [6, 7, 8, 9]. With T_0 = –10°C Eq. 1 in Sweden became known as the TT factor method (TT = temperature-time), and it has alternatively been expressed as Eq. 2 which opens the possibility to describe the equivalent time of maturity, see Eq. 3. The author in [6] confirmed that the use of T_0 = –10°C was satisfactory analysing several test series from the literature as well as on own tests. About the same datum temperature (–11,7°C) was presented in [10].

$$\beta_T = \frac{T - T_0}{T_{ref} - T_0} \tag{2}$$

$$t_e = \int_0^t \beta_T \cdot dt \tag{3}$$

where β_T = temperature dependent rate factor, usually denoted maturity function;
T_{ref} = reference concrete temperature; t_e = equivalent time of maturity.

In [5] it was shown that a strength reduction occurred if the steam curing temperature of 95°C was reached before seven hours after casting, i.e. the rate of hardening at very early ages seems to play an important role for the final strength. The findings in [11] were of importance for concrete casting in cold climate conditions, where the test results for curing temperatures about 6°C showed a compressive strength as high as or higher for equivalent age larger than 7 days compared with curing at room temperature. Shortly thereafter [12] cross over effects for curing temperatures between –4°C to 49°C were demonstrated, which again verifies the findings in [2], [5] and [11]. So, the twofold effects of the curing temperature on strength: that higher curing temperatures accelerate the hardening at early ages but might result in lower final strength, has been known at least since the 1950s. In [12] and [13] possible causes of the cross over effects are discussed, and the structure of the hydration products is assumed to be dependent on the curing temperature. This might explain the low final strength at high curing temperatures, and vice versa for low curing temperatures.

The importance of using the maturity concept at cold weather concreting was pinpointed by two collapses of concrete structure in U.S. with fatal consequences in the 1970s. These disasters started a number of investigations [14, 15], which resulted in the first versions of the standard ASTM C1074, and the current version is given in [16].

Until the mid 1970s the maturity function has been formulated empirically, but in the Scandinavian countries [17, 18] the temperature dependency was shown to work with respect to the chemically defined activation energy formulated by

$$\beta_T = \exp\left[\frac{E}{R} \cdot \left(\frac{1}{293} - \frac{1}{T + 273}\right)\right] \tag{4}$$

where E [J/mole] = apparent activation energy; R [J/mole K] = general gas constant = 8,314J/mole K; T [°C] = concrete temperature.

Unfortunately, the activation energy, E, was not always constant, which means that the so called Arrhenius equation is not used in a theoretically strict way. Nevertheless, the formulation according to Arrhenius equation is inviting, as the activation energy has a theoretical meaning in thermal activation of chemical reactions. An empirical expression for the apparent activation energy was introduced in [19] expressed as

$$\theta = \frac{E}{R} = \theta_{ref} \cdot \left(\frac{30}{T+10} \right)^{\kappa_3} \tag{5}$$

where θ [K]= "activation temperature"; θ_{ref} [K] and κ_3 [-] are empirically constants useable in most practical situations.

With the help of mercury intrusion and backscattered electron image analysis it was shown in [20] that the porosity increased with increased curing temperature at the same degree of hydration. It was also found in [21] that low curing temperatures gave a uniform distribution of hydration products, and elevated temperatures resulted in a coarser pore structure. Additionally, tests on one mortar mix showed that the maturity concept directly could be applied up to about 50% degree of hydration [22]. Above 50% degree of hydration, the tests indicate that the apparent activation energy also changes with the degree of hydration. This latter finding means that the hydration rate is decreased at higher degree of hydration, which might be designated a hydration retarding effect due to densification of the hydration products.

The "first model generation" completing the maturity concept with the cross over effect was established by separate adjustments of the strength growth by functions only dependent on the temperature without taking the retarding effect into account [23-27]. Later models [28-37] have used different techniques adding the retarding effect, either by adjusting the apparent activation energy by time or introducing separate retarding functions decreasing by time.

Another effect that retards the rate of hydration is drying, both external drying to the environment and self-desiccation at sealed conditions. The moisture effect is well known from laboratory tests [38] and observed in field tests [39], and this is taken care of by rules concerning moisture hardening in standards and specifications all over the world. Considering the drying effect separately is too difficult for most applications in practice, as the moisture state in a structure is rather complex to measure or calculate. The combined effect on hydration of temperature, moisture and retarding due to densification is possible to take into account for special applications, where the moisture plays a significant role, see for instance [40-41]. The maturity models only based on temperature might theoretically be denoted "temperature maturity models", but this refined notation is usually not considered.

It is interesting to conclude that the maturity concept also is applicable for the stiffening during the time between initial and final set, see [42-44]. This means that a comprehensive maturity model also should include this very early stage of concrete hardening.

Most results from the literature concerning maturity and evaluation of apparent activation energy is shown for separate concrete mixes, but some attempts are presented where the activation energy is estimated based on information concerning chemical and physical properties of the binder [45-46].

