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Application of maturity method to slipforming operations: Performance validation

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Abstract

During the last decades, the maturity method has been developed and used as one of the most favorable methods for estimating in-place concrete strength. Various maturity functions are considered in this study and their performance is compared based on the prediction of initial setting time using laboratory and field data of wide range of concrete mixtures to identify most suitable functions to be applied in slipforming operations. It is found that Freiesleben Hansen and Pederson (FHP) and Carino and Tank (CT) functions are better in predicting setting times compared to other functions. The apparent activation energy and temperature sensitivity factor associated with FHP and CT maturity functions are not influenced by varying the retarder dosage; or changing the method of setting time measurement. On the other hand, performance of maturity functions depends on the method of measuring setting time. In the current study two methods of setting time measurement are considered: the penetration resistance (PR) method as per ASTM C 403, and the 2 °C temperature (2C) increase method illustrated later. It is also confirmed that CT maturity functions can be used effectively with either the PR or the 2C methods in slipforming operations. However, CT function with PR (CT-PR) is found to be most suitable for predicting mock-up times for slipform when compared to those estimated from hard front generated by the rod method.

Keywords: Maturity function; Concrete; Slipforming; Mock-up times

1. Introduction

Slipforming is a construction method in which the forms move continuously during the placement of concrete. The continuity of the operation is needed in order to prevent concrete from adhering to the forms. Slipforming is usually used for casting concrete walls of great height. The forms are of 1–1.3 m height and consist of vertical panels, walings, yokes, horizontal cross bars, jacks, jack rods, and a working platform (Fig. 1) [1]. The rate of the movement depends on the concrete characteristics. The concrete that is exposed by the moving form should have the ability of supporting its own weight, keep its shape, and resist the vertical and lateral loads. Slipforming technique is cost effective for buildings of 12 stories or higher [2]. Since the slipforms are in continuous movement during the placement of the concrete, slipforming reduces the number of construction joints. Also, the speed at which the wall can be erected can be greatly increased. A slipform wall in a typical 12–20 story building can reduce the construction time by three months compared to the conventional formworks, and as the building becomes higher the cost savings become more [2].

The concrete should be designed according to the required slipforming rate so as to remain in the forms until its initial setting is reached. The safe control of the setting time of the concrete is a prerequisite for the safe control of the slipforming operation. Slipforming technique proved to be very useful if it is implemented with an appropriate planning schedule. Detailed starting plan for filling the forms should be prepared in advance, and this plan should

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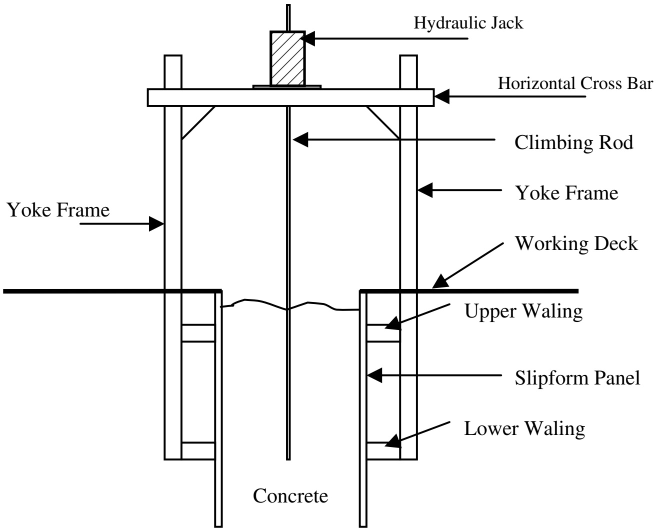

Fig. 1. Schematic diagram of a typical slipform System.

include schematic sketch of the slipform showing the thickness of each layer, the speed at which the concrete will be placed during the filling, the setting time for each layer, and the time at which lifting should commence. The beginning of the lifting process should be based on the initial setting of the first layer of the fresh concrete so that concrete that is left behind have all the above-mentioned properties but not yet hardened in order to prevent adhering to the forms.

The early-age behavior of concrete plays an important role in timing of slipforming operations as well as other construction operations. The concrete setting process represents the transition phase between a fluid and a rigid state and is an observable physical consequence of chemical activity in the concrete mixture. This gradual stiffening process is caused by continuous cement hydration. Temperature strongly affects the rate of hydration of Portland cement. High temperatures fasten the rate of cement hydration accelerating setting. The maturity approach allows for the prediction of such temperature effects on the rate of cement hydration by establishing the temperature sensitivity of the reaction quantified by the activation energy (E) and temperature sensitivity factor (B) [3–5]. Temperature effect on the gain of compressive strength and on the setting process is modeled by the maturity approach which is used to estimate strength and setting times of concrete mixtures [6–8]. The ability to model the effect of temperature by the maturity approach has great implications in performing slipforming operations, especially in variable temperature conditions, which is the case in the field for most real life construction projects. Therefore, it is believed that this approach would be of practical value to concrete practitioners, since it helps contractors and engineers in the better planning of construction operations involving slipforming techniques.

During the last decades, the maturity method has been developed and used as one of the most favorable methods for estimating in-place concrete strength. Several maturity functions have been proposed by researchers [5,9–11]. The ASTM standard provides procedures for developing the strength–maturity relationship and for estimating the in-place strength. However, still there are concerns regarding the performance and suitability of various maturity functions in practical applications [12–16]. Research should be conducted to assess the suitability of maturity functions in slipforming and to validate their performance with field applications.

