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APPLICATION OF THE MATURITY METHOD IN SLIPFORMING OPERATIONS

by

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ABSTRACT

The main objective of this thesis is to study the application of the maturity method in slipforming operations so as to provide more efficient means of the construction planning of a project. The main target of this research is to use the maturity method to establish the initial setting times and then apply those times to estimate the slipform mockup time and speed.

In this research various maturity functions are compared and the most efficient one is used. The apparent activation energy (E) and the temperature sensitivity factor (B) are examined so as to understand their effect on the maturity function and also to establish a relationship between them and the retarder dosage. Furthermore, the "FHP Strength Model (S_{FHP})" and the "Rate Constant Model (S_k)" are used to evaluate their competence in representing the strength development of a concrete mixture in the laboratory and in the field. Also, the maturity method is used to estimate the times of mockup and then compared with the "Penetration Resistance", "2°C Temperature Increase", "Rod", and "Conductivity" methods. Furthermore, an example is presented and the mock-up times are established based on various initial concrete temperatures and slipform layer arrangements. Finally a computer program is developed to establish the mockup times, time of concrete placement, and the slipform speed during the removal process.

The results of this research showed that the Carino and Tank maturity function is preferred for the calculation of the maturity indexes. Also, it is found that a linear relationship between the retarder dosage and E or B can be established. Moreover, it is shown that E or B can be estimated by the method suggested by Pinto and Hover. In addition, a new strength-maturity model is suggested. Finally, it is found that the maturity

method can be used with efficiency to establish the slipform mockup times, the time of the concrete layer, and the slipform speed.

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NOTATION

S_c – Proposed strength model suggested as improvement of the S_{FHP}.

S_{FHP} – Strength model proposed by Freiesleben and Pederson, suggesting an exponential form of the strength development of the concrete.

S_k – Rate constant strength model. This model is based on the relationship between the strength development and the rate constant.

S_L – The strength that is recorded in the laboratory.

t_a – FHP equivalent age maturity function based on a standard value of 41572 J/mol for apparent activation energy.

t_{CT} – Maturity function suggested by Carino and Tank.

t_e – FHP equivalent age maturity function based on a standard value of 34089 J/mol for apparent activation energy.

t_{FHP} – Equivalent age maturity function suggested by Freiesleben and Pederson.

t_L – The actual time that is recorded in the laboratory.

t_{NS} – Equivalent age maturity function suggested by Nurse-Saul.

t_q – FHP equivalent age maturity function based on a value of 25276 J/mol for ages up to initial setting and 34089 J/mol for later ages, for apparent activation energy.

t_R – Equivalent age maturity function suggested by Rastrup.

t_{WS} – Equivalent age maturity function suggested by Weaver and Sadgrove.

γ_a – Age conversion factor according to FHP maturity function, based on a value of 41572 J/mol for apparent activation energy.

γ_{CT} – Age conversion factor according to Carino and Tank maturity function.

γ_e – Age conversion factor according to FHP maturity function, based on a standard value of 34089 J/mol for apparent activation energy.

γ_{FHP} – Age conversion factor according to Freiesleben and Pederson maturity function.

γ_q – Age conversion factor according to FHP maturity function, based on a standard value of 25276 J/mol for ages up to initial setting and 34089 J/mol for later ages, for apparent activation energy.

γ_{NS} – Age conversion factor according to Nurse-Saul maturity function.
γ_R – Age conversion factor according to Rastrup maturity function.

γ_{WS} – Age conversion factor according to Weaver and Sadgrove maturity function.

1. Introduction

Various methods for the construction of vertical concrete elements exist and the slipforming technique is one of those. Slipforms are forms that move continuously during the placement of the concrete. The continuity of the movement is essential in order to prevent the concrete from adhering to the forms. So, in order to plan the movement of the slipforms, the initial setting time of the concrete inside the slipform is needed.

Since the knowledge of the initial setting times prior to the beginning of the construction of the project would be advantageous in the slipforming planning design, it would be beneficial if a method existed to evaluate those setting times appropriately. The maturity method could be used to evaluate the setting times and also to estimate the in-place strength of a concrete element. The questions are: how appropriate is the model that calculates the initial setting time? Which maturity function is best in accounting for the effect of temperature and hydration development within the internal structure of a concrete element? How the apparent activation energy influences the estimation of the equivalent age function? Which strength model is able to account appropriately the temperature effects and produce the correct results? How can the maturity model be used in the slipforming planning operations? These are questions that need clarification and it is the purpose of this research to clear up and recommend about those issues.

The scope of this research is to evaluate the credibility of the maturity concept in the estimation of the initial setting times of a concrete mixture and its application to the slipforming technique. The maturity concept in calculating the initial setting times was first proposed by Pinto and Hover [Pinto and Hover, 1999]. In the present study extensive research has been done based on the maturity method in calculating the initial setting times by using field and laboratory data collected from the Hibernia Project.

Hibernia is an offshore oil field located near the coast of Newfoundland, Canada. The Hibernia platform is separated into three components (the topsides, the gravity base structure, and an offshore loading system) [www.hibernia.ca]. The topsides is supported by a massive concrete pedestal called the Gravity Base Structure (GBS). The GBS, which sits on the ocean floor, is 111 meters high. It was constructed using reinforced high performance concrete. Delays to construction occurred as a result of the ground-breaking design of the GBS. In April 1994, the project announced that the construction of the platform was over budget, and the first oil start-up date was delayed by five months to December 1997. At that time, new contractors were added to the GBS construction team and the method of pouring concrete was changed from jump-forming to slipforming. From that point, every major GBS milestone was achieved on schedule and within the budget. Construction of the GBS was completed on November 1, 1996.

Laboratory data on estimating the initial setting times are collected from Hibernia project and are used for calculating the initial setting times of the mixture by the maturity method. A hardened front line is then drawn according to the maturity concept and the results are compared with the "Penetration Resistance" method according to ASTM C403, the "2°C Temperature Increase" method, the "Rod" test, and finally with the "Conductivity" method.

Also, with the use of field data from Hibernia, an evaluation of the various maturity functions is done. Then the performance of those functions is compared among themselves and suggestions for their validity in estimating the concrete's in-place strength are offered. Moreover, suggestions about the usage and importance of the apparent activation energy are presented.

Furthermore, various models representing the strength development of the concrete in place are used to evaluate field data from Hibernia. Then those models are compared with the actual results taken from the actual project and their validity in representing the strength development of the in-place concrete is discussed.

Also, the maturity method is used to estimate the initial setting times and then these initial setting times are applied to the slipform design that was used in the Hibernia project and a hardened front of a concrete wall is formed. The maturity method in estimating the hardened front line is then compared with the "2°C Temperature Increase", "Penetration Resistance", and the "Rod" methods, and its validity is examined. Also, the maturity method of calculating the initial setting times is compared with the "2°C Temperature Increase", "Penetration Resistance", "Rod", and the "Conductivity" methods. Finally, an example of a 9.9-m wall is proposed and the maturity method is applied to the slipforming technique to estimate the hardened front line of this wall. At the end, recommendations and limitations for the use of the maturity approach during the construction planning and operation of a project is presented.

2 Literature Review

2.1. Temperature Development Within a Concrete Element

Concrete today is the most widely used construction material in the world. Over the last year, six billion cubic meters of concrete had been used around the world. However, even if concrete is such a widely used material, it still remains a mystery. Many of its properties are very difficult to predict. One of the main factors that are needed in construction planning and design when concrete is used as a construction material is the compressive strength. Before proceeding with important operations such as placement, consolidation, finishing, and formwork removal, an estimation of the concrete's strength is of vital importance. So, it would be very advantageous, with respect to design but also from an economical point of view, if there is a method to establish the concrete's strength development on the site. A very good indicator of concrete's strength development is its in-situ temperature. So, by knowing the temperature history of a concrete element, we can estimate its strength at any desirable time and that could be useful in determining the time of the removal of the formworks.

2.1.1 Effect of Early Temperature on the Strength Development of a Concrete Mixture

The strength development of concrete depends on the degree of the rate of chemical reactions of hydration. So, it is rational to conclude that the acceleration of the reactions would affect beneficially the early strength of concrete. Such acceleration is possible to achieve by increasing the in-situ temperature of the concrete. Higher temperatures, during and following the initial contact of cement with water, reduce the length of the dormant period (the period from mixing until the initial setting of the concrete in which the concrete remains plastic and workable material) so that the overall structure of the hydrated cement paste becomes established very early [Neville 1996].

High temperature at early age increases the early strength of concrete, however, it might negatively affect the later strength. High early temperature leads to rapid initial hydration that leads to a poor physical structure of the concrete. This means that the concrete would be more porous and that could lead to lower long-term strength. The explanation of this behavior was given by Verbeck and Helmuth [Verbeck and Helmuth, 1968]. They suggested that high early temperature retards the hydration process and produces a non-uniform distribution of the products of hydration within the paste. The reason is that in high early temperatures, there is insufficient time for the diffusion of hydration products from the cement particles. Thus a high concentration of the hydration products is built up "in the vicinity of the hydrating particles and this retards the subsequent hydration that adversely affects the long-term strength of the concrete" [Neville 1996]. Despite the fact that high temperatures during the setting period have been found to adversely affect the development of strength, after that period, and according to the maturity rule, they accelerate the strength development.

2.1.2 Temperature Development within a Concrete Mixture

The hydration of cement inside the concrete element generates heat that causes rise in its temperature. There are internal and external restraints that lead to thermal stresses within the element.

Internal restraint develops from the fact that the surface of the concrete element comes into contact with the atmosphere. Because of the difference in the ambient temperature and the temperature within the concrete element (when the surface of the concrete loses heat to the atmosphere) the heat is not dissipated to the outside fast enough. As a result there is low thermal diffusivity of the concrete and the free thermal expansion is unequal in different parts of the concrete element, which in turn develops stresses and cracking. Therefore, it would be advantageous to use a Portland cement with a chemical composition that would develop low rate of heat development. But this is not the case when blended cement is used, because then the estimation of the heat development is more complicated [Neville 1996]. Moreover, it is not only the heat of hydration that is of interest, but also the rate at which it develops.

The solution to such problems is to limit the heat loss due to the ambient temperature and the concrete temperature. This can be accomplished by using adequate insulation and formwork at the top surface of the structure with the use of polystyrene or urethane. Also, additional insulation would be needed at edges and corners where the heat loss occurs in more than one direction and in other sensitive parts of the structure. The insulation must control loss of heat by evaporation, conduction, and radiation, and should be maintained until the temperature differential has been reduced to 10°C [Neville 1996].

The temperature at various points of an element should be monitored as well, by the use of thermocouples or other appropriate instruments so that insulation could be properly adjusted. Other specialized measures are also needed in order to prevent the existence of cold joint within the structure. One measure is a differential use of retarders so that the concrete at the lower part would remain plastic until completion of the placing.

So far, it has been discussed that not only the concrete temperature affects the development of concrete's strength, but also the ambient temperature. The problems that are caused from the ambient temperature become more crucial at very high or very low temperatures [Kosmatka et al. 2002].

2.1.3 Hot-Weather Concreting

Hot weather can affect negatively the quality of concrete by accelerating the rate of moisture loss and the rate of cement hydration. High ambient temperatures cause higher demand of water from the cement, which in turn increases the concrete's temperature. As a result, the hydration process is accelerated leading to the faster setting of concrete and lower long-term compressive strength. Detrimental hot weather conditions include [Kosmatka et al. 2002]:

- High ambient temperature,
- High concrete temperature,
- Low relative humidity,
- High wind speed, and
- Solar radiation

In very hot climates it is likely to have high temperature development inside the concrete and such temperatures would speed up the setting time of the concrete. Tests on 1:2 cement-sand mortar showed that the initial setting time was approximately halved by a change in the temperature of concrete from 28 to 46 °C [Neville 1996].

Some other problems that can be present or that are more likely to happen under hot weather conditions are:

- Increase water demand,
- Accelerated slump loss,
- Plastic shrinkage,
- Difficulties in controlling entrained air, and
- Thermal cracking

2.1.4 Cold-Weather Concreting

If the concrete is placed in a very low ambient temperature, then some problems are very probable to arise. CSA Standards A23.1 requires that when the air temperature is at or below 5°C, or when there is a probability of it falling below 5°C within 24 hours of placing, all materials and equipment needed for adequate protection and curing shall be on hand and ready for use before concrete placement is started.

If the concrete is subjected to freezing before it is set, then the water freezes and there is an increase of the volume of the concrete. As a consequence of the absence of the water and the freezing temperature there would be no chemical reactions and so there would be no strength development in the concrete (if the ambient temperature is above about -10°C, then the concrete will gain strength very slowly, but below that temperature cement hydration and concrete strength gain cease) [Kosmatka et al. 2002]. That would lead in delay of the setting and hardening period. If the concrete freezes without setting, there would be no cement paste to be disrupted by the formation of ice and as long as the low temperature continues to exist the setting will be delayed. At later age when thawing will occur, the concrete should be vibrated and it will eventually set and harden without any loss of strength [Neville, 1996]. However, since there would be no water available for the hydration process the concrete will be porous and it consequently will lead to very low compressive strength.

If freezing occurs after the concrete has set but before it has gained an appropriate development of strength of 3.5 MPa [Kosmatka et al. 2002], then disruption will occur and there would be a huge loss of strength of the concrete, which can be up to 50% of the designed strength. However, if the concrete has set and also reached the satisfactory amount of compressive strength of 3.5 MPa, then the concrete would be capable of resisting the freezing without any damage.

2.2 Maturity Method

It is well established that the strength of a concrete mixture is a function of its age and temperature history. The early affect of the temperature on the strength development of a concrete mixture is very critical. It is the temperature dependence of the concrete that causes problem in estimating its in-place strength development based on data obtained from the laboratory. Thus, there was a need for a method which would account the temperature affect on the strength development.

It was suggested that there could be a function that would be based on the temperature – time development of a concrete mixture, which would give an indication about the strength development of this concrete mixture. Saul [Saul 1951] used the temperature history of a concrete mixture to estimate a number which was indicative of the strength of the concrete. He named this factor "maturity" and he proposed the "maturity rule", which is mentioned in the next section of this chapter.

From that time until now there was extensive research [Rastrup 1954, Plowman 1956, Verbeck and Helmuth 1968, Weaver and Sadgrove 1971, Chin 1971, Freiesleben and Pederson 1977, Carino and Tank 1992, Pinto and Hover 1999] on the maturity method and today the maturity method is considered a useful tool in accounting approximately the in-place strength of a concrete mixture in order to proceed with critical operations. The maturity method is used during the curing period of the concrete and it is not applicable to existing structures.

In this chapter, various maturity functions proposed throughout the years until today are presented. Also, the accuracy of these maturity methods in calculating the strength development of concrete is presented and different models for representing this strength are suggested.

2.2.1 Maturity Functions

A "maturity function" is a mathematical expression that uses the measured temperature of a concrete mixture during its curing period in order to calculate an index that would be indicative of the maturity at the end of that period [ASTM C1074-98]. Maturity functions have been used to convert a curing temperature-time history of a concrete mixture, to a factor that would be indicative of the development of the strength of that concrete.

Saul (1951) first suggested that maturity could be calculated with respect to a "datum temperature", which is the temperature at which the concrete begins to develop its compressive strength [Saul 1951]. A "datum temperature" is the temperature that is subtracted from the measured concrete temperature for calculating the temperature-time factor based on the following equation [ASTM C1074-98].

$$M = \Sigma(T - T_o)\,\Delta t \qquad (2.1)$$

Where,

M = maturity at age t, °C Hours,

T = average temperature of concrete at the interval Δt, °C, and

T_o = datum temperature, °C.

It is generally accepted today that there is not a unique value for the datum temperature, but instead there is only one datum temperature for every concrete mixture. For that reason, this temperature has to be calculated based on experimental results as required by ASTM C1074 – 98.

The maturity rule states that *concrete of the same batch and the same maturity, has the same strength, in reasonable and acceptable deviation, of the concrete at any temperatures-time that is used to derive the same maturity* [Saul, 1951].

Verbeck and Helmuth [Verbeck and Helmuth, 1968] states that a high initial temperature increases the rate of hydration, so that there is a rapid strength development at the early ages of concrete. This increase in hydration causes a non-uniform distribution of the hardening paste, so the concrete will have a lower development of strength at later ages.

Saul's maturity function (Eq. 2.1) can also be used to develop an equivalent age factor "t_e". Equivalent age is the time that a concrete mixture would need to cure under any temperature conditions, if the same concrete mixture would have been cured at a reference temperature. The reference temperature in Europe is usually 20°C, while 23°C is used in North America [Carino and Lew, 2001]. ASTM C1074-98 defines the "equivalent age" as the number of days or hours at a specified temperature required to produce a maturity equal to the maturity achieved by a curing period at temperatures different from the specified temperature (where specified temperature stands for the reference temperature) [ASTM C1074-98]. The equivalent age "t_e" can be derived as:

$$t_e = \Sigma\ [(T-T_o)/(T_r - To)]\ \Delta t \qquad (2.2)$$

Where,

t_e = equivalent age at the reference temperature (Hrs).

T_r = reference temperature (°C).

Δt = a time interval (Hrs).

Eq. 2.2 can be written as:

$$t_e = \Sigma\ \gamma\ \Delta t \qquad (2.3)$$

Where,

$$\gamma = (T - T_o)/(T_r - T_o) \qquad (2.4)$$

The factor "γ" is called the "age conversion factor" or the "affinity ratio" and is used to convert a curing interval "Δt", to the equivalent curing interval at the reference temperature.

Rastrup (1954) proposed an equation for the calculation of the equivalent age:

$$t_e = \Sigma\ 2^{(T - Tr)/10}\ \Delta t \qquad (2.5)$$

The concept of this equation is based on a chemistry axiom: "the reaction velocity is doubled if the temperature is increased by 10°C".

In 1971, Weaver and Sadgrove [Weaver and Sadgrove 1971], provided a procedure for the determination of setting times. They suggested a formula to calculate the equivalent age (t_e), at 20°C.

$$t_e = \Sigma\ [(T+16)^2/1296]\ \Delta t \qquad (2.6)$$

Freiesleben and Pederson (1977) based on an earlier suggestion by Verbeck (1968), proposed Eq. 2.7, based on the Arrhenius equation [Freiesleben and Pederson 1977]:

$$t_e = \Sigma\, e^{-E/R\{[1/(273+T)] - [1/(273+Tr)]\}}\, \Delta t \tag{2.7}$$

Where,

t_e = equivalent age at the reference curing temperature, Hrs.

T = average temperature of concrete at time interval Δt, °C

T_r = reference temperature of concrete, °C

E = activation energy, KJ/mol

R = universal gas constant, 8.3144J/(mol k)

Δt = time interval, Hrs

Carino and Tank (1992) suggested another formula (Eq. 2.8) for calculating the equivalent age, which is similar to the Freiesleben and Pederson function (Eq. 2.7).

$$t_e = \Sigma\, e^{B(T-Tr)}\, \Delta t \tag{2.8}$$

Where,

B = temperature sensitivity factor, 1/°C

T = average concrete temperature during a time interval Δt, °C

T_r = reference temperature, °C

2.2.2 Apparent Activation Energy

The activation energy was proposed by Svante Arrhenius in 1888. The activation energy is described as the minimum energy that is needed for a reaction to occur. By the formation of activation energy, Arrhenius explained why chemical reactions do not occur instantaneously when reactants are brought together, eventhough the reaction products are at a lower energy state. He suggested that before a lower energy state is achieved, the reactants must have sufficient energy to overcome an energy barrier separating the unreacted and reacted states [Carino and Lew, 2001].

For molecular systems, the reactant molecules are in a constant motion and the energy is transferred when they collide. From those molecules, it is a certain number that will reach the lower energy state, and these molecules will need to acquire a sufficient amount of energy in order to acquit this. As the system is heated, the kinetic energy of the molecules increases and more molecules will acquire the energy needed to form the reaction products. Arrhenius states that the rate of reactions increases with the increase of the temperature and he derives what is known as the Arrhenius equation:

$$\mathbf{k = A\ e^{-Q/(273+T)}} \qquad \textbf{(2.9)}$$

Where,

k = rate constant, 1/days

Q = E/R

T = temperature, °C

A = frequency factor

From Eq. 2.9 it can be seen that the ratio of two rate constants at two different temperatures is the age conversion factor proposed by Freiesleben and Pederson (1977), and if one temperature is the reference temperature then we have,

$$\mathbf{k_r = A\ e^{-Q/(273+T_r)}} \qquad \textbf{(2.10)}$$

By dividing Eq. 2.10 by Eq. 2.9 we get the age conversion factor "γ" for the Freiesleben and Pederson equation (Eq. 2.7)

$$\mathbf{k / k_r = [e^{-Q/(2733+T)}] / [e^{-Q/(273+Tr)}] \Leftrightarrow \gamma = e^{-Q[1/(273+T) - 1/(273+Tr)]}} \qquad \textbf{(2.11)}$$

Arrhenius stated the activation energy concept for homogeneous systems undergoing a single reaction. However, this is not the case in concrete. 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 Freiesleben and Pederson function (Eq. 2.7). According to many researchers [Malhotra and Carino 1991, Carino and Lew 2001] the apparent activation is unique for every cementitious mixture, and according to ASTM C1074 – 98, it should be calculated based on lab experiments.

2.2.3 Strength Development Relationships

For economical reasons the removal of the formworks is established as soon as the concrete has gained a sufficient amount of strength so as to be able to safely support its self-loading and other construction loads. The basic method that is used until today is the field-cured cylinders. There is though, an uncertainty if these cylinders are truly representative of the concrete element under consideration, because the curing history of the specimens in the laboratory and the structure will not be identical, and it is for that reason that the strength of those two will not be similar at the same ages. So, it is suggested that a representation of the in-place strength of concrete elements can be accurately approximated by the maturity method.

In 1956 Plowman [Plowman, 1956] suggested a formula to calculate the strength development of in-place concrete based on the maturity principle:

$$\mathbf{S = a + b \log M} \qquad \mathbf{(2.12)}$$

Where,

S = strength,

M = maturity index, and

a and b = regression coefficients

It can be seen that this formula predicts infinite strength as the maturity approaches infinity. However, researchers have proved that Plowman's model is only a good approximation of strength-maturity data for intermediate maturity values [Carino et al. 1983].

Chin (1971) proposed another model for representing the strength development in concrete elements. The original form of the equation was:

$$\mathbf{S = M / (1/A + M/S_u)} \qquad \textbf{(2.13)}$$

Where,

S = strength,

M = maturity,

S_u = ultimate strength, and

A = initial slope of the strength maturity curve

The formula suggested by Chin does not take into account the period at which concrete does not gain strength, but instead it assumes that concrete gains strength at the time of mixing of the water with the cement, which is not true. So, Malhotra and Carino (1991) suggested an "offset" maturity "M_o", which represents the maturity at which concrete starts to develop its strength. So by substituting "M" with "$M - M_o$", Eq. 2.13 becomes:

$$\mathbf{S = (M - M_o) / [1/A + (M - M_o)/S_u]} \qquad \textbf{(2.14)}$$

Eventhough the model can approximate the strength development in the concrete, it still has some limitations, which stands to be the main limitation for all the proposed strength-maturity models up to today. Such limitation is due to different curing procedures in indoor specimens and the outdoor in-place concrete elements. The ultimate strength calculated based on the data from indoor concrete specimens, might not be the actual one for the structure, and that would lead to variations in strength-maturity models. So, in order to use such models it must be ensured that the indoor and the outdoor concretes will go under similar curing conditions.

The key in developing the correct model for representing the strength development of a concrete mixture is the variation of the rate constant with the curing temperature. The "rate constant" model is very effective in calculating the development of strength with temperature [Carino and Lew, 2001]. So, as long as the rate constant at the reference temperature "k_r", the age at which the concrete mixture starts to develop its strength "t_{or}", and the ultimate strength are known, an estimation of the strength development can take place, by the use of the following model [Malhotra and Carino, 1991]:

$$\mathbf{S = S_u \{k_r (t_e - t_{or}) / [1 + k_r (t_e - t_{or})]\}} \qquad \textbf{(2.15)}$$

Where,

S = strength, MPa

S_u = ultimate strength, MPa

k_r = rate constant, 1/(days or hours or minutes)

t_e = equivalent age, Hours

t_{or} = age at which the concrete starts to gain its strength, Hours

This model would produce erroneous results if the initial curing temperatures of the indoor and outdoor concretes were different. So, it was suggested to calculate the relative strength development "S/S_u" in terms of the equivalent age. Eq. 2.15 would transform into:

$$\mathbf{S/S_u = k_r (t_e - t_{or}) / [1 + k_r (t_e - t_{or})]} \qquad \textbf{(2.16)}$$

Eq. 2.16 leads to the following modified maturity rule "*samples of a given concrete mixture which have the same equivalent age and which have had a sufficient supply of moisture for hydration will develop equal fractions of their limiting strength irrespective of their actual temperature histories*" [Carino and Lew, 2001].

Freiesleben and Pedersen (1985) proposed another equation for representing the strength development of a concrete mixture:

$$\mathbf{S = S_u \cdot e^{-(\tau/t)^{\alpha}}} \qquad \textbf{(2.17)}$$

Where,

S = strength, MPa

S_u = ultimate strength, MPa

τ = a time constant at reference temperature, Hours,

α = a shape parameter, and

t_e = equivalent age, Hours.

This equation can model gradual strength development during the setting period and it is also asymptotic to an ultimate strength. The time constant "τ" is the time at which the strength reaches 37% of the ultimate strength. Thus the value $1/\tau$ is the rate constant for this model.

2.3 Maturity Instruments

The maturity method is based on temperature-time relationship; therefore a device is needed to record the temperature of concrete as a function of the time. Analog strip chart recorders or digital data loggers connected to thermocouples embedded into the concrete are suitable [Malhotra and Carino, 1991]. The thermal history given by this method is converted to a maturity index using the maturity functions available or the calculations can be automatically done by the use of spreadsheet software [Dilly et al. 1988].

A more convenient approach is to use "maturity meters". These instruments monitor the temperature history of the concrete and automatically perform the maturity calculations. The concrete temperature history is monitored by using reusable probes or with expendable thermocouple wires. Multi channel models are available where each channel can be activated independently, as the corresponding sensor is embedded in the concrete.

Freiesleben and Pedersen (1977) developed a "mini maturity meter" as an alternative to high cost maturity computers. The mini maturity meter device includes a glass capillary containing a fluid as shown in Fig. 2.1. This method is based on the principle that the affect of temperature on the rate constant for evaporation of the fluid from the capillary tube is governed by the Arrhenius equation. Thus, the evaporation of the fluid and the strength development of a concrete mixture are both influenced by the temperature, in the same way.

