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Development of a computer aided program for slipforming operations incorporating maturity approach

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Abstract. Slipforming is a construction method in which the forms move continuously during the placement of concrete. This paper presents the development of a computer aided program designated as "CADSLIPFORM" for slipforming operations. The program incorporates maturity methods for the prediction of initial setting times of slipform concrete layers using laboratory data (time-temperature histories and setting times of concrete mixtures at different temperatures) and generates slipform mock-up times. The performance of CADSLIPFORM is validated by comparing simulated mock-up times with those estimated in the field through conventional hard front by rod (R) method. Moreover, the program versatility is demonstrated by illustrating mock-up simulations for different cases with variable slipform parameters such as: number and thickness of concrete layers, concrete temperature (simulating variable setting times) and slipform speed. The program also incorporates the choice of Freiesleben Hansen & Pederson (FHP) and Carino & Tank (CT) maturity functions. CADSLIPFORM can assist user to develop reliable schedule of slipforming operation suitable for a specific project by optimizing various slipform parameters.

Keywords: maturity function; concrete; slipforming; mock-up times; computer aided program.

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 minimize or even eliminate the formation of construction joints. Slipforming is usually used for casting concrete walls of great height. The forms are of 1 to 1.3 m height and consist of vertical panels, walings, yokes, horizontal

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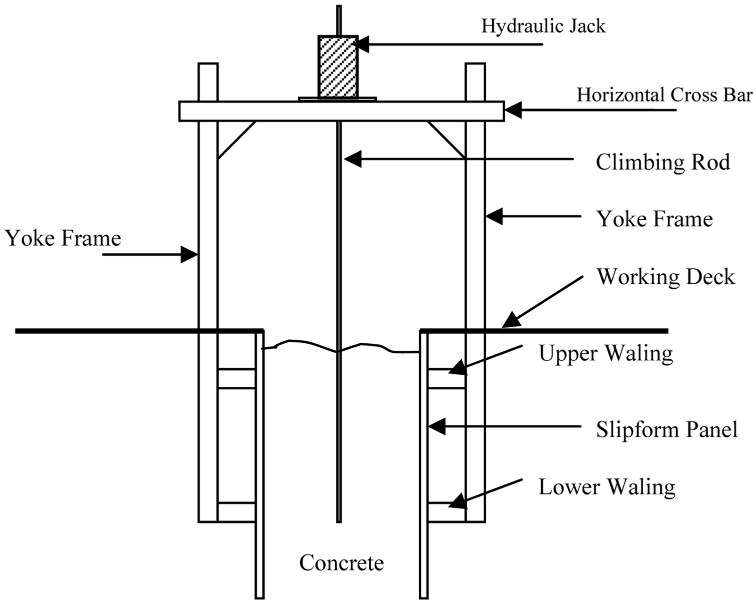


Fig. 1 Schematic diagram of a typical slipform System (Fossa 2001)

cross bars, jacks, jack rods, and a working platform (Fig. 1) (Fossa 2001). The rate of the movement depends on the concrete characteristics. The concrete that will be left out should have the ability of supporting its own weight, keep its shape, and resist the vertical and lateral loads. In parallel, the movement of the forms has to occur before the hardening of the concrete to prevent the material from adhering to the forms. Slipforming technique is cost effective for 12 stories building or higher (Elimov 2003). Also, the speed at which the wall can be erected can be incredibly increased. A slipform wall in a typical 12 to 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 (Elimov 2003).

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 is proved to be very useful if implemented with an appropriate planning schedule. Detailed starting plan for filling the forms should be prepared in advance, and this plan should 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 has 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 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 increase the rate of cement hydration and accelerate the 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) (Verbeck and Helmuth 1968, Carino and Tank 1992, Freiesleben Hansen and Pedersen 1997, Kim, *et al*. 2001). 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 (Tank and Carino 1991, Kjellsen and Detwiler 1993, Pinto and Hover 1999, Carino and Lew 2001, Schutter 2004, Topçu and Toprak 2005).

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 (Saul 1951, Rastrup 1954, Weaver and Sadgrove 1971, Carino and Tank 1992, Freiesleben Hansen and Pedersen 1997). The ASTM standard provides procedures for developing the strength-maturity relationship and for estimating the in-place concrete strength. Research has been conducted on the performance and suitability of various maturity functions in practical applications especially in slipforming (Anagnostopoulos 2003, Hossain, *et al*. 2005). The ability to model the effect of temperature by the maturity approach has great implications in performing slipforming operations, especially in changing temperature conditions, which is the case in the field for most real life construction projects. 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.

This paper presents the development of a computer program for slipforming operations incorporating maturity approach. The program incorporates Freiesleben Hansen & Pederson (FHP) (1997) and Carino & Tank (CT) (1992) maturity functions for the prediction of initial setting times of slipform concrete layers using laboratory data and then generates slipform mock-up times. The performance of the computer program is validated through field application as well as through parametric studies with variable slipform parameters.

2. Development of computer aided program for slipform operations

A schematic diagram of a typical slipform with concrete layers (j varies from 1 to m) and its application in the slipforming operations of a typical wall is shown in Fig. 2(a)-(b). The total thickness of concrete layers in a slipform should be limited to the slipform height (h) which is typically around 1.0 to 1.3 m. The total number concrete layers (k) in the structure are variable and can vary from 1 to n layers. The value of n depends on the practicality of construction project such as: casting schedule, setting time of concrete, thickness of layers, concrete types, concrete batching schedule etc. Slipform moves upward at the onset of the setting of a concrete layer (known as mock-up time) as shown in Fig. 2(b) allowing gradual casting of concrete for the subsequent layers at the top.

The computer aided program named as “CADSLIPFORM” is developed using Microsoft Excel with its visual basic interface (VBI). The program can generate the most efficient concrete layer arrangement and time of concrete placement as well as incorporate different types of concrete in a slipform placed at various temperatures. Using actual data of concrete and slipform operations (provided as INPUT), CADSLIPFORM can generate necessary data to calculate mock-up times for slipform operations and guide the user to derive optimum mock-up schedule for a specific project.