This paper compares the performance of various maturity functions based on the prediction of initial setting time of concrete mixtures using laboratory and field data. The effect of retarder dosages and methods of prediction of initial setting time on apparent activation energy and temperature sensitivity factor used in maturity functions is presented. This paper also identifies appropriate maturity functions that can be used effectively in the prediction of initial setting times over the whole spectrum of concrete time–temperature development, and hence can be applied in the prediction of reliable mock-up times in slipforming. By the term mock-up, it is meant to characterize the time at which the slipform is ready to be moved.

2. Overview of maturity functions

In the early 1950s the idea was raised in Europe that strength development of concrete could be related to the so-called maturity [9]. The maturity concept is based on the temperature history of a concrete mixture during its curing period to estimate a factor known as maturity (M) that would be indicative of the strength development. The maturity concept, proposed by Saul, states that samples of a given concrete will acquire the same strength when equal maturities are reached, irrespective of their temperature histories. According to Saul's maturity equation sometimes referred to as Nurse–Saul (NS) function, the maturity M can simply be expressed as the product of time and temperature, taking into account a certain datum temperature T_0 below which hardening is unlikely to occur [9]:

$$M(t) = \sum (T - T_0)\Delta t \tag{1}$$

where M is the maturity at age t (°C h), T is the average temperature of concrete during time interval Δt (°C), and T_0 is the datum temperature (°C).

The datum temperature is the lowest temperature at which the strength gain is observed, and Saul proposed a datum temperature of -10.5 °C. According to ASTM C1074-98 [17], it is recommended that the datum temperature be determined experimentally or may be taken as 0 °C if ASTM Type I cement is used without admixtures and the expected curing temperature is within 0 and 40 °C. However, the T_0 value used for decades and still used by most maturity instruments is -10 °C, which is approximately the temperature at which the hydration of cement ceases.

Bergstrom [18] demonstrated that the maturity method was valid for concretes cured at normal curing temperatures. McIntosh [19] concluded that the maturity function of Eq. (1) could not accurately estimate the effect of temperature on the strength development of concrete. Alexander and Taplin [12] reported the same conclusion as McIntosh. It was soon recognized that the hardening of concrete is not a linear function of the curing temperature. To correct the shortcoming of Saul's maturity function which assumes that temperature has a linear effect on strength development, extensive research was conducted and various maturity functions were proposed [3–5,10,11,20,21].

In 1954, Rastrup introduced the equivalent age (t_{eq}) as an alternative approach [10], defined as the time during which the concrete would have to be cured at a constant reference temperature (T_r) to achieve the same maturity as the concrete undergoing the actual curing history. Rastrup (R) equation is based on a chemistry axiom "the reaction rate is doubled if the temperature is increased by 10 °C"

$$t_R = \sum 2^{\frac{T-T_r}{10}} \Delta t \qquad (2)$$

where t_R is the equivalent age at the reference temperature (h); T_r is the reference temperature (°C), Δt is a time interval (h). The reference temperature T_r is considered to be 20 °C.

Nurse–Saul (NS) maturity function (Eq. (1)) can also be used to develop an equivalent age factor t_{eq}. The equivalent age t_{eq} at the reference temperature suggested by Nurse–Saul noted as t_{NS} can be derived as

$$t_{NS} = \sum \left[\frac{T - T_0}{T_r - T_0}\right] \Delta t \qquad (3)$$

In 1971, Weaver and Sadgrove (WS) [11], suggested the following formula for equivalent age (t_{WS}) at the reference temperature of 20 °C:

$$t_{WS} = \sum \frac{(T+16)^2}{1296} \Delta t \qquad (4)$$

Freiesleben Hansen and Pederson (FHP) [3] based on an earlier suggestion by Verbeck and Helmuth [4], proposed the following equation for equivalent age designated as t_{FHP} (h), based on the Arrhenius equation:

$$t_{FHP} = \sum e^{-Q\left[\frac{1}{273+T} - \frac{1}{273+T_r}\right]} \Delta t \qquad (5)$$

where $Q = E/R$, E is the activation energy (kJ/mol) and R is the universal gas constant, 8.3144 J/K mol.

Activation energy first proposed by Svante Arrhenius in 1888 is described as the minimum energy that is needed for a reaction to occur. Arrhenius stated that the rate of reactions increases with the increase of the temperature and Arrhenius equation is derived as

$$k = Ae^{-\frac{Q}{273+T}} \qquad (6)$$

where k is the rate constant (1/h), and A is the frequency factor.

Arrhenius established the activation energy concept for homogeneous systems undergoing a single reaction. Concrete is a non-homogeneous chemical system and so the activation energy is not the actual one, so the term "apparent activation energy" is preferred when referring to the FHP function (Eq. (5)).

According to many researchers [7,22], the apparent activation energy (E) is unique for every cementitious mixture. According to ASTM C1074-98 [17], for concrete made with type I cement without admixtures, an E value of 41.5 kJ/mol is recommended. For other conditions or when maximum accuracy is desired, the activation energy should be determined experimentally. Chanvillard and D'Aloia [23] reported that the apparent activation energy could not be considered as a constant independent of time except during the beginning of hydration, and the extent of hydration with a constant apparent activation energy was lower than 40%. Kada-Benameur et al. [24] stated that the apparent activation energy remained more or less constant at a degree of hydration a ranging between 5% and 50%, but it varied considerably outside this range.

Carino and Tank [5] suggested the following formula for equivalent age (t_{CT}):

$$t_{CT} = \sum e^{\frac{B}{T-T_r}} \Delta t \qquad (7)$$

where B is the temperature sensitivity factor, 1/°C.

