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Applicability of degree of hydration concept and maturity method for thermo-visco-elastic behaviour of early age concrete

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Abstract

Whereas the degree of hydration concept and the maturity method are often treated as two competitive approaches for dealing with properties of early age concrete, it is shown in this contribution that both methods principally yield the same results and conclusions. Moreover, the applicability of both methods for the delayed mechanical behaviour of the early age concrete (basic creep and relaxation) is outlined as well. In this way, together with the well known applicability for strength and stiffness development, both methods now can be recognized as valid tools for modelling the total thermo-visco-elastic behaviour of early age concrete.

Keywords: Early age concrete; Degree of hydration; Maturity; Strength development; Basic creep

1. Introduction

The engineering characteristics of a hardening cement-based material are to a very large extent depending on the microstructural development, and thus on the hydration reactions of the cement. In a fundamental approach, the relation between the driving processes on the microscopic level, and the macroscopic engineering properties can be studied by means of the degree of hydration, using sometimes detailed general hydration models. In a more traditional approach, the effect of ongoing hydration can be estimated by defining maturity or, similarly, by considering the equivalent age of the cementitious material.

In this contribution, the harmony between the maturity method and the degree of hydration concept is illustrated mathematically. It is shown that the maturity concept using an appropriate temperature function (Arrhenius function) is completely equivalent with the degree of hydration method based on a temperature independent strength—degree of hydration relationship. The improvement of the maturity concept, as proposed by Chengju [1] in general terms, is also evaluated, and seems to be completely comparable to the degree of hydration concept.

Furthermore, the applicability of both methods is outlined, not only for the strength and the elastic properties of the hardening concrete, but also for the thermal and the visco-elastic behaviour. The application of the degree of hydration concept for strength and stiffness development has the advantage that, thanks to a direct link with phenomenological models for structural development, an accurate answer is obtained for the time 'zero' issue. Time 'zero' in this approach coincides with the microstructural percolation threshold for the degree of hydration [2]. Especially the applicability of maturity method and degree of hydration concept for early age basic creep behaviour is discussed in more detail.

2. Harmony between maturity method and degree of hydration concept

2.1. Maturity method

In the early 1950s the idea was raised in Europe that strength development of concrete could be related to the so-called maturity. The maturity concept, proposed by Saul, states that samples of a given concrete will acquire

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the same strength when equal maturities are reached, irrespective of their temperature histories. According to Saul, the maturity M can simply be expressed as the product of time and temperature, taking into account a certain datum temperature θ_0 below which hardening is unlikely to occur [1]:

$$M = \int_0^t (\theta(t) - \theta_0)\,\mathrm{d}t \qquad (1)$$

where $\theta(t)$ is the temperature of the concrete at age t.

In 1954 Rastrup introduced the equivalent age t_{eq} as an alternative approach [1], defined as the time during which the concrete would have to be cured at a constant reference temperature θ_r to achieve the same maturity as the concrete undergoing the actual curing history. Hence:

$$t_{eq} = \int_0^t \frac{\theta(t) - \theta_0}{\theta_r - \theta_0}\,\mathrm{d}t = \int_0^t \gamma(\theta)\,\mathrm{d}t \qquad (2)$$

The temperature function $\gamma(\theta)$ is called the affinity ratio with reference to θ_r [1]. In the following the reference temperature θ_r is considered to be 20 °C.

It has soon been recognized that the hardening of concrete is not a linear function of the curing temperature. Many researchers proposed a new affinity ratio $\gamma(\theta)$ to replace the linear Saul function. The best known is the Arrhenius function:

$$\gamma(\theta) = \exp\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273 + \theta(t)}\right) \qquad (3)$$

with E the apparent activation energy of the cement hydration (expressed in kJ/mol) and R the universal gas constant (expressed in kJ/mol K).

If a realistic description of the affinity ratio is available, the maturity concept yields an equivalent age, which allows to predict the concrete strength by making use of an experimentally obtained relation between strength and equivalent time [3]. However, the quantitative effect of curing temperature on the ultimate strength is an important practical problem deserving further study. For this reason Carino [3] discusses the relative strength development, being the ratio of the actual strength to the ultimate strength. The influence of the early age curing temperature on the ultimate strength is not considered in the following.