The maturity concept, as a method to follow up the strength growth in concrete structures, has been used for up to 50 years in several countries. When the concrete maturity properties are well known, the general conclusion is that the maturity concept is a good quality control tool for assessments of in-situ strength in concrete structures during hardening [47-48]. One consequence is that field cubes in Sweden have been replaced by temperature measurements on site since the beginning of the 1990s. In contrast to this, some countries in Europe still use field cubes and compression tests when estimating strength on site, probably due to “traditional” use of existing local standards and since long established practical procedures.

4. MODEL FOR STRENGTH DEVELOPMENT

4.1 Choice of time periods

It is important that different time periods are defined with respect to the behaviour on site, and that the periods can be defined from properties of concrete. Starting from casting, three periods connected to the treatment of concrete are here defined as

I. Fresh concrete period
II. Surface finishing period
III. Hardening period

These three time periods are in line with what is used in [42, 43, 44], see Figure 1. Some preliminary tests have shown that the influence of the temperature might be different within these time periods, and the modelling presented below is structured to take this into account.

Here the first period is denoted “fresh” concrete as the contractor is able to place and vibrate the concrete without damaging the structure of the cement paste.

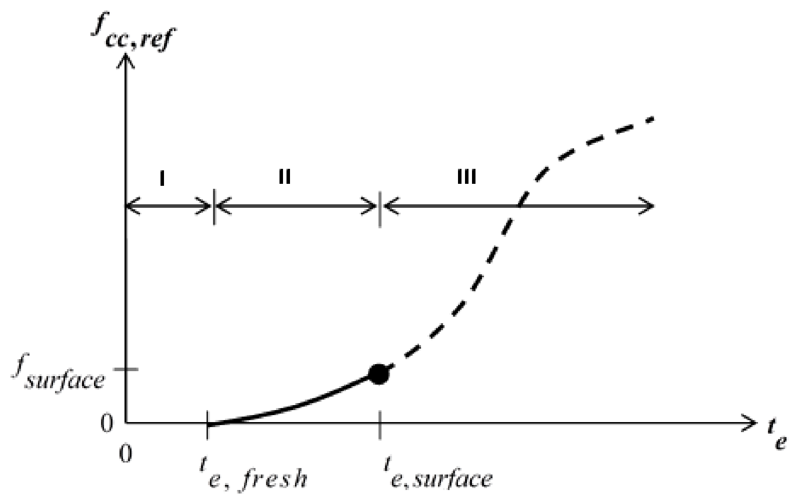

Figure 1 – Reference strength ($f_{cc,ref}$) as a function of equivalent time (t_e). Note that t_e may be calculated differently within each period, see further Eqs. 9, 11 and 14.

The second period in Figure 1 may approximately be regarded as the time between initial and final setting, which in practice means that the contractor is able to process the surface finishing within this period. The limits for the surface finishing period are usually defined by penetration resistance in cement paste [44] or mortar. Here, concrete strength is used to describe the surface finishing period by

$$f_{fresh} = 0\text{MPa} \tag{6}$$

$$f_{surface} = 0{,}5\text{MPa} \tag{7}$$

where f_{fresh} = 0MPa from casting to the equivalent time at the end of the fresh concrete period, $t_{e,\,fresh}$, when the concrete mix no longer is workable; $f_{surface}$ = the strength value when the surface no longer can be processed, which occurs at the equivalent time, $t_{e,surface}$, at the end of the surface finishing period. The notation strength is here used for compression tests performed on 100mm or 150mm cubes.

4.2 Strength development during the fresh concrete period

The parameter $t_{e,\,fresh}$ may be taken as the time when the concrete surface is walkable with a permanent imprint of about 5–10mm [49]. The strength growth and the equivalent time during the fresh concrete period are described by

$$I : f_{cc,ref} = 0 \qquad \text{for} \qquad 0 \le t \le t_I \tag{8}$$

and

$$I : t_e = \beta_\Delta \cdot \int_0^t \beta_T \cdot dt + \Delta t_{e0} \qquad \text{for} \qquad 0 \le t \le t_I \tag{9}$$

where $f_{cc,ref}$ [MPa] = strength growth at reference conditions as a function of equivalent time, t_e [h]; t [h] is real time; t_I [h] is the time when $t_e = t_{e,\,fresh}$ using Eq. 9 with $\theta_{ref} = \theta_{ref,I}$ and $\kappa_3 = \kappa_{3,I}$ for calculation of β_T, see Eqs. 4-5; and $\beta_\Delta = \beta_{\Delta,I}$. The parameters $t_{e,\,fresh}$ [h], $\theta_{ref,I}$ [K], $\kappa_{3,I}$ [-], $\beta_{\Delta,I}$ [-] and Δt_{e0} [h] are evaluated from fitting of test data.