It is suggested that the temperature sensitivity factor (B) has more physical significance than the apparent activation energy [12]. It is also suggested that for each temperature increment of $1/B$ the rate constant "k" for strength development increases by a factor of approximately 2.7. The temperature sensitivity factor is similar to the apparent activation energy and is simpler. So, it would be efficient to use Carino and tank (CT) maturity function that incorporates "B" instead of FHP function.

3. Performance analysis of maturity functions

3.1. Laboratory and field investigations

Both laboratory and field data of the Hibernia project have been used. Hibernia is the Canada's first major offshore oil project off the coast of Newfoundland [2]. The construction operations for the Hibernia project took place earlier in the 1990s. Data include the time–temperature history of concrete mixture in a tie-wall of the gravity base structure in the Hibernia project. The details of the concrete mixture used in the tie-wall designated as MNDC69 are presented in Table 1.

Laboratory investigations were carried out with the MNDC69 concrete mixture by varying the retarder dosage from 0 to 400-ml/100 kg of cement to simulate concrete mixtures with wide range of initial setting time (t_i). Concrete mixtures with various retarder dosages were cured

Table 1
Mix design of MNDC69 concrete mixtures

MNDC69 concrete mixture
Cement (C) = 450 kg/m^3; water = 152 kg/m^3; coarse aggregate = 910 kg/m^3; fine aggregate = 830 kg/m^3; superplasticizer (SP) = 1400 ml/100 kg of C; air entraining agent (AEA) = 15 ml/100 kg of C; retarder: 0–400 ml/100 kg of C; initial concrete temperature: 10, 15 and 20 °C

at initial concrete temperatures of 10, 15 and 20 °C termed as 10, 15 and 20 °C concrete, respectively. Initial setting times (t_i) of concrete mixtures were calculated by penetration resistance (PR) as per ASTM C403 [25] and 2 °C temperature increase (2C) method, also known as "box method".

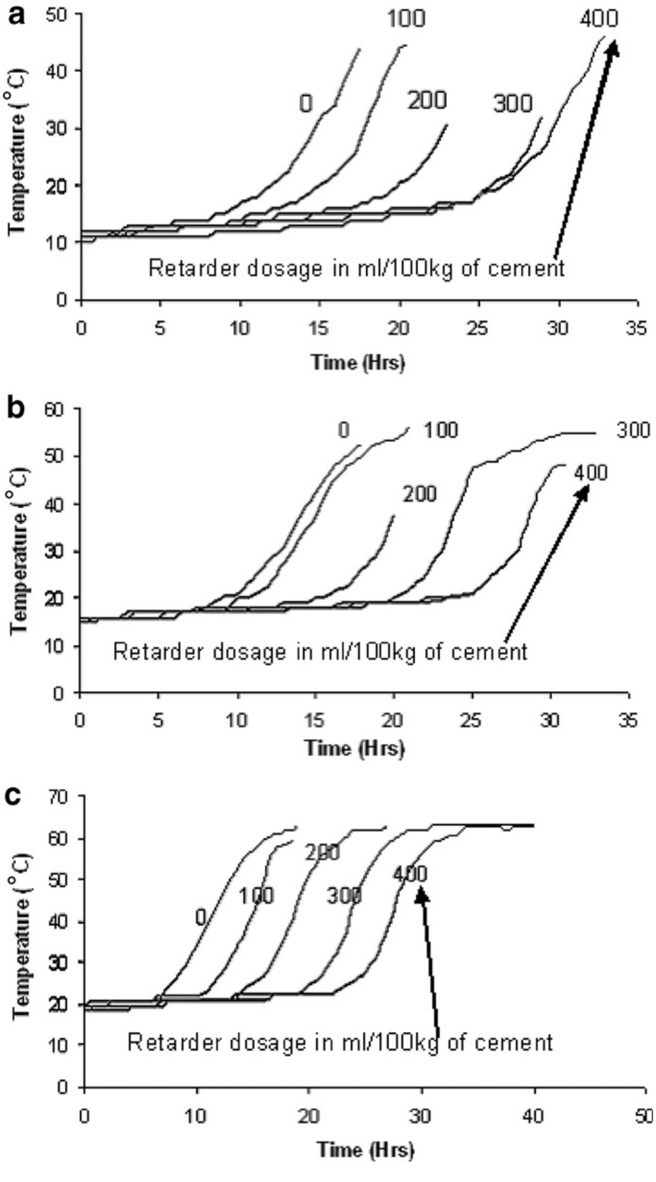

Fig. 2. Temperature development in laboratory for the (a) 10 °C concrete, (b) 15 °C concrete, (c) 20 °C concrete.