CADSLIPFORM has various visual basic function modules (BBFM) written in visual basic (using

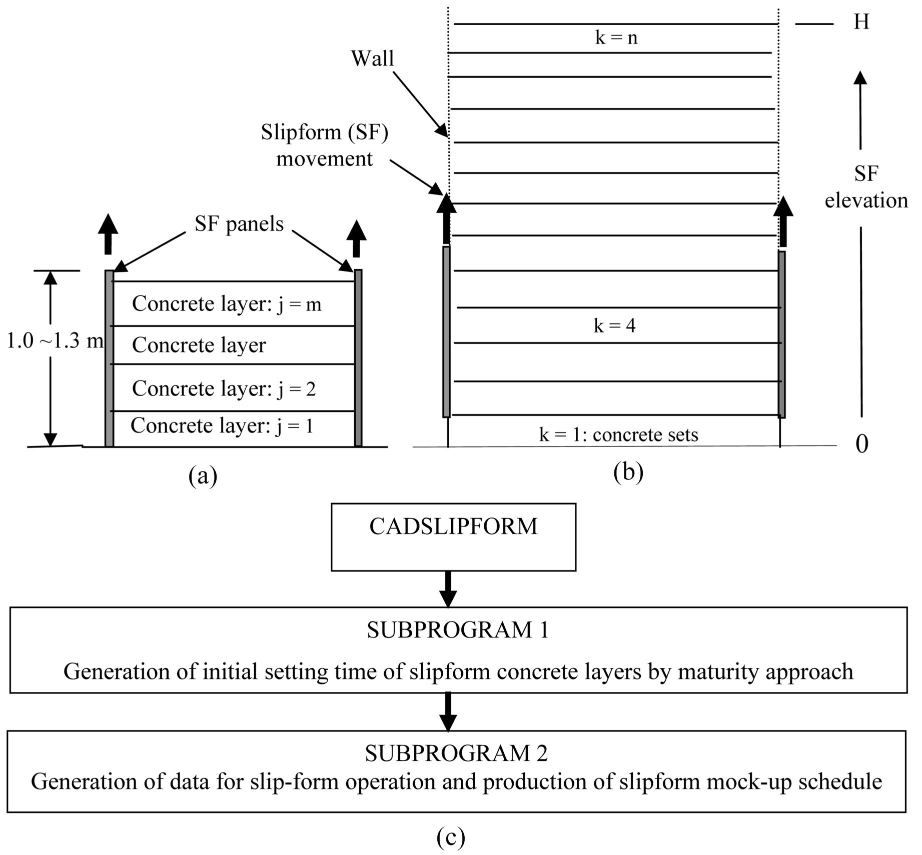


Fig. 2 (a) Typical slipform with concrete layers, (b) Slipforming operation in a wall, (c) CADSLIPFORM Subprograms

built in visual basic editor in Excel) to perform logical operations relating input variables such as: type of maturity function, concrete type, slipform height (*h*), total height of structures (*H*) and slipform speed. These BBFM are called in the main Excel worksheet for data generation. The incorporation of BBFM enhances the flexibility and the versatility of the program in choosing appropriate and desired variables. The program fully utilizes computational and graphical capabilities of Excel. CADSLIPFORM has two subprograms: SUBPROGRAM 1 and SUBPROGRAM 2 (Fig. 2c).

2.1. SUBPROGRAM 1: Generation of initial setting time of concrete mixtures by maturity approach

Extensive research has been conducted by the authors on the performance and suitability of various maturity functions in predicting initial setting of time of concrete using data from laboratory and field investigations (Anagnostopoulos 2003, Hossain, *et al.* 2005). The performance of two maturity functions namely FHP (Freiesleben Hansen and Pedersen 1997) and CT (Carino and Tank 1992) is found better than other functions and these two functions (FHP and CT) are implemented in the development of "CADSLIPFORM". Both FHP and CT functions calculate the time required at a reference temperature named as "equivalent age" for the concrete to achieve the same level of development under the influence of the actual time-temperature history. The FHP and CT exponential functions for equivalent age (t_{eq}) are presented as Eqs. (1) and (2), respectively.

$$t_{eq} = \sum e^{-\frac{E}{R}\left[\frac{1}{273+T}-\frac{1}{273+T_r}\right]} \Delta t \tag{1}$$

$$t_{eq} = \sum e^{B(T-T_r)} \Delta t \tag{2}$$

where T is the average temperature of concrete during time interval Δt (°C), T_r is the reference temperature (°C) which is considered to be 20°C, Δt is a time interval (Hrs) and R is the universal gas constant, 8.3144J/K mol. Both FHP and CT functions require a measure of thermal sensitivity of the hydration reaction by introducing activation energy 'E' (J/mol) and thermal sensitivity factor 'B' (1/°C), respectively.

FHP function is based on Arrhenius equation (Eq. 3), which states that the rate of reactions increases with the increase of the temperature:

$$k = A e^{-\left[\frac{Q}{273+T}\right]} \tag{3}$$

where k is the rate constant (1/days), A is the frequency factor and $Q = E/R$.

According to many researchers, the apparent activation energy (E) is unique for every cementitious mixture (Carino and Lew 2001, Malhotra and Carino 1991). For concrete made with ASTM type I cement without admixtures, an E value of 41.5 kJ/mol is recommended (ASTM C1074 2001). When maximum accuracy is desired, the activation energy should be determined experimentally. The temperature sensitivity factor is similar to the apparent activation energy but has more physical significance (Alexander and Taplin 1962). 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.

2.1.1. Theoretical model for the simulation of initial setting time with illustration

The model for the prediction of initial setting time by maturity functions involves three steps.

Step 1: Prediction of E and B

The determination of E for FHP and B for CT maturity functions for concrete mixtures used in

Table 1 Mix design of MNDC69 concrete mixtures

MNDC69 concrete mixture			
Type HSF Cement (C) = 450 kg/m^3; Water = 152 kg/m^3; Coarse aggregate = 910 kg/m^3; Fine aggregate = 830 kg/m^3; SP = 1400 ml/100 kg of C; AEA = 15 ml/100 kg of C Retarder: 300 ml/100kg of C; Initial concrete temperature (T_i): 10, 15 and 20 °C			
T_i (°C)	Initial setting time (t_i) by PR (ASTM C 403) (hrs.)	T_{av} (°C)	Q = 3757; E = 31237 J/mol; B = 0.045 °C^{-1}
10	24.7	13.8	
15	20.7	17.1	
20	18.4	20.4	

the slipform is based on data from laboratory investigations. For the calculation of *E* and *B*, initial setting times of concrete mixtures at different temperatures (at least two) as well as average concrete temperature up to initial setting (T_{av}) obtained from laboratory tests are needed. T_{av} can be obtained from the time-temperature history of concrete mixtures in the laboratory.

The *E* and *B* determination procedures are illustrated for a concrete mixture designated as MNDC69 used in the Hibernia project in Canada (Elimov 2003). Hibernia is the Canada's first major offshore oil project off the coast of Newfoundland.

The details of MNDC69 concrete mixture are presented in Table 1. Type HSF (8.5% silica fume) cement, a naphthalene based superplasticizer (SP), a hydrocarboxilic based retarder and a fatty acid based air entraining agent (AEA) were used in the concrete mixture. The particle size of the fine aggregate varied between 0 and 5-mm while those of the coarse aggregate varied between 5 and 14-mm. MNDC69 concrete mixtures were cured at initial concrete temperatures (T_i) of 10, 15 and 20°C. Initial setting times (t_i) of MNDC69 concrete mixture obtained by penetration resistance as per ASTM C403)(ASTM C403 1999) in the laboratory is used. For the purpose of this research, initial setting time of the concrete mixture was controlled by varying retarder dosages. Hence, comparatively higher values of initial setting times of the concrete mixture (as compared to concretes, normally used in practical applications) for the particular retarder dosage was anticipated (Table 1). Thermocouples were embedded in the MNDC69 concrete specimens to record time-temperature history. T_{av} is calculated from the time-temperature development history as shown in Fig. 3.