2.2. Degree of hydration concept

It is well established that the rate of strength gain of plain concrete is correlated with the formation of the structure of the hardening cement matrix. During the hydration process the hydration products make mutual contacts and build up a three-dimensional percolating structure around the still hydrating anhydrous cores. On macroscale this process of structure formation is observed as the development of material properties like strength, hardness, stiffness and permeability [2,4,5]. The state-of-the-art of structure versus strength determination is much more advanced for simple silicate systems than it is for complex silicate systems like portland cement [6]. Once the structure has been determined it might be possible to determine how hydrating portland cement develops its strength.

At this moment, a practical approach for relating strength development to structure formation is the degree of hydration concept. The degree of hydration $\alpha(t)$ of a hardening cementitious material at time t is defined as the fraction of the cement that has already hydrated, and can be determined experimentally by X-ray diffraction analysis or by measuring the nonevaporable water content of a sample, and relating this to the nonevaporable water content of the fully hydrated sample [7]. A more practical method to estimate the degree of hydration is based on the exothermic character of the hydration process [8]:

$$\alpha(t) = \frac{Q(t)}{Q_{max}} \qquad (4)$$

with $Q(t)$ the total heat developed at time t (expressed in J/g) and Q_{max} the total heat development corresponding to (ideal) complete hydration (also expressed in J/g). The total heat development $Q(t)$ can be calculated by a time integration of the heat development rate $q(t)$ (expressed in J/g h).

From isothermal hydration tests [8,9] it is concluded that for portland cement the heat production q can be expressed as:

$$q(\alpha, \theta) = q_{max,20} \cdot f(\alpha) \cdot g(\theta) \qquad (5)$$

with $q_{max,20}$ the maximum value of the heat production at 20 °C isothermal hydration, $f(\alpha)$ a function describing the influence of degree of hydration on the heat development rate, and $g(\theta)$ a function describing the influence of temperature on the heat development rate (e.g. Arrhenius function).

At any moment t the degree of hydration of the hardening concrete can be calculated by an explicit stepwise time integration:

$$\alpha(t + \mathrm{d}t) = \alpha(t) + \mathrm{d}\alpha(t) = \alpha(t) + \frac{\mathrm{d}Q(t)}{Q_{max}} = \alpha(t) + \frac{q_{max,20}}{Q_{max}} \cdot f[\alpha(t)] \cdot g[\theta(t)] \cdot \mathrm{d}t \qquad (6)$$

In case of nonisothermal curing, the temperature $\theta(t + \mathrm{d}t)$ can be calculated by available numerical methods taking into account the boundary conditions of the concrete element [9].

Concrete gains strength in a gradual way, as a result of chemical reactions between cement and water, and for a specific concrete mixture, strength at any age and under normal curing conditions is related to the degree of hydration [2,4,10]. For each W/C-ratio one particular relationship between strength f_c and degree of hydration α exists. In literature [2,4] it is concluded that a linear relationship holds quite well:

$$f_c = k \cdot (\alpha - \alpha_p) \tag{7}$$

with k constant, and α_p the percolation threshold for the degree of hydration from which value on strength starts to develop. The percolation threshold α_p coincides with 'time zero', the time resembling the start of strength development of the hardening concrete. By means of such a relation, a prediction of the degree of hydration α automatically includes an estimation of the concrete strength.

2.3. Agreement between both strength evaluation methods

Chengju showed that two concrete specimens with equal maturity but with different temperature history might not have equal strength [1]. More recent research states that the degree of hydration concept is a more fundamental method [2,4]. However, for concrete made with portland cement it can be shown that the maturity concept yields the same strength predictions as the degree of hydration method. Consider the temperature-time histories shown in Fig. 1A and B, which both start at the same reference time t_0, the same equivalent age t_{eq}^0, and the same degree of hydration α_0. These parameters might be equal to zero, representing freshly cast concrete.

It is obvious that at the end of both temperature histories $(t = t_0 + t_1 + t_2)$ equal equivalent ages are reached $(t_{eq}^* = t_{eq}^0 + \gamma(\theta_1) \cdot t_1 + \gamma(\theta_2) \cdot t_2)$. Consequently, according to the maturity concept, equal concrete strength should obtained. Using the temperature independent relation (7) between strength and degree of hydration, it will be shown in the sequel that the degree of hydration method also yields equal concrete strengths in both situations, i.e. $\alpha_{A2} = \alpha_{B2}$. The proof starts from Eq. (6), from which it can easily be shown that:

$$\frac{d\alpha}{f(\alpha)} = \frac{q_{max,20}}{Q_{max}} \cdot g(\theta_1) \cdot dt \quad \text{for } t_0 < t < t_0 + t_1 \tag{8}$$

$$\frac{d\alpha}{f(\alpha)} = \frac{q_{max,20}}{Q_{max}} \cdot g(\theta_2) \cdot dt \quad \text{for } t_0 + t_1 < t < t_0 + t_1 + t_2 \tag{9}$$