4.3 Strength development during the surface finishing period

The strength $f_{surface}$ is here proposed to be 0,5MPa. In practice it has been shown that the actual surface finishing normally can be performed between the strength of about 0,1MPa to 0,4MPa [50] which is within the limits defined by Eqs. 6 and 7. Exact limits for different kinds of surface finishing treatments must be tested separately for each mix. The strength growth and the equivalent time during the surface finishing period are described by

$$II: f_{cc,ref} = f_{surface} \cdot \left(\frac{t_e - t_{e,fresh}}{t_{e,surface} - t_{e,fresh}} \right)^{n_{surface}} \qquad \text{for} \qquad t_I < t \le t_{II} \qquad (10)$$

with

$$II: t_e = t_{e,fresh} + \beta_\Delta \cdot \int_{t_I}^{t} \beta_T \cdot dt \qquad \text{for} \qquad t_I < t \le t_{II} \qquad (11)$$

where $f_{cc,ref}$ [MPa] = strength growth at reference conditions as a function of equivalent time, t_e [h]; t_{II} [h] is the time when $t_e = t_{e,surface}$ using Eq. 11 with $\theta_{ref} = \theta_{ref,II}$ and $\kappa_3 = \kappa_{3,II}$ for calculation of β_T, see Eqs. 4-5; and $\beta_\Delta = \beta_{\Delta,II}$. The parameters $n_{surface}$ [-], $t_{e,surface}$ [h], $\theta_{ref,II}$ [K], $\kappa_{3,II}$ [-] and $\beta_{\Delta,II}$ [-] are evaluated from fitting of test data.

4.4 Tendency curve during the concrete hardening period

The strength growth according to Eurocode 2 [51] is expressed by

$$f_{cc,ref} = f_{cc,28d} \cdot \exp\left\{ s \left[1 - \left(\frac{672}{t} \right)^{1/2} \right] \right\} \qquad (12)$$

Where $f_{cc,28d}$ [MPa] = 28 days compressive strength for reference conditions; s [-] is a coefficient which depends on the type of cement; and t [h] is the time for mean temperature of 20°C and moist curing.

From the basic formulation in Eq. 12, the strength growth during the hardening period (III) is here modified as

$$III: f_{cc,ref} = f_{cc,28d} \cdot \exp\left\{ s \left[1 - \left(\frac{672 - t^*}{t_e - t^*} \right)^{n_{cc,28d}} \right] \right\} \qquad \text{for} \qquad t > t_{II} \qquad (13)$$

with

$$III: t_e = t_{e,surface} + \beta_\Delta \cdot \int_{t_{II}}^{t} \beta_T \cdot dt \qquad \text{for} \qquad t > t_{II} \qquad (14)$$

where $f_{cc,ref}$ [MPa] = strength growth at reference conditions as a function of equivalent time, t_e [h]; t_{II} [h] is the time when $t_e = t_{e,surface}$, see Eq. 11. Application of Eq. 13 means that Eq. 14 shall be used with $\theta_{ref} = \theta_{ref,III}$ and $\kappa_3 = \kappa_{3,III}$ for calculation of β_T, see Eqs. 4-5, and $\beta_\Delta = \beta_{\Delta,III}$. The parameters $f_{cc,28d}$ [MPa], s [-], $n_{cc,28d}$ [-], $\theta_{ref,III}$ [K], $\kappa_{3,III}$ [-] and $\beta_{\Delta,III}$ [-] are evaluated from fitting of test data. t^* [h] is introduced to fit the data point ($t_{e,surface}$, $f_{surface}$), which means that the end point of time period II has to be the same as the start point of time period III, see Figure 1. The numerical value of t^* has no physical meaning and is calculated by

let $\quad f_{surface} = f_{cc,ref}\left(t_{e,surface}\right)$

calculate using Eq.13 $\quad \delta_c = \left(1 - \ln \frac{f_{surface}}{f_{cc,28d}} \cdot \frac{1}{s}\right)^{1/n_{cc,28d}}$ (15)

and finally $\quad t^* = \frac{672 - \delta_c \cdot t_{e,surface}}{1 - \delta_c}$

When evaluating a specific recipe for the first time the parameters $\beta_{\Delta,j}$ [-] {j=I, II, III} are usually set = 1, and parameter Δt_{e0} is usually set = 0. Then, if only the type of admixture is changed, it might be possible only to introduce $\beta_{\Delta,j} \neq 1$ and/or $\Delta t_{e0} \neq 0$ as additional parameters to existing model data for a basic recipe.

4.5 Strength reduction

The typical behaviour when cross over effects occur is shown in Figure 2. The notation cross over originates from plotting linear strength as a function of real time, see left part of Figure 2. When time is transformed to equivalent time it is possible to use the term strength reduction for temperatures above a chosen reference temperature, here 20°C, see right part of Figure 2. The strength for temperatures below reference temperature also shows a cross over effect (or strength gain), but this part is here ignored and might be regarded as an extra margin.