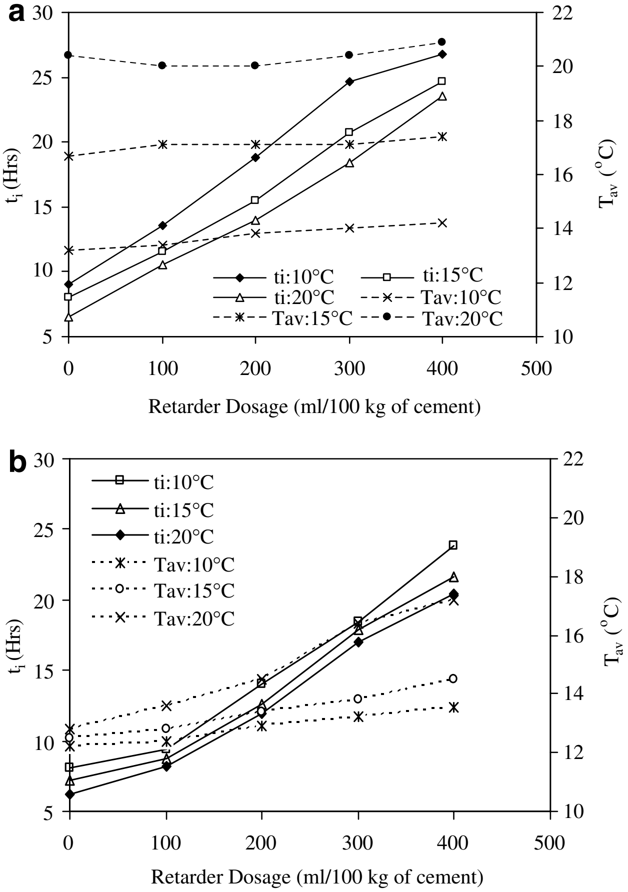

Fig. 3. Initial setting time (t_i) and average concrete temperature (T_{av}) by (a) PR method and (b) 2C method.

The box method is not a standardized one, but it has been used extensively by Norwegian contractors [2]. A concrete sample of 30–40 l produced at a predetermined temperature is placed in the box (570 mm × 570 mm) and a thermocouple is installed in the centre of the fresh concrete. The time–temperature history is monitored and when an increase in temperature of 2 °C occurs within 1 h, that time corresponds to the initial set of the concrete.

The average concrete temperature (T_{av}) up to the initial setting is calculated from the temperature development history as shown in Fig. 2a–c. Fig. 3a and b shows t_i and T_{av} of concrete mixtures as function of retarder dosages obtained from PR and 2C methods.

The tie-wall had embedded maturity meters located at three different positions (designated as Channel 1, Channel 2, and Channel 3) within the 950-mm wall width and at an elevation of 10.5-m (Fig. 4). Channel 3 is at the centre of the wall while Channel 1 and channel 2 are at 25 and 300-mm from the side surface of the wall, respectively. Fig. 4 shows the field temperature development within the MNDC69 concrete with 300 ml/100 kg of cement used in the tie-wall. As expected, the temperature in channel 1 (close to the surface of the wall) is lower compared to channel 2 and channel 3.

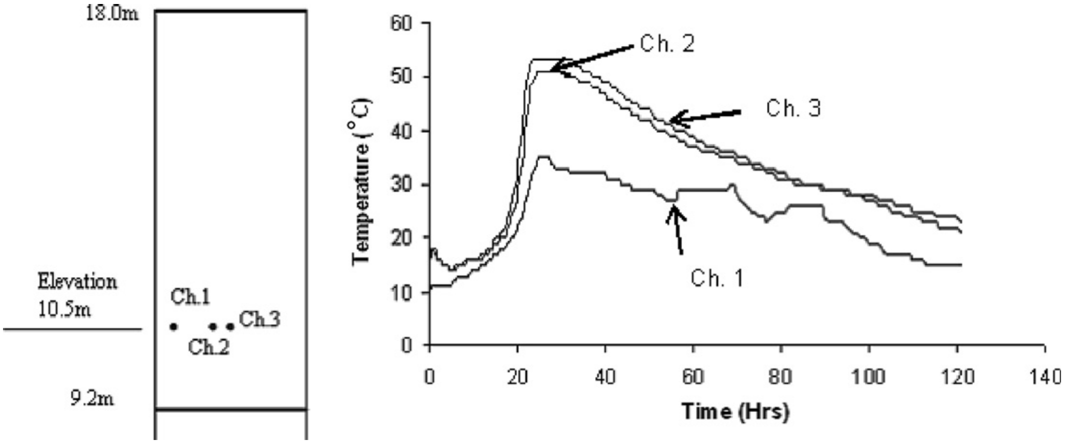

Fig. 4. Channel locations and field temperature development of concrete in the tie-wall.

3.2. Influence of setting time prediction method and retarder dosage on apparent activation energy (E) and temperature sensitivity factor (B)

The apparent activation energy is unique for a particular concrete and it should be calculated before using the FHP function model (Eq. (5)) to calculate the equivalent ages [6]. It is suggested by ASTM C1074 that the apparent activation energy should be calculated based on laboratory tests as each concrete mixture has its own specific characteristics in the process of hardening and temperature development. Hydration reactions occurring in the first few hours after batching are somewhat different from those taking place at later ages. As a result, E should also differ at various stages of development [26,27]. The E of a concrete mixture is different before and after the setting age because of changes in dissimilar hydration process with age and can vary from 10 to 47 kJ/mol at various stages of development [6]. Furthermore, at any given stage of development, E depends on the specific cement, admixture combination and composition of the concrete mixture. It is important to study the effect of varying retarder dosages on E over the whole spectrum of concrete ages.

Apparent activation energy can be calculated from an Arrhenius plot using Eq. (6) which relates the rate constant (k) to temperature for several experimentally observed cases. The slope of the best fit line of the plot of natural logarithm of the inverse of the initial setting times (t_i) represented as rate constant ($k = 1/t_i$) against the inverse of the average concrete temperatures (T_{av}) represents the fraction Q of E. Typical Arrhenius plots of MNDC 69 concrete mixtures at various retarder dosages using t_i from PR method are shown in Fig. 5a.

The temperature sensitivity factor (B) for maturity function (Eq. (7)) suggested by Carino and Tank (CT) can be calculated in a similar manner as illustrated in Arrhenius plot for the calculation of the apparent activation energy. The slope of the best fit straight line of the plot of average concrete temperatures versus the natural logarithm of the inverse of the initial setting times represents B. Typical plots using t_i from PR method are shown in Fig. 5b.