Integration leads to:

$$\int_{\alpha_0}^{\alpha_{A1}} \frac{d\alpha}{f(\alpha)} + \int_{\alpha_{A1}}^{\alpha_{A2}} \frac{d\alpha}{f(\alpha)} = \frac{q_{max,20}}{Q_{max}} \cdot [g(\theta_1) \cdot t_1 + g(\theta_2) \cdot t_2] \tag{10}$$

In fact, $g(\theta)$ introduced in (5) is identical to $\gamma(\theta)$ in (3). Both $g(\theta)$ and $\gamma(\theta)$ represent the same Arrhenius function for the concrete considered. Consequently, equation (10) results in:

$$\int_{\alpha_0}^{\alpha_{A2}} \frac{d\alpha}{f(\alpha)} = \frac{q_{max,20}}{Q_{max}} \cdot (t_{eq}^* - t_{eq}^0) \tag{11}$$

Analogously, situation B results in:

$$\int_{\alpha_0}^{\alpha_{B2}} \frac{d\alpha}{f(\alpha)} = \frac{q_{max,20}}{Q_{max}} \cdot (t_{eq}^* - t_{eq}^0) \tag{12}$$

Comparing Eqs. (11) and (12), and remarking that $f(\alpha)$ is a positive function, it is concluded that $\alpha_{A2} = \alpha_{B2}$. Consequently, the degree of hydration concept also yields equal concrete strengths in both situations A and B.

More generally, it can be shown that when equal equivalent ages have been reached, also equal degrees of hydration are found, on the condition that the maturity

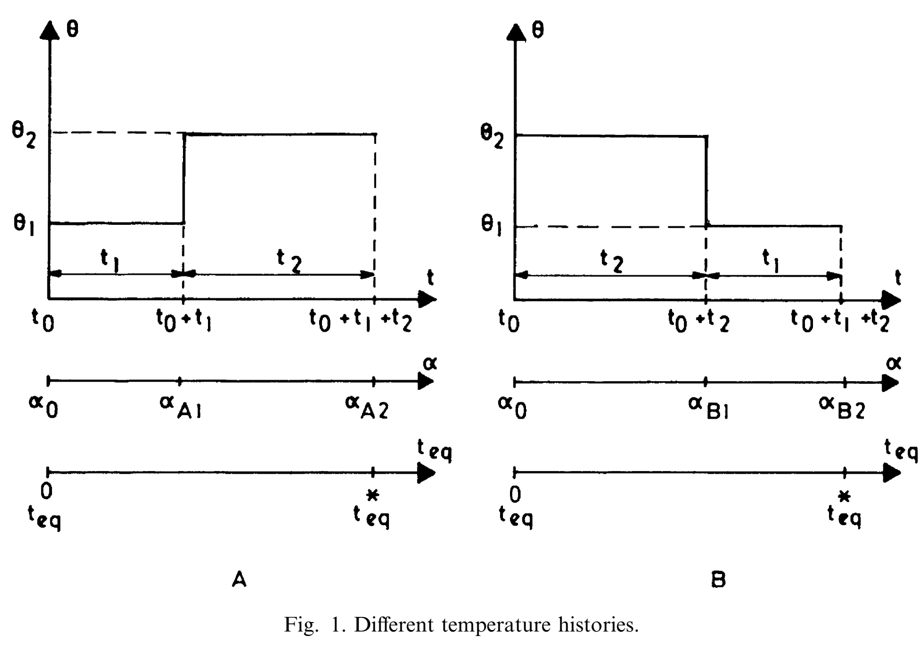

Fig. 1. Different temperature histories.