E is calculated from an Arrhenius plot based on Eq. (3) which relates the rate constant ($k = 1/t_i$) to temperature for several experimentally observed cases. The slope of the best fit line of the plot of natural logarithm of the inverse of t_i against the inverse of T_{av} represents the fraction *Q* of *E* as illustrated by Pinto and Hoover (1999). Arrhenius plot for the prediction of *E* of MNDC69 concrete mixture is illustrated in Fig. 4(a). *B* is calculated as the slope of the best fit straight line of the plot of T_{av} versus the natural logarithm of the inverse of t_i. A plot for the prediction of B of MNDC69 concrete mixture is illustrated in Fig. 4(b). Predicted values of *E* and *B* for the MNDC69 concrete mixture are presented in Table 1.

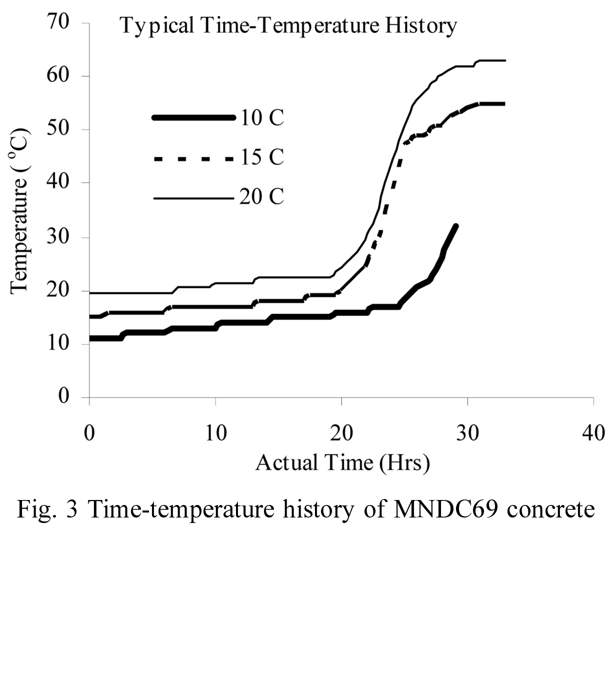


Fig. 3 Time-temperature history of MNDC69 concrete

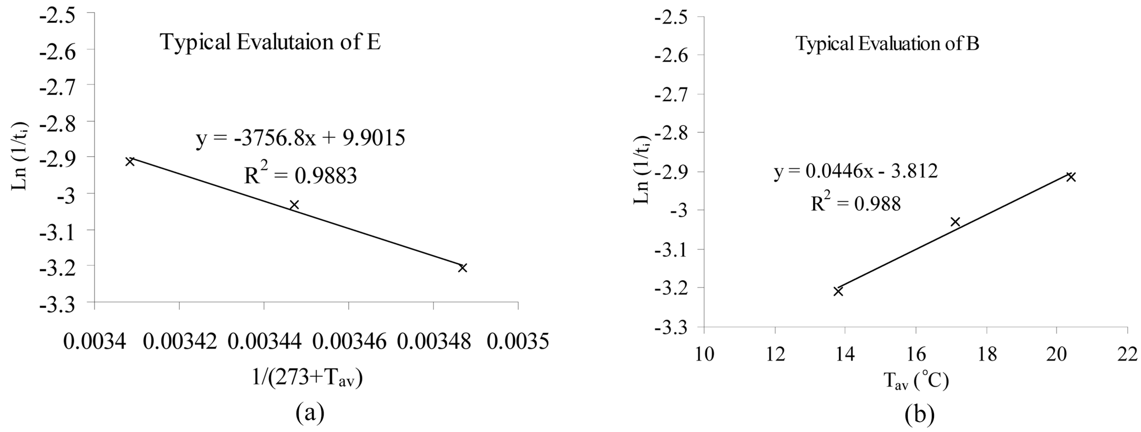


Fig. 4 (a) Arrhenius plot for the prediction of Q and E, (b) Procedure for the prediction of B

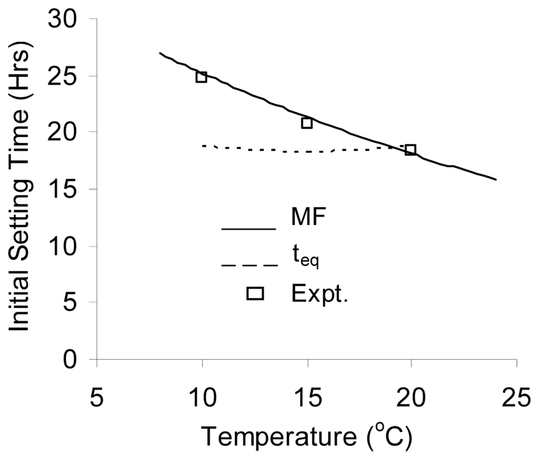


Fig. 5 Prediction of initial setting time

Step 2: Prediction of mean equivalent initial setting time (t_{eq})

This involves the conversion of actual initial setting times (t_i) to equivalent initial setting times (t_{eq}) by maturity functions (using calculated values of E and B) based on average concrete temperature up to initial setting time (T_{av}) of concrete mixture at various temperatures and then evaluation of mean equivalent initial setting time. Fig. 5 shows the calculated values of equivalent initial setting time by CT function (Eq. 2) for MNDC69 concrete mixture at temperatures of 10, 15 and 20°C. While the actual initial setting times (experimental) varied considerably with temperature, the computed equivalent initial setting times (t_{eq}) are far more uniform (ranges between 18.2 and 18.7 hrs) with a mean value of 18.5 hrs (Fig. 5). For the MNDC69 mixture, it can be said that initial set occurs at an equivalent age of 18.5 hrs.

Step 3: Prediction of initial setting time at any temperature of interest

This involves the determination of actual initial setting time for the particular concrete mixture at any temperature of interest based on maturity functions (MF) using calculated mean equivalent initial setting time (mean t_{eq}) and value of E or B. For the MNDC69 concrete mixture, predicted initial setting times by CT maturity function at temperatures ranging from 8 to 24°C are compared with the experimental results in Fig. 5. Initial setting times by MF and experiment are found to be in good agreement. This confirms that procedure with MF can be used with confident to determine initial setting time of a concrete mixture at any temperature of interest once the mean equivalent initial setting time is established based on laboratory results such as: initial setting time at different temperatures and corresponding time-temperature histories.

2.1.2. Influence of setting time testing methods and their selection

Extensive research has been conducted to study the influence of different setting time testing methods on the prediction of E or B and subsequently initial setting time by maturity function (Anagnostopoulos 2003, Hossain, *et al.* 2005). The laboratory based 'penetration resistance (PR) method as per ASTM C 403' and '2°C temperature increase (2C) also known as Box method' as well as field based 'Rod (R) method' were used.