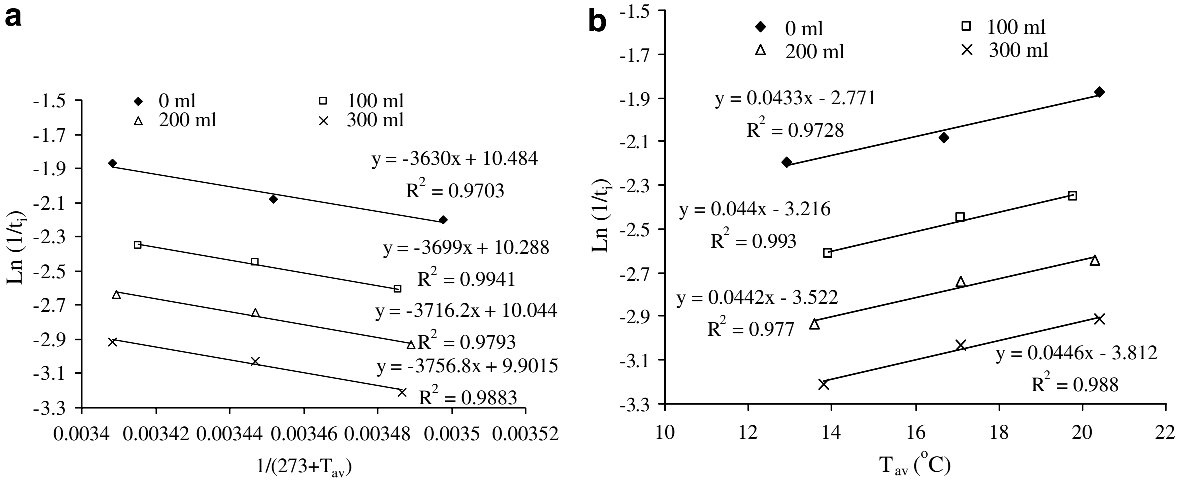

Fig. 5. Typical Arrhenius plot and prediction of B. (a) Arrhenius plot for E (PR method), (b) prediction of B (PR method).

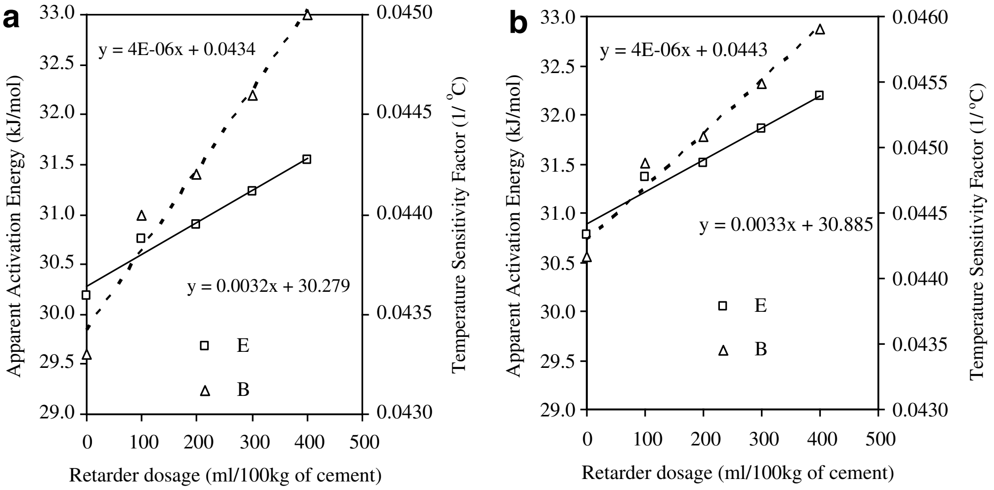

Fig. 6. Influence of retarder dosage and method of prediction of t_i on E and B. (a) Based on PR method, (b) based on 2C method.

Fig. 6 shows that an increase in the retarder dosage from 0 to 400 ml/100 kg of cement increases E linearly from 30.2 to 31.6 kJ/mol (for PR method) and from 30.6 to 32.2 kJ/mol (for 2C method). Fig. 6 also shows a linear relationship between the B and the retarder dosage, as is the case with E. An increase in the retarder dosage from 0 to 400 ml/100 kg of cement increases the value of B from 0.043 to 0.046 (for both PR and 2C methods). It can be concluded that both PR and 2C methods provide similar values of E and B and the method of prediction of t_i has no influence.

Also, only about 6% increase in E and B with an increase in retarder dosages from 0 to 400 ml/100 kg of cement suggests that unique values of E and B could characterize the concrete mixture independently of its retarder dosage. This is in agreement with the previous research where the effect of the superplasticizer dosage on E was studied [28].

3.3. Prediction of initial setting time by maturity functions

R, NS, WS, FHP and CT functions (Eqs. (2)–(5) and (7), respectively) are used. The procedure for calculating initial setting by maturity functions involves four steps:

- *Step 1*: determination of initial setting time for three different temperatures as performed for 10, 15 and 20 °C MNDC69 concrete mixtures as shown in Fig. 3.
- *Step 2*: determination of E and B for FHP and CT maturity functions as presented for MNDC69 concrete mixtures. Fig. 6 shows the values of E and B for MNDC concrete mixtures.
- *Step 3*: conversion of actual initial setting times to equivalent initial setting times by using maturity functions (Eqs. (2)–(5) and (7)) based on average concrete temperature up to initial setting for 10, 15 and 20 °C MNDC69 concrete mixtures, and calculation of mean equivalent initial setting time. Fig. 7 shows calculated values of mean equivalent initial setting time for different maturity functions. All the functions provide almost the same values with R and WS functions showing slightly lower values than the others.
- *Step 4*: determination of actual initial setting time–maturity functions (using predicted values of E and B in case of FHP and CT functions as per Fig. 6) are used to calculate equivalent age at the reference temperature (t_{eq}) at different time interval of the field time–temperature history of concrete mixture (Fig. 2). Actual initial setting time is the time on the field time–temperature history where equivalent age at reference temperature t_{eq} corresponds to the mean equivalent initial setting time (calculated in step 3 and shown in Fig. 7).