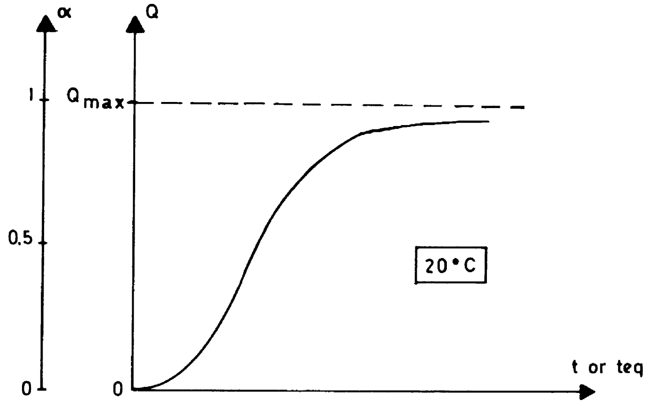

Fig. 2. Evolution of degree of hydration.

method is based on the appropriate temperature factor $\gamma(\theta)$ equal to $g(\theta)$. In fact, this can immediately be found from equation (6). Moreover, at 20 °C isothermal curing conditions, there is a unique relationship between time t, which in this case is equal to the equivalent age t_{eq}, and the degree of hydration, as can be seen from the hydration curve given in Fig. 2. From these findings, it can be concluded that even for the general nonisothermal case, a unique relation exists between equivalent age t_{eq} and degree of hydration α. Hence, the maturity concept is completely equivalent to the degree of hydration method, yielding the same strength prediction.

2.4. Possible improvement of the maturity method

In 1989 Chengju [1] stated that an ideal maturity function should be a function of time and temperature, which is directly proportional to the cumulative amount R_n of cement reacted up to any given instant:

$$R_n(t) = \sum_0^t k(\theta, t) \cdot \Delta t \tag{13}$$

$$M = A \cdot R_n(t) \tag{14}$$

with $k(\theta, t)$ the reaction rate of cement hydration at age t and temperature θ, and A a coefficient of proportionality.

If the amount of hydrated cement is measured by means of the heat development, then:

$$R_n(t) = \frac{Q(t)}{Q_{max}} \cdot C = \alpha(t) \cdot C \tag{15}$$

with C the cement amount originally present in the concrete. Combining equations (14) and (15), it can be concluded that the maturity M proposed by Chengju is directly proportional to the degree of hydration α as defined in [3]. Moreover, the reaction rate $k(\theta, t)$ proposed by Chengju is directly related to the product $f(\alpha) \cdot g(\theta)$ as indicated in equation (5).

Thus, it can be concluded that the modified maturity concept as proposed by Chengju, is completely similar to the degree of hydration concept. A more accurate strength prediction indeed is to be found in the degree of hydration concept, but with relations between strength and degree of hydration also depending on the temperature or temperature history. An indication for this improvement is found in [11,12]. In this way, more accurate strength predictions should be possible, taking into account the effect of the early age curing temperature.

3. Applicability of degree of hydration concept and maturity method for thermo-visco-elastic behaviour

3.1. Thermo-visco-elastic behaviour of early age concrete

In extension of the application of degree of hydration concept and maturity method for short-term properties like strength, the applicability for time-dependent thermo-visco-elastic behaviour during hardening will be outlined in this section. Although creep is mainly a long term effect caused by sustained loading, it is also a very important phenomenon for early age concrete. Due to relatively high creep deformations and considerable stress relaxation, early age thermal stresses and stresses induced by autogenous shrinkage can be greatly reduced. In many cases a reduction of thermal and autogenous shrinkage stresses by about 50% due to stress relaxation in hardening concrete has been reported [13–15].

In this paper, only the basic creep is considered. For many practical problems related to early age concrete, especially in massive structures, there is no significant moisture exchange with the environment. In this way, drying creep is of less importance.

Historically, some information on the relation between basic creep and hydration has already been presented by Ross in 1959 [16]. This paper already introduced some link between basic creep and maturity. In 1964 Ali and Kesler [17] introduced the degree of hydration in the early age basic creep study. This idea was followed in 1970 by Meyers and Slate [18], however still only considering the degree of hydration at the time of loading. In [19,20] it became clear that not only the degree of hydration at the time of loading is important, but also the evolution of the degree of hydration during the time under load. Khalil and Ward [21] in 1977 showed that the maturing creep or basic creep is clearly related to the progress of hydration while under load, and not only to the state of hydration at the age of loading.