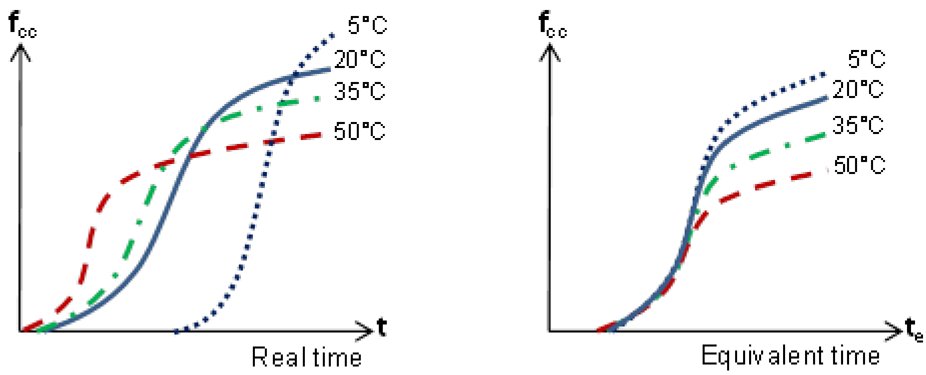

Figure 2 – Typically strength results for specimens cured between 5°C and 50°C, at left plotted in real time and to the right in equivalent time.

The strength reduction due to elevated hardening temperatures is only calculated for the hardening period (III) by

$$f_{cc} = f_{cc,ref} - \gamma_{drop} \cdot \Delta_{drop,28d}^{\max} \cdot f_{cc,28d} \qquad \text{for} \qquad t > t_{II} \qquad (16)$$

where $\Delta_{drop,28d}^{\max}$ [-] = maximum strength reduction at t_e = 672h; γ_{drop} {0,1} is the factor taking into account the temperature effect on strength reduction.

The technique to describe the reduction in strength according to Eq. 16 is here characterized by the following observations

1) The drop in strength starts at some minimum temperature, reflected by γ_{Temp} (Eq. 20).

2) Elevated temperatures influence the strength drop after a certain time, reflected by γ_{time} (Eq. 21).

3) The retarding effect at later ages [22] is here modelled by the "relative" rate of reaction ($d\alpha^* / dt_e$, see Eqs. 22 and 23).

These three phenomena can be described by the following material related empirical model

$$\gamma_{drop} = \frac{\delta_{drop}}{\delta_{ref}} \tag{17}$$

with

$$\delta_{drop} = \int_0^{t_e} \gamma_{Temp} \cdot \gamma_{time} \cdot \frac{d\alpha^*}{dt_e} \tag{18}$$

and

$$\delta_{ref} = \int_0^{672h} \gamma_{time} \cdot \frac{d\alpha^*}{dt_e} \cdot dt_e \tag{19}$$

The functions reflecting temperature and time effects, γ_{Temp} and γ_{time}, see Eqs. 20 and 21, are chosen to be exponential formulas, which are inviting to use within a certain range as they are within the interval {0,1}. This gives a robust type of modelling, and they can easily be extended to a broader range, if such test data are added afterwards.

$$\gamma_{Temp} = \exp\left(-\left[\frac{T}{Temp_D} \right]^{-\kappa_{Temp}} \right) \tag{20}$$

$$\gamma_{Time} = \exp\left(-\left[\frac{t_e}{time_D} \right]^{-\kappa_{time}} \right)$$

(21)

Where $Temp_D$ [°C]; $time_D$ [h]; κ_{Temp} [-] and κ_{time} [-] together with $\Delta_{drop,28d}^{\max}$ are evaluated by fitting against test data where strength reduction has occurred.

The hydration rate is described in Eq. 22 from [52]. The derivative with respect to the temperature equivalent maturity age is presented in Eq. 23.

$$\alpha^{*} = \exp\left(-\left[\ln\left(1+\frac{t_e}{t_1}\right)\right]^{-\kappa_1}\right) \tag{22}$$

$$\frac{d\alpha^{*}}{dt_e} = \frac{\alpha^{*}}{t_1+t_e}\cdot\kappa_1\cdot\left[\ln\left(1+\frac{t_e}{t_1}\right)\right]^{-(\kappa_1+1)} \tag{23}$$

where α^{*} [-] is the "relative" degree of hydration; t_1 [h] and κ_1 [-] are parameters decided from calorimetric tests. The notation relative means that α^{*} = 1 reflects the ultimate heat of hydration (corresponding to ultimate degree of reaction) in relation to the individual final value for a tested concrete.

The use of Eqs. 22 and 23 is based on the existence of test data from calorimetric measurements, which at Luleå University of Technology is a standard behaviour testing early age concrete. Eq. 23 starts and stops at $d\alpha^{*}/dt_e$ = 0. Somewhere in between, it has a maximum value mainly depending on the type of cement and the w/c ratio. Hereby, the rate of hydration depending on cement composition and w/c ratio is taken into account in a material related way.

5. TEST RESULTS AND EVALUATION ACCORDING TO PROPOSED MODEL

5.1 Test setup

Strength developments on 100mm cubes cured in water baths of different temperature levels, 20°C, 35°C and 50°C respectively, have been performed [52]. All cubes for each recipe originate from one physical mix to avoid variations due to differences in mix conditions [53]. The concrete temperatures are registered and the individual temperature-time behaviour is considered in the evaluation. The main test and evaluation methodology is given in [53]. The cements used are Anläggningscement (AnlC) and Byggcement (ByggC), and the cement compositions are presented in Table 1. Totally five concrete recipes have been tested, see main constituents in Table 2.