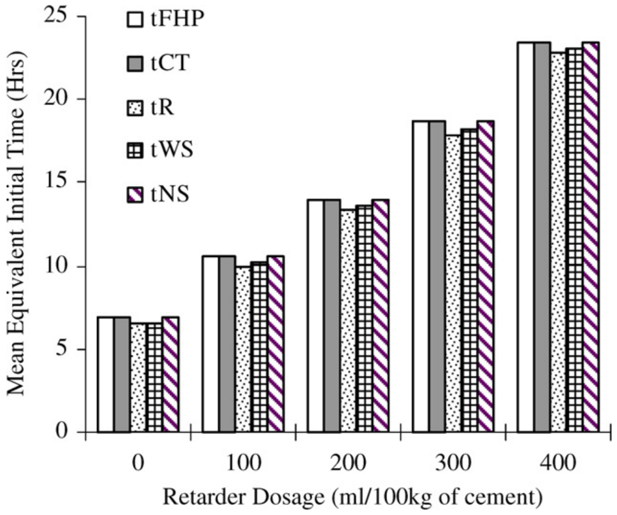

Fig. 7. Mean equivalent initial setting times for various maturity functions.

Fig. 8 compares initial setting times predicted by various maturity functions with those from experiments (2C method) by showing the effect of retarder dosage and initial

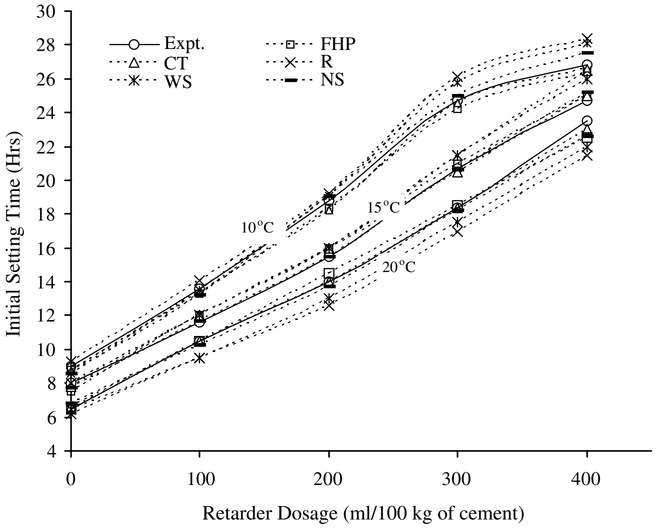

Fig. 8. Comparison of experimental and analytical actual initial setting times.

concrete temperature. The initial setting time increases with the increase of retarder dosage from 0 to 400 ml/100 kg of cement and decreases with the increase of initial concrete temperature from 10 to 20 °C, as expected. FHP, CT and NS functions seem to predict initial setting time better than R and WS functions especially at higher retarder dosages. The R and WS functions underpredict the initial setting time for 20 °C concrete mixture and overpredict initial setting time for 10 and 15 °C concrete mixtures at higher retarder dosages.

To study the performance of maturity functions in the field, MNDC69 concrete mixture used at channel 3 location (with 300 ml/100 kg of cement) is considered. The initial temperature of the concrete in the wall was 15 °C. By using mean equivalent initial setting as presented in Fig. 7 and applying maturity functions on the field time–temperature history of concrete at channel 3 (Fig. 4), initial setting times are calculated (following steps 1–4). All maturity functions predict a value of 20.5 h for initial setting time which is very close to 20.7 h as expected (Table 2). This is in good agreement with the findings shown in Fig. 8 that all maturity functions can provide satisfactory initial setting times for 15 °C concrete with comparatively lower retarder dosages.

For concrete mixtures used in this study, FHP and CT functions seem to be good in predicting initial setting time over the whole spectrum of retarder dosages and initial temperatures. As a result, it is decided to use only FHP and CT maturity functions to study the influence of setting time measurement procedures.

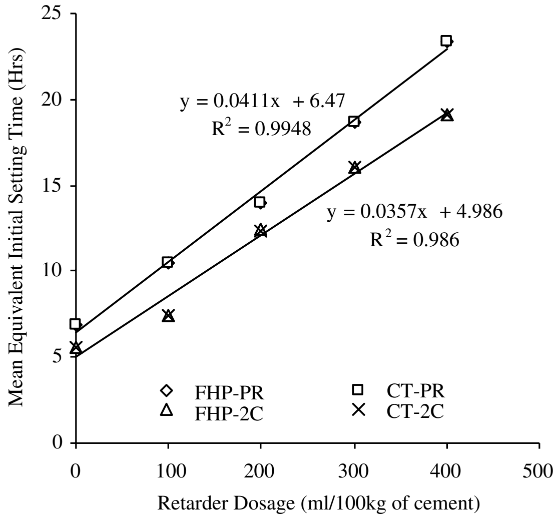

Fig. 9. Influence of setting time procedures on mean equivalent setting time prediction.