Another idea of the "maturity meter" is to measure the chemical shrinkage of the cement paste as it hydrates. In this method, a cement paste at the same water-to-cement ratio (w/c) as the concrete is placed in a vessel and covered by water. This vessel, known as dilatometer, contains a small dilatometer tube to monitor the decrease in water level as the paste hydrates and undergoes chemical shrinkage. A large of low volatility fluid such as oil is used to prevent evaporation of water from the tube. The vessel would be placed into the fresh concrete so that the paste would experience the same temperature history as the concrete. The fall in water level with time would indicate the chemical shrinkage. It has been shown that there is a linear relationship between chemical shrinkage and strength, and that this relationship is independent of the curing temperature.

Generally there is a variety of commercial devices which can automatically calculate the in-place maturity. The user should keep in mind that such computations are based on specific values of datum temperature and activation energy. Thus, they will only account correctly, for temperature effects if these values are applicable to the materials being used [Dilly et al. 1988].

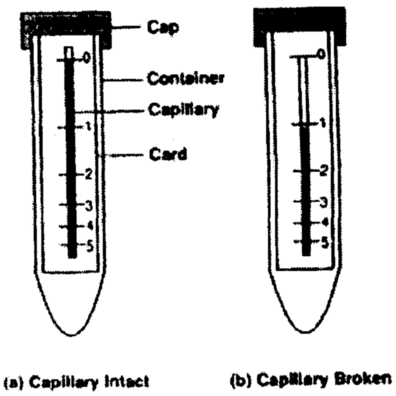

Figure 2.1. Mini maturity meter device [Malhotra and Carino, 1991]

2.4 Limitations of the Maturity Method

It has been established that for same maturities there can be different values of concrete's compressive strength [Malhotra and Carino, 1991]. At early ages, high initial curing temperature would result in higher values of early strength, but in later ages, it would produce lower results when compared with the same concrete mixture cured under low early initial temperature [Malhotra and Carino, 1991].

It was suggested by Saul (1951) that the temperature-time factor (Eq. 2.1) cannot account for the initial temperature affects when the temperature of the laboratory is significantly different from the temperature of the elements that are cured in the field. However with the use of the equivalent age concept, the differences of the initial temperatures cannot cause a problem in the accurate calculation of the maturity indexes, because the apparent activation energy is taking into account for these affects. So, by the use of these functions this limitation of the maturity method had been cancelled.

Eventhough those functions overcame the early maturity problem they are not able to account for the effects of the early age temperature on the later age strength. This deficiency can be overcome by the use of the relative strength concept. By using this method to calculate the relative strength and the measured equivalent age of the concrete in the field, one can estimate the 28-day strength of the mixture, but it is not possible to know the 28-day strength without additional testing of the concrete with other non-destructive testing methods. This is an inherent limitation of the maturity method.

2.5 The Slipforming Technique

Slipforming is a form which moves continuously during the placing of concrete. The continuity of the forms is needed in order to prevent concrete from adhering to the forms and to avoid the formation of cold joints. Slipforming is usually used for casting concrete walls of great height. The forms are of 1 to 1.3-m height and are consist of vertical panels, walings, yokes, horizontal cross bars, jacks, jack rods, and a working platform (Fig. 2.2).

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. It should also resist any asymmetrical loads, inclination of the walls, and restrain the climbing rods from buckling.

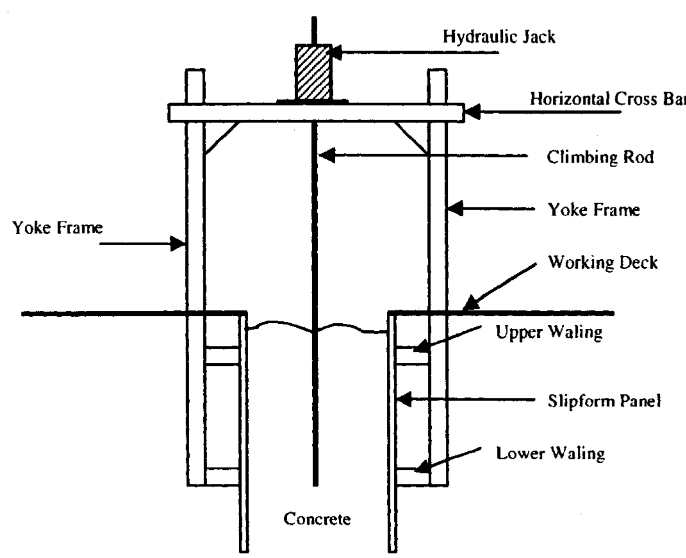

Figure 2.2. Slipform System [Fossa, 2001]

The slipforming technique could be proved very useful if it is implemented in a proper way. It is vital that a very good planning schedule is done and performed in the appropriate way. Operations such as forming, concrete placing, reinforcement and embedment placing, concrete hardening, form removal, quality control and inspections, and correction of defects and surface finishing, should be completed in the limited time during which the forms are moving upwards.

Since the concrete that is left behind should have all the properties mentioned above but not yet hardened in order to prevent adhering to the forms, it is a vital issue to its initial setting time and its early age strength. 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.

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 slipform.

2.5.1 Slipforming Advantages

The slipforming technique is cost effective for 12 stories building or higher [Elimov, 2003]. Since the slipforms are in continuous movement during the placement of the concrete, it reduces the number of construction joints. Also, the speed at which the wall can be erected can be incredibly increased. A slipform wall in a 12 to 20 story building can reduce the construction time by three months when compared with the conventional formworks, and as the building becomes higher the cost savings become more [Elimov, 2003]. Another advantage of the usage of the slipforming method is that the level of safety can be significantly increased.

2.6 Transportation of Concrete

Changing in the initial setting time of a concrete mixture can occur due to the pumping of concrete under high pressure. Usually concrete that is pumped through a long slick line develops its setting time earlier than the same concrete mixture would have done under laboratory tests. So, it is advisable to perform tests on the concrete mixture after its arrival to the site in order to take into account the differences in the setting times and utilize them respectively [Hoff et al. 1997].

2.7 Setting Time

Since slipforming technique is greatly based on the initial setting time, it would be essential to analyze the methods for obtaining this time.

Setting is a term which describes the stiffening of the cement paste. Generally speaking setting is the transition stage at which concrete passes from its fluid condition to a rigid state, after which the concrete is assumed to gain its strength. The setting behavior of a concrete mixture has great significance in estimating the time available for placement, consolidation, finishing, and form removal.

2.8 Setting Time Curves

Curves that give the relation between the temperature, the initial setting time, and the retardation dosage, are of great importance in slipforming operations. In Fig. 2.3, typical setting time curves for different concrete temperatures are shown. These curves are called “setting time curves”, “slipforming curves”, or “retardation curves”. At a predetermined temperature, which is expected that the concrete will develop in the forms on the actual site during the slipforming operation, the initial setting time for the concrete mixture is established for different dosages of the retarder, and the appropriate curves are drawn. When such curves are properly established, they can be used for planning in advance, the slipforming operation.

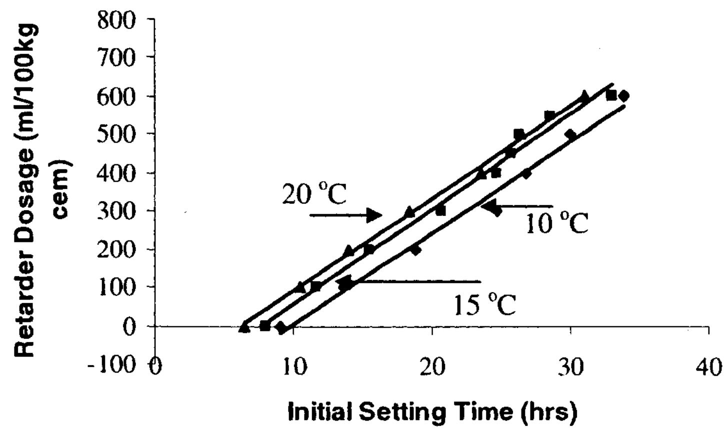

Figure 2.3. Setting Time Curves

2.9 Methods of Establishing Initial Setting Times

There are three methods that are used today in the slipforming operation for establishing the initial setting time. First is the "Penetration Resistance" method described in the ASTM C403. Second is the "Rod" method used for the measurement of the hardened concrete level during the slipforming operations, and third is the "2°C Temperature Increase".

2.9.1 The Penetration Resistance Method

This method is for estimating the time that a concrete mixture reaches its initial and final setting, by means of a penetrometer as per ASTM C403/C 403M – 99. A mortar sample is obtained by sieving the concrete mixture which one is interested in its setting. The mortar sample is then placed in a cylindrical container and stored under a specified ambient temperature. At regular time intervals its resistance is measured by a penetrometer. Finally a graph of the penetration resistance against the elapsed time is drawn, and the initial and final setting times are determined.

2.9.2 The Rod Method

The rod method [ACI Manual of Concrete Inspection 1992, Neville 1999] is used to determine the level of concrete that has reached its initial setting. 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 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.

2.9.3 The 2°C Temperature Increase Method

This is not a standardized method, but it has been used extensively in the past and there is a lot of experience with it [Elimov 2003]. Of great importance is to stimulate the temperature conditions that will exist in the field and in the concrete during the time that it will remain in the forms. The box method has been used extensively by Norwegian contractors. A concrete sample of 30 – 40 liters produced at a predetermined temperature is placed in the box (570 × 570 mm) and a thermocouple is installed in the centre of the fresh concrete. The temperature is monitored and when an increase of 2 °C from the temperature which is established in the box as initial concrete temperature occurs within 1 hour, then that time corresponds to the initial set of the concrete. Note that when concrete is enclosed in the box, the concrete temperature slowly rises. That rise of the temperature is not due to the hydration process and it might exceed the value of 2°C. This should not be confused with the rise mentioned above.

2.9.4 The Conductivity Method

Thermal conductivity refers to the method that is used to measure the ability of the material to conduct heat and is defined as the ratio of the flux of heat to temperature gradient. The conductivity of the material is little affected by the temperature in the room region [Neville, 1996].

Elimov (2003) used the conductivity method to determine the initial setting times of concrete mixtures and concluded that when compared with the conventional methods of estimating the initial set of concrete it provided a useful tool in the slipforming operations. In his research, he used two apparatus to test the electrical conductivity of the fresh concrete. He noted that for slipforming operations it is important to know the shape of the conductivity curve when it is plotted versus the time, and not the value of the conductivity which is affected by many variables. So, the essence is to know the points of "break" of the conductivity curves or the changes of the slope of the curves. By using an instrument called CR10X, he derived curves with two breaking points. The first point represents the time of the initial set of the concrete. When an instrument called CDM210 was used for calculating the conductivity, the derived curves showed three changes in the slopes. The first two of these three are of interest for slipforming operations. The first breaking point corresponded to the start of portlandite precipitation, and the second one to the time of the initial setting of the concrete.

2.9.5 Application of the Maturity Method

Pinto and Hover (1999) studies on the calculation of the initial and final setting times with the approach of the maturity method. In their study the Freiesleben and Pederson (FHP) model (Eq. 2.7) for representing the maturity function of equivalent age was used. Few hours after batching the hydration reactions are different than those taking place at 12 to 24 hours and furthermore those are different from reactions at later ages. It was suggested that the apparent activation energy would also be different at those ages. This suggestion has also been made by various researchers through the years [Pinto and Hover, 1999]. Hence, the apparent activation energy should be estimated for those periods of time.

2.10 Conclusion

The knowledge of the removal time for slipform removal is essential, hence it is beneficial to estimate those times in the most effective way. Knowing that these times represent the initial setting times, methods for calculating the initial setting times should be used.

The maturity is a method that can be applied to calculate the initial setting times. The maturity method could be advantageous when used for slipforming planning, since it can be an adequate method in estimating the initial setting times for laboratory testing as well as for field confirmation.

Next in this study, various aspects that affect a maturity function will be discussed. Since a maturity function will be used to calculate the initial setting times, the validity of various functions will be studied by applying them to laboratory and field data collected from the Hibernia project.

3 Influence of the Apparent Activation Energy on the FHP Maturity Function

3.1. Introduction

The apparent activation energy is an important factor for estimating the equivalent age based on FHP model (Eq. 2.7). It represents the energy that is needed for reactions to take place during the concrete hardening. For that reason, it was stated that the apparent activation energy is not similar for all concrete mixtures, instead it is unique and it must be calculated before using the Arrhenius model to calculate the equivalent ages [Pinto and Hover, 1999]. In this chapter, the effect of the apparent activation energy at the whole spectrum of concrete's ages will be discussed. Also, the effect of the retarder dosage on the apparent activation energy will be explained.

It is suggested by ASTM C1074 that the apparent activation energy should be calculated based on laboratory tests. The reason for this is that each concrete mixture has its own specific characteristics, so the hardening process and temperature development will differ from mixture to mixture. It was also proposed that the apparent activation energy of a concrete mixture is different before and after the setting age [Pinto and Hover, 1999], because the hydration process at these ages is dissimilar.

3.2. Collection and Presentation of Data

For the purpose of this study, data from the Hibernia project have been used. Data from both laboratory and field are used. More specific, the time-temperature history of a tie-wall of the gravity base structure from Hibernia project is used. The tie-wall had embedded maturity meters into various locations along the height and the width of the wall. Data that are used are from maturity meters that were located at three different positions within the wall width at an elevation of 10.5-m (Fig. 3.1). These locations are labeled as Channel 1, Channel 2, and Channel 3. Channel 1 is at 25-mm from the side surface of the wall. Channel 2 is 300-mm from the side of the wall, and Channel 3 is at the centre of the wall. The composition of the MNDC 69 concrete mixture used in this wall is presented in Table 3.1.

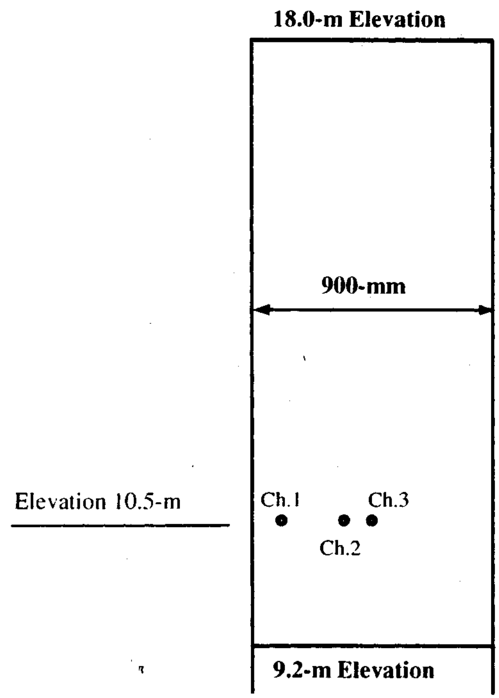

Figure 3.1. Tie-wall from Hibernia platform

Material	Dosage
Cement	450 kg/ m^3
Water	152 kg/ m^3
Fine Aggregates	830 kg/ m^3
Coarse Aggregates	910 kg/ m^3
Superplasticizer EU-37	1400 ml/100 kg cement
Water Reducer TCDA-37	300 ml/100 kg cement
Air Entraining Agent AEX	15 ml/100 kg cement

Table 3.1. MNDC 69 concrete mixture proportions

Type HSF (8.5% silica fume) cement was used. The particle size of the fine aggregate varied between 0 and 5-mm while the particle size of the coarse aggregate varied between 5 and 14-mm. A naphthalene based superplasticizer (EU-37) and a hydrocarboxilic based water reducer (TCDA-37) were used. A fatty acid based air entraining agent was used in the concrete mixture.

Also, for the presentation of the effect of the retarder dosages on the apparent activation energy, laboratory data are used. The same mix with the MNDC 69 (Table 3.1) was used but the dosage of the retarder was varied from 100 to 300 ml/100 kg of cement. Concrete specimens based on the retarder dosages of 100, 200, and 300 ml/100 kg of cement were cured at initial concrete temperatures of 15 and 20°C, and their initial setting times were calculated with the "2°C Temperature Increase" or "Box Method". For that reason, thermocouples were embedded in the concrete specimens and their temperature history was recorded. The concrete with the 15°C initial temperature will be designated as 15°C concrete and the concrete with the 20°C initial temperature will be designated as 20°C concrete. The data are presented in Table 3.2, and in Figs. 3.2 and 3.3.

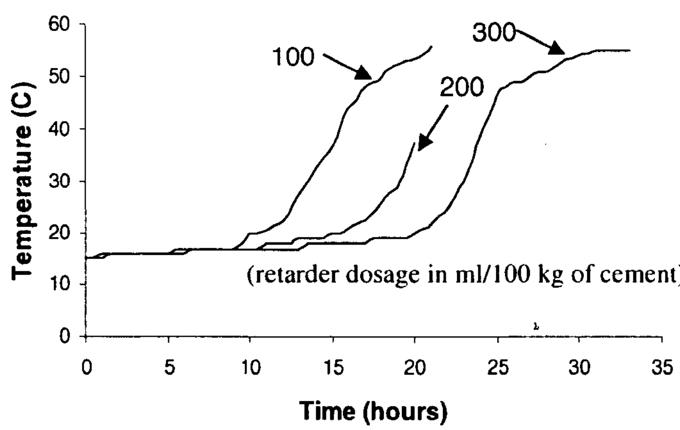

Figure 3.2. Temperature development in laboratory for the 15°C concrete

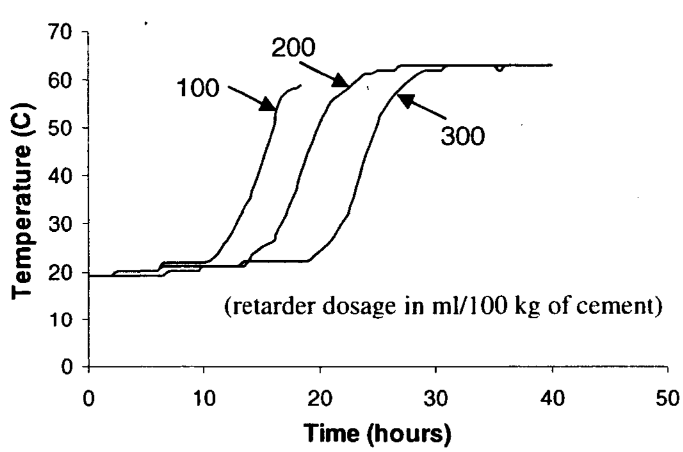

Figure 3.3. Temperature development in laboratory for the 20°C concrete

	15°C Concrete			20°C Concrete		
Trial Number	11	14	10	5	2	6
Material	**Dosage**			**Dosage**		
Cement (kg)	450	450	450	450	450	450
Water (kg)	152	152	152	152	152	152
C. Aggregate (kg)	910	910	910	910	910	910
F. Aggregate (kg)	830	830	830	830	830	830
EU37 (ml/100 kg)	1400	1400	1400	1400	1400	1400
DX (ml/100 kg)	100	200	300	100	200	300
AEX (ml/100 kg)	15	15	15	15	15	15
Initial Setting Time by the "2°C Temperature Increase" (Hrs)	**11.6**	**15.5**	**20.7**	**10.5**	**14.0**	**18.4**

Table 3.2. Initial setting times at various retarder dosages

3.3. Calculation of the Apparent Activation Energy with the Maturity Concept

The initial setting times has been estimated by the "2°C Temperature Increase" method at two different temperatures (15°C and 20°C). The natural logarithm of the inverse of these setting times (Table 3.2) is then calculated and is plotted versus the inverse of the average concrete temperature. The average concrete temperature is calculated from the temperature development shown in Figs. 3.2 and 3.3, and is the average temperature up to the initial setting time. The results are shown in Table 3.3.

The plot is based on the Arrhenius equation (Eq. 2.9) of the rate constant presented for convenience again as Eq. 3.1.

$$\mathbf{k = A \cdot e^{-Q[1/(273+Tav)]}} \qquad \textbf{(3.1)}$$

If the natural logarithm is applied in Eq. 3.1, then Eq. 3.2 is obtained. From Eq. 3.2 it can be seen that if the natural logarithm of the rate constant is plotted against the average concrete temperature, then Q, which represents the slope of the best fit straight line, can be calculated.

$$\mathbf{Ln(k) = Ln(A) - Q \cdot [1/(273+Tav)]} \qquad \textbf{(3.2)}$$

By using the data from Table 3.3, the apparent activation energy can be calculated. The natural logarithm of the inverse of the initial setting times shown in Table 3.3 are plotted (Fig 3.4) against the inverse of the average concrete temperatures calculated in Table 3.3. Then the best fit straight line is drawn and the slope of that line represents the fraction (Q) of the apparent activation energy (E) with the universal gas constant (R). So, the apparent activation energy, based on Eq. 3.3 and Fig. 3.4, for the period between mixing of the concrete with the water and the initial setting time would be 3040*8.3144, which is 25,276 J/mol as per Eq. 3.3.

$$E = Q \cdot R \tag{3.3}$$

Initial Setting Time (t_i) (Hours)	Average Concrete Temperature(T_{av}) (Kelvin)	$Ln(1/t_i)$	$1/T_{av}$
20.7	290.2	-3.03013	0.003446
18.4	293.5	-2.91235	0.003407

Table 3.3. Data for the calculation of the apparent activation energy (300 ml/100 kg of cement)

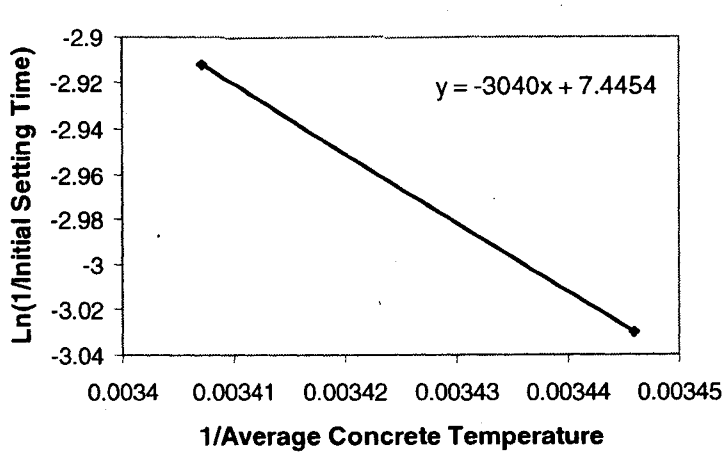

Figure 3.4. Calculation of the fraction Q = E/R

3.4. Effect of the Apparent Activation Energy on the Equivalent Ages

For the MNDC69 concrete mixture, the apparent activation energy used for calculating the equivalent age was based on a standard value of 41572 J/mol. This value represents the standard value of the maturity meters. In this study, different values of the apparent activation energy are used and then compared. The data of the time-temperature history of the MNDC69 mixture used in the tie wall element (Hibernia project) at 10.5 m elevation was used for this purpose.

Maturity meters were used in the specific locations from where the data were obtained. The maturity meters were calibrated for apparent activation energy of 41572 J/mol. Instead of this value for the apparent activation energy, a value of 34089 J/mol has been used in this analysis in order to compare the validity of the maturity meters. This value was derived from tests that had been done in Sherbrooke University [Kada-Benaceur and Duthoit 1997]. Furthermore, based on the concept that the hydration process differs in the very early ages of concrete, another value of 25276 J/mol for the apparent activation energy is used for ages up to the initial setting time. For later ages a value of 34089 J/mol is used.

Three locations across the width of the concrete wall element were used (at 25 mm, 300 mm, and centre line) (Fig. 3.1). Fig. 3.5 shows the temperature development within the MNDC 69 concrete tie-wall. The age conversion factors "γ" based on the FHP model (Eq. 2.11) are then calculated (Appendix Tables A, B, and C). As it was stated previously, the age conversion factor is a factor that is used to convert the age of the concrete to its equivalent age at the reference temperature. Figs. 3.6 to 3.8 show the age conversion factor versus the temperature at different locations. In Figs. 3.6 to 3.8, the age conversion factors are calculated based on the FHP model and are separated into three different cases as it is mentioned above. The first case, where the age conversion factor "γ" is based on a value of 41572 J/mol of the apparent activation energy, is symbolized with the letter "γ_a". In the second case, the calculation of "γ" is based on a value of 25276 J/mol for ages up to the setting time, and 34089 J/mol for later ages. This case is symbolized with the letter "γ_e". Finally in the third case, the "γ" is based on a value of 34089 J/mol of the apparent activation energy and is symbolized with the letter "γ_q".

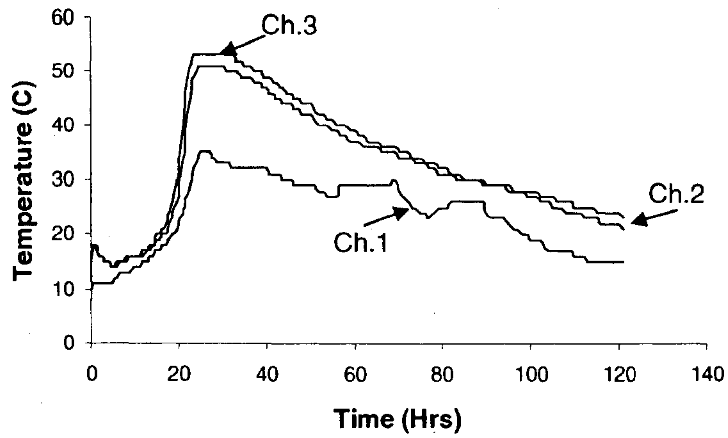

Figure 3.5. Temperature development in the tie-wall element.

In channel 1 (25 mm from the side surface of the wall) the temperature variations were between 8 and 35°C (Fig. 3.5). As expected, the concrete element did not produce high temperatures at this location, because it was near the surface. Channel 1 is represented in Fig. 3.6 and it can be seen that as the temperature draws away from the reference temperature (20°C) within a limit of ±5°C, the age conversion factor seems to be significantly affected by the apparent activation energy. Finally the variations of the age conversion factor increases as the temperature draw away from the reference temperature. At temperatures greater than 25°C the age conversion factor seems to be greatly depended on the value of the apparent activation energy, as the case seems to be for temperatures lower than 15°C.

In channel 2 location (300 mm form the side surface of the wall) the temperature varied between 12 and 51°C (Fig. 3.5). It was expected that at this location, the temperatures would be higher than those at channel 1 location, since the location of channel 2 is closer to the center of the concrete element. It can be observed though, that the same rule as in channel 1 is valid. The apparent activation energy is greatly affecting the age conversion factor as the temperature draws away from 15°C, while at temperatures between 15°C and 25°C the age conversion factor seems to be independent from the value of the apparent activation energy. However, it is more clearly shown in Fig. 3.7 that the values of E affecting the values of the age conversion factor at high temperatures.

The same concept is confirmed in Fig. 3.8, which represents the data from channel 3 at the centre of the concrete wall. It can be seen that the rule of ±5°C from the reference temperature still applicable and that the apparent activation energy produces greater effects on the age conversion factor as the temperature draws away from the reference temperature. Since the temperatures are higher at this location (vary between 11 and 53°C), it can be seen more clearly that the affect of E is more significant at higher temperatures.