Table 1 – Oxides, clinker minerals and specific surface of tested cements. ByggC is of type CEM II/A-LL 42,5 R containing about 13% LL, and AnlC is of type CEM I 42,5 N MH/SR/LA (CEMENTA AB).

Cement	Oxides [%]					Clinker minerals [%]				Specific surface [m²/kg]
	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	C_3S	C_2S	C_3A	C_4AF	
ByggC	61,4	18,7	3,9	2,8	3,5	54,1	8,9	5,1	7,8	460
AnlC	64,1	22,4	3,7	4,5	2,4	48,0	28,0	2,1	13,8	316

Table 2 – Main constituents of tested concretes.

Recipe	Cement	Cement content [kg/m³]	w/c
1	ByggC	285	0,70
2	ByggC	360	0,55
3	ByggC	470	0,38
4	AnlC	340	0,55
5	AnlC	455	0,38

5.2 Evaluation procedure

The evaluation procedure for the model outlined here is aimed to be performed in three steps, one separate evaluation for each time period (I, II and III) in Figure 1. A possible "complete sequence of evaluation" behaviour is presented below.

If tests have been performed concerning time period I the evaluation can be done as follows

Ia) For an individual, basic recipe $\theta_{ref,I}$ and $\kappa_{3,I}$, see Eq. 5, and $t_{e,fresh}$, see the denotation list in connection to Eq. 9, are determined for $\Delta t_{e0} = 0$ and $\beta_{\Delta,I} = 1$.

Ib) When a basic evaluation exists, a possibility is to use $\Delta t_{e0} \neq 0$ and $\beta_{\Delta,I} \neq 1$, when effects from other types of admixtures are analysed.

If tests have been performed in time period II the evaluation can be done as follows

IIa) For an individual, basic recipe $\theta_{ref,II}$ and $\kappa_{3,II}$, and $t_{e,surface}$, see the denotation list in connection to Eq. 11, are determined for $\beta_{\Delta,II} = 1$.

IIb) When a basic evaluation exists, a possibility is to use $\beta_{\Delta,II} \neq 1$, when effects from other types of admixtures are analysed.

If tests have been performed in time period III the evaluation can be done as follows

IIIa) For an individual, basic recipe $\theta_{ref,III}$, $\kappa_{3,III}$, s, $n_{cc,28d}$ and $f_{cc,28d}$, are determined for $\beta_{\Delta,III} = 1$, see Eqs. 13-14. The parameter t^* in Eq. 13 has no physical meaning and is not an independent fitting parameter. t^* is calculated separately according to Eq. 15.

IIIb) When a basic evaluation exists, a possibility is to use $\beta_{\Delta,III} \neq 1$, when effects from other types of admixtures are analysed.

A complete evaluation sequence is only possible when test data exist within all three time periods. Many other alternatives are possible in practice.

Here, only test data exist within the hardening period (III), and the consequence is that the strength development can only be estimated with high credibility within time period III. The parameters for time periods I and II are here chosen as follows

$$\theta_{ref,I} = \theta_{ref,II} = \theta_{ref,III} = \theta_{ref} \quad \text{and} \quad \kappa_{3,I} = \kappa_{3,II} = \kappa_{3,III} = \kappa_3 \tag{24}$$

The meaning of Eq. 24 is that the maturity function has only two fitting parameters (θ_{ref}, κ_3) formally valid for all time periods.

Besides, here the evaluations are regarded as individual basic recipes, which is described by

$$\Delta t_{e0} = 0 \quad \text{and} \quad \beta_{\Delta,I} = \beta_{\Delta,II} = \beta_{\Delta,III} = \beta_{\Delta} = 1 \tag{25}$$

The meaning of Eq. 25 is that the parameters Δt_{e0} and $\beta_{\Delta,j}$ are excluded from the evaluation sequence.

The remaining parameters for time periods I and II are here set to reasonable “theoretical” values chosen to be the same for all recipes by

$$t_{e,\,fresh} = 3\text{h}, \quad t_{e,surface} = 5\text{h} \quad \text{and} \quad n_{surface} = 3 \tag{26}$$

The parameters in Eq. 26 are probably functions of the water-cement ratio (w/c), but such test data are not available for the concretes analysed here.

The remaining parameters for the strength reference curve for each recipe ($f_{cc,28d}$, s and $n_{cc,28d}$), and the corresponding maturity functions (θ_{ref} , κ_3) have to be determined by fitting procedure by regression analysis using the so called least square method. With this procedure it was recognized that $n_{cc,28d} \approx 0{,}5$, $\theta_{ref} \approx 2750\,\text{K}$ and $\kappa_3 \approx 0$ for all analysed recipes. Therefore, these three parameters were fixed to these values, see Table 3. So, the remaining fitting parameters for each recipe analysed here are $f_{cc,28d}$ and s , respectively. The final resulting parameters are shown in Table 3 and the corresponding reference curves are presented in Figure 3 and Figure 4 as the plotted curves denoted f_cc_ref.