Lokhorst and Van Breugel studied the influence of microstructural development on the creep behaviour of hardening concrete [22]. In this way the importance of further hydration while under load was emphasized once more. In [23] Van Breugel stated that traditional relaxation theories can only partly explain the stress reduction in the early stage of hydration. For this reason, he tried to relate the early relaxation behaviour to microstructural changes in the hardening paste, using the evolution of the degree of hydration. According to [24], both magnitude and kinetics of short-term creep are strongly influenced by the hydration reaction through the volume growth of the hydration product in the capillary space.

3.2. Degree of hydration-based modelling of early age thermo-visco-elastic behaviour

In [25] the evolution of the degree of hydration while under load is introduced as an important parameter for the modelling of early age basic creep behavior. Based on simple but fundamental physical observations, a simple Kelvin model with degree of hydration-based stiffness and viscosity is developed for the simulation of the visco-elastic behaviour of early age concrete, including instantaneous deformation and basic creep. The validity of the model was verified by means of creep tests under constant or varying stresses. With this degree of hydration-based Kelvin model the coupling between visco-elastic behaviour of early age concrete and the microstructural development was illustrated once more.

In a further approach, a basic creep model for hardening concrete was introduced with the evolution of the degree of hydration as the main parameter for the evolution of the basic creep strain [26,27]. The basic creep evolution is related to the evolution of the hydration process and the microstructural development by means of the degree of hydration. Time is no longer an explicit parameter. The resulting basic creep model can be written in the following way:

$$\varepsilon_{cc}(\alpha, \alpha_b, \eta_b) = \varepsilon_{c0}(\alpha_b, \eta_b) \cdot \varphi_c(\alpha, \alpha_b) \tag{16}$$

in which $\varepsilon_{c0}(\alpha_b, \eta_b)$ is the instantaneous deformation due to the stress level η_b at loading, α_b is the degree of hydration at loading, α is the degree of hydration, and

$$\varphi_c(\alpha, \alpha_b) = c_1(\alpha_b)\left(\frac{\alpha - \alpha_b}{1 - \alpha_b}\right)^{c_2(\alpha_b)} \tag{17}$$

For blast furnace slag cement CEM III/B 32.5 $c_1(\alpha_b) = 2.081 - 1.608\alpha_b$ and $c_2(\alpha_b) = 0.130 + 0.386\alpha_b$. For other cement types, the same basic creep formulation can be maintained, with slightly different expressions for the parameters c_1 and c_2.

As a consequence, all phenomena influencing the degree of hydration thus influence the basic creep behaviour. The temperature influence is implemented automatically through the temperature influence incorporated in the hydration model applied for the calculation of the degree of hydration.

The results obtained in [26,27] give further evidence to the main conclusions of the historical results given before. There is undoubtedly a very strong correlation between the basic creep at very early age and the ongoing hydration. The correlation is even so strong that the basic creep evolution can be simulated merely by means of the knowledge of ongoing hydration, without explicitly knowing the time evolution. The degree of hydration concept can be applied for the simulation of early age basic creep behaviour under varying temperature conditions.

3.3. Maturity-based modeling of basic creep

If the degree of hydration-based approach is a valid one for the basic creep evolution for early age concrete, than this would imply that the effect of temperature on early age basic creep could also be simulated by means of the maturity method. Both methods (the maturity method and the degree of hydration concept) indeed lead to same results if they are based on a realistic and similar temperature function, e.g. the Arrhenius function, as shown before.

Independently from De Schutter [26,27], Gutsch [28,29] also studied the visco-elastic behavior of early age concrete. However, he used the maturity method instead of the degree of hydration concept in order to deal with the effect of temperature.

Based on tensile creep and relaxation tests Gutsch showed that the maturity method is indeed applicable for the basic creep behavior of early age concrete. By introducing the equivalent time under load, creep and relaxation curves under nonisothermal elevated temperatures can be transformed into curves under 20 °C isothermal conditions, provided the degree of hydration at first loading is identical.

3.4. Discussion

Independently from each other, different research teams showed that the basic creep and relaxation behavior of early age concrete can be modeled by means of the maturity method or by means of the degree of hydration concept. Although the methods differ, the main conclusion is similar. The visco-elastic behaviour of early age concrete seems to be determined mainly by microstructural development. As for the strength or stiffness development, this can be modeled by the combined effect of temperature and time (maturity, equivalent time), or by the degree of hydration as a parameter for the description of the evolution of the hydration process.