This behavior agrees with the previous studies done by other researchers [Malhotra and Carino, 1991]. This happens because as the temperature increases and reaches very high levels, the rate of the reactions inside the concrete element becomes much faster and is not very much dependent on the apparent activation energy. This means that the reactants do not have a problem in leading to a reaction no matter the energy that is needed for this reaction to occur. So, the only relationship that the apparent activation energy would have with the age conversion factor is that based on the Arrhenius equation, which states that the age conversion factor is proportionally related with the apparent activation energy. Consequently, higher apparent activation energies would produce higher values of the age conversion factor at high temperatures (above 25°C). The opposite stands for low temperatures. At very low temperatures, the rate of reactions becomes slower and is much dependable on the apparent activation energy. For high apparent activation energies at low temperatures, and consequently slow reaction rate, it would be difficult for the reactants to lead to a reaction. But for lower apparent activation energies, the reactants would more easily lead to a reaction. This directs to the fact that lower apparent activation energies would produce higher values for the age conversion factor at low temperatures (below 15°C). It is also stated that the age conversion factor values for temperatures lower than the reference temperature tend to produce a straight line when drawn against the average concrete temperature. This is also true here in this case. It can be seen from Figs. 3.6 to 3.8, that the age conversion factor for temperatures below the reference produces a straight line. However at higher temperature the line starts to lose its linearity and takes the shape of a curve.

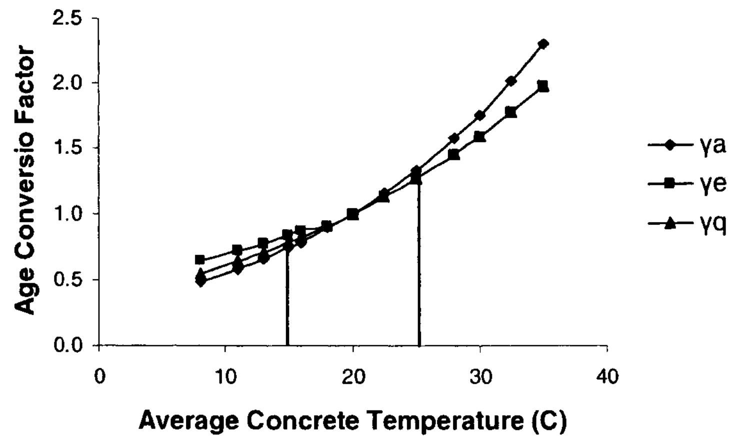

Figure 3.6. Age conversion factors based on FHP model for channel 1

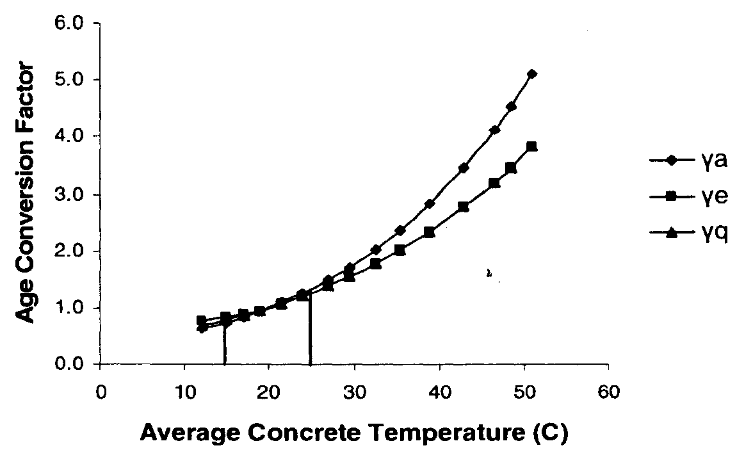

Figure 3.7. Age conversion factors based on FHP model for channel 2

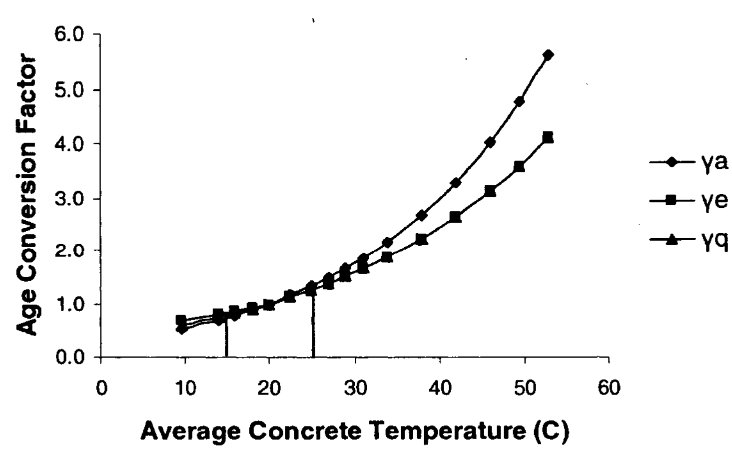

Figure 3.8. Age conversion factors based on FHP model for channel 3

3.5 Effect of the Apparent Activation Energy for Ages up to Setting

The apparent activation energy is different at the very early ages of a concrete mixture. As it was referred previously, different values for the apparent activation energy can be used for the ages before the setting and after. In this section, the effect of the apparent activation energy for ages up to the initial setting is discussed. The initial setting for the MNDC 69 mixture is estimated according to the "2°C Temperature Increase" and is found to be 20.5 hours for Channel 1, 18.0 hours for Channel 2, and 17.5 hours for Channel 3 (Appendix Tables A, B, and C).

Based on the three different values of the apparent activation energy, according to the FHP model (Eq. 2.11), that are used for the MNDC69 mixture, three graphs have been developed representing the effect of the temperature development for the ages up to the initial setting time. Each graph represents different locations across the wall width (Fig. 3.1), where different temperature development occurs (Fig. 3.5). As it can be seen from Fig. 3.9, the age conversion factor based on the different values of the apparent activation energy produces unlike results for a temperature development between 8 and 13°C. The same behavior is noted for locations closer to the centre of the wall element (Fig. 3.10 and 3.11). However, it can be noticed that as the temperature increases and becomes closer to 20°C, the results become closer. In particular, when the temperature approaches 15°C, the age conversion factors become much closer for the above values of the apparent activation energy. Therefore, for concrete elements with very early temperatures (temperature development until the setting age) below 15°C or above 25°C, the apparent activation energy should be carefully calculated and applied to the FHP maturity function.

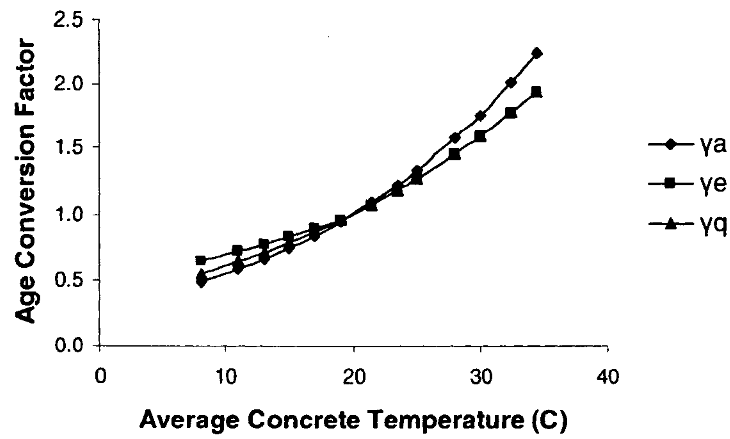

Figure 3.9. Age conversion factors for ages up to initial setting for Channel 1.

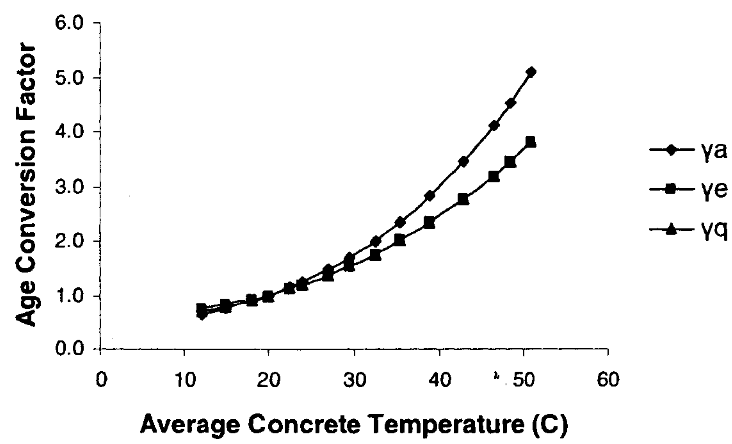

Figure 3.10. Age conversion factors for ages up to the initial setting for Channel 2.

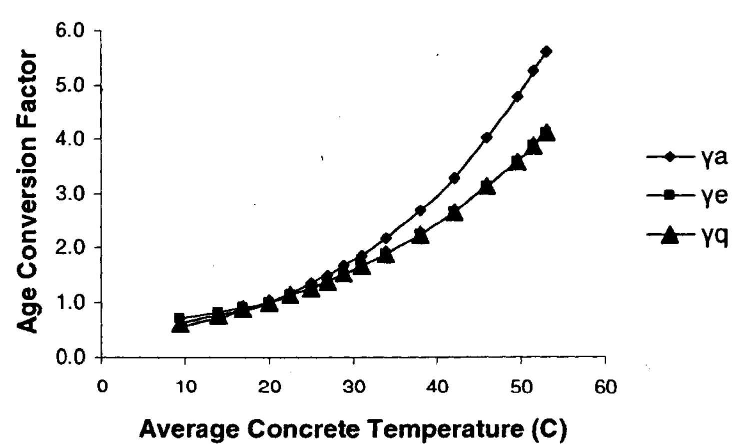

Figure 3.11. Age conversion factors for ages up to the initial setting for Channel 3.

It is shown in Figs. 3.9 to 3.11 that the apparent activation energy does affect the early equivalent ages based on the Arrhenius equation, but does it affect significantly and if it does which value should be used? In order to answer this question the initial setting times for the MNDC 69 concrete mixture at channel 3 location are calculated based on the maturity method by using three different values of the apparent activation energy. Then they are compared with the in-field 2°C temperature increase method, which represents the actual time of the initial setting.

The procedure for calculating the initial setting times based on the maturity method is based on the apparent activation energy, the initial setting time as estimated in the laboratory by the "2°C Temperature Increase" method, and the average concrete's temperature up to the setting time. Three different values of the apparent activation energy are used and so the procedure is separated into three cases. The first case is based on a value of 25276 J/mol and its initial setting time is symbolized as "t_e". In the second case, a value of 34089 J/mol is used and its initial setting time is symbolized as "t_q". Finally, in the third case the standard maturity meter value of the apparent energy (41572 J/mol) is used and its initial setting time is symbolized as "t_a". The initial concrete temperature for channel 3 is 15°C, the initial setting time based on the "2°C Temperature Increase" method is found to be 20.7 hours (Table 3.2). The average concrete temperature at that time, according to Figs 3.2 and 3.3 is 17.2°C and 20.9 °C for initial concrete temperatures of 15°C and 20°C respectively. The equivalent initial setting times based on the FHP model (Eq. 3.7) for the three different cases are calculated and presented in Table 3.4.

Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Average Temp. (°C)	1/ Average Temp. (°K^{-1})		t_a (Hrs)	t_q (Hrs)	t_e (Hrs)
15	20.7	17.2	0.003446		17.56	18.09	18.73
20	18.4	20.9	0.003403		19.39	19.21	18.99
				Average	**18.47**	**18.65**	**18.86**

Table 3.4. Equivalent initial setting times (t_a, t_q, and t_e)

By applying Eq. 2.7 into Table 3.4 the equivalent initial setting times can be calculated. It can be seen that the equivalent initial setting time for Q = 5000 is 18.5 hours, for Q = 4100 is 18.7 hours, and finally for Q = 3040 is 18.9 hours. So, by applying these equivalent ages based on three different apparent activation energies to the channel 3 time-temperature history, the actual setting time can be calculated (Appendix Table D). The results are presented in Table 3.5.

Method		**Initial Setting Time (Hrs)**
Maturity Method	E = 25276	20.5
	E = 34089	20.5
	E = 41572	20.5
In-Field 2°C Temperature Increase		20.7

Table 3.5. Initial Setting Times of MNDC 69: Channel 3

It can be seen from Table 3.5 that the value of 25273 J/mol for the apparent activation energy produces the same result with the other two values, so it could be concluded that the apparent activation energy does not have a significant role in calculating the initial setting time with the maturity method. This is mainly due to the fact that the temperature development of this mixture for these ages is very close to 15°C, which means (as stated previously) that the apparent activation energy does not affect significantly the age conversion factor and consequently the equivalent ages at this temperature. But since, the value of 25273 J/mol for the early apparent activation energy does not produce any deficiency and it is compatible, for better practice it would be preferable to be estimated for these ages by the maturity method as shown above. It could also play a significant role when estimating the in-place strength of the concrete or when calculating the initial setting times for temperatures much lower than the ± 5°C from the reference temperature.

3.6 Effect of the Retarder Dosage on the Apparent Activation Energy

Since the apparent activation energy depends on the composition of the concrete structure, the retarder dosage would affect its value. Here in this section the relationship of the retarder dosage with the apparent activation energy is studied. Based on the maturity method of calculating the apparent activation energy for ages up to the initial setting times for different concrete temperatures, it is possible to determine the apparent activation energy for different retarder dosages. By using data of Figs. 3.2 and 3.3 the average concrete temperature up to initial setting times found from Table 3.2 can be calculated. The results are presented in Table 3.6. Then the apparent activation energy can be estimated by the maturity method. The graphs are shown in Figs. 3.12 to 3.14.

Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Average Temp. (°C)	1/ Average Temp. (°K^{-1})
Retarder Dosage = 100 ml/100 kg of cement			
15	11.6	17.1	0.003447
20	10.5	20	0.003413
Retarder Dosage = 200 ml/100 kg of cement			
15	15.5	17.1	0.003447
20	14.0	20	0.003413
Retarder Dosage = 300 ml/100 kg of cement			
15	20.7	17.1	0.003447
20	18.4	20.4	0.003408

Table 3.6. Data for the calculation of the apparent activation energy

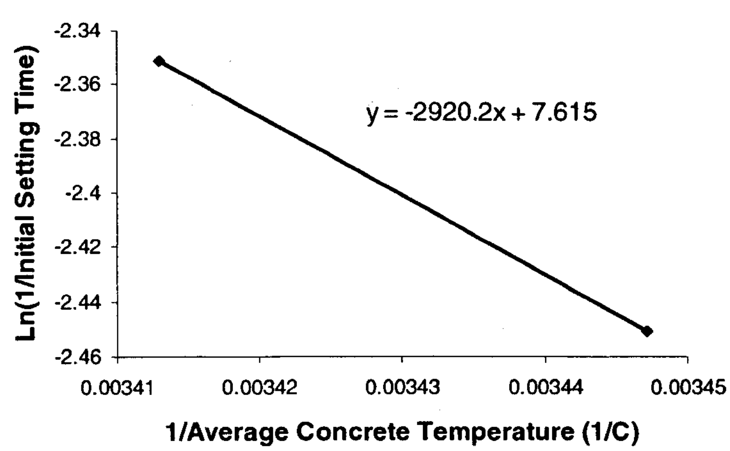

Figure 3.12. Apparent activation energy for 100ml of retarder dosage.

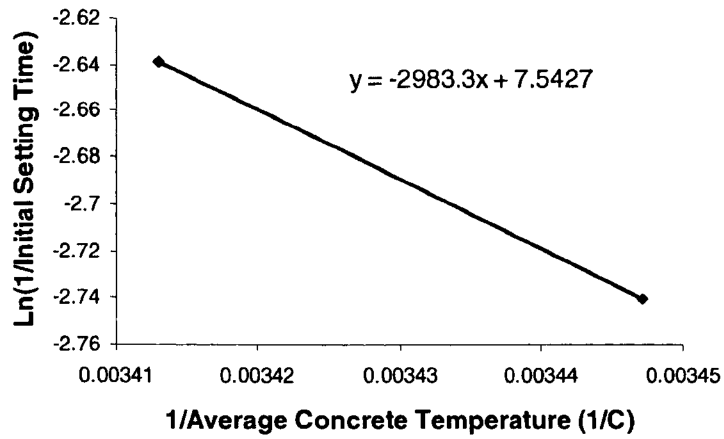

Figure 3.13. Apparent activation energy for 200ml of retarder dosage.

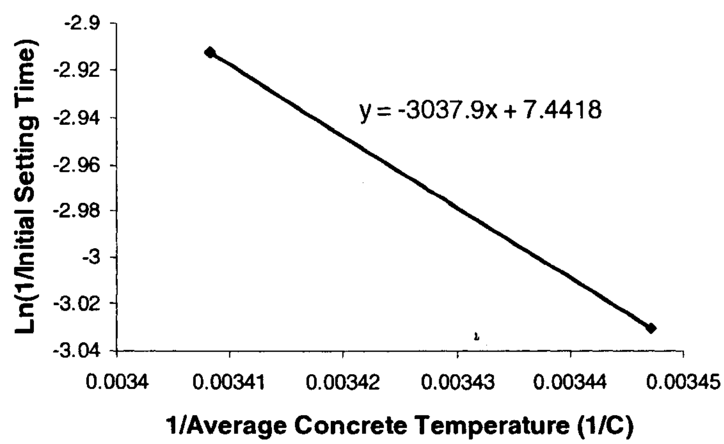

Figure 3.14. Apparent activation energy for 300ml of retarder dosage.

From Figs. 3.12 to 3.14 the apparent activation energy can be calculated. The slope of these lines is representing the value of Q which is equal to E/R, where R is the universal gas constant and has a value of 8.3144 J/mol. So, by multiplying the value of Q with R we can get the apparent activation energy (E). The results are shown in Table 3.7.

Retarder Dosage (ml/100 kg cement)	**Apparent Activation Energy (J/mol)**
100	24,278
200	24,802
300	25,259

Table 3.7. Apparent Activation Energy for the Corresponding Retarder Dosage.

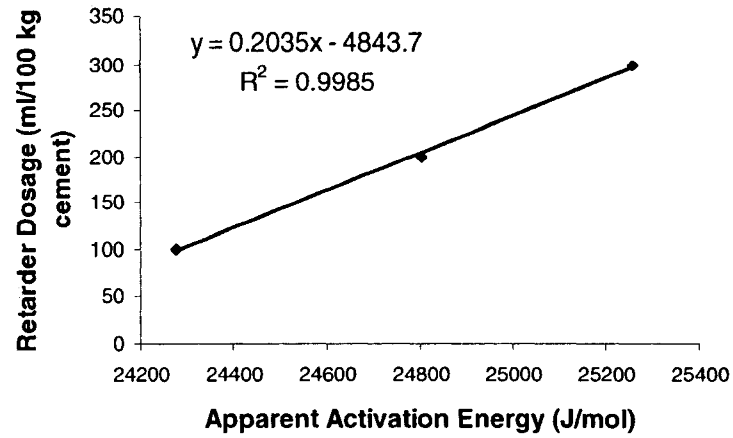

Figure 3.15. Retarder Dosage versus the Apparent Activation Energy.

By drawing the best fit straight line in Fig. 3.15, it can be seen that as the retarder dosage increases the apparent activation energy to some extent increases as well. Also, this relationship can be represented with a straight line. Consequently, the apparent activation energy of any retarder dosage can be calculated by knowing the apparent activation energies for two (preferably three) different retarder dosages, and by using the best fit straight line equation. This behavior also agrees with the fact that higher apparent activation energies would lead into slower rate of the reactions and as a result slower setting of the concrete. However, since the values of the apparent activation energies according to their respective retarder dosages are not varied significantly, it would be rational to conclude that one value of the apparent activation energy could characterize the mixture well independently of its retarder dosage.

3.7 Conclusion

In conclusion, it could be said that the age conversion factor and in consequence the equivalent ages are affected by the apparent activation energy. So, it could be proved unreliable to use a constant value of 41573 J/mol for the apparent activation energy (E) irrespective of concrete mixtures as is the case with the maturity meters. It is strongly recommended that the apparent activation energy to be determined according to ASTM C1074 procedures and then applied to the maturity function for calibration. Also, it is believed that different apparent activation energy should be used at ages below the setting of concrete if the temperatures at these ages are much lower than the ±5°C limit of the reference temperature. Otherwise the age conversion factor could be affected by the value of E. Since the value of E will be different after the setting, extended tests should be done to calculate the apparent activation energy at those ages. If maturity meters are going to be used, then they should be calibrated to the correct apparent activation energy. However, a constant value of the apparent activation energy can be used over the whole spectrum of ages, if the initial concrete temperatures are not far apart from the ±5°C limit. So, for a concrete of initial temperature of 10°C it would not be necessary to calculate different apparent activation energy for the ages below setting.

Finally, it was shown that the retarder dosage affects the apparent activation energy in a proportional manner. The increase of the dosage of the retarder increases the apparent activation energy. This means that the increase of the apparent activation energy decreases the rate of reactions within the concrete structure. It is also shown that by knowing at least two, but preferably three, activation energies for their respective retarder dosages, an equation based on the best fit straight line can be used to calculate any apparent activation energy at any dosage of retarder for a particular concrete mix. Lastly it is suggested that the retarder dosage does not have a significant effect on the apparent activation energy, so a unique value could be used for a mixture no matter the retarder dosage.

4 Maturity Functions

4.1 Introduction

The maturity function is very important in calculating the strength of the in-place concrete at any desirable time. It is also vital for determining the initial setting times. It is the use of the maturity function that would lead to truthful or false results. So, it is crucial to establish and use the correct function in order to produce accurate and safe construction procedures.

Here in this chapter field data from the Hibernia Project are used and the various maturity functions that are presented previously in this study are applied to calculate the corresponding maturity indexes and then are compared. A "maturity index" is an indicator of maturity that is calculated from the temperature history of a cementitious mixture by using a maturity function [ASTM C 1074 – 98].

4.2 Presentation of Data

The field data from the Hibernia project that are used for this study include the time-temperature history of the MNDC 69 concrete mixture that was used to build the tie-wall element referred in Chapter 3. The time-temperature history in the specific locations was recorded by the use of maturity meters. The maturity meters were set up into three different locations within the horizontal line of the wall, whose width was 950 mm (Fig. 3.1). The mix design used for the MNDC 69 concrete is presented in Table 3.1.

4.3 Analysis of Data

The maturity meters that were used for these data had a standard value of the datum temperature (T_o) and the apparent activation energy (E), of -10°C and 41572 J/mol, respectively. In this chapter, the FHP function (Eq. 2.7) has been based on a value of the apparent activation energy that was derived after tests in Sherbrooke University [Kada-

Benaceur and Duthoit 1997]. Also, a different value of the apparent activation energy, for ages up to initial setting, is used, which is derived by the maturity approach based on the setting time presented in Chapter 3.

4.3.1 Comparison of the Various Maturity Functions

The maturity functions presented in Chapter 2 are applied to the Hibernia field data. The maturity indexes are then compared with the values of the maturity meters. The equations for the maturity functions used for this purpose are presented briefly for convenience. The function suggested by Nurse – Saul (Eq. 2.2) for representing the equivalent ages is noted as "t_{NS}" and is presented as Eq. 4.1. Also, the functions suggested by Rastrup (Eq. 2.5), and Weaver and Sadgrove (Eq. 2.6) are noted as "t_R" and "t_{WS}", respectively and are presented as Eqs 4.2 and 4.3. Finally, the functions suggested by Freiesleben and Pederson (Eq. 2.7), and Carino and Tank (Eq. 2.8), are noted as "t_{FHP}" and "t_{CT}" respectively and presented as Eqs 4.4 and 4.5.

$$t_{NS} = \Sigma\ [(T-T_o)/(T_r - To)]\ \Delta t \tag{4.1}$$

$$t_R = \Sigma\ 2^{(T - Tr)/10}\ \Delta t \tag{4.2}$$

$$t_{WS} = \Sigma\ [(T+16)^2/1296]\ \Delta t \tag{4.3}$$

$$t_{FHP} = \Sigma\ e^{-E/R\{[1/(273+T)] - [1/(273+Tr)]\}}\ \Delta t \tag{4.4}$$

$$t_{CT} = \Sigma\ e^{B(T-Tr)}\ \Delta t \tag{4.5}$$

The value for the datum temperature in Eq. 4.1 is taken as -10°C. The value for the apparent activation energy in Eq. 4.4 is separated into two cases. In the first case, a value of E/R of 4100 is used according to the test results that have been done at Sherbrooke University [Kada-Benaceur and Duthoit 1997]. For the second case, a value of 3040 for the ages up to the setting of MNDC 69 concrete mix (24.7 hours for channel 1 location and 20.7 hours for channels 2 and 3) is applied. For later ages, a value of 4100 is used. The purpose for the different values of the apparent activation energy is to compare the credibility of the field maturity meters in calculating the equivalent age. Finally, in Eq. 4.5 a value of 0.046 is used for B. The data and the results are presented in Tables A, B, and C in the Appendix. The graphs of these results are presented in Figs. 4.1 to 4.3. For reasons of clarity it would be easier to represent various parameters of FHP based equations as:

t_a & γ_a: values based on the maturity meter results

t_e & γ_e: FHP maturity function with E = 25276 J/mol for ages up to setting and 34089 J/mol for later ages

t_q & γ_q: FHP maturity function with a constant value of E = 34089 J/mol

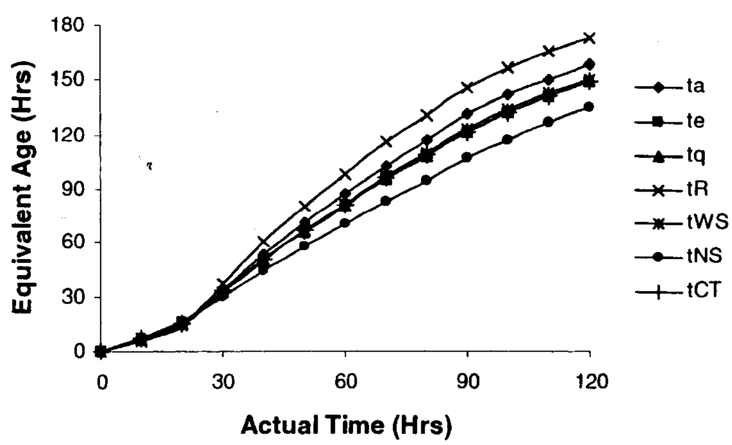

Figure 4.1. Equivalent ages comparison at Channel 1

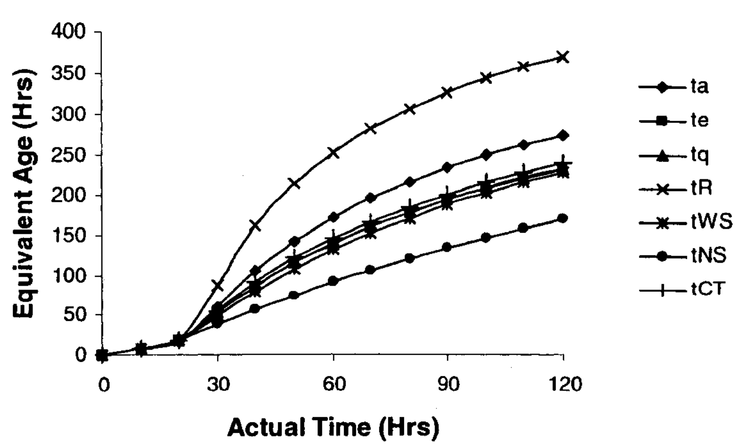

Figure 4.2. Equivalent ages comparison at Channel 2

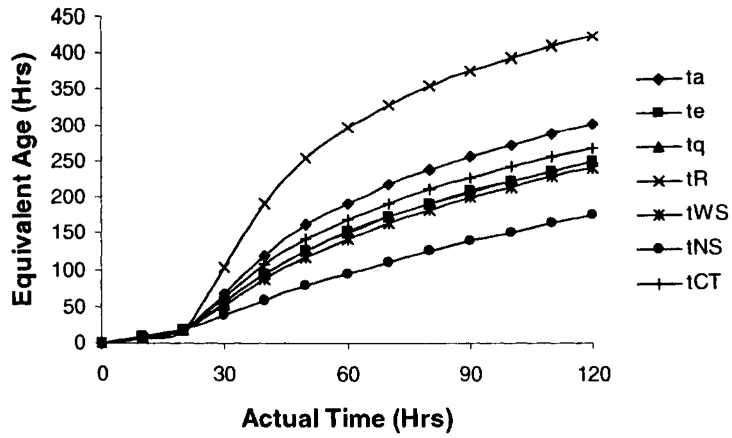

Figure 4.3. Equivalent ages comparison at Channel 3

As can be seen from Fig. 4.1 the Nurse-Saul function "t_{NS}" (Eq. 4.1) approximates linearity and its values are much lower than the values of the other equations. On the other hand Rastrup's equation "t_R" (Eq. 4.2) seems to produce the highest values of equivalent age. The FHP equation "ta" (Eq. 4.4) based on the maturity meter gives similar values compared with the FHP equations based on different values of apparent activation energy "t_e" and "t_q". The FHP equation and the exponential equation suggested by Carino and Tank "t_{CT}" (Eq. 4.5) give very similar results.