Box method is not a standardized method, but it has been used extensively by Norwegian contractors (Elimov 2003). A concrete sample of 30-40 liters produced at a predetermined temperature was placed in the box (570×570-mm) and a thermocouple was installed in the centre of the fresh concrete to record the time-temperature history. The initial set of the concrete was the time when an increase in temperature of 2°C was observed within 1 hour.

The R method is used to determine the level of concrete that has reached its initial setting in a field application (ACI Manual 1992, Neville 1999). 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 as hard as possible until it stops to the hardened level.

The E, B and initial setting time predicting ability of PR, 2C and R based maturity functions was investigated based on the MNDC 69 concrete mixture having SP, AEA and retarder dosages as shown in Table 2 (Anagnostopoulos 2003, Hossain, *et al.* 2005). Initial setting times were determined by PR, 2C and R methods at different initial temperatures ranging from 10 to 25°C (Table 2). Average concrete temperatures are calculated from the temperature developments of the concrete mixture (Table 2). For the concrete mixtures, it is found that setting times predicted by all three methods are reasonably close. It is also concluded that the method of determination of initial

Table 2 Initial setting time of concrete mixture by different procedures

MNDC69 concrete mixture				
Type HSF Cement (C) = 450 kg/m^3; Water = 152 kg/m^3; Coarse aggregate = 910 kg/m^3; Fine aggregate = 830 kg/m^3; SP = 1600 ml/100 kg of C; AEA = 25 ml/100 kg of C; Retarder: 100 ml/100kg of C				
T_i (°C)	T_{av} (°C)	Initial setting time (t_i) (hrs.)		
		PR	2C	R
10	15.1	13.75	13.50	13.00
15	17.2	10.33	10.75	10.75
20	20.8	7.50	7.70	7.70
25	27.7	6.20	6.25	6.25

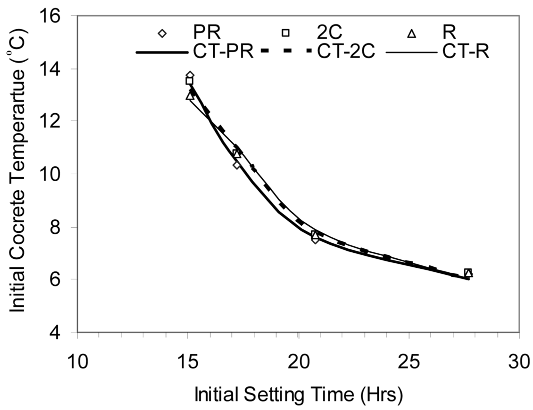


Fig. 6 Comparison of actual and predicted initial setting times

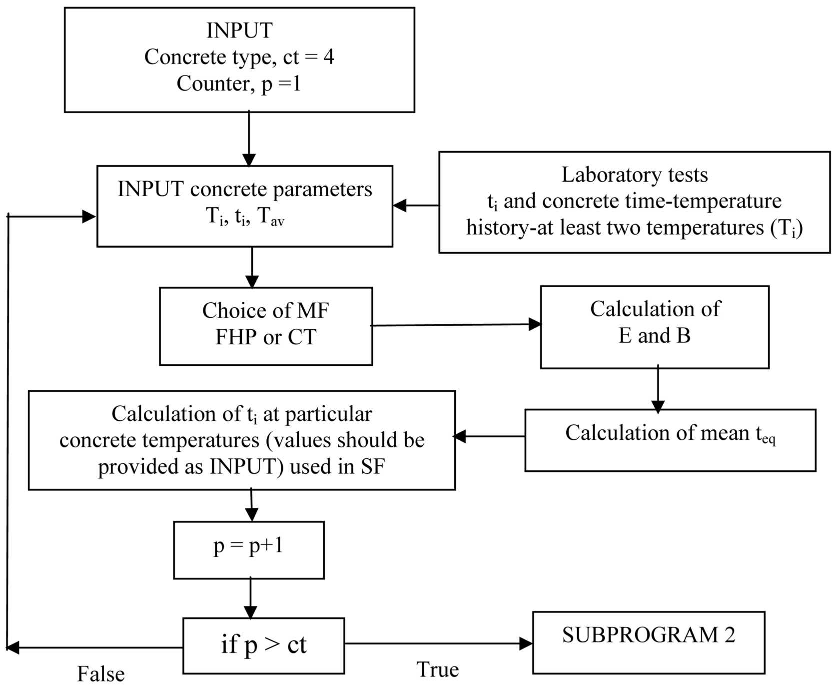


Fig.7 Flow chart of SUBPROGRAM 1

setting time (PR or 2C or R) has little influence on the prediction of *E* and *B*. The use of FHP and CT functions with a particular setting time method (either PR or 2C or R) produces similar mean equivalent initial setting time and will predict similar actual initial setting time. So either FHP or CT function can be used for the prediction. Actual initial setting times (from PR, 2C and R methods) are compared with those predicted by CT function based on PR (CT-PR), 2C (CT-2C) and R (CT-R) in Fig. 6. Predicted values are found to be in good agreement with the actual values and overall, maturity methods are able to predict initial setting time at different concrete temperatures.

In CADSLIPFORM, user can choose initial setting time obtained from any of the three methods (either PR or 2C or R) to generate E or B and subsequently to predict setting times of a concrete mixture at different temperatures.

It was inferred that PR based predictions are more efficient than 2C based prediction. This can be attributed to the fact that 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 2C method should be carefully interpreted. On the other hand, R based prediction is a good indicator of the performance in field applications. So it is suggested to check the performance of PR and 2C based predictions compared with R-based predictions.

2.1.3. SUBPROGRAM 1 of CADSLIPFORM with demonstration

Flow chart of SUBPROGRAM 1 for the generation of initial setting times (t_i) of concrete mixtures (used in the slipform) at any particular temperature (corresponding to the field condition) is shown in Fig. 7. The program allows four concrete mixtures (ct = 4). The practicality of a construction may limit the use of four different concrete mixtures in the slipform. However, the provision of using multiple concrete mixtures definitely increases the versatility of the program without hindering its efficiency. The program calculates E and B values based on input values of t_i and T_{av} and subsequently, mean equivalent initial setting time (t_{eq}) for each of the concrete mixtures based on either FHP or CT function. Finally, provisions are made in SUBPROGRAM 1 to generate t_i at desired temperatures although these values are not needed in SUBPROGRAM 2. This facility