The major questions however remain unanswered. The applicability of both modelling techniques does not reveal the origin of the basic creep in cement-based materials. Is the phenomenon of increasing deformations under constant load at very early age really a creep deformation in a traditional sense, or is it a load-induced alteration of the microstructural development? Are creep and hydration at very early ages two distinct phenomena of different kinetics? Is the correlation merely phenomenological, or are both creep and hydration at very early age more fundamentally coupled? For a significant improvement of the engineering models related to the visco-elastic response of early age concrete, these fundamental questions have to be answered.

4. Case studies

By means of the degree of hydration concept or the maturity method, including its applicability for the visco-elastic behaviour of early age concrete, a holistic modelling of early age thermal cracking in hardening massive concrete elements can be followed. This is briefly illustrated in some practical case studies, using the degree of hydration as an internal parameter.

As an example, the HARO armour unit for breakwaters (Fig. 3) is simulated by means of a degree of hydration based finite element method, with implementation of degree of hydration-based strength and stiffness properties, and using the degree of hydration concept to simulate thermo-visco-elastic behaviour during hardening. The height of the unit considered is 76 cm, the width is 96 cm, and the length is 126.5 cm. The concrete volume is about 625 liter. The size of the simulated unit is smaller than the ones used in the harbour of Zeebrugge, Belgium. The simulated HARO unit is of the same size as already used in the harbour of Pakistan, and as will probably be used in the harbour of Oostende, Belgium, in the near future. Due to symmetry only one fourth of the unit was simulated, as illustrated in Fig. 3. The finite element mesh consisted of 705 nodes and 252 elements.

Concrete was considered based on blast furnace slag cement CEM III/B 32.5. A cement content of 300 kg/m^3 was applied, with a water cement ratio of 0.5. The casting temperature of the concrete as well as the environmental temperature were set at 20 °C.

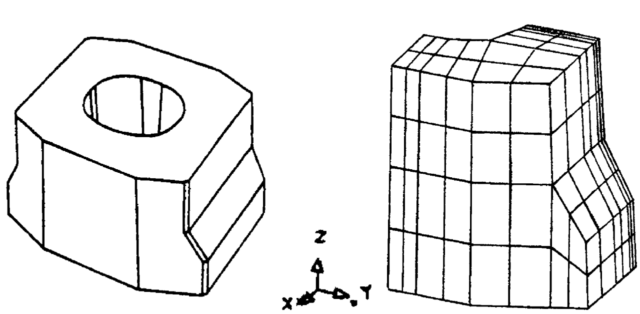

Fig. 3. HARO armour unit and finite element model (1/4th).

The parameters in the fundamental material laws were determined by means of an extensive experimental program carried out at the Magnel Laboratory for Concrete Research. These material laws, including visco-elastic behaviour, were implemented in the degree of hydration based finite element method. The highest temperature during hardening is 27.9 °C after a hardening time of 25 h. The highest temperature difference between core and surface is 6 °C. After 25 h the highest tensile stresses occur at the surface of the unit, however, without reaching the tensile strength. After cooling of the unit, the tensile stresses at the surface of the unit change towards compressive stresses. Tensile stresses now occur at the core of the unit, however also without initiation of cracking. The conclusion that no early age thermal cracking occurs in this case was confirmed experimentally at the Magnel Laboratory for Concrete Research. Several blocks were made, and none of them showed early age thermal cracking.

Cracking however is simulated and experimentally observed in grooved cubes with side length 2.36 m as applied in Zeebrugge. The early age thermal cracking observed in Zeebrugge was confirmed by means of the degree of hydration based three-dimensional simulation procedure.

The simulation procedure was also applied for the verification of early age thermal cracking in massive quay walls built at the harbour of Antwerp. Based on the simulation results it was concluded that only little thermal cracking would occur in the quay walls. This was confirmed during construction. Some minor cracking, with a maximum crack width up to 0.3 mm was reported.

5. Conclusions

For concrete made with portland cement, a verification of the maturity concept by means of the degree of hydration shows that the maturity concept using an appropriate temperature function is equivalent with the degree of hydration concept based on a temperature independent relation between degree of hydration and strength development.

The improvement of the maturity concept as proposed by Chengju in general terms leads to a method which in fact is completely comparable to the degree of hydration concept.

Both the degree of hydration concept and the maturity method can be applied not only for strength and stiffness predictions, but also for the thermo-visco-elastic behaviour of early age concrete. This confirms the fundamental coupling between basic creep and hydration at very early age. The origin of this coupling however remains to be further investigated.

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