As observed from Fig. 4.2, the Nurse-Saul's and Rastrup's functions produce the lowest and the highest values of equivalent ages, respectively. The Weaver-Sadgrove function "t_{WS}" (Eq. 4.3) along with the "t_e", "t_q", and "t_{CT}" functions seem to give very similar results over the whole spectrum of ages. Finally "t_a", "t_e", and "t_q", which are based on the FHP function but on different values of the apparent activation energy seems to produce variations when calculating the equivalent age.

The observations from Figs. 4.1 and 4.2 are also valid for Fig. 4.3. The linear function gives the lower results and the Rastrup's function the highest, and as the location is moving closer to the centre of the concrete element (from channel 1 to channel 3) the Rastrup's function gives greater variations compared to the functions based on FHP and Carino and Tank.

It can also be observed from Figs. 4.1 through 4.3 that up to a specific time the values of the equivalent ages based on the different functions are very similar and approach linearity. At the location of channel 1, until the 28th hour of the actual time (Table A, Appendix), it can be seen that the results based on the different functions are very similar. In Fig. 4.2, at the location of channel 2, the same is true for an actual time of 22 hours, and the same can be observed in Fig. 4.3 for channel 3, (Tables B and C, Appendix). For all of these three locations, these times represent approximately the time at which the concrete element, at these locations, sets. Also, it can be noticed that from placing until these times the average concrete temperature is approximately 20°C. So, by observing these figures, it could be said that there is no significant error in using any of these maturity functions in calculating the equivalent time when they are used up to the time at which setting occurs.

However for later ages the maturity functions do produce significantly different results and care should be given in the decision of the most appropriate maturity function for use. It can be suggested that the FHP (Eq. 4.4) and the Carino and Tank (Eq. 4.5) functions produce very similar results and they account more effectively for calculating the equivalent ages. Finally, it is suggested that the correct apparent activation energy should be used and when the maturity meters are to be used in a project, then their apparent activation energy should be checked to comply with the apparent activation energy of the concrete mixture.

To gain a more clear perspective of this behavior, the age conversion factors based on Eqs. 4.6 to 4.10 are drawn versus their respective average concrete temperatures (Tables A, B, and C, Appendix). The results are presented in Figs. 4.4 through 4.6. It can be seen that the values of the age conversion factor based on the different maturity functions produce similar results for temperatures between 15°C and 25°C. However, the Rastrup function "γ_R" (Eq. 4.7) along with Nurse-Saul's "γ_{NS}" (Eq. 4.6), and the maturity meter's "γ_a", do produce variations with the rest of the functions, and the problem becomes more obvious as the temperature draws apart from the reference (20°C). This agrees with previous studies done by others [Malhotra and Carino, 1991].

$$\gamma_{NS} = (T-T_o)/(T_r - To) \quad (4.6)$$

$$\gamma_R = 2^{(T - Tr)/10} \quad (4.7)$$

$$\gamma_{WS} = (T+16)^2/1296 \quad (4.8)$$

$$\gamma_{FHP} = e^{-E/R\{[1/(273+T)] - [1/(273+Tr)]\}} \quad (4.9)$$

$$\gamma_{CT} = e^{B(T-Tr)} \quad (4.10)$$

It has been proposed that the FHP function (Eq. 4.9) is valid for the whole spectrum of temperatures. It was suggested by researchers that the Nurse-Saul function (Eq. 4.6) is good for representing the temperature-time history of a concrete mixture only for a limited range of temperatures. When observing Figs. 4.4 through 4.6 it could be said that all the functions are acceptable in representing the temperature-time history for a range of temperatures between 15°C and 23°C.

On the contrary it can be seen from Figs. 4.4 through 4.6 that above 23°C, various maturity functions produce significantly different values. The linear function gives the lowest values of all the functions while the Rastrup's function produces the highest values. The "γ_a" function seems to give good results but somewhat different from the "γ_e" and "γ_q". The "γ_e" function though seems to agree more with the Nurse-Saul function (Eq. 4.6) up to the time of setting (24.7 hrs for channel 1 and 20.7 hrs for channels 2 and 3) but at later ages it begins to take the shape of a curve rather than a straight line. Another interesting observation that could be noticed from all of those figures is that the exponential function suggested by Carino and Tank (Eq. 4.10) produces very close values to the FHP function, which would reach to a conclusion that its use might be advantageous because of its simplicity.

Finally, it can be concluded that the FHP equation "γ_q" based on Eq. 4.9, the Carino and Tank (Eq. 4.10), and the Weaven and Sadgrove (Eq. 4.8) functions generate very similar results. On the contrary the Nurse-Saul (Eq. 4.6) and Rastrup's (Eq. 4.7) functions along with the FHP based on the maturity meter values "γ_a", do give variations and this becomes clearer at very high temperatures. The FHP equation "γ_e" produces different results from "γ_q" for ages up to the setting time and it tends to give similar results with the Nurse-Saul function (Eq. 4.6), but at later ages it has a very good correlation with "γ_q". So, attention should be given if the temperature development within a concrete element is expected to fluctuate in very high values (above 25°C). In such situations the most appropriate maturity function should be used.

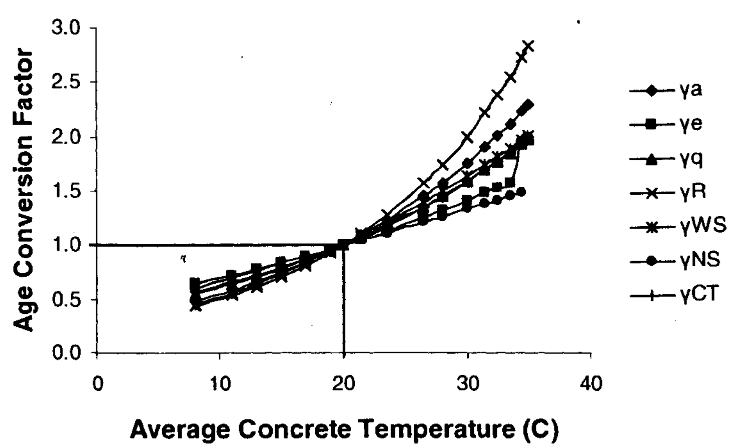

Figure 4.4. Age conversion factor at channel 1

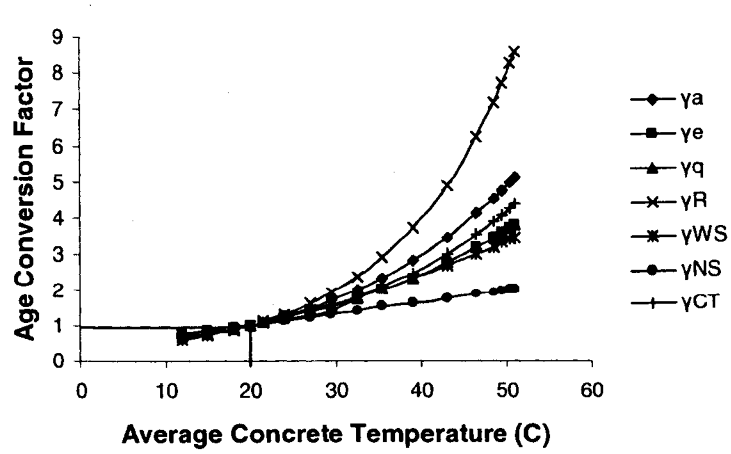

Figure 4.5. Age conversion factor at channel 2

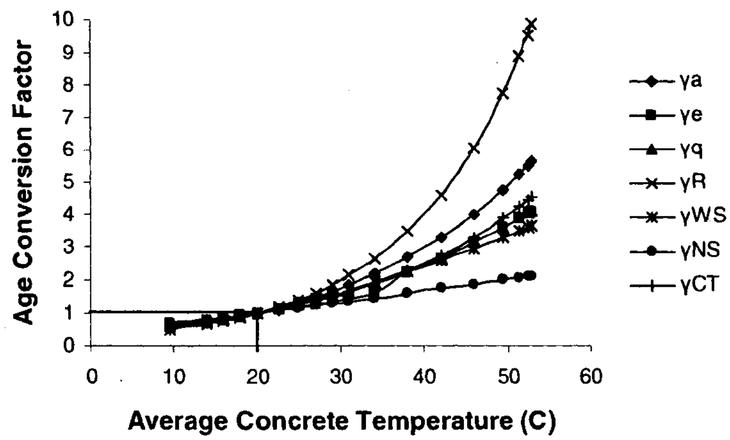

Figure 4.6. Age conversion factor at channel 3

But which function is the best one? In order to suggest the best function to present the equivalent ages, the values of the equivalent ages based on the various functions are calculated and their respective strength is compared. Laboratory compressive strength tests had been done on the MNDC 69 concrete mixture (Table 3.1) that was used at the locations shown in Fig. 3.1. The data are presented in Table 4.1 and the compressive strength versus time graph is shown in Fig. 4.7. Also, in Table 4.1 the temperature development of the mixture is provided, so the equivalent age can be calculated. By using Eqs. 4.11 to 4.17, the equivalent ages at the laboratory can be estimated (Table 4.1) and the strength versus equivalent age graph for the MNDC 69 mixture can be plotted (Fig. 4.7). "t_L" represents the time for temperature development in concrete at the laboratory.

$$t_{NS} = \Sigma\ [(T+10)/(20+10)] \cdot \Delta t \quad (4.11)$$

$$t_R = \Sigma\ 2^{(T-20)/10}\ \Delta t \quad (4.12)$$

$$t_{WS} = \Sigma\ [(T+16)^2/1296]\ \Delta t \quad (4.13)$$

$$t_a = \Sigma\ e^{-5000\{[1/(273+T)] - [1/(273+20)]\}}\ \Delta t \quad (4.14)$$

$$t_q = \Sigma\ e^{-4100\{[1/(273+T)] - [1/(273+20)]\}}\ \Delta t \quad (4.15)$$

$$t_e = \Sigma\, e^{-3040\{[1/(273+T)] - [1/(273+20)]\}}\, \Delta t \quad \text{for } t \leq 20.7 \text{ hours and}$$

$$t_e = \Sigma\, e^{-4100\{[1/(273+T)] - [1/(273+20)]\}}\, \Delta t \quad \text{for } t > 20.7 \text{ hours and} \tag{4.16}$$

$$t_{CT} = \Sigma\, e^{0.046(T-20)}\, \Delta t \tag{4.17}$$

t_L (Hrs)	Strength (MPa)	Average Temp. (°C)	t_a (Hrs)	t_e (Hrs)	t_q (Hrs)	t_R (Hrs)	t_{WS} (Hrs)	t_{NS} (Hrs)	t_{CT} (Hrs)
24	16.5	24.4	30.9	29.5	29.5	32.6	30.2	27.5	29.4
29	37.5	40	45.8	41.7	41.7	52.6	42.3	35.9	41.9
40	43	24	59.6	55.0	55.0	67.1	55.9	48.3	55.2
48.5	46	19.4	67.8	63.3	63.3	75.2	64.1	56.7	63.4
72	51	18.9	89.9	85.6	85.6	97.0	86.2	79.3	85.8
168	63	20.9	191.0	185.8	185.8	199.2	187.1	178.2	185.8

Table 4.1. Strength development in the laboratory

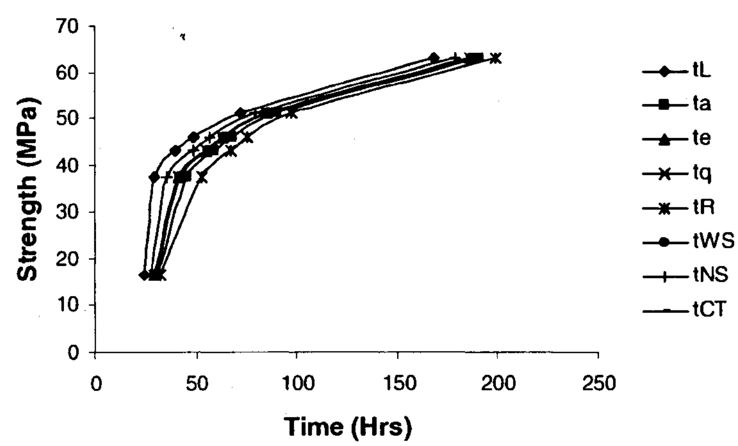

Figure 4.7. Laboratory strength development for MNDC 69 mixture

Based on Table 4.1 and Fig. 4.7 it is possible to calculate the strength development of the MNDC 69 field concrete element at channel 1, 2, and 3 locations (Fig. 3.1), by applying these maturity functions to the temperature development of the element (Appendix Tables A, B, and C). So, by taking any value of the field equivalent age (Appendix Tables A, B, and C) and applying it in Fig. 4.7 it is possible to estimate the in-field compressive strength of the element at that equivalent age and then transform it to its actual field age (Appendix Table E).

Figs. 4.8 to 4.17 represent the strength at various ages calculated by various maturity functions. It can be seen from Fig. 4.8 that the functions seem to produce similar results regarding the strength development of the in-place concrete for ages between 27 and 67 hours. However, for channel 2 and 3 (Figs. 4.9 and 4.10), the strength development significantly differs based on the maturity function that is used. For example, at 25 hours the strength based on the Nurse-Saul function is approximately 20 MPa. When the FHP, Carino and Tank, and Weaven and Sadgrove, functions are used, the strength varies between 30 and 35 MPa. Finally, when the function suggested by Rastrup is used, the strength is approximately 40 MPa.

So, it can be seen that the maturity function does have a significant role in this case. This behavior occurs because of the temperature development. In channel 1 (Fig. 4.8), the concrete undergoes temperature variances of 11°C (at very early ages) to 35°C (at ages of 25 hours). On the other hand, channel 2 and 3 undergo much higher temperature variations. In channel 2 (Fig. 4.9) the temperatures fluctuate between 18°C (at very early ages) and 51°C (at ages of 25 hours). So, there is a high temperature development in the concrete at early ages and this causes the variations produced in the strength presented by the various maturity functions. It is also stated previously that at high temperatures, the various maturity functions tend to produce variations. This is also the case for channel 3 (Fig. 4.10) where the temperatures vary between 18°C and 53°C.

Consequently, it can be concluded that if a concrete element is expected to tolerate temperatures between 20°C and 35°C, the maturity functions would produce identical strength development. However, if this is true, by keeping a constant temperature of 30°C within a concrete element it would mean that whatever maturity function is used the strength results would be the same. When observing Fig. 4.16 it can be seen that at early ages the strength development by different functions significantly differs. It can also be seen that at temperatures of 15°C (Fig. 4.11), 18°C (Fig. 4.12), and 40°C (Fig. 4.17) the strength development is very much unlike when different functions are used. The later is the case in channels 2 and 3 (Figs. 4.9 and 4.10) where the temperature development reaches 51°C and 53°C respectively. Though, when observing Figs. 4.13 to 4.15, where the temperature is at 20°C, 22°C, and 25°C respectively, it can be seen that the maturity functions do produce identical strength developments except the functions that are suggested by Weaven and Sadgrove (Eq. 4.13) and Rastrup (Eq. 4.12). That would mean that if the concrete's temperature is kept between 15°C and 35°C with average temperatures of 20°C to 25°C, the strength development would be the same no matter what the maturity function is used (except Eq. 4.12 and 4.13), which is the case in channel 1.

Finally, as to the question of which maturity function should be used? It is the author's belief that the FHP function (Eq. 4.4) along with the Carino and Tank (Eq. 4.5) one, are the two functions that should be used in representing the equivalent ages for a concrete element. Because these functions have been proved adequate in representing the concrete's strength for a wide range of temperatures. However, care should be exercised to the matter of the temperature sensitivity factor (value of B in Eq. 4.5) and the apparent activation energy, when these functions are to be used. It is previously suggested and it can also be seen from Figs. 4.8 through 4.17 that the maturity meters are not adequate enough for all the concrete mixtures and the apparent activation energy and the sensitivity factor should be calculated first and then applied to the model.

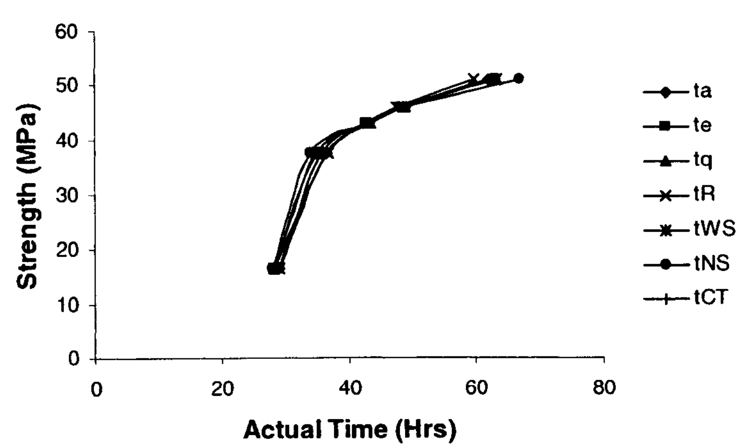

Figure 4.8. Strength development at Channel 1

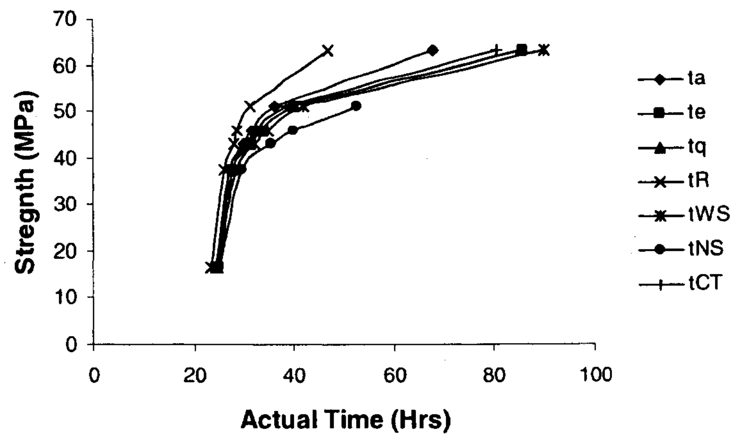

Figure 4.9. Strength development at Channel 2

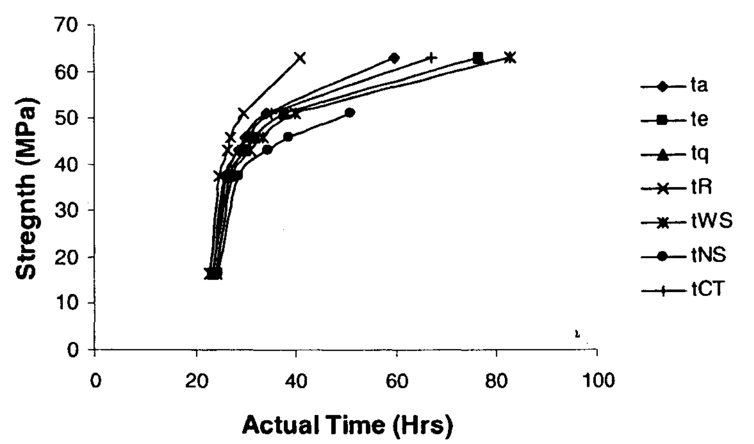

Figure 4.10. Strength development at Channel 3

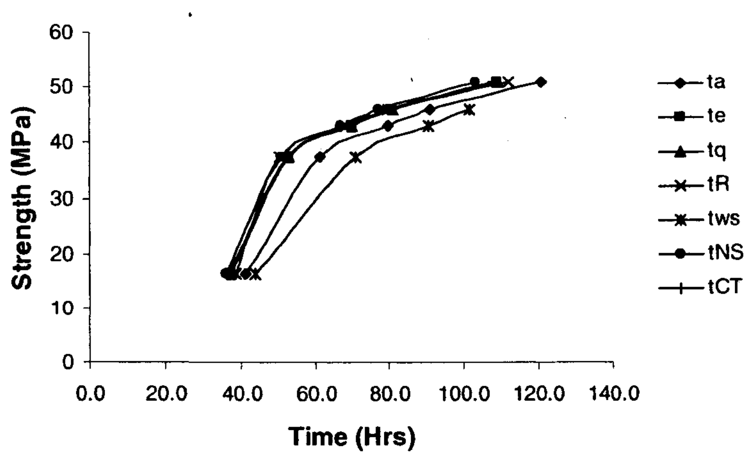

Figure 4.11. Strength development for constant temperature of 15°C

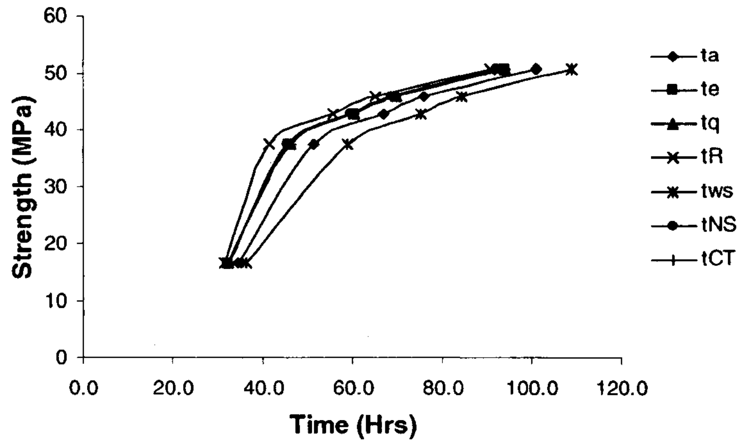

Figure 4.12. Strength development for constant temperature of 18°C

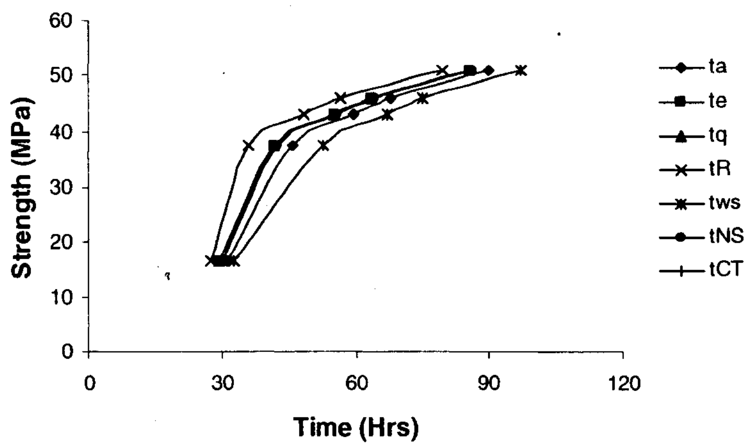

Figure 4.13. Strength development for constant temperature of 20°C

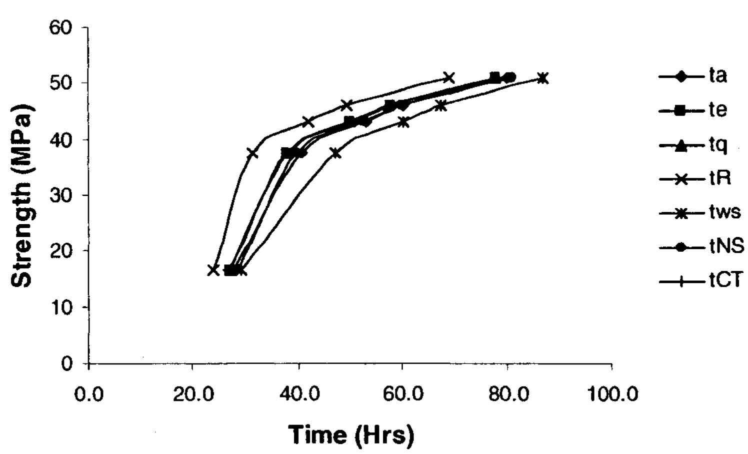

Figure 4.14. Strength development for constant temperature of 22°C

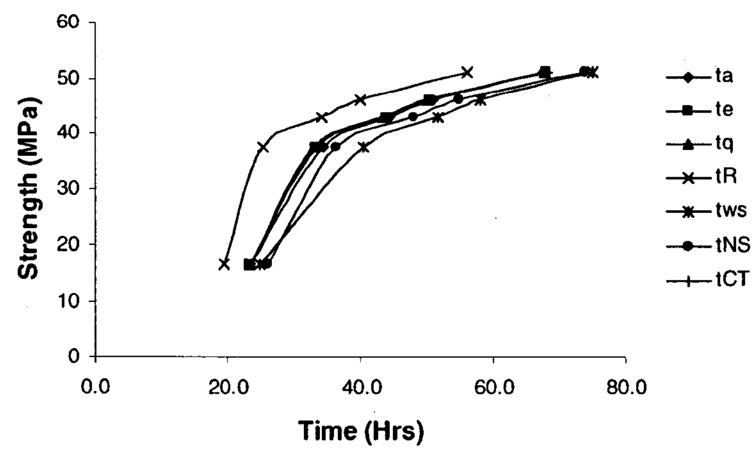

Figure 4.15. Strength development for constant temperature of 25°C

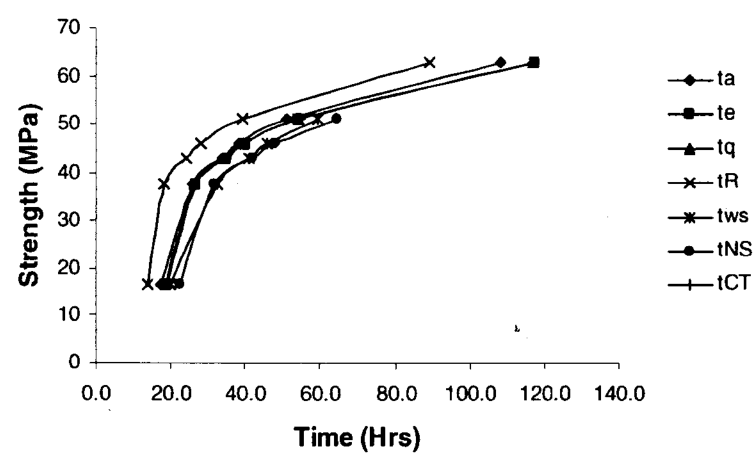

Figure 4.16. Strength development for constant temperature of 30°C

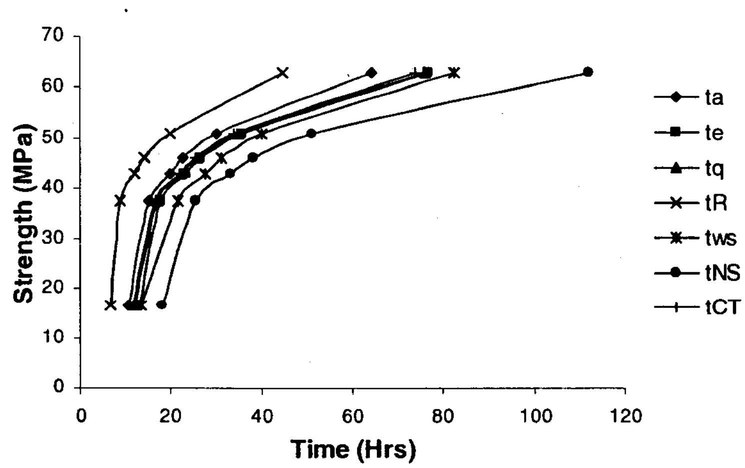

Figure 4.17. Strength development for constant temperature of 40°C

4.4 Conclusion

By concluding the results from Figs. 4.1 to 4.6, it can be suggested that the linear Nurse-Saul's function (Eq. 4.1) is not able to represent effectively the equivalent ages over the wide range of temperature. Also, Rastrup's function (Eq. 4.2) seems to overestimate the results at high temperatures. The most convenient function to estimate the equivalent ages seems to be the FHP function (Eq. 4.4) and the Carino and Tank (Eq. 4.5). These two functions give very similar results and they are prevailed in comparison with the others. Finally due to the development of temperature gradient in the wall as observed from the development of higher temperature at the centre, it would be advantageous to use a maturity function that would be representative in the whole range of temperatures. It would also be practical to use a function that would be as simple as possible. Thus, based on the results that are presented in the Figs. 4.1 through 4.17, it could be concluded that the Carino and Tank function can be used due to its simplicity and similarity with the FHP function with regards to the temperature-time influence in estimating the equivalent ages.