In Figure 3 the blue squares, the green triangles and the red rotated squares are test results at the temperature levels shown in the legend. The larger green square is the evaluated 28 days strength, $f_{cc,28d}$ in Eq. 13, and the larger red square represents the maximum possible strength reduction for evaluated temperatures, $\Delta_{drop,28d}^{\max}$ in Eq. 16. The continuous line marked f_cc_ref in Figure 3 means the reference curve at $T \equiv 20\,°\text{C}$, see Eq. 13, and the three lines marked T20 C, T35 C and T50 C are calculated strength developments based on measured temperatures for each temperature level.

As can be seen in Figures 3 and 4 the different temperature levels are measured up to equivalent age of about 200h. The reason is that the primarily interest is to create information to predict or estimate strength growth at variable temperature the first days after casting. Hereby, decisions can be taken on site with respect to time and need of measures for frost protection, time of post tensioning and time of form striking. In addition, we are always measuring and evaluating the 28-day-strength (28d = 672h), which is a “key” parameter in concrete design.

Basically, the same notations are used in Figure 4 as in Figure 3, but, without strength reductions.

So far the reference curve is evaluated, and the cross over effect or strength reduction is ignored. It is obvious in our test series that concretes with ByggC show strength reduction, but cement AnlC does not show any significant strength drop. Earlier tests on strength growth at Luleå University of Technology have also shown strength reduction using ByggC [54] but not when using AnlC [55]. AnlC is a moderate heat cement, formally an OPC with reduced production of hydration heat. AnlC is aimed for use in civil engineering structures and ByggC is aimed for more general castings. Civil engineering structures means structures exposed to severe environmental conditions, for example bridges, tunnels, harbours, water towers etc. In Sweden the production of AnlC is about 16% of the total cement production.

Table 3 – Model parameters received for maturity function and reference strength by using regression analysis with Eqs. 4 - 6.

w/c	Recipe	$f_{cc,28d}$ [MPa]	s [-]	$n_{cc,28d}$ [-]	$t_{e,\,fresh}$ [h]	$t_{e,surface}$ [h]	$f_{surface}$ [MPa]	$n_{surface}$ [-]	θ_{ref} [K]	κ_3 [-]	Δt_{e0} [h]	β_Δ [-]
0,70	1	33,2	0,190	0,5	3	5	0,5	3	2750	0	0	1
0,55	2	49,6	0,163	0,5	3	5	0,5	3	2750	0	0	1
0,38	3	79,9	0,122	0,5	3	5	0,5	3	2750	0	0	1
0,55	4	49,4	0,350	0,5	3	5	0,5	3	2750	0	0	1
0,38	5	83,8	0,237	0,5	3	5	0,5	3	2750	0	0	1

5.3 Strength reduction

The modelling of strength reduction is described in Eqs. 16 – 23. Fitting using the least square method resulted in individual parameters for recipe 1 – 3, see Table 4. According to the test results in Figure 4 the use of cement type AnlC did not seem to show any significant strength reduction, which in Table 4 is shown by $\Delta_{drop,28d}^{\max}$ = 0.

Table 4 – Model parameters for strength reduction and relative degree of hydration.

Recipe	Strength reduction					Degree of hydration	
	$\Delta_{drop,28d}^{\max}$ [-]	$Temp_D$ [ºC]	κ_{Temp} [-]	$time_D$ [h]	κ_{time} [-]	t_1 [h]	κ_1 [-]
1	0,41	39	7	25	2,00	8,57	1,31
2	0,45	38	5	35	1,75	6,52	2,18
3	0,48	36	3	40	1,50	5,19	3,25
4	0	-	-	-	-	7,56	1,80
5	0	-	-	-	-	19,0	0,62

The strength reduction functions, γ_{Temp} and γ_{time} (Eqs. 20 and 21), for the concretes using ByggC are dependent on the w/c ratio. Also the value of $\Delta_{drop,28d}^{\max}$ is higher for lower w/c ratios, see Table 4. The observed dependency of the w/c ratio indicates that these functions reflect differences in the pore structure in the paste matrix.

From Figure 5 it is seen that the relative rate of hydration is strongly dependent on the w/c ratio for concretes using ByggC, which probably contributes to the higher strength reduction for lower w/c ratios, see Figure 3. Figure 5 also shows that the relative rate of hydration using AnlC is dependent on the w/c ratio, but the values are lower than using ByggC. No significant strength reduction was observed using AnlC in the tests, see Figure 4, which probably is a consequence of both cement composition and a lower value of specific surface, see Table 1. Although, in Figure 4, there is a tendency that the lower w/c ratio (0,38) indicates a strength reduction from about 100h equivalent time. But, with no information at later ages, strength reduction for AnlC is not regarded here. To clarify this, further tests are needed.