3.4. Influence of setting time measurement procedures on maturity function

Fig. 9 compares mean equivalent initial setting time calculated by applying FHP and CT maturity functions on t_i and T_{av} data (presented in Fig. 3) obtained from both PR and 2C methods for 10, 15 and 20 °C concrete mixtures. Mean equivalent initial setting time increases linearly with an increase in retarder dosage. Fig. 9 also shows correlation equations. The use of FHP and CT functions with a particular setting time procedure (either PR or 2C) designated as (FHP-PR, FHP-2C, CT-PR and CT-2C) produces similar mean equivalent initial setting time and predicts similar actual initial setting time. Hence, any of these functions can be used for the prediction of actual setting time and it is decided to use CT function for the rest of the study. However, the mean equivalent initial setting time is affected by setting time procedures with PR method producing higher values compared to 2C and hence, actual predicted setting times will also differ.

Fig. 10 compares predicted values of initial setting times from CT function with PR (designated as CT-PR) and 2C (designated as CT-2C) methods and those obtained from PR and 2C methods. It is found that the maturity function produces very similar initial setting times with the method it is based upon. Setting times predicted by CT-PR are very similar to PR while those predicted by CT-2C are very similar to 2C. However, variations in initial setting times are observed between CT-2C and 2C especially at 20 °C.

Table 2
Prediction of initial setting time in field conditions

Retarder dosage ml/100 kg of C	Expected initial setting time (h)	Initial temperature (°C)	Channel	Predicted initial setting time (h)				
				FHP	CT	R	WS	NS
300	20.7	15	3	20.5	20.5	20.5	20.5	20.5

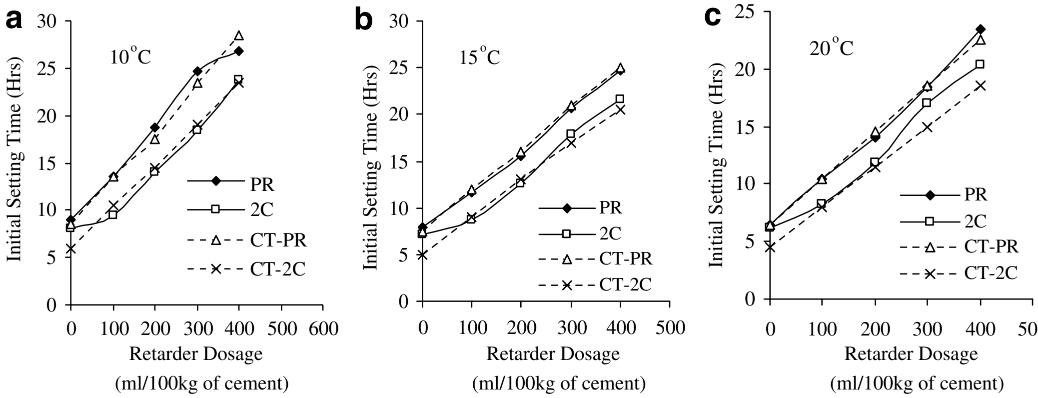

Fig. 10. Prediction of initial setting time by CT maturity function.

CT-2C also produces lower initial setting times compared to CT-PR. It can be stated that PR based predictions are more efficient than 2C based prediction. This can be attributed to the fact that PR method is more efficient than 2C method. 2C method depends on the time–temperature history of concrete mixture and rise of concrete temperature by 2 °C. Sometimes rise in temperature due to placing of concrete in an enclosed box as used in 2C method might exceed the value of 2 °C and can be easily misunderstood as the temperature rise due to hydration process. So, temperature rise in 2 °C method should be carefully interpreted.

Overall, maturity methods are able to predict initial setting time at different retarder dosages and at different concrete temperatures and their accuracies depend on adopted setting time measurement procedure.

4. Application of maturity method to slipforming operations

Field data from a wall construction are used to study the performance of maturity method in slipforming operations. The performance of maturity based methods (CT-PR and CT-2C) is compared to PR, 2C and Rod (R) methods based on the prediction of mock-up time of the slip-form. The performance of maturity methods is then validated by comparing slip-form mock-up times obtained in the field by rod (R) method.

The R method is used to determine the level of concrete that has reached its initial setting [29,30]. That level is called the "hard front" and it is measured from the top of the forms to the level which has reached its initial setting. A smooth steel rod of 10-mm in diameter without a point end is used, and it is pushed from the top to the bottom inside the concrete until it reaches the hardened concrete. The rod should be pushed manually as hard as possible until it stops to the hardened level.

The slipform system and arrangement of concrete layers used in the field wall is presented in Fig. 11. The concrete mixture used for this wall is similar to that presented in Table 1 but having varying retarder dosages in different layers as shown in Fig. 11. Thermocouples were embedded at four different locations (T_1, T_2, T_3 and T_4) within the slipform to monitor temperature development of concrete in different layers. Initial concrete temperature and concrete placement time at different elevations are presented in Table 3. Hard front elevations and times as determined by R method are also presented in Table 3.

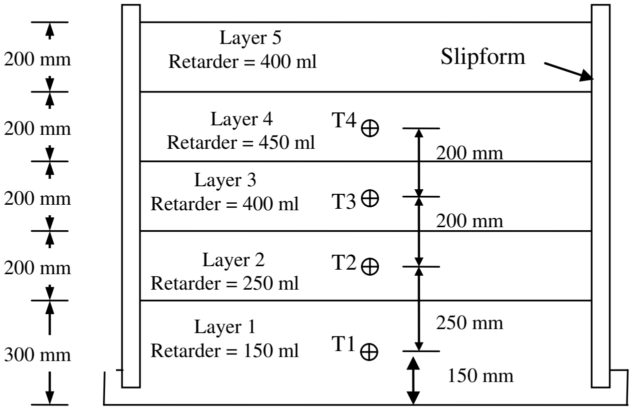

Fig. 11. Layer arrangement of slipform in the wall.