5 Strength – Maturity Relationships

5.1 Introduction

In this chapter various strength functions are applied to the data from the Hibernia project and then a comparison of these functions is done. Also, an improved strength model is suggested and applied to the laboratory and field data. The purpose of this study is to conclude on the efficiency of the strength models in predicting the strength development of a concrete element.

5.2 Presentation of the Strength Functions

Strength functions that are presented in section 2.2.3 are used for this analysis. The functions used are presented again in Eqs. 5.1 and 5.2 for purposes of convenience.

$$S_k = S_u \{k_r (t_e - t_{or}) / [1 + k_r (t_e - t_{or})]\} \quad (5.1)$$

$$S_{FHP} = S_u \cdot e^{-(\tau/t)^{\alpha}} \quad (5.2)$$

S_k represents the rate constant model (Eq. 2.15) and S_{FHP} represents the exponential model suggested by Freiesleben and Pederson (Eq. 2.17).

5.2.1 Rate Constant Model (S_k)

The rate constant model (Eq. 5.1) is one of the best models in representing the strength development of a concrete element. In this model, it is assumed that the strength development is dependent on the rate constant at the reference temperature. So, to use this formula it is necessary to know the rate constant value at the reference temperature, the ultimate strength, which is the strength assuming 100% hydration of the concrete, and the age at which the concrete starts to develop its strength. In this model the strength development during the setting period is ignored.

5.2.1.1 Calculation of S_u, k_r, and t_{or}

The data for the calculation of S_u, k_r, and t_{or} factors are based on laboratory tests on MNDC 69 (Table 3.1) concrete samples for compressive strength (Table 5.1) and the calculation of the equivalent ages is based on the FHP function "t_{FHP}" (Eq. 5.3) and the Carino and Tank model "t_{CT}" (Eq. 5.4), which has been manually done. The results are shown in Table 5.1. The notation "t_L" represents the time recorded in the laboratory and "S_L" represents the laboratory strength development. Fig. 5.1 shows the laboratory strength development of the MNDC 69 concrete mixture presented in Table 3.1 versus the equivalent age based on the Carino and Tank maturity function (Eq. 5.4).

$$t_{FHP} = e^{\{-4100\cdot[1/(273+T_{av})-1/293]\}}\cdot\Delta t \tag{5.3}$$

$$t_{CT} = e^{[0.046\cdot(T_{av}-20)]}\cdot\Delta t \tag{5.4}$$

t_L (Hrs)	S_L (MPa)	Temp. (°C)	t_{FHP} (Hrs)	t_{CT} (Hrs)
24	16.5	23.3	24.8	24.7
29	37.5	40	33.3	33.3
40	43	24	52.4	52.4
48.5	46	19.4	61.6	61.6
72	51	18.9	84.1	84.2
168	63	20.9	179.7	179.7

Table 5.1. Laboratory strength development of MNDC 69

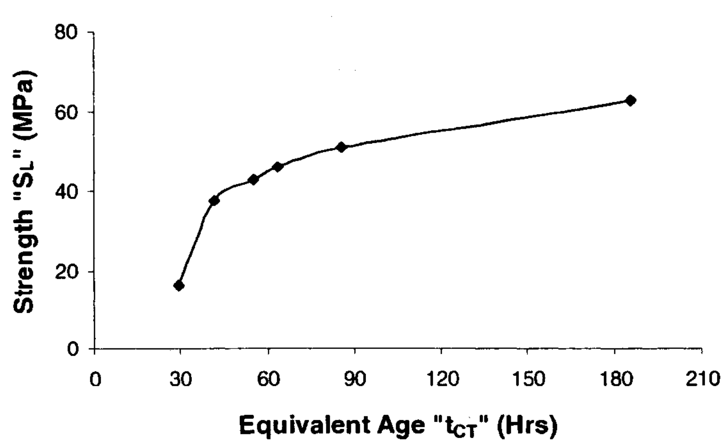

Figure 5.1. Laboratory strength development of MNDC 69

t_L (Hrs)	S_L (MPa)	Temp. (°C)	t_{FHP} (Hrs)	t_{CT} (Hrs)	$1/S_L$	$1/t_{CT}$	$S/(S_u\text{-}S)$
24	16.5	23.3	24.8	24.7	-	-	0.265273
29	37.5	40	33.3	33.3	-	-	0.910194
40	43	24	52.4	52.4	0.0233	0.019092	1.204482
48.5	46	19.4	61.6	61.6	0.0217	0.016242	1.406728
72	51	18.9	84.1	84.2	0.0196	0.011881	-
168	63	20.9	179.7	179.7	0.0159	0.005564	-

Table 5.2. Laboratory equivalent ages for MNDC 69

It can be seen from Table 5.2 that the FHP "t_{FHP}" and the Carino and Tank "t_{CT}" functions produce identical results, so for purpose of simplicity the second will be used. The next step is to calculate the ultimate strength (S_u). For that purpose the inverse of the strength of the latest four equivalent ages according to Table 5.2 is plotted against these four latest equivalent ages (Table 5.2) and the graph is shown in Fig. 5.2 [ASTM C1074 – 98].

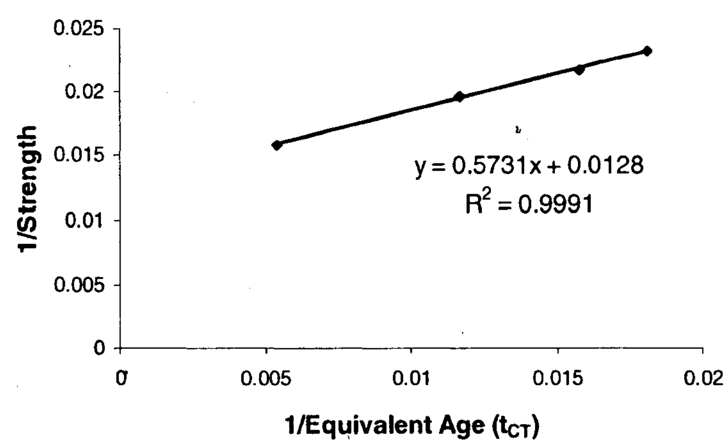

Figure 5.2. Calculation of the S_u

The ultimate strength (S_u) is the inverse of the value of the interception with the y axis and the ultimate strength (S_u) is calculated to be 78.1 MPa (1/0.0128). Then the first four ages, since we are interested for the time at which the concrete begins to gain its strength according to ASTM C1074 – 98, are plotted against the $S/(S_u\text{-}S)$ (Table 5.2) and the graph is shown in Fig. 5.3.

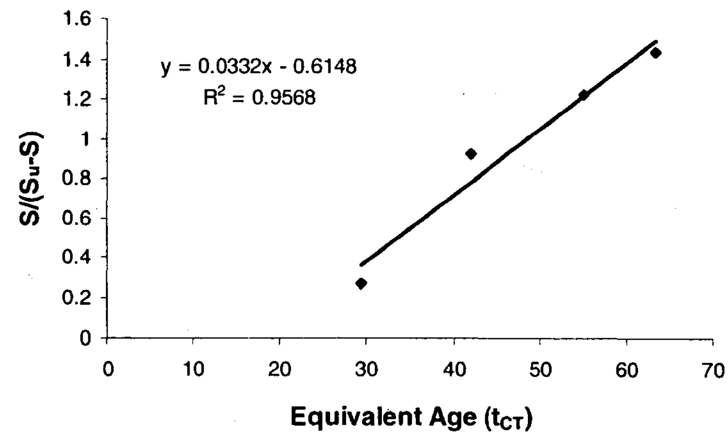

Figure 5.3. Calculation of the k_r and t_{or}

From Fig. 5.3, the rate constant at the reference temperature "k_r" and the "t_{or}" can be calculated. The slope of the best fit straight line represents the rate constant value (k_r), and the interception with the x-axis represents the age at which the concrete begins to gain strength (t_{or}).

$S_u = 78.1$ MPa

$k_r = 0.033\ h^{-1}$

$t_{or} = 18.5$ h

Fig. 5.4 shows the correlation between the lab measurements and the rate constant model for the strength calculation. The data is shown in Table 5.3, where "S_L" represents the strength from laboratory tests and "S_k" represents the strength derived by the rate constant model (Eq. 5.1).

t_L (Hrs)	t_{CT} (Hrs)	S_L (MPa)	S_k (MPa)
24	29.4	16.5	20.6
29	41.9	37.5	34.1
40	55.2	43	42.8
48.5	63.4	46	46.6
72	85.8	51	53.8
168	185.8	63	66.1

Table 5.3. Compressive strengths based on lab tests and the rate constant model.

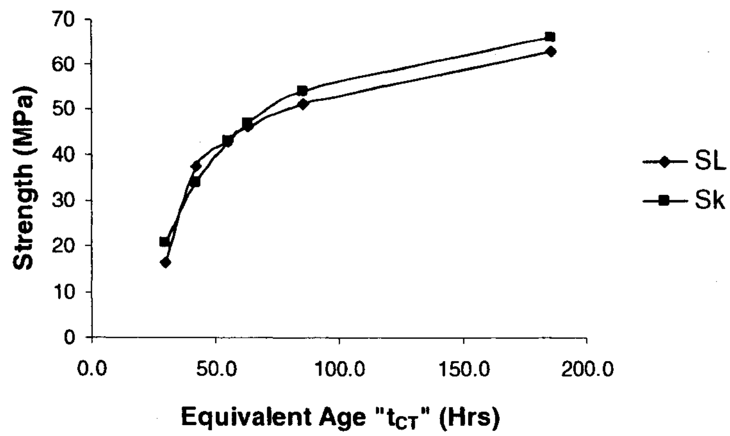

Figure 5.4. Strength development based (S_L) and (S_k)

The correlation coefficient (R^2) for the rate constant model and the data from the laboratory tests is 0.98. It can be seen that the rate constant model can represent the strength development of the concrete mixture efficiently for ages above the first day, since at early ages there is a variation that needs attention.

5.2.2 FHP Strength Model

Freiesleben and Pederson (1985) have also suggested a model for representing the strength development for a concrete mixture (Eq. 5.2). In that model the rate constant factor has been replaced by the inverse of a time constant at the reference temperature. Since there are no restrictions with regard to the beginning of the gain of strength, the FHP strength model is able to account for the strength development at the very early ages (during the setting) as well.

5.2.2.1 Calculation of Time Constant "τ" and Shape Parameter "α"

The calculation of "τ" and "α" is based on equivalent ages according to the Carino and Tank function (t_{CT}) (Eq. 5.4).

First the ultimate strength (S_u) is estimated. The same procedure as used for the previous model is used in this one as well. Then, the logarithm of the natural logarithm of the fraction of the ultimate strength (S_u) and the laboratory tested strength (S_L) is plotted against the logarithm of the equivalent time (t_{CT}) for the latest four ages (55.2, 63.4, 85.8, and 185.8 in Table 5.4). After that, the best fit straight line is drawn and the slope and the interception point are estimated. The slope of the line represents the shape parameter "α", and the interception with the y-axis represents the "$\alpha \cdot \text{Log}(\tau)$", so the value for the time constant "τ" can be obtained with a simple calculation. The value of Su is 78.1 MPa as calculated in section 5.2.1.1.

t_L (Hrs)	S_L (MPa)	t_{CT} (Hrs)	Log $[\text{Ln}(S_u/S_L)]$	Log (t_{CT})
24	16.5	29.4	-	-
29	37.5	41.9	-	-
40	43	55.2	-0.22418	1.741567
48.5	46	63.4	-0.27626	1.802235
72	51	85.8	-0.37042	1.933294
168	63	185.8	-0.66785	2.269092

Table 5.4. Calculation of "α" and "τ"

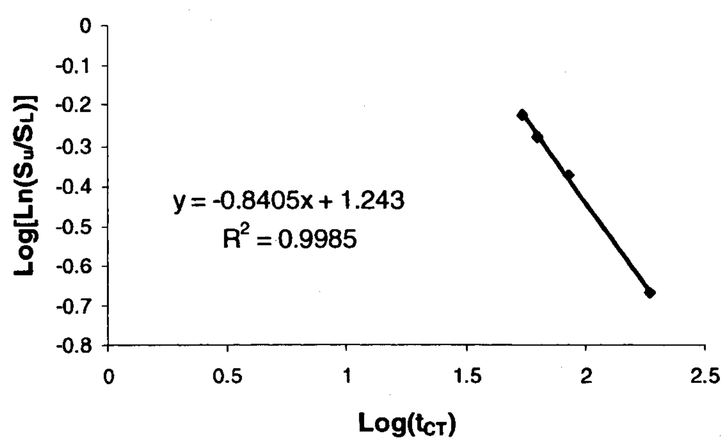

Figure 5.5. Calculation of "α" and "τ"

So, the shape parameter "α", which is the slope of the best fit straight line of Fig. 5.5, is 0.841. Then the time constant value for the MNDC 69 concrete mixture can be calculated. The intercept with the y-axis is 1.243 which represents the value of "α·Log (τ)". So, the value of "τ" would be $10^{(1.243/0.841)}$, which is 30.1 hours. It was suggested [Carino and Lew, 2001] that the inverse of "τ" represents the value of the rate constant "k". Thus, "k_r" in that case would be 1/30.1 which is 0.033 h^{-1}. This value agrees with the value derived from the rate constant model whose use is currently suggested by the ASTM C1074-98.

So, based on these data the strength development of the concrete mixture in the lab environment can be calculated by using Eqs. 5.2 and 5.4, and the values of "α" and "τ" as derived above. The results are shown in Table 5.5 and Fig. 5.6. As it can be seen from Fig. 5.6, the FHP model can represent the concrete's strength development with an excellent correlation (R^2 = 0.999) with the laboratory compressive strength for ages above the first day of concrete curing. For earlier ages, the model produces variations and should not be used.

t_L (Hrs)	t_{CT} (Hrs)	S_L (MPa)	S_{FHP} (MPa)
24	29.4	16.5	28.3
29	41.9	37.5	35.4
40	55.2	43	42.6
48.5	63.4	46	45.7
72	85.8	51	51.8
168	185.8	63	62.8

Table 5.5. Compressive strength based on S_L and S_{FHP}.

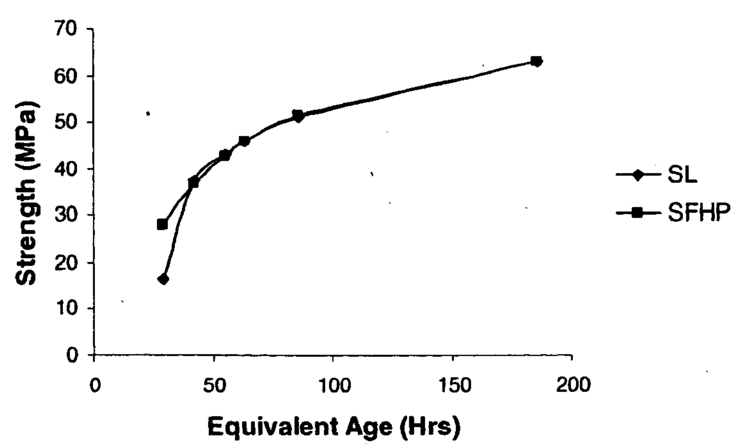

Figure 5.6. Strength development based on S_L and S_{FHP}

5.2.3 Improved FHP Strength Model

As it is stated in the previous section, the FHP strength model is not able to account for very early ages. The reason could be that the strength development based on that model is assumed to begin as soon as the concrete is mixed with the water. As it can be seen in Tables 5.6 to 5.8, at the time of the initial setting of the concrete at channels 1, 2, and 3 (Fig. 3.1) respectively, which are 20.5, 18.0, and 17.5 hours according to the 2°C temperature increase method, the strength calculated by the FHP model is 15.8 MPa, 14.4 MPa, and 13.9 MPa respectively which is not possible. The equivalent ages in Tables 5.6, 5.7, and 5.8 are calculated based on the Carino and Tank formula "t_{CT}' (Eq. 5.4).

Actual Time (Hrs)	Temp. (°C)	Average Temp. (°C)	t_{CT} (Hrs)	S_{FHP} (MPa)
0	8	8	0.0	-
0.5	11	9.5	0.3	0.0
1	11	11	0.7	0.0
1.5	11	11	1.1	0.0
2	11	11	1.5	0.0
2.5	11	11	1.8	0.0
3	11	11	2.2	0.0
3.5	11	11	2.6	0.0
4	11	11	2.9	0.1
4.5	11	11	3.3	0.1
5	11	11	3.7	0.2
5.5	12	11.5	4.0	0.3
6	12	12	4.4	0.5
6.5	13	12.5	4.8	0.7
7	13	13	5.2	1.0
7.5	13	13	5.6	1.3
8	13	13	6.0	1.6
8.5	13	13	6.4	2.0
9	13	13	6.8	2.3
9.5	14	13.5	7.2	2.8
10	14	14	7.6	3.2
10.5	14	14	8.0	3.7
11	14	14	8.4	4.2
11.5	15	14.5	8.8	4.7
12	15	15	9.2	5.2

12.5	15	15	9.7	5.8
13	15	15	10.1	6.4
13.5	16	15.5	10.5	6.9
14	16	16	10.9	7.5
14.5	17	16.5	11.4	8.1
15	17	17	11.8	8.7
15.5	17	17	12.3	9.3
16	18	17.5	12.8	10.0
16.5	18	18	13.2	10.6
17	18	18	13.7	11.2
17.5	19	18.5	14.2	11.9
18	19	19	14.6	12.5
18.5	20	19.5	15.1	13.1
19	20	20	15.6	13.8
19.5	21	20.5	16.1	14.4
20	22	21.5	16.7	15.1
20.5	23	22.5	17.2	**15.8**

Table 5.6. Strength Development of Channel 1 according to FHP Strength Model

Actual Time (Hrs)	Temp. (°C)	Average Temp. (°C)	t_{CT} (Hrs)	S_{FHP} (MPa)
0	12	12	0.0	-
0.5	18	15	0.4	0.0
1	18	18	0.9	0.0
1.5	17	17.5	1.3	0.0
2	16	16.5	1.8	0.0
2.5	16	16	2.2	0.0
3	15	15.5	2.7	0.0
3.5	15	15	3.1	0.1
4	15	15	3.5	0.2
4.5	14	14.5	3.9	0.3
5	14	14	4.3	0.5
5.5	14	14	4.7	0.7
6	15	14.5	5.1	0.9
6.5	15	15	5.6	1.3
7	15	15	6.0	1.6
7.5	15	15	6.4	2.0
8	16	15.5	6.8	2.4
8.5	16	16	7.3	2.9
9	16	16	7.7	3.4
9.5	16	16	8.2	3.9
10	16	16	8.6	4.4
10.5	16	16	9.0	5.0

11	16	16	9.5	5.5
11.5	16	16	9.9	6.1
12	16	16	10.3	6.7
12.5	17	16.5	10.8	7.3
13	17	17	11.2	7.9
13.5	17	17	11.7	8.5
14	18	17.5	12.1	9.1
14.5	18	18	12.6	9.8
15	19	18.5	13.1	10.4
15.5	19	19	13.6	11.1
16	20	19.5	14.1	11.7
16.5	20	20	14.6	12.4
17	20	20	15.1	13.0
17.5	21	20.5	15.6	13.7
18	22	21.5	16.1	**14.4**
18.5	23	22.5	16.6	15.0
19	25	24	17.2	15.8
19.5	26	25.5	17.8	16.5
20	28	27	18.4	17.3
20.5	31	29.5	19.1	18.1

Table 5.7. Strength Development of Channel 2 according to FHP Strength Model

Actual Time (Hrs)	**Temp. (°C)**	**Average Temp. (°C)**	**t_{CT} (Hrs)**	**S_{FHP} (MPa)**
0	11	9.5	0.0	-
0.5	18	14.5	0.4	0.0
1	17	17.5	0.9	0.0
1.5	17	17	1.3	0.0
2	16	16.5	1.8	0.0
2.5	16	16	2.2	0.0
3	15	15.5	2.6	0.0
3.5	15	15	3.1	0.1
4	15	15	3.5	0.2
4.5	14	14.5	3.9	0.3
5	14	14	4.3	0.5
5.5	14	14	4.7	0.7
6	14	14	5.1	0.9
6.5	15	14.5	5.5	1.2
7	15	15	6.0	1.6
7.5	15	15	6.4	2.0
8	15	15	6.8	2.4
8.5	16	15.5	7.2	2.8
9	16	16	7.7	3.3

9.5	16	16	8.1	3.8
10	16	16	8.5	4.4
10.5	16	16	9.0	4.9
11	16	16	9.4	5.5
11.5	17	16.5	9.9	6.0
12	17	17	10.3	6.6
12.5	17	17	10.8	7.3
13	17	17	11.2	7.9
13.5	18	17.5	11.7	8.5
14	18	18	12.1	9.1
14.5	19	18.5	12.6	9.8
15	20	19.5	13.1	10.4
15.5	20	20	13.6	11.1
16	21	20.5	14.1	11.8
16.5	21	21	14.6	12.5
17	22	21.5	15.2	**13.2**
17.5	23	22.5	15.7	13.9
18	24	23.5	16.3	14.6
18.5	26	25	16.9	15.3
19	28	27	17.5	16.1
19.5	30	29	18.2	16.9
20	32	31	18.9	17.8
20.5	36	34	19.7	18.7

Table 5.8. Strength Development of Channel 3 according to FHP Strength Model

So, it is suggested by the author that the time at which strength begins based on the FHP model should be after the time of the initial setting, since at initial setting the strength of a concrete mixture has been suggested to be between 0.1 and 0.24 MPa [Dinesku and Radulescu 1984, Reddi et al. 1985]. So, if at initial setting time the concrete's strength is approximately 0.2 MPa, the later strength approximation based on the model would not be significantly affected. The equivalent time of the initial setting can be calculated based on the maturity method as it has been discussed in the previous chapter. So, by applying the initial setting to the FHP strength model (Eq. 5.2) the proposed model can be derived as Eq. 5.5.

$$S_c = S_u \cdot e^{-[\tau/(t_{CT}-t_{ir})]^{\alpha}} \qquad \textbf{(5.5)}$$

Where, t_{ir} represents the initial setting time at the reference temperature (20°C). This model is able to characterize the strength development in a more efficient way as it can be seen in Figs. 5.9 to 5.11. This is due to the fact that the S_c model (Eq. 5.5) is based on the FHP strength model (Eq. 5.2), which is able to represent the strength development of the concrete with great accuracy at ages beyond the setting time. Moreover, the S_c model has the advantage that is able to represent the strength development at ages prior to the setting time. According to this model (Eq. 5.5) when the age beyond the initial setting time (t_{ir}) is equal to the inverse of the rate constant, then the compressive strength is equal to 37% of the ultimate strength of the concrete mixture (Eq. 5.6). This means that the time constant (τ) of this model is equal to the inverse of the rate constant (k) [Carino and Lew 2001].

$$\left.\begin{array}{l} S_c = S_u \cdot e^{-[\tau/(t_{CT}-t_{ir})]^{\alpha}} \\ \tau = t_{CT} - t_{ir} \end{array}\right\} \quad S_c = S_u \cdot e^{-1^{\alpha}} \Leftrightarrow S_c = S_u/e \Leftrightarrow S_c = 0.37 \cdot S_u \qquad (5.6)$$

In order to compare the relationship of the strength development based on the lab tests and the model, Eq. 5.5 is applied to the lab data and the results are shown in Table 5.10 and Fig. 5.8. From Table 3.4, the equivalent initial setting time "t_{ir}" for the MNDC 69 mixture (Table 3.1) is 18.7 hours. So, by plotting the logarithm of the natural logarithm of the "$t_{CT} - t_{ir}$" against the natural logarithm of the "S_u/S_L", the value of "τ" and "α" can be obtained as in section 5.2.2.1 (Table 5.9 and Fig. 5.7). For S_u the value of 78.1 MPa is used and for the equivalent ages t_{CT} Eq. 5.4 is employed.

t_L (Hrs)	S_L (MPa)	t_{CT} - t_{ir} (Hrs)	Log [Ln(S_u/S_L)]	Log (t_{CT} - t_{ir})
24	16.5	10.5	-	-
29	37.5	20.5	-	-
40	43	35.2	-0.22418	1.549227
48.5	46	43.5	-0.27626	1.64035
72	51	66.8	-0.37042	1.825891
168	63	165.0	-0.66785	2.218024

Table 5.9. Calculation of "α" and "τ"

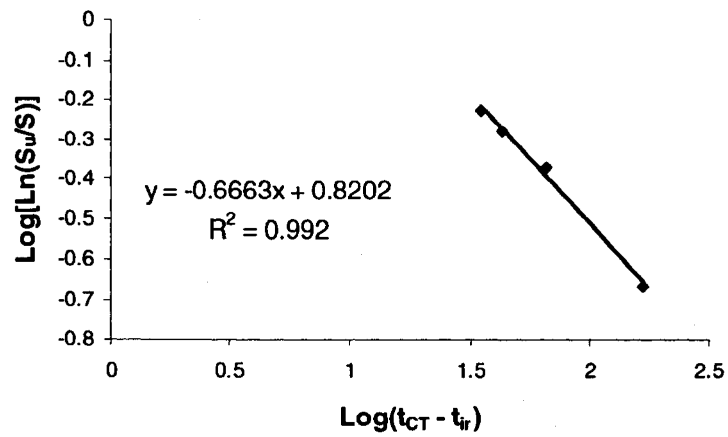

Figure 5.7. Calculation of "α" and "τ"

So, from Fig. 5.7 the value for "α" and "τ" can be estimated. The slope of the best fit straight line in Fig. 5.7 represents the value of "α" and the interception with the y-axis represents the "α · Log(τ)".