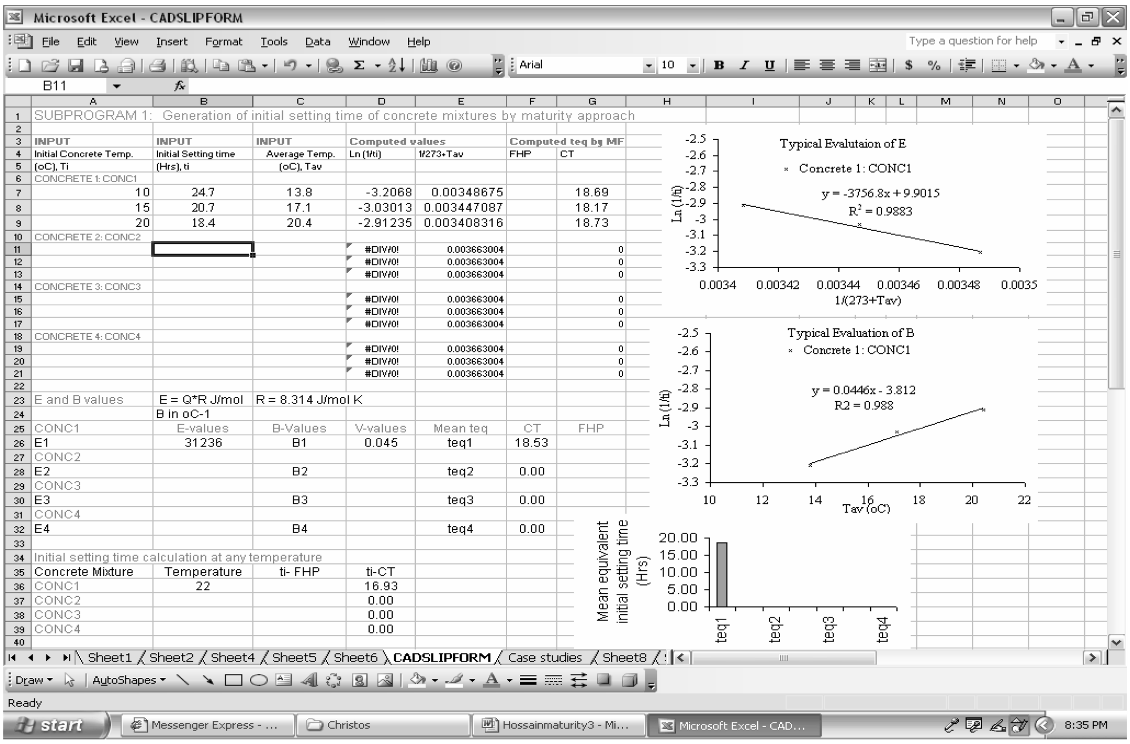


Fig. 8 A snapshot demonstrating the SUBPROGRAM 1

can be used to check the accuracy of maturity function prediction compared to existing laboratory and field data. In SUBPROGRAM 2, t_i is calculated directly by maturity function (either FHP or CT) based on the values of mean t_{eq} (calculated in SUBPROGRAM 1) and input temperature prevailed in the slipform for a particular concrete layer.

A snapshot of the performance of SUBPROGRAM 1 is shown in Fig. 8 where four concrete mixtures are designated as CONC1, CONC2, CONC3 and CONC4. User can INPUT values for T_i, t_i and T_{av} for each of the concrete mixtures in respective Excel columns. The program then calculates the values of E_p (E1, E2, E3, E4), B_p (B1, B2, B3, B4), mean t_{eqp} (teq1, teq2, teq3, teq4) where p = 1, 2, 3, 4 representing four concrete mixtures CONC1, CONC2, CONC3 and CONC4, respectively. Finally, initial setting time (t_i) for concrete mixtures can be calculated for an arbitrary input temperature (T) based on either FHP or CT maturity function. The snapshot shown in Fig. 8 demonstrates the calculation for MNDC69 concrete mixture (as illustrated in the theoretical model of SUBPROGRAM 1). The data of MNDC69 concrete mixture is represented as CONC1 and the program generates (based on CT function) values of apparent activation energy "*E*1 (= 31236 J/ mol)", temperature sensitivity factor "*B*1 (= 0.045°C^{-1}) and mean equivalent initial setting time "teq1 (= 18.53 hrs) showing some graphical outputs. The snapshot also shows the calculation of initial setting time (t_i) at an arbitrary input temperature (T) of 22°C for MNDC69 concrete (CONC1) based on CT function which is 16.93 hrs.

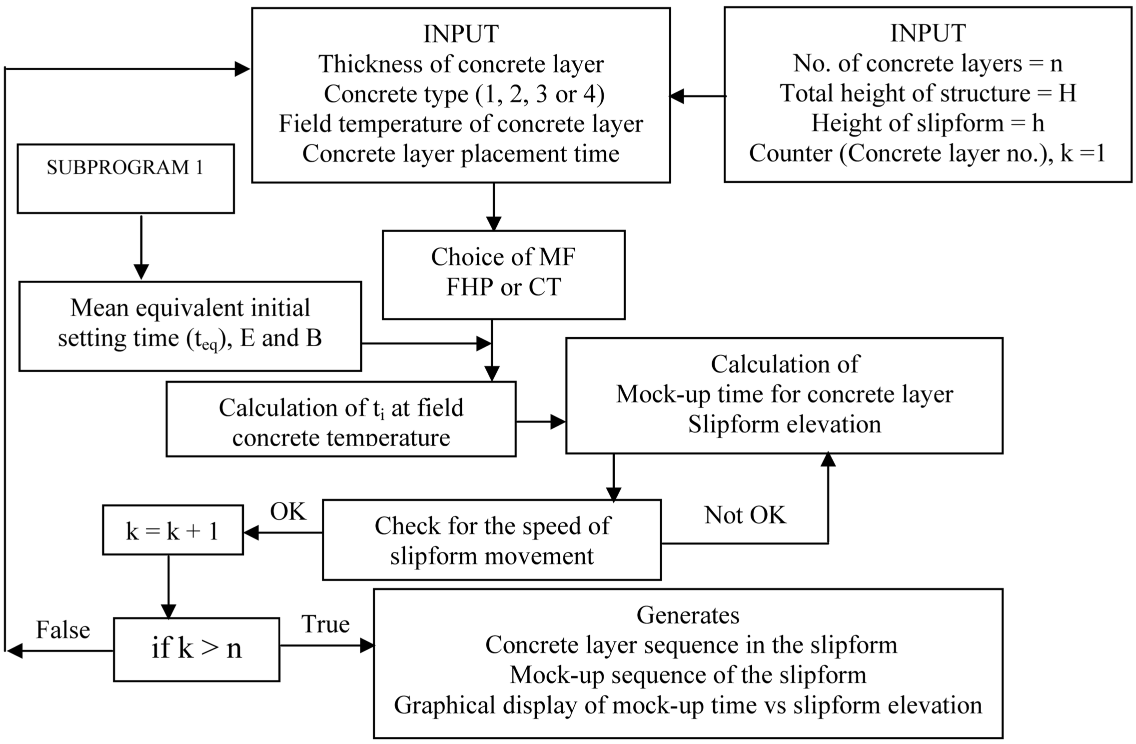


Fig. 9 Flow chart of SUBPROGRAM 2

2.2. SUBPROGRAM 2: Generation of data for slipform operation and production of slip-form mock-up schedule

Fig. 9 shows a flow chart for SUBPROGRAM 2 of CADSLIPFORM program. SUBPROGRAM 2 requires parameters such as: number of concrete layers (n), total height of the structure (H), height of a slipform (h), thickness of concrete layers in a slipform (as illustrated in Fig. 2) as well as concrete types, field temperatures (T) and time of placement (t_p) of slipform concrete layers as input variables. Using either FHP or CT maturity function and incorporating values of mean equivalent initial setting time (mean t_{eq}) and E or B, the SUBPROGRAM 2 calculates initial setting times (t_i) for each concrete layers at specified field temperatures (T). Once the initial setting time of a concrete layer is known, slipform mock-up time for that layer is then calculated by adding t_i to the time of concrete layer placement (t_p). The mock-up time (m_t) for slipform layer k can be calculated as:

$$[m_t] = [t_p]_k + [t_i]_k \tag{4}$$

where $[m_t]_k$ is the slipform mock-up time for layer k, $[t_p]_k$ is the placement time of layer k, $[t_i]_k$ is the initial setting time of layer k at the specified field temperature and k varies from 1 to n (Fig. 2).

By the term mock-up, it is meant to characterize the time at which the slipform is ready to be moved. Slipforming is an important and dangerous work. Plastic concrete placed into the top of the form should achieve strength and be stable by the time the formwork leaves it below and should therefore not sag. A penetration resistance of between 0.34 and 1.4 MPa measured in accordance with ASTM C 403 (less than 3.4 MPa required for initial setting time) is normally required at the trailing edge of the formwork (Shaw and Xu 1998). Therefore, after attaining initial setting, strength and stability of concrete would be adequate for slipform to move upward.

In addition to attainment of initial set, the slipform speed should also be checked for the mock-up operation to be safe. For this, program also calculates speed of slipform movement for each concrete layer to ensure that it is within allowable limit. If calculated speed exceeds allowable limit then it is adjusted using allowable values and mock-up time is revised accordingly. The speed of the slipform movement depends on the type of the structure. For ordinary silos, towers and piers (where reinforcement is simple), the speed can go up to 8 m per day, which is approximately 333 mm per hour (Elimov 2003). For offshore oil platforms, the speed can go up to 2.5 m per day which is approximately 104 mm per hour (Elimov 2003). The calculation of the slipform speed can be adjusted by knowing the initial setting time of the layer from which the slipform should be moved, the initial setting time of the layer above, the duration of transportation of concrete, placement time and the layer thickness (Elimov 2003). Generally without transportation and placement times, the slipform speed would be the layer thickness divided by the difference of the initial setting times of the two layers. Thus by adjusting the slipform speed to be within the limits and as uniform as possible, the time of layer placement and the time of setting can be arranged to produce an efficient and economical construction planning.

It is important for the program to calculate accurately the setting time of concrete mixtures used in the slipform. Construction company should ensure that concrete actually delivered and installed in the slipform is in fact the same concrete that has been used in the CADSLIPFORM to generate mock-up schedule through the generation E or B and the initial setting time (by maturity functions). For this, initial setting time at different initial temperatures and temperature development history of slipform concrete mixtures are to be determined before hand and provided as inputs to the CADSLIPFORM.

SUBPROGRAM 2, generates concrete layer sequence in the slipform. It advices the user whether the total height of concrete layers in a slipform exceeds maximum limit '*h*' or overall height of the slipform layers exceeds total height (*H*) of the structure. It calculates mock-up times for each slipform layer in the process of generating mock-up sequence and also generates slipform elevations. It also provides a graphical display of mock-up time versus slipform elevation.