The prediction of mock-up times includes the determination of actual initial setting times of concrete layers. The procedure for prediction of initial setting time by maturity methods (CT-PR and CT-2C) involves:

- The determination of mean equivalent initial setting times by using Fig. 9 (or correlation equations shown in Fig. 9) for concrete layers 1–4 with retarder dosages of 150, 250, 400, and 450 ml/100 kg cement, respectively (Fig. 11).
- The estimation of actual setting times by applying mean equivalent initial setting times to the time–temperature history (Fig. 12) of concrete mixture in different layers. Predicted initial setting times of concrete mixtures used in different layers by CT-PR and CT-2C are presented in Table 3 as well as those predicted by PR and 2C.

So, by knowing the initial setting time, and the time at which the concrete is placed, it is possible to estimate the time of mock-up.

Table 3
Data on temperature, placement time, setting time and hard front elevations

Elevation (mm)	Initial concrete temperature (°C)	Retarder dosage ml/100 kg of cement	Placement time Day h:min	Initial setting time (h)				Rod method	
				CT-PR	CT-2C	PR	2C	Hard front elevation mm	Time Day h:min
300	13.0	150	Day 1 11:48	14.5	10.7	14.4	10.5	300 (14.7)[a]	Day 2 1:32
500	16.0	250	Day 1 15:45	18.0	15.9	17.7	15.5	500 (17.2)[a]	Day 2 8:55
700	16.0	400	Day 1 20:53	24.5	22	24.5	21.7	700 (23.7)[a]	Day 2 20:35
900	14.0	450	Day 2 01:17	26.5	22.5	25.8	22.3	900 (25.0)[a]	Day 3 2:15

[a] Initial setting time by Rod method at hard front (h).

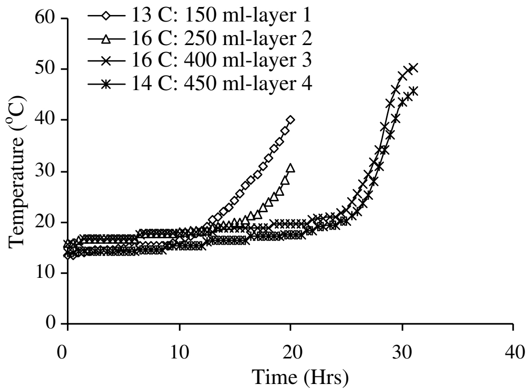

Fig. 12. Temperature development of concrete layers.

From Fig. 13, it can be observed that mock-up times by maturity functions CT-PR and CT-2C correlate very well with PR and 2C, respectively as has been found earlier. It is interesting to note that mock-up times (Fig. 13) as well as initial setting times (Table 3) calculated by CT-PR and PR are in close agreement with those obtained from R method which suggests that CT-PR prediction is better than CT-2C. It can be concluded that the maturity functions are able to predict the initial setting times as well as times of mock-up for slipform operations.

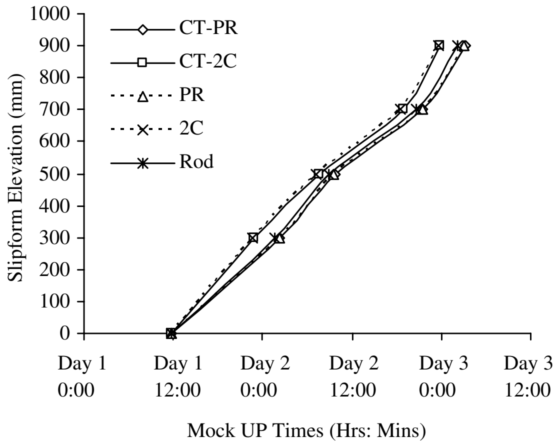

Fig. 13. Comparison of slip-form mock-up times.

5. Conclusions

This paper discusses various maturity models including those of Nurse–Saul (NS), Rastrup (R), Weaver and Sadgrove (WS), Freiesleben Hansen and Pederson (FHP) and Carino and Tank (CT). Performance study of these models in predicting initial setting time as well as their application in slipforming in both laboratory and field conditions led to the following conclusions:

- An increase in the retarder dosage from 0 to 400 mL/100 kg of cement linearly increases the value of apparent activation energy (*E*) and temperature sensitivity factor (*B*) associated with FHP and CT functions, respectively. However, only 6% increase in the value of both *E* and *B* indicates that retarder dosages do not constitute a significant effect. It is also found that the use of different methods of measuring setting times such as penetration resistance (PR) as per ASTM C 403 or 2 °C temperature rise increase (2C) also has negligible influence on both *E* and *B*.
- FHP and CT functions perform better than other functions in predicting initial setting time over the whole spectrum of retarder dosages and initial temperatures both in field and laboratory conditions.
- FHP and CT functions are able to predict initial setting times at different retarder dosages and at different concrete temperatures and their accuracies depend on adopted setting procedure either PR or 2C. Hence, any of these functions can be used for the prediction of actual setting time and CT function is proposed for its simplicity. However, CT function with PR based predictions (CT-PR) is more efficient than CT function with 2C based prediction (CT-2C).
- Maturity functions are able to predict times of mock-up for slipforming operations. Mock-up times calculated by CT-PR are in close agreement with those obtained from hard front elevations in the field by the rod (R) method which suggests that CT-PR prediction is better than CT-2C.

This research suggests that maturity method can be used as an effective tool for predicting setting time of concrete mixtures and hence, mock-up times in slipforming operations.

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