$\alpha = 0.6663$

$\tau = 10^{(0.8202 / 0.6663)} = 17.0$ hours

Then the values of "α" and "τ" can be used to estimate the strength development based on the proposed improved strength model "S_c" (eq. 5.5) (Table 5.10).

t_L (Hrs)	S_L (MPa)	t_{CT} (Hrs)	S_c (MPa)
24	16.5	29.4	20.0
29	37.5	39.4	32.4
40	43	54.1	42.3
48.5	46	62.4	45.8
72	51	85.7	52.3
168	63	183.9	62.7

Table 5.10. Compressive strength based on S_L and S_c.

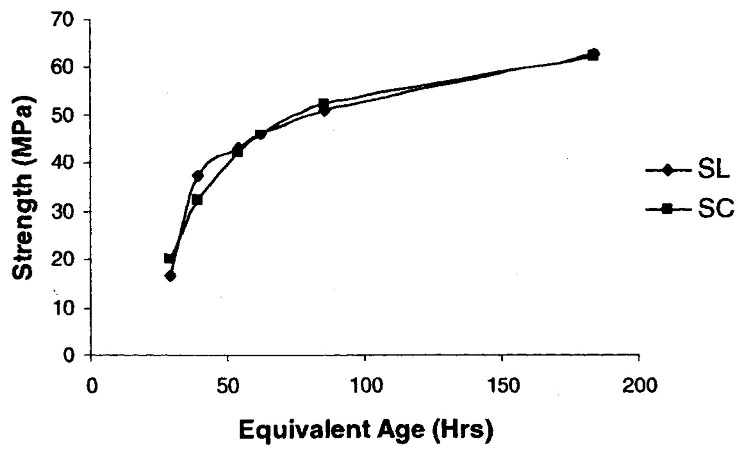

Figure 5.8. Strength development based on S_L and S_c.

It can be seen from figure 5.8 that the proposed model (S_c) can represent the laboratory strength development in a very efficient way with a correlation coefficient (R^2) of 0.984 at the whole range of ages. So, once the initial setting time at the reference temperature is calculated, the proposed model (Eq. 5.5) can be applied for estimating the strength development of concrete in the laboratory.

5.3 Application of the Strength Models on the MNDC69 Field Data

It has been studied so far how these strength models represent the strength development of the concrete under the laboratory environment. In this section, the rate constant (S_k), the FHP (S_{FHP}), and the proposed (S_C) models are applied to the MNDC 69 field data (Appendix Tables F, G, and H). The temperature time history of the MNDC69 concrete mixture at three locations (channel 1, 2, and 3) at an elevation of 10.5 m is used (Fig. 3.1). Tables 5.11, 5.12, and 5.13 show the field strength development for channels 1, 2, and 3 respectively. These data are used to plot Figs. 5.9, 5.10, and 5.11 which show the field strength development of the MNDC 69 concrete mixture mentioned above. The full data are presented in Tables F, G, and H of the Appendix. The strength development based on the "S_k", "S_{FHP}", and "S_c" models is calculated according to the Eqs. 5.1, 5.2, and 5.5 respectively. The equivalent age used for those models is based on the Carino and Tank maturity function "t_{CT}" (Eq. 5.4).

Actual Time (Hrs)	t_{CT} (Hrs)	S_{FHP} (MPa)	S_k (MPa)	S_c (MPa)	S_L (MPa)
0	0.0	-	-122.41	-	0
10	7.6	3.22	-43.96	-	0
20	16.7	15.10	-5.01	-	0
30	33.0	30.98	25.32	25.48	24.20
40	50.6	40.91	40.14	40.44	41.65
50	66.3	46.69	47.82	47.22	47.37
60	80.9	50.54	52.58	51.26	49.33
70	96.1	53.59	56.17	54.26	51.38
80	108.7	55.61	58.46	56.18	53.07
90	121.7	57.35	60.37	57.80	54.83
100	132.6	58.59	61.71	58.93	56.29
110	141.5	59.50	62.66	59.75	57.49
120	149.6	60.24	63.43	60.42	58.58

Table 5.11. Strength development of Channel 1.

Actual Time (Hrs)	t_{CT} (Hrs)	S_{FHP} (MPa)	S_k (MPa)	S_c (MPa)	S_L (MPa)
0	0	-	-122.4	-	0
10	8.6	4.4	-38.0	-	0
20	18.4	17.3	-0.1	-	0
30	50.4	40.8	40.0	40.3	41.6
40	88.4	52.1	54.5	52.8	50.3
50	118.4	56.9	59.9	57.4	54.4
60	142.6	59.6	62.8	59.8	57.6
70	163.2	61.4	64.6	61.4	60.4
80	181.2	62.6	65.8	62.5	62.8
90	197.2	63.6	66.8	63.4	-
100	211.8	64.3	67.5	64.1	-
110	224.6	64.9	68.1	64.6	-
120	235.9	65.4	68.5	65.0	-

Table 5.12. Strength development of Channel 2.

Actual Time (Hrs)	t_{CT} (Hrs)	S_{FHP} (MPa)	S_k (MPa)	S_c (MPa)	S_L (MPa)
0	0	-	-122.41	-	0
10	8.5	4.36	-38.27	-	0
20	18.9	17.79	1.00	0.00	0
30	54.6	42.62	42.48	42.55	43.16
40	97	53.75	56.35	54.41	51.50
50	130.4	58.36	61.46	58.72	56.00
60	156.7	60.84	64.06	60.96	59.54
70	178.4	62.43	65.66	62.38	62.46
80	197.1	63.57	66.77	63.38	-
90	213.4	64.42	67.59	64.14	-
100	228.2	65.10	68.24	64.74	-
110	241.8	65.67	68.77	65:24	-
120	254.1	66.13	69.20	65.65	-

Table 5.13. Strength development of Channel 3.

The SL values from Tables 5.11, 5.12, and 5.13 are calculated based on the t_{CT} values of these tables and Fig. 5.1. The t_{CT} have been corresponded to the graph in Fig. 5.1 and the respective strength values have been established.

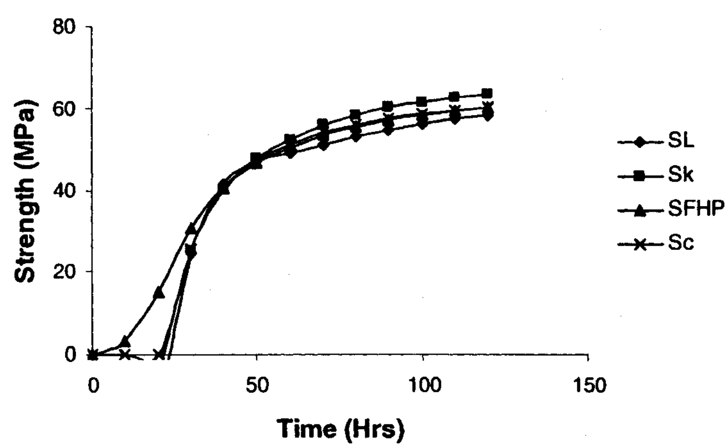

Figure 5.9. Strength development of Channel 1

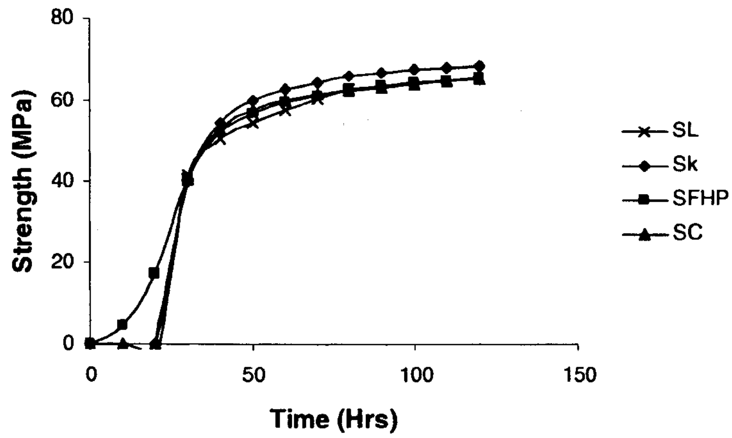

Figure 5.10. Strength development of Channel 2

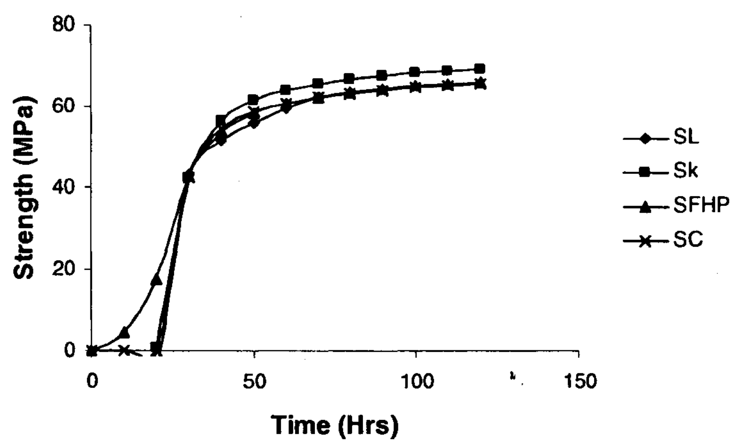

Figure 5.11. Strength development of Channel 3

It can be seen from the graphs in Figs. 5.9 to 5.11 that the FHP strength model "S_{FHP}" (Eq. 5.2) is not efficient for very early ages (below 24 hours). On the other hand, it can be seen from Figs. 5.9 to 5.11 that the rate constant model "S_k" (Eq. 5.1) seems to produce very good results for those ages. The opposite is true for the later ages (above 24 hours). The rate constant model seems to overestimate the strength development for ages above 24 hours. On the contrary, the FHP model for these ages appears to produce excellent results when compared with the strength versus equivalent age relationship produced in the laboratory. Finally, the improved FHP model "S_c" (Eq. 5.5) seems to be able to represent the strength development in the whole spectrum of ages producing very good results. This is confirmed from all of the figures from 5.9 to 5.11.

5.4 Conclusion

In conclusion, it could be said that the FHP strength model is not good enough to account for the strength development at ages below the 30 hours, but when it is used for later ages it produces very good results. The opposite is true for the rate constant model. The proposed model is adequate for the whole spectrum of ages. Once the initial setting time at the reference temperature is obtained, the proposed model can be successfully used to predict the development of strength of concrete in the laboratory.

Concerning the field strength development, these models can be complicated. The problem in calculating the strength of the field concrete by any of those models is the ultimate strength (S_u). This is the case when the construction takes place in very hot weather or in very cold weather. In such situations, the ultimate strength of the field concrete might differ from the one calculated in the laboratory [Malhotra and Carino 1991]. So, even though the models seem to give a good approximation of the strength development of the in place concrete (Figs. 5.9, 5.10, and 5.11) their efficiency can be questioned if the temperature development of the concrete cured in the laboratory is different from the field curing temperature. In such a case, the ultimate strength would be different for the field concrete and the laboratory concrete and since none of these models is able to account for such effects, they could possibly produce inefficient results.

Therefore, care should be taken when these models are used to predict the strength development of field concrete. It is suggested that, if the field curing conditions are expected to be significantly different from the laboratory setting, then instead of using these models to estimate the strength, they could more efficiently be used to calculate the relative strength "RS". The relative strength is the ratio of the strength to the ultimate strength (S/S_u). More appropriately, it is suggested by Carino and Lew [Carino and Lew 2001], that the 28-day strength should be used instead of the ultimate strength. The relationship between the ultimate strength and the 28-day strength "S_{28}" could be established by the use of the factor "β". The value of "β" is equal to the fraction of the ultimate strength and the 28-day strength (S_u/S_{28}). Further investigation in this matter should be done to efficiently apply the strength models in the field regardless of the field weather conditions.

6 The Maturity Method in Slipforming Technique

6.1 Introduction

It is possible to estimate the initial setting times by using the maturity method [Pinto and Hover 1999]. In this chapter, a validation of the predicting ability of the maturity method will be presented by using data from the Hibernia project. Subsequently, the initial setting times derived by the maturity method will be compared with those obtained from various methods used in the Hibernia project such as “2°C Temperature Increase (2 C) or Box”, “Rod (R)”, and “Penetration Resistance (PR)”. Also, the performance of another method for calculating the initial setting times, known as the “Conductivity (C)” method [Elimov 2003] will be compared with the maturity method.

The initial setting times that are calculated by the maturity method are based on laboratory results implemented by the “2°C Temperature Increase (2 C) or Box”, “Rod (R)”, “Penetration Resistance (PR)”, and the “Conductivity (C)” methods. These methods are also used to estimate the actual initial setting times and then compared with the initial setting times estimated by maturity method. So, the “2°C Temperature Increase (2 C) or Box”, “Rod (R)”, “Penetration Resistance (PR)”, and the “Conductivity (C)” methods, are used as a tool in the laboratory for estimating the initial setting times by the maturity method, and also, for comparing their calculated initial setting times [Elimov 2003] with the one calculated by the maturity method.

The main objective of this chapter is to develop a method to determine a hardened front elevation of concrete layers within the slipforms. By knowing the hardened front elevation, which implies knowing of the time at which a specific part of the concrete inside the slipform has hardened, the slipform speed can be prearranged, and the planning of the slipforming mock-up (removal of the slipform) could be efficiently designed.

6.2 Presentation of Data

It is important to simulate the temperature conditions of the concrete inside the slipping forms, as they influence significantly the initial setting time of the concrete. Simulation of the initial concrete temperatures is important in order to arrange the layers within the slipform in an efficient manner. So, the knowledge of initial setting time for each initial concrete temperature is of great importance.

The concrete temperature development has been simulated at initial concrete temperatures of 10°C, 15°C, and 20°C. Also, different retarder dosages have been used in order to ensure the best mixture solution. Retarder dosages of 0, 100, 200, 300, 400, and 500 ml/100 kg of cement have been used for this purpose. The concrete mixture used for this study is the one used in the Hibernia project for the construction of the base gravity structure (Table 6.1).

Material	Mix proportions
Cement	450 kg/ m^3
Water	152 kg/ m^3
Fine Aggregates	830 kg/ m^3
Coarse Aggregates	910 kg/ m^3
Superplasticizer EU-37	1400 ml/100 kg cement
Water Reducer TCDA-37	0, 100, 200, 300, 400, 500 ml/100 kg cement
Air Entraining Agent AEX	15 ml/100 kg cement

Table 6.1. Hibernia base gravity structure mixture

In the Hibernia project, the "2°C Temperature Increase (2 C)" and the "Penetration Resistance (PR)" methods have been used to determine the initial setting times in the laboratory and the "Rod (R)" method has been used in the field as a confirmation. These methods are introduced in section 2.9 of this thesis. The laboratory results of the concrete initial setting times are presented in the Tables 6.2 and 6.3.

Retarder Dosage (ml/100 kg cement)	Initial Setting Time at 15°C (Hrs)	Initial Setting Time at 20°C (Hrs)
0	8.0	6.5
100	11.6	10.5
200	15.5	14.0
300	20.7	18.4
400	24.7	23.5

Table 6.2. Initial setting times by the "2°C Temperature Increase (2 C)" method

Retarder Dosage (ml/100 kg cement)	Initial Setting Time at 10°C (Hrs)	Initial Setting Time at 15°C (Hrs)
100	9.4	8.7
300	20.4	17.9
400	23.75	21.62
500	26.0	23.5

Table 6.3. Initial setting times by the "Penetration Resistance (PR)" method.

6.3 Maturity Approach

The concept of the maturity method in determining the initial setting times is to calculate the equivalent initial setting time at the reference temperature in the laboratory. Then the simulation of the temperature development of the concrete mixture is taking place in the laboratory and the equivalent initial setting time is applied so as to estimate the actual initial setting time that the concrete is expected to have on site. Following the method suggested by Pinto and Hover (1999) the equivalent initial setting times are estimated based on laboratory results of the "2°C Temperature Increase (2 C)" and the "Penetration Resistance (PR)" methods. According to Pinto and Hover (1999) if the initial setting times of a concrete mixture cured under two different temperatures are known, then the apparent activation energy and consequently the equivalent initial setting time can be calculated. In order to calculate the equivalent initial setting time, the average concrete temperature for the period up to the initial setting time is needed. For that reason, the knowledge of the temperature development of the concrete mixture is necessary. So, after knowing the initial setting times and the temperature development for the mixture (presented in Table 6.1), the equivalent initial setting time can be established. The concept suggested by Pinto and Hover (1999) was based on the maturity function suggested by Freiesleben and Pederson "t_{FHP}" (Eq. 6.1). It was also suggested in Chapter 4 that the Carino and Tank maturity function "t_{CT}" (Eq. 6.2) can be used instead. In this section, both "t_{FHP}" and "t_{CT}" functions will be used and the results will be compared, but in order to estimate the initial setting times for the various dosages of the retarder accurately, the temperature sensitivity factor corresponding to the different retarder dosages should be firstly estimated. For that purpose, a similar procedure to the one suggested by Pinto and Hover (1999) (Chapter 3) will be followed to estimate the temperature sensitivity factor (B).

The equivalent initial setting time is calculated from laboratory results based on the setting times estimated by both the "2°C Temperature Increase (2 C)" method (Table 6.2) and the "Penetration Resistance (PR)" method (Table 6.3). The average concrete temperature up to the initial setting time is calculated based on Figs. 6.5, 6.6, and 6.7 (Appendix Tables I, J, and K).

$$\mathbf{t_{FHP} = e^{-Q\cdot\{[1/(273+T_{av})] - 1/293\}} \cdot t_i} \qquad \mathbf{(6.1)}$$

$$\mathbf{t_{CT} = e^{B\cdot(T_{av} - 20)} \cdot t_i} \qquad \mathbf{(6.2)}$$

The notation Q stands for the fraction of the apparent activation energy (E) and the universal gas coefficient (R), and "t_i" stands for the initial setting time calculated either by the "2°C Temperature Increase" method or the "Penetration Resistance" method.

6.3.1 Estimation of Temperature Sensitivity Factor for the Various Retarder Dosages

In the maturity function that was suggested by Carino and Tank (Eq. 4.5), the temperature sensitivity factor (B) can be calculated with the same procedure that was used for the calculation of the apparent activation energy (Chapter 3). So, by using the data from Table 3.2 and Figs. 3.2 and 3.3, the temperature sensitivity factor (B) can be estimated. The data for the calculation of the temperature sensitivity factor (B) that are based on Table 3.2 and Figs. 3.2 and 3.3, are shown in Table 6.4.

Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Average Concrete Temp. (°C)
Retarder Dosage = 100 ml/100 kg of cement		
15	11.6	17.1
20	10.5	20
Retarder Dosage = 200 ml/100 kg of cement		
15	15.5	17.1
20	14.0	20
Retarder Dosage = 300 ml/100 kg of cement		
15	20.7	17.1
20	18.4	20.4

Table 6.4. Data for the calculation of B

Based on Table 6.4 the average concrete temperature can be plotted against the natural logarithm of the inverse of the initial setting time (Figs. 6.1, 6.2 and 6.3). Based on these figures the slope of the best fit straight line represents the temperature sensitivity factor (B), as was the case with the apparent activation energy (Chapter 3). The temperature sensitivity factors for each retarder dosage are shown in Table 6.5.

Retarder Dosage (ml/100kg cement)	Temperature Sensitivity Factor (B) (1/°C)
100	0.0344
200	0.0351
300	0.0357

Table 6.5. Values of B for different retarder dosages.

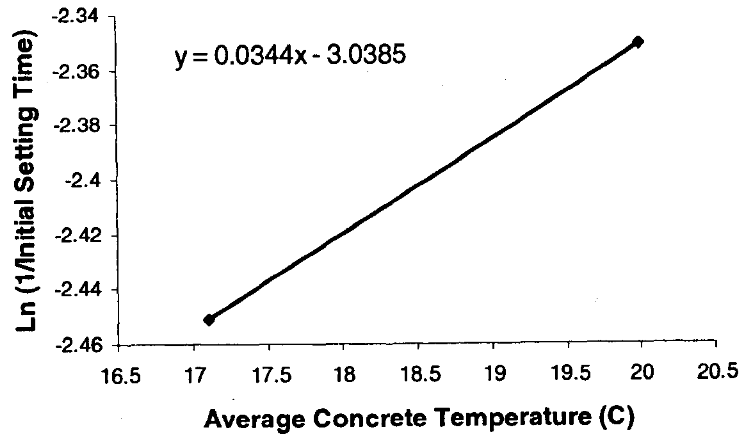

Figure 6.1. B for retarder dosage of 100 ml/100 kg of cement

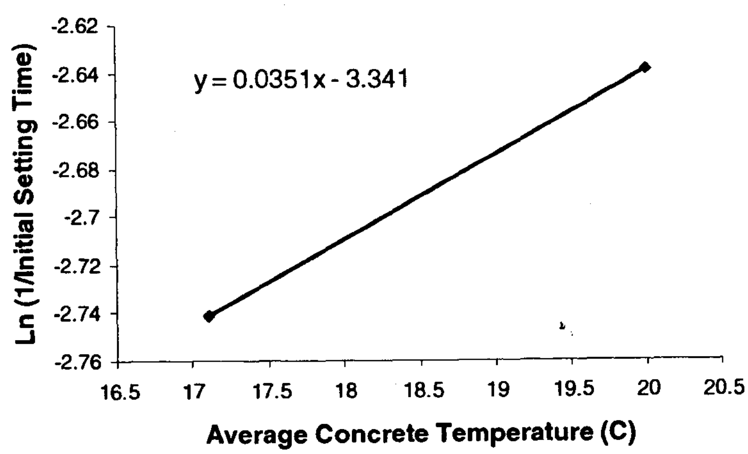

Figure 6.2. B for retarder dosage of 200 ml/100 kg of cement

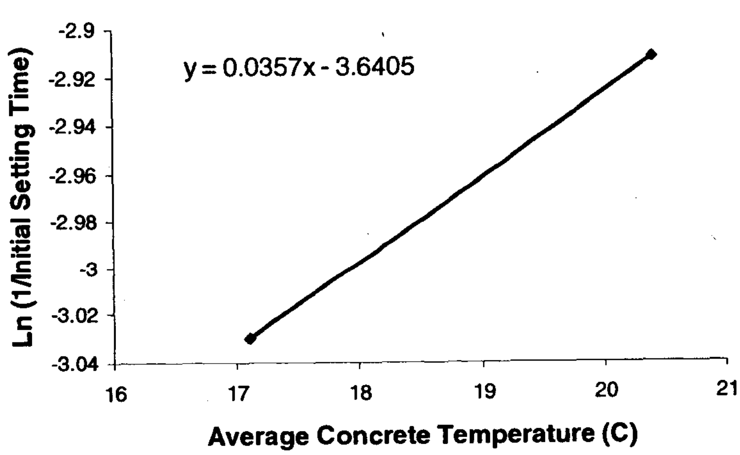

Figure 6.3. B for retarder dosage of 300 ml/100 kg of cement

Fig. 6.4 shows the relationship between the temperature sensitivity factor and the retarder dosage based on Table 6.5.

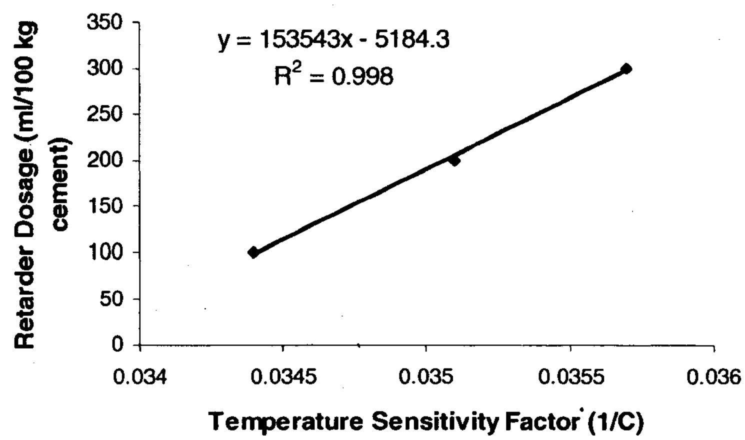

Figure 6.4. Relationship of B with the retarder dosage

It can be seen from Fig. 6.4 that the temperature sensitivity factor (B) has a linear relationship with the retarder dosage, as was the case with the apparent activation energy (E) (Fig. 3.15). So, it can be concluded that the temperature sensitivity factor (B) can be estimated for any retarder dosage of a mixture if it is known only for two (preferred three) different retarder dosages.

In conclusion, it can be seen that the temperature sensitivity factor "B" is similar to the apparent activation energy "E". So, it would be efficient to use "B" instead of the apparent activation energy since it is simpler. Also, it is suggested that the temperature sensitivity factor has more physical significance than the apparent activation energy [Carino and Lew 2001]. 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.