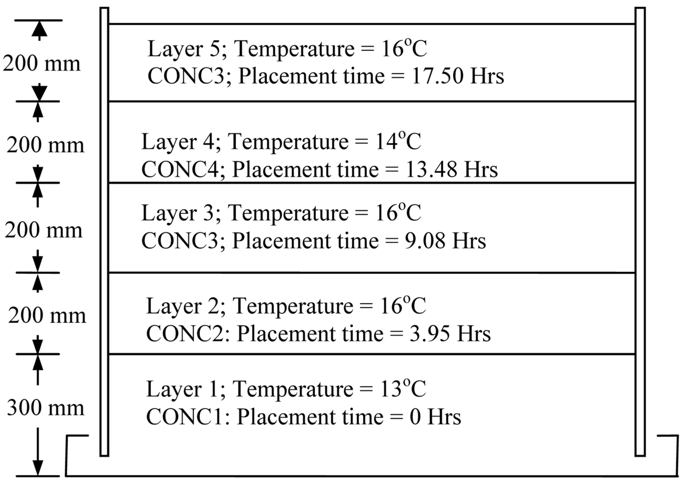


Fig. 10 Layer arrangement of slipform in the wall

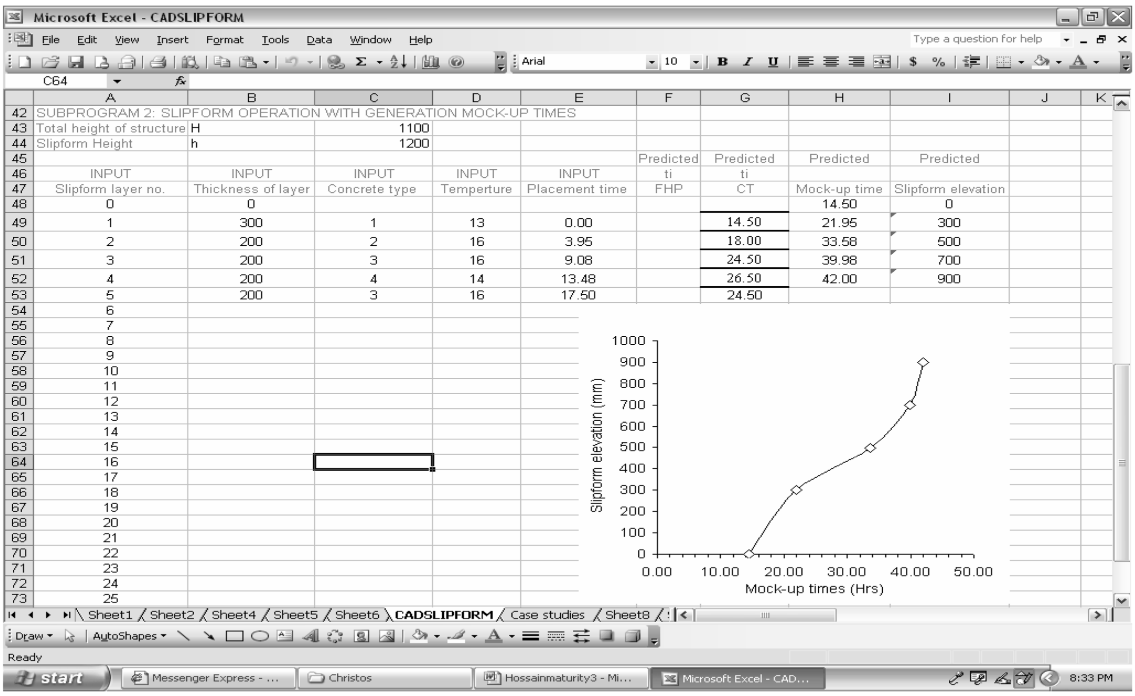


Fig. 11 A snapshot demonstrating the SUBPROGRAM 2

2.2.1. Demonstration of SUBPROGRAM 2

Field data from a wall construction are used to demonstrate the performance of SUBPROGRAM 2. The slipform system and arrangement of concrete layers used in the field wall is presented in Fig. 10. Four different concrete mixtures (CONC1, CONC2, CONC3 and CONC4) having various initial setting times designed specifically for this field test were used. Thermocouples were embedded at each concrete layers within the slipform to monitor temperature development. The concrete field temperatures and placement times of each concrete layers are presented in Fig. 10. Laboratory data of four concrete mixtures are used to calculate values of B (as CT function is used in this demonstration) and mean equivalent initial times for each mixture using SUBPROGRAM 1 whose performance procedures are already demonstrated.

Fig. 11 presents a snapshot of SUBPROGRAM 2 demonstrating the generation of mock-up times for the slipforming operation of the field wall. The snapshot presents input variables such as: layer sequence/number (5 layers in this case), thickness of layers, concrete types/numbers, field temperature in concrete layers and placement time of concrete layers (as shown in Fig. 10). The snapshot (Fig. 11) also shows predicted values of initial setting time (based on CT function), mock-up times and slipform elevation. A graphical display of mock-up time versus slipform elevation is also presented for the user.

2.3. Validation of CADSLIPFORM program

Performance of CADSLIPFORM program is validated through the simulation of slipforming operation for the field wall (Fig. 10) illustrated in section 2.2.1. The performance of maturity based methods used in SUBPROGRAM 2 in predicting slipform mock-up times is validated by comparing with those obtained in the field by rod (R) method. The R method is used to determine the level of concrete from the top of the forms that has reached its initial setting called the "hard front". Hard front elevations and corresponding times are used to calculate mock-up times and slipform elevations.

Fig. 12 compares mock-up times obtained from CADSLIPFORM and field R method. It can be

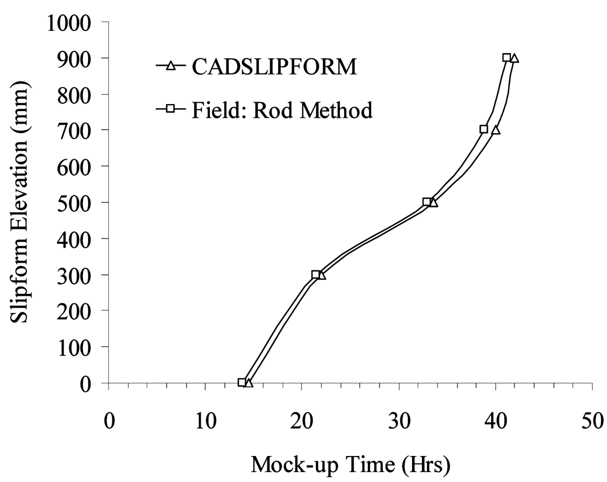
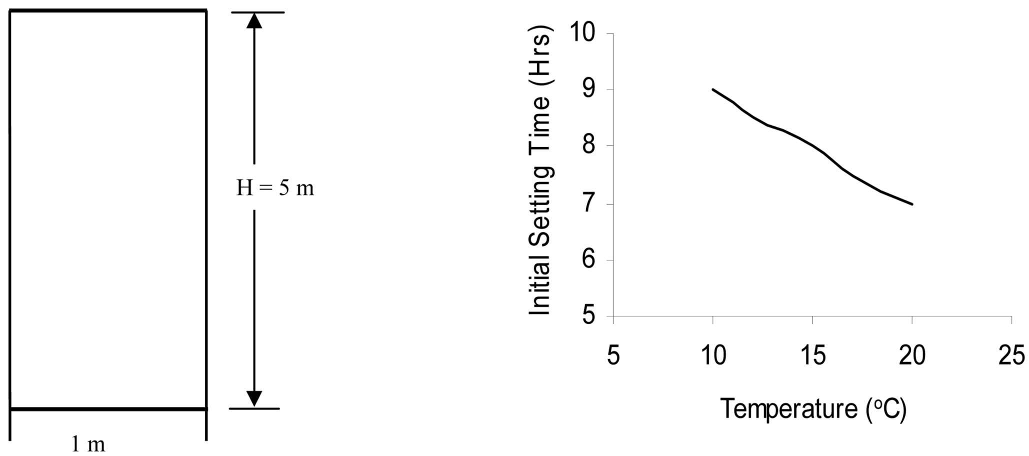


Fig. 12 Comparison of slip-form mock-up times



(a) (b)

Fig. 13 (a) Wall element for parametric study, (b) Initial setting time by SUBPROGRAM 1

observed that mock-up times by CADSLIPFORM correlate very well with those obtained with the R method. It can be concluded that the maturity function based CADSLIPFORM is able to predict the initial setting times as well as times of mock-up for slipform operations and can be used with confidence in practical applications.

3. Parametric studies with CADSLIPFORM

Theoretical parametric studies are performed on a structural wall element having a width of 1.0 m and a total height (H) of 5 m (Fig. 13a). A concrete mixture similar to MNDC69 (Table 1) whose initial setting time was controlled by varying retarder dosages is used. Laboratory data of the concrete mixture are incorporated in SUBPROGRAM 1 of CADSLIPFORM to calculate B (CT maturity function is used) and mean t_{eq}. The calculated values of B and mean t_{eq} are found to be 0.034°C^{-1} and 7.0 hrs, respectively. These values are used to generate t_i of the concrete mixture at any temperature as shown in Fig. 13(b).