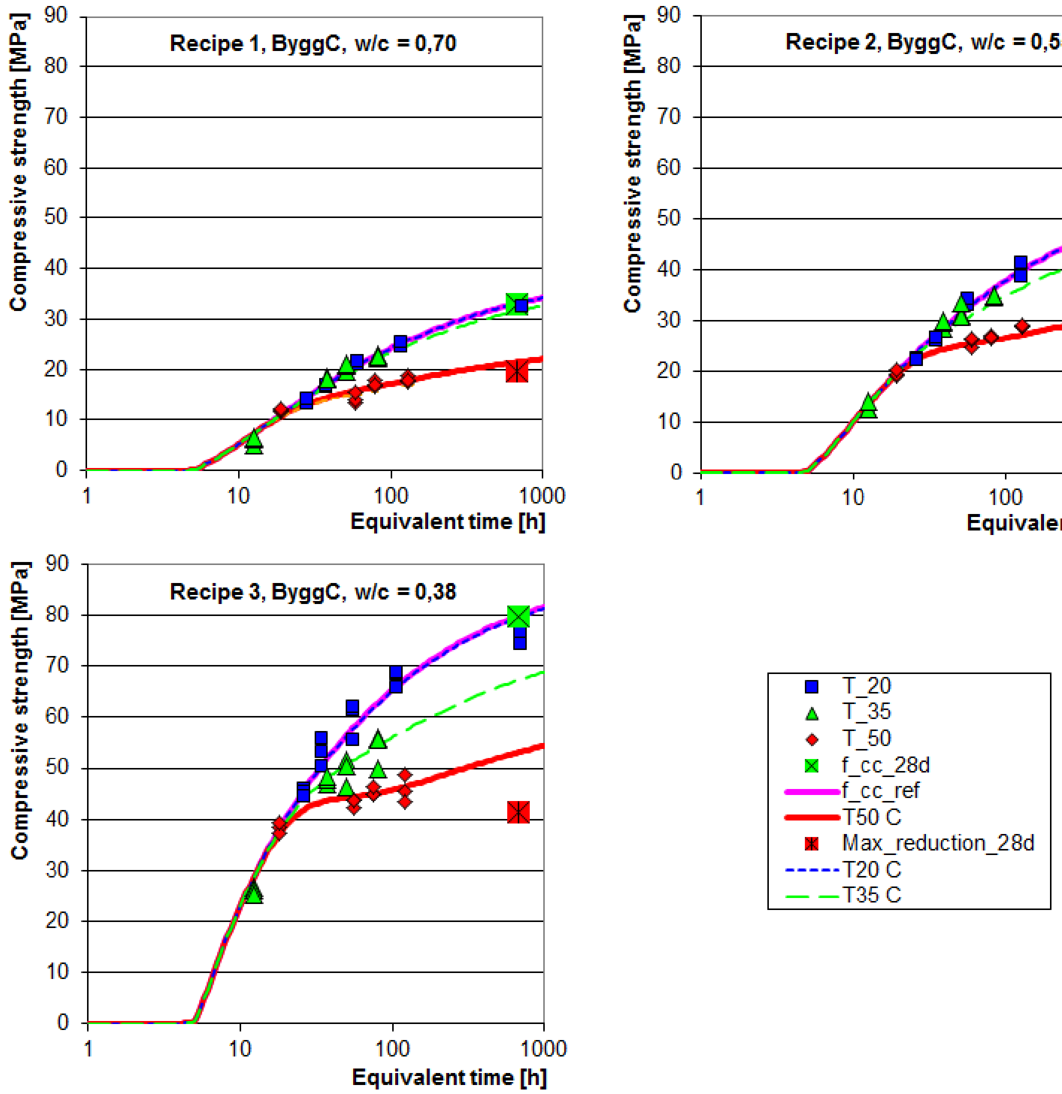

Figure 3 – Reference and strength reduction curves for all ByggC recipes.

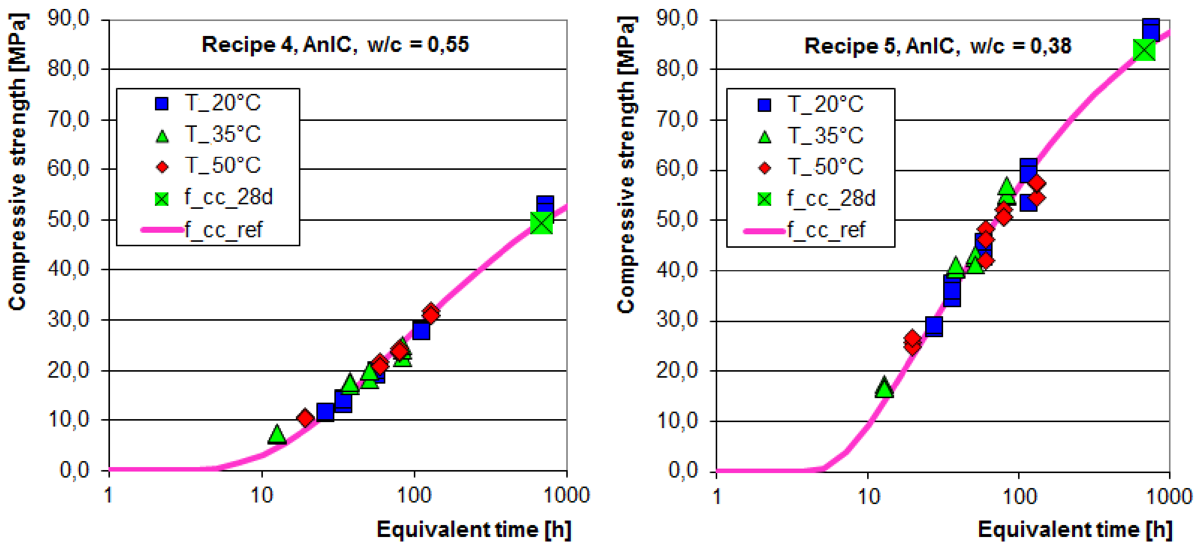

Figure 4 – Reference strength curves for recipe 4 – 5, AnlC.