6.3.2 Estimation of the Initial Setting Times by the Maturity Method

In order to calculate the equivalent initial setting time by FHP "t_{FHP}" (Eq. 6.1) and Carino and Tank "t_{CT}" (Eq. 6.2) maturity functions, both the apparent activation energy (E) and the temperature sensitivity factor (B) must be known. These values are calculated according to Eqs. 6.3 and 6.4, which are derived from Figs. 3.15 and 6.4, respectively. Then, by applying these values to the maturity function, the equivalent initial setting time can be estimated. The equivalent initial setting times based on the "2°C Temperature Increase" method of estimating the initial setting times and the "Penetration Resistance" method are presented in Tables 6.6 and 6.7, respectively.

$$\textbf{Retarder Dosage} = \mathbf{0.2035 \cdot E - 4843.7} \qquad \textbf{(6.3)}$$

$$\textbf{Retarder Dosage} = \mathbf{153{,}543 \cdot B - 5184.3} \qquad \textbf{(6.4)}$$

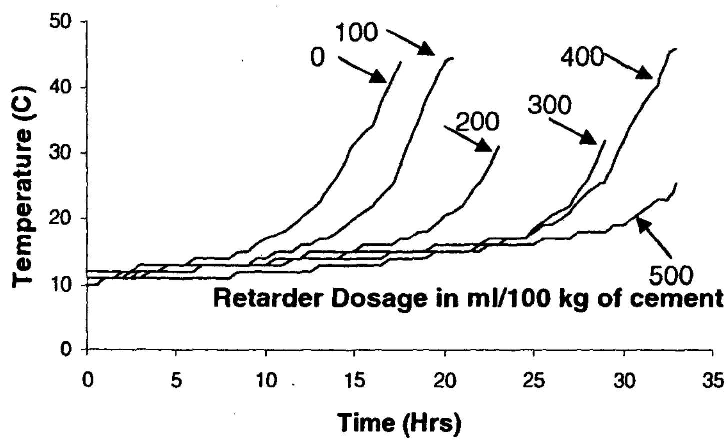

Figure 6.5. Temperature development for various retarder dosages at 10°C

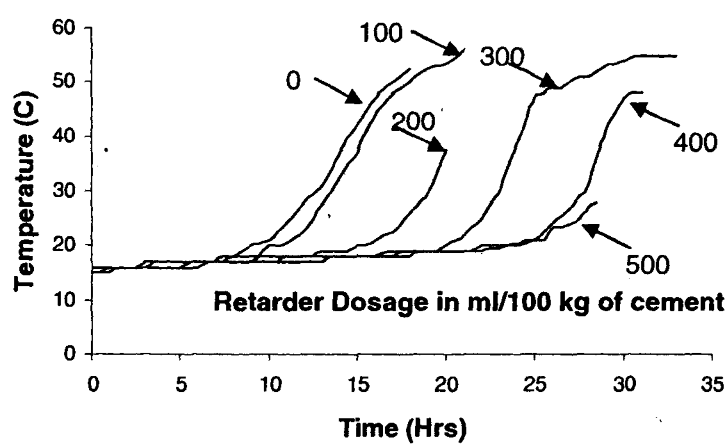

Figure 6.6. Temperature development for various retarder dosages at 15°C

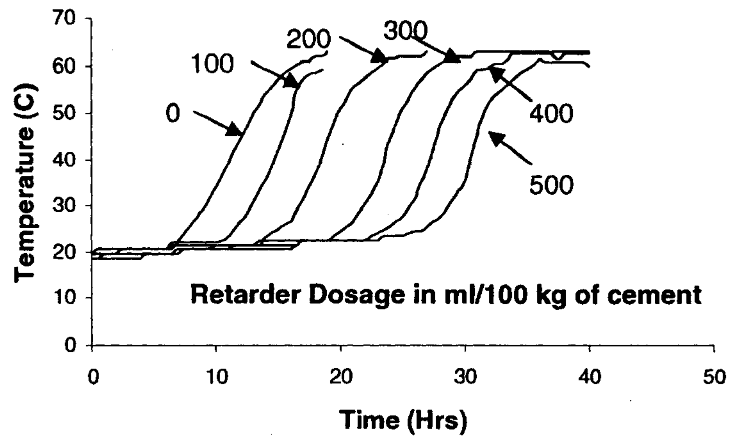

Figure 6.7. Temperature development for various retarder dosages at 20°C

Initial Setting Time "t_i" (Hrs)	Average Concrete Temperature "T_{av}" (°C)	Equivalent Initial Setting Time "t_{FHP}" (Hrs)	Equivalent Initial Setting Time "t_{CT}" (Hrs)
Retarder Dosage = 0 ml, E = 23,802 J/mol, B = 0.034 °C^{-1}			
8.0	16.7	7.2	7.2
6.5	20.4	6.6	6.6
Average Equivalent Initial Setting Time		**6.9**	**6.9**
Retarder Dosage = 100 ml/100 kg of cement, E = 24,293 J/mol, B = 0.034 °C^{-1}			
11.6	17.1	10.5	10.5
10.5	20	10.5	10.5
Average Equivalent Initial Setting Time		**10.5**	**10.5**
Retarder Dosage = 200 ml/100 kg of cement, E = 24,785 J/mol, B = 0.035 °C^{-1}			
15.5	17.1	14.0	14.0
14.0	20	14.0	14.0
Average Equivalent Initial Setting Time		**14.0**	**14.0**
Retarder Dosage = 300 ml/100 kg of cement, E = 25,276 J/mol, B = 0.036 °C^{-1}			
20.7	17.1	18.7	18.6
18.4	20.4	18.7	18.7
Average Equivalent Initial Setting Time		**18.7**	**18.65**
Retarder Dosage = 400 ml/100 kg of cement, E = 25,768 J/mol, B = 0.036 °C^{-1}			
24.7	17.4	22.5	22.4
23.5	20.9	24.3	24.3
Average Equivalent Initial Setting Time		**23.4**	**23.35**

Table 6.6. Equivalent initial setting time based on "2°C Temperature Increase" method

Initial Setting Time "t_i" (Hrs)	Average Concrete Temperature "T_{av}" (°C)	Equivalent Initial Setting Time "t_{FHP}" (Hrs)	Equivalent Initial Setting Time "t_{CT}" (Hrs)
Retarder Dosage = 100 ml/100 kg of cement, E = 24,293 J/mol, B = 0.034 $^{\circ}C^{-1}$			
9.4	12.4	7.2	7.3
8.7	16.3	7.7	7.7
Average Equivalent Initial Setting Time		**7.45**	**7.45**
Retarder Dosage = 300 ml/100 kg of cement, E = 25,276 J/mol, B = 0.036 $^{\circ}C^{-1}$			
20.4	13.4	16.1	16.1
17.9	16.9	16.0	16.0
Average Equivalent Initial Setting Time		**16.05**	**16.05**
Retarder Dosage = 400 ml/100 kg of cement, E = 25,768 J/mol, B = 0.036 $^{\circ}C^{-1}$			
23.75	13.5	18.7	18.8
21.62	17.2	19.5	19.5
Average Equivalent Initial Setting Time		**19.1**	**19.15**
Retarder Dosage = 500 ml/100 kg of cement, E = 26,259 J/mol, B = 0.037 $^{\circ}C^{-1}$			
26.0	13.0	20.0	20.1
23.5	17.9	21.7	21.7
Average Equivalent Initial Setting Time		**20.85**	**20.9**

Table 6.7. Equivalent initial setting time based on "Penetration Resistance" method

The predicted average equivalent initial setting times are shown in Tables 6.6 and 6.7. The values for the equivalent initial setting times obtained by FHP maturity function (Eq. 6.1) and Carino and Tank maturity function (Eq. 6.2) presented in Tables 6.6 and 6.7 are summarized in Table 6.8 for convenience.

Retarder Dosage (ml/100 kg of cement)	2°C Temperature Increase		Penetration Resistance	
	Equivalent Initial Setting Time "t_{FHP}" (Hrs)	Equivalent Initial Setting Time "t_{CT}" (Hrs)	Equivalent Initial Setting Time "t_{FHP}" (Hrs)	Equivalent Initial Setting Time "t_{CT}" (Hrs)
0	6.9	6.9	-	-
100	10.5	10.5	7.45	7.45
200	14.0	14.0	-	-
300	18.7	18.65	16.05	16.05
400	23.4	23.35	19.1	19.15
500	-	-	20.85	20.9

Table 6.8. Equivalent initial setting times

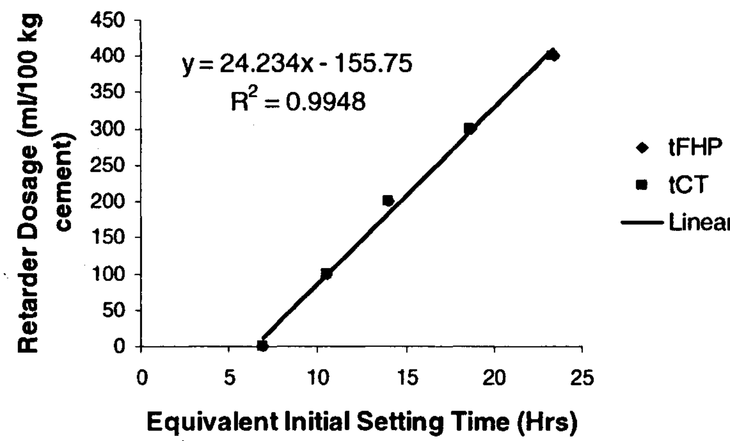

Figure 6.8. Relationship between the retarder dosage and the equivalent initial setting times based on the "2°C Temperature Increase" method

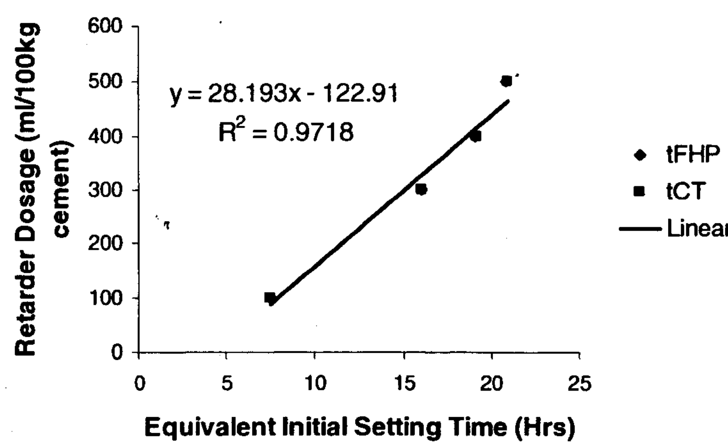

Figure 6.9. Relationship between the retarder dosage and the equivalent initial setting times based on the "Penetration Resistance" method

Figs. 6.8 and 6.9 (based on Table 6.8), represent the relationship between the equivalent initial setting time (based on the FHP and the Carino and Tank maturity functions) and the dosage of the retarder. It can be observed from these figures that the two maturity functions produce exactly the same initial setting times when they are based on either the "2°C Temperature Increase" or the "Penetration Resistance" methods. So the use of each of these functions would be appropriate. However the Carino and Tank "t_{CT}" maturity function (Eq. 6.2) is preferred due to its simplicity. It would now be essential to compare the actual initial setting times derived by the equivalent initial setting times using the "t_{CT}" maturity function with those obtained by the "2°C Temperature Increase" and the "Penetration Resistance" methods.

From the temperature development, which took place in the laboratory, in Figs. 6.5 to 6.7 it is possible to calculate the actual time of the initial setting of the concrete on site if only its initial temperature is known. If the "t_{CT}" maturity function is applied to the temperature development of the mixture, the actual initial setting time would be the time that would correspond to the equivalent initial setting time (Appendix Tables I, J, and K). So, for example if the "t_{CT}" maturity function is applied for the mixture presented in Table 6.1 with 100 ml/100 kg of cement retarder dosage at an initial concrete temperature of 15°C (Fig. 6.6), the actual initial setting time would be the one that would correspond to the 10.5 hours of "t_{CT}" based on the "2°C Temperature Increase" and 7.45 hours based on the "Penetration Resistance" according to Eqs. 6.5 and 6.6, respectively. Eqs. 6.5 and 6.7 are characterizing the best fit straight line in Figs. 6.8 and 6.9 respectively. So, for any retarder dosage the equivalent initial setting time can be estimated by using these equations. The results are presented in Tables 6.9 to 6.11. In these tables and Figs. 6.10 to 6.12, the notation "2 C" stands for the initial setting times derived by the "2°C Temperature Increase" method in the laboratory, the notation "PR" stands for the initial setting times derived by the "Penetration Resistance" method in the laboratory, the notation "MI" stands for the actual initial setting time calculated by the "t_{CT}" maturity function based on the "2°C Temperature Increase" method, and finally the notation "MP" stands for the actual initial setting time calculated by the "t_{CT}" maturity function based on the "Penetration Resistance" method.

$$\textbf{Retarder Dosage} = 24.234 \cdot (\textbf{Equivalent initial setting time}) - 155.75 \qquad (6.5)$$

$$\textbf{Retarder Dosage} = 28.193 \cdot (\textbf{Equivalent initial setting time}) - 122.91 \qquad (6.6)$$

Retarder Dosage (ml/100 kg of cement)	2°C Temperature Increase (2 C) (Hrs)	Penetration Resistance (PR) (Hrs)	MI (Hrs)	MP (Hrs)
0	9.0	-	8.5	6.0
100	13.6	9.4	13.5	10.5
200	18.8	12.5	17.5	14.5
300	24.7	18.4	23.5	19.0
400	26.8	23.8	28.5	23.5
500	30.0	26.0	33.0	28.0

Table 6.9. Initial setting times at 10°C

Retarder Dosage (ml/100 kg of cement)	2°C Temperature Increase (2 C) (Hrs)	Penetration Resistance (PR) (Hrs)	MI (Hrs)	MP (Hrs)
0	8.0	7.2	7.5	5.0
100	11.6	8.7	12.0	9.0
200	15.5	12.6	16.0	13.0
300	20.7	17.9	21.0	17.0
400	24.7	21.62	25.0	20.5
500	26.4	23.5	28.5	24.0

Table 6.10. Initial setting times at 15°C

Retarder Dosage (ml/100 kg of cement)	2°C Temperature Increase (2 C) (Hrs)	Penetration Resistance (PR) (Hrs)	MI (Hrs)	MP (Hrs)
0	6.5	6.25	6.5	4.5
100	10.5	9.9	10.5	8.0
200	14.0	13.9	14.5	11.5
300	18.4	19.0	18.5	15.0
400	23.5	22.2	22.5	18.5
500	26.5	26.3	26.0	22.0

Table 6.11. Initial setting times at 20°C

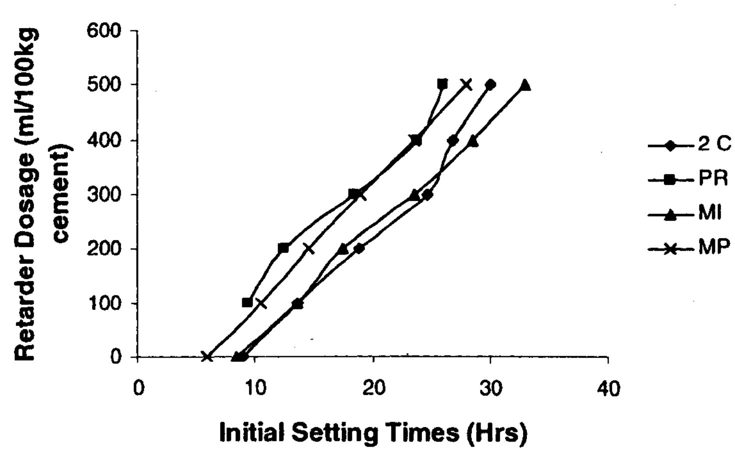

Figure 6.10. Relationship between the initial setting times and the retarder dosage at 10°C.

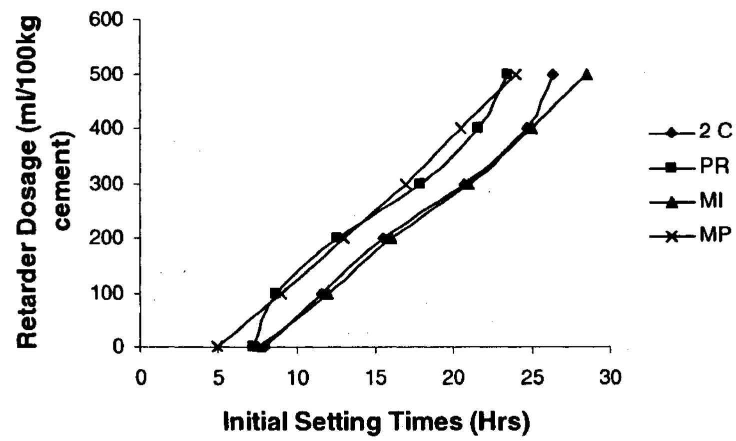

Figure 6.11. Relationship between the initial setting times and the retarder dosage at 15°C.

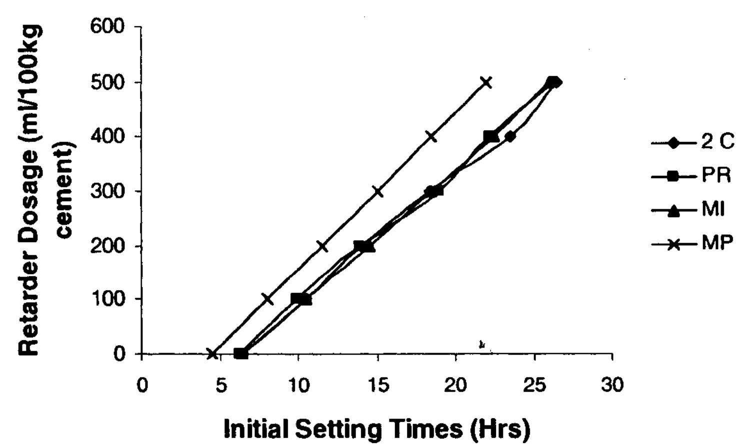

Figure 6.12. Relationship between the initial setting times and the retarder dosage at 20°C.

Figs. 6.10 to 6.12 show the relationship between the "2°C Temperature Increase (2 C)", "Penetration Resistance (PR)", and the "Maturity" methods MI and MP. It can be observed that the maturity method produces very similar results with the method that is based upon. For example the MI results are very similar with the "2°C Temperature Increase (2 C)" results, and the MP results are similar to the "Penetration Resistance (PR)" results. However when the maturity method (MP) is based on the penetration resistance method at 20°C it does produce variations compared with the other two methods ("2°C Temperature Increase (2 C)" and the MI methods) (Fig. 6.12).

Nevertheless it can be seen from Figs. 6.10 and 6.11 that the results based on the maturity method follow an almost perfect straight line, while the other two methods produce variances, with the penetration resistance method to generate the most varied results. It is interesting though that, according to the "Penetration Resistance (PR)" method the initial setting times increase instead of decrease as the temperature rises from 15°C to 20°C, since the concrete mixture is kept the same. At 20°C, the three methods ("MI", "MP", and "2°C Temperature Increase (2 C)") agree regarding the prediction of the initial setting times, while the "Penetration Resistance (PR)" method produces different results. It could be said that the "2°C Temperature Increase (2 C)" and the maturity method are more efficient than the "Penetration Resistance (PR)" method for this case. Finally it could be said that the maturity method is able to predict the initial setting times at different retarder dosages and at different concrete temperatures provided an appropriate method of estimating the initial setting times is used,

6.4 Field Practice of the Maturity Method in Estimating the Initial Setting Times

In this section the maturity method of estimating the initial setting times, as described in section 6.3, is applied in the field data from an ice wall construction in the Hibernia project. The arrangement of the slipform used in the Hibernia project is presented in Fig. 6.13. The concrete mixture used for this ice wall is presented in Table 6.12.

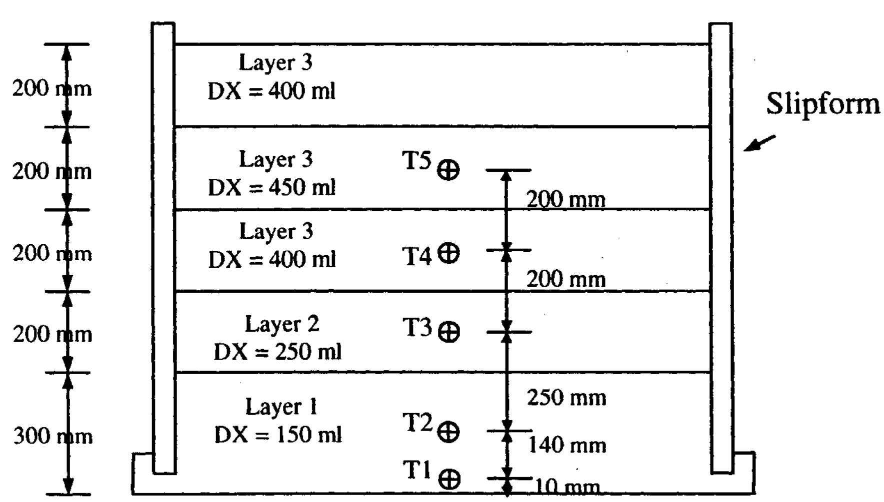

Figure 6.13. Layer arrangement of Hibernia slipform design

Material	Dosage
Cement (HSF Silica Fume 8.5%)	450 kg/m3
Water	152 kg/m3
Fine Aggregates (0-5 mm)	830 kg/m3
Coarse Aggregates (5-14 mm)	910 kg/m3
Superplasticizer EU-37	1400 ml/100 kg cement
Water Reducer TCDA-DX	Variable: 0-450 ml/100 kg cement
Air Entraining Agent AEX	20 ml/100 kg cement

Table 6.12. Hibernia base gravity structure concrete mixture

6.4.1 Field Data

Thermocouples were embedded in 5 different locations within the concrete (Fig. 6.13):

Thermocouple #1: 10.0 mm from the bottom of the wall
150 ml of retarder dosage

Thermocouple #2: 150.0 mm from the bottom of the wall
150 ml of retarder dosage

Thermocouple #3: 400.0 mm from the bottom of the wall
250 ml of retarder dosage

Thermocouple #4: 600.0 mm from the bottom of the wall
400 ml of retarder dosage

Thermocouple #5: 800.0 mm from the bottom of the wall
450 ml of retarder dosage

The equivalent initial setting times are obtained by using Eq. 6.5 for each of the retarder dosages (150, 250, 400, and 450 ml/100 kg cement). Then, these equivalent initial setting times are applied to the time-temperature history (Fig. 6.15), which was measured through interpolation from Figs. 6.5, 6.6, and 6.7 (see Appendix: Table L), in order to estimate the actual setting times of the concrete mixture "MI". The notation "MI" stands for the actual initial setting times calculated by the maturity method based upon the results of the "2°C Temperature Increase (2 C)" method in the laboratory. So, by knowing the initial concrete temperature at each layer, its corresponding initial setting time "MI", and the time at which the concrete is placed, it is possible to estimate the time of mock-up. By the term mock-up, it is meant to characterize the time at which the slipform is ready to be moved. The equivalent initial setting times and the actual initial setting times "MI" are shown in Table 6.13. Also, through interpolation from Tables 6.9 to 6.11 and Figs. 6.5 to 6.7, the initial setting times and the time of mockup are calculated based on the "2°C Temperature Increase (2 C)" and the "Penetration Resistance (PR)" methods (Tables 6.14, 6.15, and 6.16).

Retarder Dosage (ml/100 kg cement)	**Initial Concrete Temp. (°C)**	**Equivalent Initial Set. Time (Hrs)**	**Actual Initial Set. Time "MI" (Hrs)**	**Initial Set. Time "PR" (Hrs)**	**Initial Set. Time "2 C" (Hrs)**
150	13.0	12.6	14:30	10:48	14:24
150	16.0	12.6	13:30	10:56	13:18
250	16.0	16.7	18:00	15:30	17:42
400	16.0	22.9	24:30	21:42	24:30
450	14.0	25.0	28:00	22:18	25:48

Table 6.13. Actual initial setting times by the various method.

Slipform Elevation (mm)	**Initial Concrete Temperature (°C)**	**Retarder Dosage (ml/100 kg cement)**	**Placement Time (Month/Day) (Hrs:Mins)**	**Initial Setting Time by "MI" (Hrs)**	**Estimated Mockup (Month/Day) (Hrs:Mins)**
10	13.0	150	March/23 11:48	14:30	March/24 02:18
150	16.0	150	March/23 11:48	13:30	March/24 01:18
400	16.0	250	March/23 15:45	18:00	March/24 09:45
600	16.0	400	March/23 20:53	24:30	March/24 21:23
800	14.0	450	March/24 01:17	28:00	March/25 05:17

Table 6.14. Mockup times for the slipform shown in Fig. 6.14 by "MI"

Slipform Elevation (mm)	Initial Concrete Temperature (°C)	Retarder Dosage (ml/100 kg cement)	Placement Time (Month/Day) (Hrs:Mins)	Initial Setting Time by "PR" (Hrs)	Estimated Mockup (Month/Day) (Hrs:Mins)
10	13.0	150	March/23 11:48	10:48	March/23 22:36
150	16.0	150	March/23 11:48	10:56	March/23 22:44
400	16.0	250	March/23 15:45	15:30	March/24 07:15
600	16.0	400	March/23 20:53	21:42	March/24 18:35
800	14.0	450	March/24 01:17	22:18	March/24 23:35

Table 6.15. Mockup times for the slipform shown in Fig. 6.14 by "PR"

Slipform Elevation (mm)	Initial Concrete Temperature (°C)	Retarder Dosage (ml/100 kg cement)	Placement Time (Month/Day) (Hrs:Mins)	Initial Setting Time by "2 C" (Hrs)	Estimated Mockup (Month/Day) (Hrs:Mins)
10	13.0	150	March/23 11:48	14:24	March/24 02:12
150	16.0	150	March/23 11:48	13:18	March/24 01:06
400	16.0	250	March/23 15:45	17:42	March/24 09:27
600	16.0	400	March/23 20:53	24:30	March/24 21:23
800	14.0	450	March/24 01:17	25:48	March/25 03:05

Table 6.16. Mockup times for the slipform shown in Fig. 6.13 by "2 C"

From Tables 6.14, 6.15, and 6.16, it can be observed that the location of the thermocouple has a very significant role when the "MI" or the "2 C" methods are used. If the thermocouple number 1 (T1) was waived and thermocouple number 2 (T2) was used as the only indicator of layer number 1, then the initial setting time would have been occurred 13.5 hours after placement, which means that the slipform could have been removed at 01:18 of March 24. However this is not the case. Since in the location which is 10 mm from the bottom of the slipform, the initial setting time would be 14.5 hours after placement, the slipform should be moved at 02:18 of March 24. So, if the thermocouple at 10 mm was not installed the slipform would have been moved at 01:18

instead of 02:18 hours and a possible damage could have been occurred. So, care should be taken in considering the critical locations of the instruments. Locations close to the surface and at the centre of the concrete element should be considered as possible locations for the thermocouples or maturity meters, to have a good knowledge of what is happening at the whole width of the concrete element, since the temperature development through the width of massive concrete elements can vary significantly.