3.1. Effect of slipform layer arrangement

The following three types of slipform arrangement (SFA) are used where the number of layer in the slipform (j), the thickness of slipform layer and the total number of layers in the structures (k) are varied (as indicated in Fig. 2):

- SFA1: j = 4, k = n = 17 and thickness of all concrete layer = 300 mm except 200 mm for the 17th layer,
- SFA2: j = 6, k = n = 25 and thickness of all concrete layer = 200 mm
- SFA3: j = 10, k = n = 50 and thickness of all concrete layer = 100 mm

The concrete temperature is kept constant at 10°C. The slipform speed for all these arrangements is also maintained constant at 100 mm/hr. Fig. 14 shows mock-times and placement times of SFA1, SFA2 and SFA3. It is found that by varying placement time schedules of slipforming with different

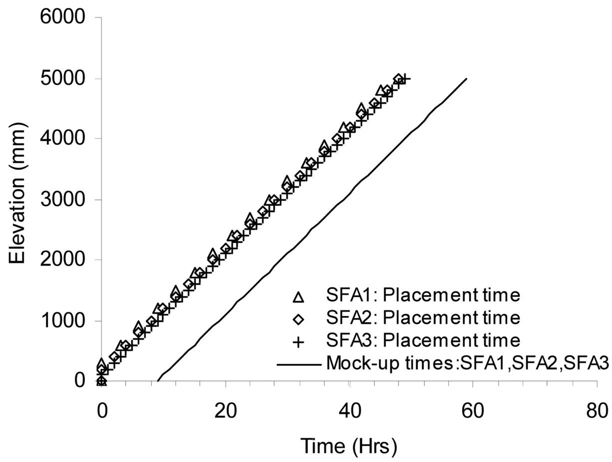


Fig. 14 Effect of slipform layer arrangement on mock-up times

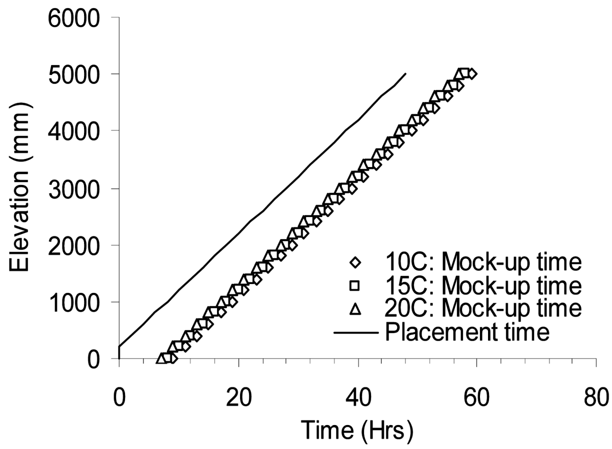


Fig. 15 Effect of variable constant temperature (in all layers) on mock-up time

layer arrangement, it is possible to achieve similar mock-up times. In this case, SFA1, SFA2 and SFA3 produce similar mock-up schedules with a total mock-up time of 59 hours.

3.2. Influence of slipform concrete temperature: all concrete layers subjected to a constant temperature

The slipform arrangement SFA2 is used to study the influence of different concrete temperatures of 10, 15 and 20°C but having a similar placement time schedule for concrete layers. The slipform speed for all these arrangements is maintained constant at 100 mm/hr. Fig. 15 shows that the total mock-time is decreased from 59 hrs to 58 hrs when the concrete temperature is increased from 10 to 15°C while it decreased from 58 hrs to 57 hours when the concrete temperature is increased from 15 to 20°C. This decrease in total mock-up time is equal to the decrease in initial setting of concrete with the increase of temperature. The initial setting time of concrete is decreased from 9 to 8 hrs and from 8 to 7 hrs as the temperature is increased from 10 to 15°C and 15 to 20°C, respectively

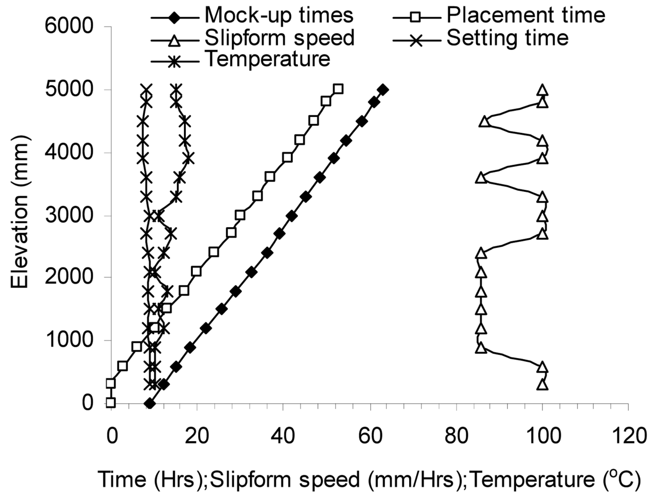


Fig. 16 Effect of variable concrete temperature in concrete layers and slipform speed on mock-up rime

(Fig. 13b). It should be noted that only 2 hour decrease in initial setting for the rise of 10°C (counter to typical concrete behavior, where an approximate 10°C increase will halve the setting rate) is specific to the particular MNDC69 concrete mix whose setting time was controlled by the specific retarder dosage. So, changes in the field concrete temperature (though only one hour for the particular case of simulation) can change the total mock-up time of slipforming operation.

3.3. *Influence of concrete temperature: allowing variable concrete temperature in different layers and variable slipform speed*

The slipform arrangement SFA1 with 17 concrete layers in the wall structure but with a concrete placement schedule (shown in Fig. 16) different than that used in section 3.1 is used. The concrete temperature in concrete layers ranges between 10 and 18°C and the initial setting time of concrete ranges between 7.5 and 9.0 hours (Fig. 16). The slipform speed ranges between 85.7 and 100 mm/hrs as shown in Fig. 16. The total mock-up time is found to be 63 hrs which is 6 hours more than that obtained from slipforming with a constant temperature of 20°C in all concrete layers. It can be noted that the influence of variable concrete temperature in different layers of the slipform on mock-up time is more pronounced than the change of a temperature applied constantly to all concrete layers. Presence of variable temperature within the slipform concrete layers needs to be carefully considered in order to optimize slipforming operations.

4. Conclusions

The maturity method has been developed as an effective method to model the effect of variable temperature conditions (as exists in the field for most real life construction projects) on setting time and strength of concrete. This paper presents the development of a computer program named as "CADSLIPFORM" for slipforming operations incorporating Freiesleben Hansen & Pederson (FHP) and Carino & Tank (CT) maturity functions. The program is developed using Microsoft Excel with its visual basic interface (VBI). The following conclusions are drawn from development and performance validation of CADSLIPFORM:

- incorporation of various visual basic function modules (BBFM) to perform logical operations relating input variables such as: type of maturity function, concrete type, slipform height, total height of structures and slipform speed enhances the flexibility and the versatility of the program in choosing appropriate and desired variables.
- utilization of computational and graphical capabilities of the Microsoft Excel makes the program user friendly: a person with knowledge of Excel and slipforming operations will be able to use the program.
- maturity functions are proved to be effective tools for predicting setting time of concrete mixtures under variable field temperature conditions and hence, mock-up times in slipforming operations.
- program can generate efficient concrete layer arrangement and time of concrete placement as well as incorporate different types of concrete in a slipform at various temperatures.
- program is reliable in generating an optimum slipform mock-up schedule for a specific project as confirmed from its performance validation through field prediction of hard front using rod method in a typical wall construction. However, more trials in the field will fine tune the program to adopt practicality of construction involving slipforming operations. Investigations are in progress to this direction.

It is anticipated that concrete practitioners, contractors and engineers can use CADSLIPFORM as a practical tool for better planning of construction operations involving slipforming in the future.

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