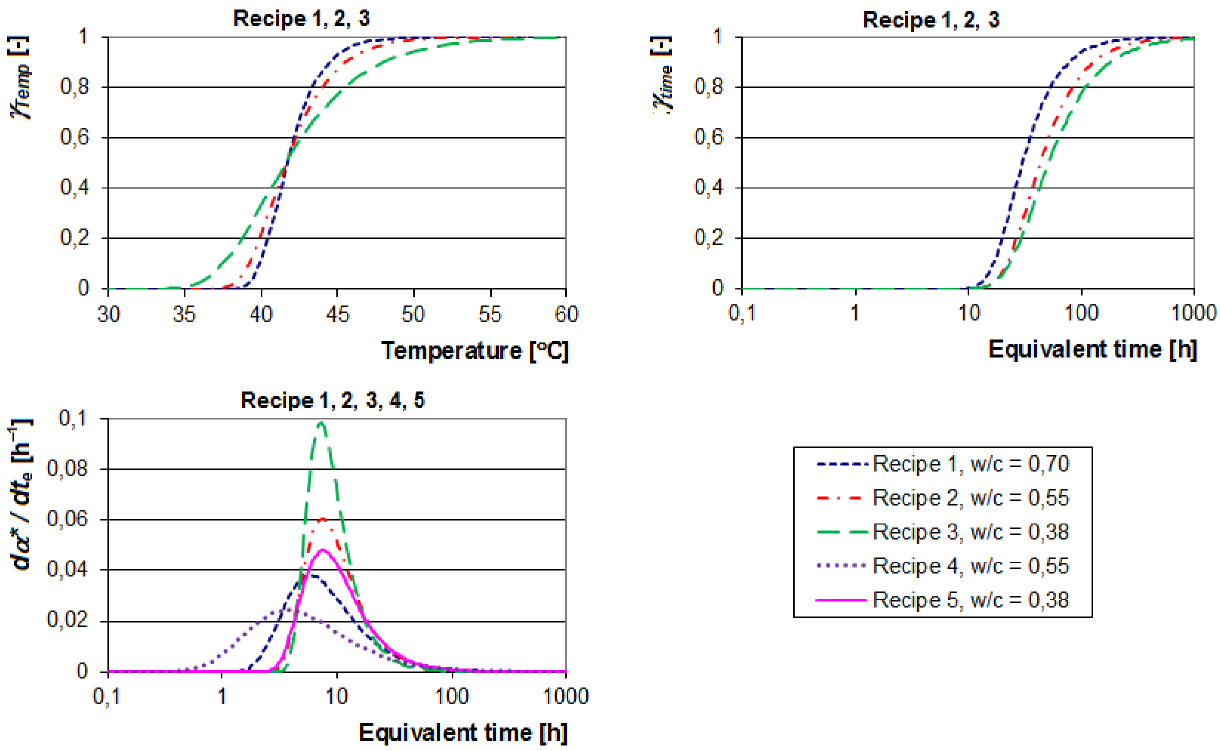

Figure 5 – Functions used in modelling strength reduction for analysed concretes, recipe 1 – 5. Numerical values for use of Eqs. 20, 21 and 23 are given in Table 4.

6. SUMMARY AND CONCLUSIONS

- The defined time periods for different models of strength growth are strongly adapted to the contractors behaviour on site, denoted I) Fresh concrete period, II) Surface finishing period and III) Hardening period. By introduction of individual strength growth and maturity functions within each time period, tests and modelling may be treated separately within the periods. This opens a possibility to study and analyse the period that is of most interest for a specific application. In the most comprehensive modelling all three periods may be combined to a complete sequence. In the paper it is shown that if tests results only are available during the time period III, high credibility can be achieved with reasonable assumptions also within time periods I and II. In summary, the presented model with three time periods is shown to be very flexible with respect to available test data.

- The strength development is modelled separately within time period II and III. Within time period III the model is based on an established formula in Eurocode 2, and modifications are introduced with respect to continuation in strength at the end of time period II. This modification is straight forward and simple to apply for the strength at reference conditions, which here means curing at 20°C. For curing at elevated temperatures, a robust model has been developed taking into account effects of time, temperature and rate of reaction. These three areas are modelled separately which seems to be appropriate with respect to observed strength developments. In the paper the model has been applied successfully for five concrete mixes. The tests were performed with two types of cements, of which one showed strength reduction.

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