Concrete Elevation (mm)	Estimated Mockup by "PR" (Month/Day) (Hrs:Mins)	Estimated Mockup by "2 C" (Month/Day) (Hrs:Mins)	Estimated Mockup by "MI" (Month/Day) (Hrs:Mins)
0	March/23 22:36	March/24 02:12	March/24 02:18
300	March/24 07:15	March/24 09:27	March/24 09:45
500	March/24 18:35	March/24 21:23	March/24 21:23
900	March/24 23:35	March/25 03:05	March/25 05:17

Table 6.17. Estimated mockup times by the various methods

The time at which the slipform has to be moved at specific elevations estimated by different methods ("PR", "2 C", and "MI") is shown in Table 6.17. For example, it can be seen (from Tables 6.12, 6.13, and 6.14) that at 10 mm the time of mockup is "March/24 02:12" according to the "2 C" method, "March/23 22:36" according to the "PR" method, and "March/24 02:18" according to the "MI" method. So, the concrete at 10 mm above the bottom of the first layer is ready to stand alone at those times. Thus, these are the times at which the slipform should start to be lifted from the first layer. This means that at 0 mm elevation of the concrete, the time of mockup would be "March/23 22:36" if the "PR" method is used, "March/24 02:12" if the "2 C" method is used, or "March/24 02:18" if the "MI" method is used. The procedure is similar for the rest of the layers (Figs. 6.14 and 6.15).

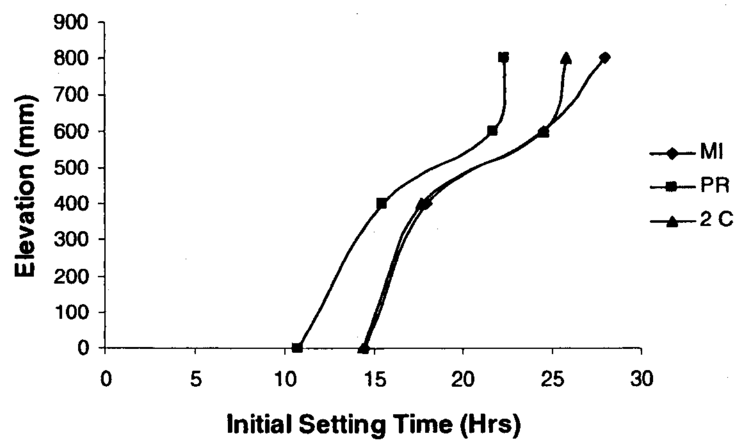

Figure 6.14. Initial setting times by the different methods.

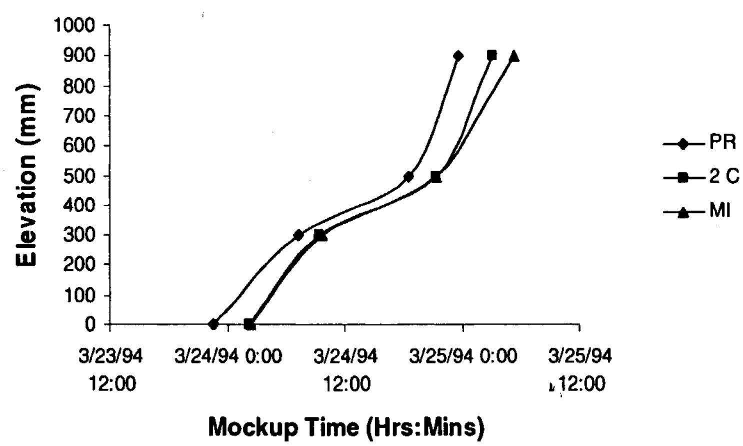

Figure 6.15. Mockup time estimated by the different methods.

From Figs. 6.14 and 6.15, it can be seen that the maturity method "MI" correlates very good with the "2 C" method but not with the "PR" method. The reason is that the "MI" method is based upon the "2 C" method. It is stated elsewhere in this chapter, that the maturity method gives a very good correlation, regarding the initial setting times, when compared with the method it is based upon. So, it can be concluded that the maturity method is able to predict the initial setting times and the time of mock-up efficiently, if the results from the method that is based upon in the laboratory are adequate.

6.5 Comparison of the Various Methods for Estimating the Initial Setting Times

So far the maturity method for calculating the initial setting time of a concrete element was compared with the "2°C Temperature Increase (2 C)" and the "Penetration Resistance (PR)" methods only. In this section, all these methods are compared with the "Rod (R)" and the "Conductivity (C)" methods. The data for the initial setting times and the time-temperature history are taken from experiments that had been conducted by Elimov [Elimov 2003]. Extensive analysis has been conducted to determine the initial setting times by the maturity method and then compare the results with all the other methods.

Concrete mixtures are produced at four different initial concrete temperatures 10°C, 15°C, 20°C, and 25°C. At each temperature, the initial setting time is calculated. The time-temperature histories are shown in Fig. 6.16 and the concrete mixture design is shown in Table 6.18. The initial setting times based on various methods except the maturity method are shown in Tables 6.19, 6.20, 6.21, and 6.22. The average concrete temperatures up to the initial setting times are derived from the Appendix: Table M.

Material	**Quantity**
Cement (Type 10E-SF)	450 kg/m^3
Water	152 l/m^3
Coarse Aggregate (5-14 mm)	910 kg/m^3
Fine Aggregate (0-5 mm)	830 kg/m^3
Superplasticizer (EU-37)	1600 ml/100 kg of cement
Water Reducer (TCDX)	200 ml/100 kg of cement
Air-entraining Agent (Airextra)	25 ml/100 kg of cement

Table 6.18. Concrete mix design

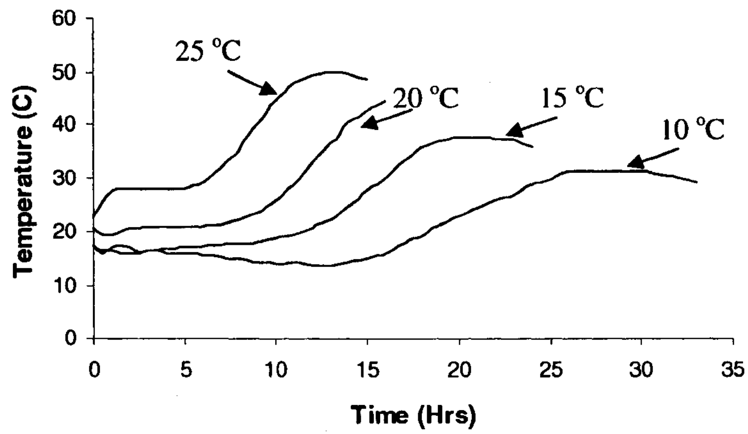

Figure 6.16. Temperature Development for various initial temperatures

Initial Concrete Temperature (°C)	Average Concrete Temperature Up to Initial Setting Time (°C)	Initial Setting Times By Penetration Resistance "PR" (Hrs)
10	15.1	13:45
15	17.2	10:20
25	27.5	6:10

Table 6.19. Initial setting times by the "Penetration Resistance"

Initial Concrete Temperature (°C)	Average Concrete Temperature Up to Initial Setting Time (°C)	Initial Setting Times By Conductivity "C" (Hrs)
10	15.2	13:30
15	17.3	10:45
20	20.8	7:40
25	27.7	6:15

Table 6.20. Initial setting times by "Conductivity"

Initial Concrete Temperature (°C)	Average Concrete Temperature Up to Initial Setting Time (°C)	Initial Setting Times By Rod "R" (Hrs)
10	15.2	13:00
15	17.3	10:45
20	20.8	7:40
25	27.7	6:15

Table 6.21. Initial setting times by "Rod"

Initial Concrete Temperature (°C)	Average Concrete Temperature Up to Initial Setting Time (°C)	Initial Setting Times By 2°C Temperature Increase "2 C" (Hrs)
10	15.2	16:00
15	17.6	12:10
20	21.1	8:45
25	27.7	6:30

Table 6.22. Initial setting times by "2°C Temperature Increase"

6.5.1 Initial Setting Times by the Maturity Method based on the "Penetration Resistance" Method

For the calculation of the equivalent ages the Carino and Tank maturity function is used "t_{CT}" (Eq. 2.8). Based on Tables 6.19 to 6.22, the value for the temperature sensitivity factor "B" can be calculated according to the different methods. For that purpose, the natural logarithm of the inverse of the initial setting times is plotted versus the average concrete temperatures. Then the equivalent initial setting time at 20°C is calculated, and finally using the time temperature history from (Fig. 6.16), the actual initial setting time for each initial temperature is determined (Appendix: Table M).

The equivalent initial setting time is calculated in the laboratory based on the "Penetration Resistance (PR)" method by using Table 6.19. First the temperature sensitivity factor "B" is calculated and then the Carino and Tank equivalent age model (Eq. 2.8) is applied to the temperature development of the mixture (Fig. 6.16) in the laboratory. Then the actual initial setting times "MP", which are the actual times that correspond to the equivalent initial setting time, are calculated for each initial concrete temperature (10°C, 15°C, 20°C, and 25°C). In order to calculate the temperature sensitivity factor "B", the natural logarithm of the inverse of the initial setting times estimated by the "Penetration Resistance" method are plotted against the average concrete temperature up to the initial setting times (Table 6.19). Then, the best fit straight line is drawn and the slope of that line represents the value of the temperature sensitivity factor "B" (Fig. 6.17). Finally based on Eq. 6.2, the equivalent initial setting time is calculated (Table 6.23).

Average Concrete Temperature (°C)	Initial Setting Times (Hrs)	Ln(1/Initial Setting Time)	Equivalent Initial Setting Times (Hrs)
15.1	`	-2.62104	10.2
17.2	10.33	-2.33505	8.7
27.5	6.17	-1.8197	9.7
Average Equivalent Initial Setting Time			**9.6**

Table 6.23. Equivalent initial setting time

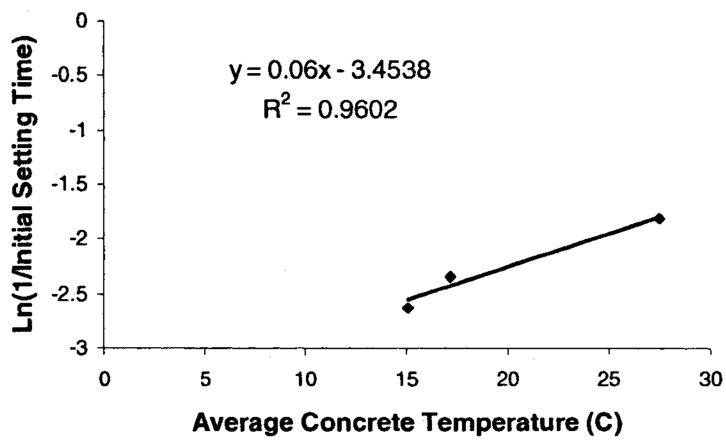

Figure 6.17. Calculation of "B"

As can be seen from Fig. 6.17, the value for "B" up to the initial setting time according to the "Penetration Resistance" method is 0.06 $^{o}C^{-1}$. So, this value is applied in Eq. 6.2 and the equivalent initial setting time is estimated in Table 6.23. Next, the equivalent age (Eq. 2.8) is applied to the temperature development and the actual initial setting times "MP" are estimated (Appendix Table M). The results are presented in Table 6.24 and Fig. 6.18.

	Initial Setting Times (Hrs)	
Initial Concrete Temperature (°C)	**Penetration Resistance "PR"**	**"MP"**
10	13:45	13:00
15	10:20	11:30
20	-	9:00
25	6:10	6:00

Table 6.24. Initial setting times

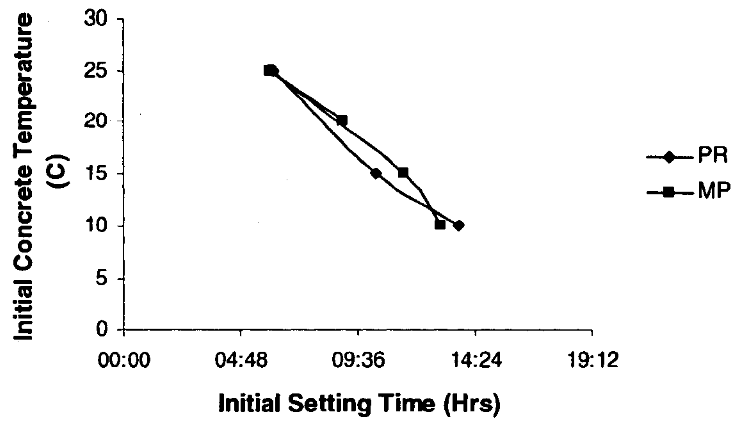

Figure 6.18. Relationship between "MP" initial setting times and the "PR"

6.5.2 Initial Setting Times by Maturity Method based on "Conductivity"

The same procedure as in section 6.5.1 is followed in this section as well. The "B" value is calculated according to the data from Table 6.25 that are presented in Fig. 6.19. The data in Table 6.25 are based on those of Table 6.20.

Average Concrete Temperature (°C)	Initial Setting Times (Hrs)	Ln(1/Initial Setting Time)	Equivalent Initial Setting Times (Hrs)
15.2	13:30	-2.60269	10.1
17.3	10:45	-2.37491	9.1
20.8	7:40	-2.03732	8.0
27.7	6:15	-1.83258	9.9
Average Equivalent Initial Setting Time			**9.3**

Table 6.25. Equivalent initial setting time

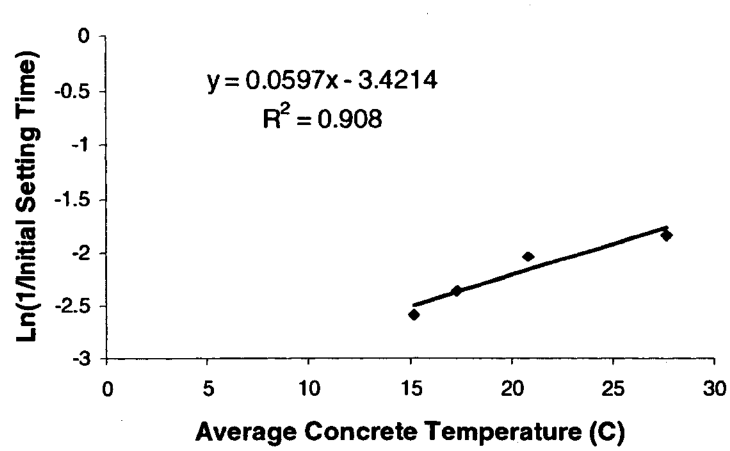

Figure 6.19. Calculation of "B"

As can be seen from Fig. 6.19, the value for "B" up to the initial setting time according to the "Conductivity" method is approximately 0.06 $^{o}C^{-1}$. So, this value is applied in Eq. 6.2 and the equivalent initial setting time is estimated and presented in Table 6.25. Next, the equivalent age (Eq. 2.8) is applied to the temperature development and the actual initial setting times "MC" are estimated (Appendix Table M). The results are presented in Table 6.26 and Fig. 6.20.

	Initial Setting Times (Hrs)	
Initial Concrete Temperature (°C)	**Conductivity "C"**	**"MC"**
10	13:30	12:30
15	10:45	11:00
20	7:40	9:00
25	6:15	6:00

Table 6.26. Initial setting times

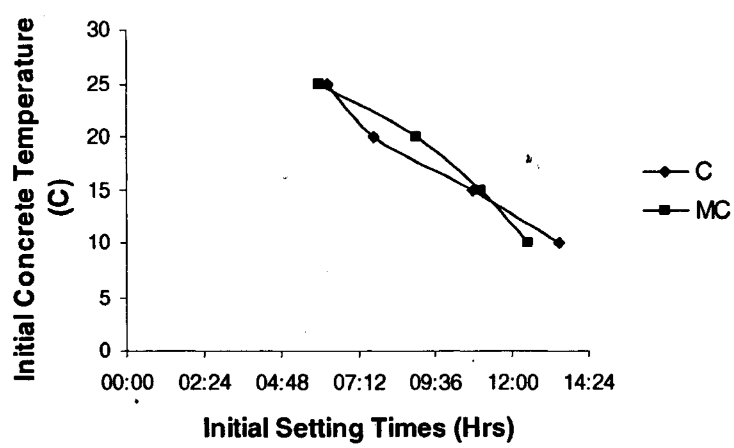

Figure 6.20. Relationship of the "MC" initial setting times and the "C"

6.5.3 Initial Setting Times by the Maturity Method based on "Rod" Method

The same procedure as in section 6.5.1 is followed in this section as well. The "B" value is calculated according to the data from Table 6.27 that are presented in Fig. 6.21. The data in Table 6.27 are based on those in Table 6.21.

Average Concrete Temperature (°C)	Initial Setting Times (Hrs)	Ln(1/Initial Setting Time)	Equivalent Initial Setting Times (Hrs)
15.2	13:00	-2.56495	9.8
17.3	10:45	-2.37491	9.2
20.8	7:40	-2.03732	8.0
27.7	6:15	-1.83258	9.8
Average Equivalent Initial Setting Time			**9.2**

Table 6.27. Equivalent initial setting time

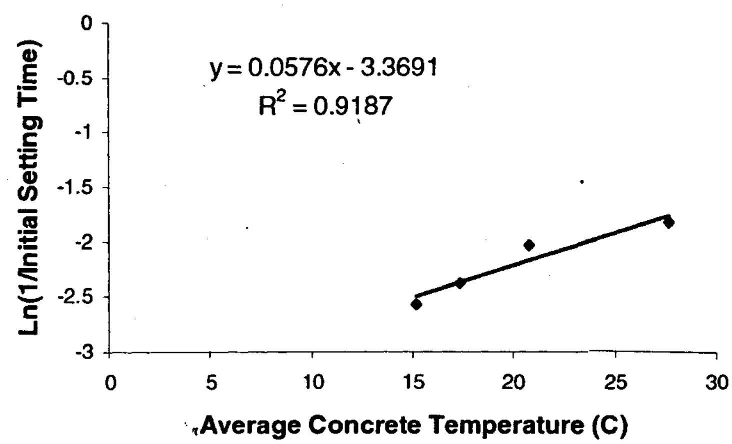

Figure 6.21. Calculation of "B"

As can be seen from Fig. 6.21, the value for "B" up to the initial setting time according to the "Rod" method is approximately 0.058 $^oC^{-1}$. So, this value is applied in Eq. 6.2 and the equivalent initial setting time is estimated in Table 6.27. Next, the equivalent age (Eq. 2.8) is applied to the temperature development and the actual initial setting times "MR" are estimated (Appendix Table M). The results are presented in Table 6.28 and Fig. 6.22.

Initial Concrete Temperature (°C)	Initial Setting Times (Hrs) Rod "R"	Initial Setting Times (Hrs) "MR"
10	13:00	12:00
15	10:45	11:00
20	7:40	9:00
25	6:15	6:00

Table 6.28. Initial setting times

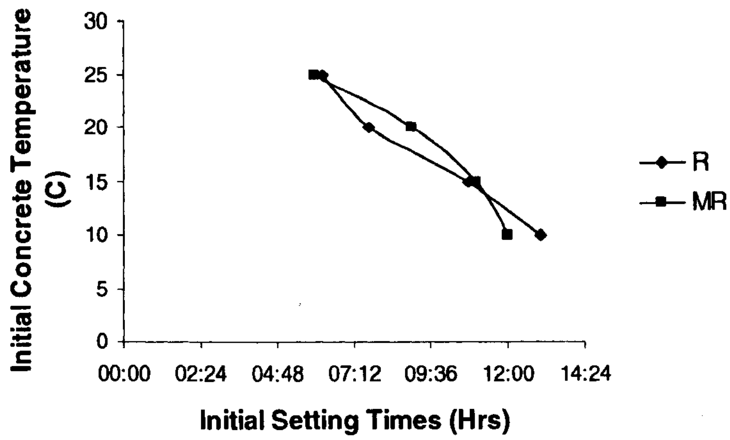

Figure 6.22. Relationship of the "MR" initial setting times and the "R"

6.5.4 Initial Setting Times by the Maturity Method based on "2°C Temperature Increase" Method

The same procedure as in section 6.5.1 is followed in this section as well. The "B" value is calculated according to the data from Table 6.29 that are presented in Fig. 6.23. The data in Table 6.29 are based on those in Table 6.22.

Average Concrete Temperature (°C)	Initial Setting Times (Hrs)	Ln(1/Initial Setting Time)	Equivalent Initial Setting Times (Hrs)
15.2	16:00	-2.77259	11.4
17.6	12:10	-2.49897	10.3
21.1	'8:45	-2.16905	9.5
27.7	6:30	-1.8718	11.1
Average Equivalent Initial Setting Time			**10.6**

Table 6.29. Equivalent initial setting time

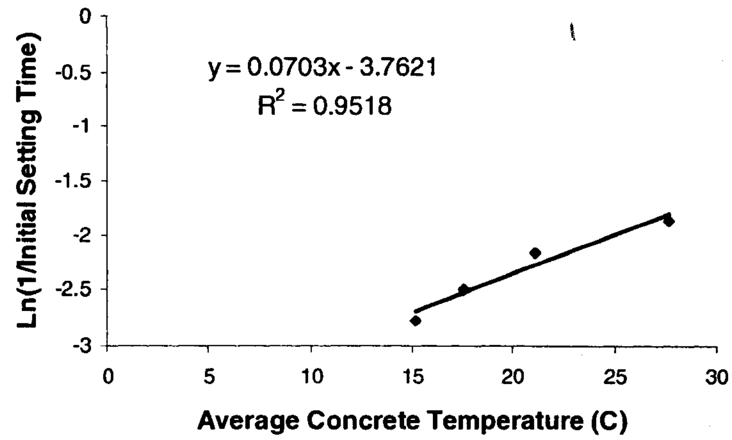

Figure 6.23. Calculation of "B"

As can be seen from Fig. 6.23, the value for "B" up to the initial setting time according to the "2°C Temperature Increase" method is approximately 0.07 $°C^{-1}$. So, this value is applied in Eq. 6.2 and the equivalent initial setting time is estimated in table 6.29. Next the equivalent age (Eq. 2.8) is applied to the temperature development and the actual initial setting times "MI" are estimated (Appendix table M). The results are presented in Table 6.30 and Fig. 6.24.

	Initial Setting Times (Hrs)	
Initial Concrete Temperature (°C)	**2°C Temperature Increase "2 C"**	**"MI"**
10	16:00	15:00
15	12:10	12:30
20	8:45	9:30
25	6:30	6:30

Table 6.30. Initial setting times

	Maturity Method			
Temperature (°C)	**(MP)**	**(MC)**	**(MR)**	**(MI)**
10	13:00	12:30	12:00	15:00
15	11:30	11:00	11:00	12:30
20	9:00	9:00	9:00	9:30
25	6:00	6:00	6:00	6:30

Table 6.31. Initial setting times by maturity

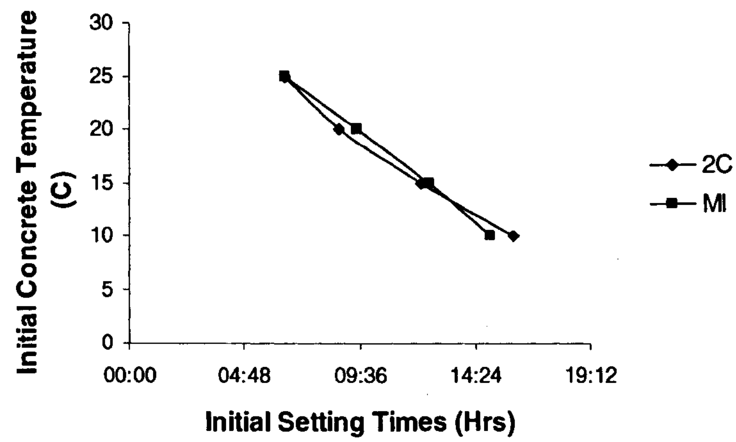

Figure 6.24. Relationship of the "MI" initial setting times and the "2 C"

Table 6.31 and Fig. 6.25 compare all the results derived by the maturity method. It can be seen that the results are similar and specifically this is the case for the "MP", "MC", and "MR" methods. The "MI" method seems to vary in relation with the other, but this is due to the fact that the "2°C Temperature Increase (2 C)" varies with the "Penetration Resistance (PR)", the "Conductivity (C)", and the "Rod (R)" methods.

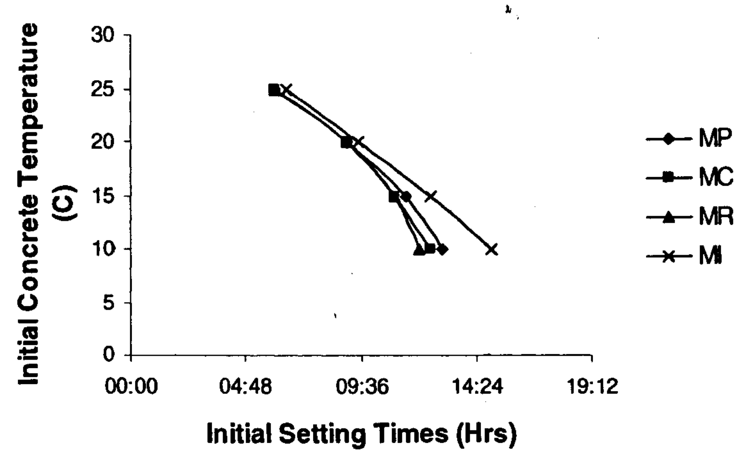

Figure 6.25. Relationship of the initial setting times by maturity

In general, the maturity method produces very close results when compared with the method that it is based on it. It can be seen from Figs. 6.18, 6.20, 6.22, and 6.24 that when the maturity method is compared with the method that it is based upon, then the correlation is very good. The "MR" method is selected to be compared with the

"Penetration Resistance (PR)", the "Conductivity (C)", the "Rod (R)", and the "2°C Temperature Increase (2 C)" methods, since the "Rod (R)" method, which "MR" is based upon, is a very good indicator of the initial setting times and has been successfully used in field operations [Elimov 2003]. Fig. 6.26 compares all the methods and it can be seen that "MR" correlates very good with the other methods.

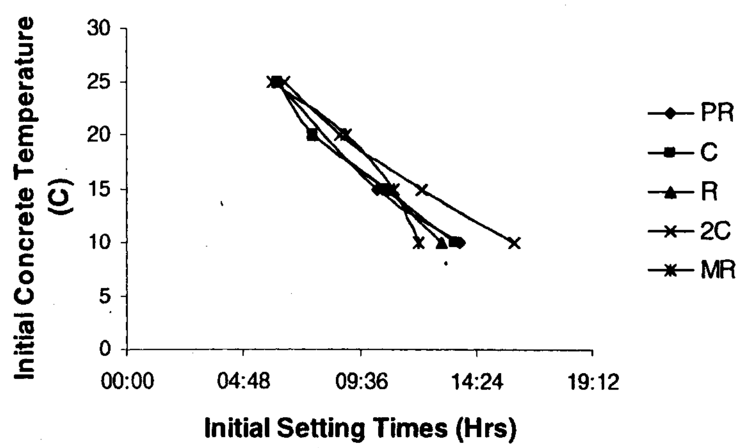

Figure 6.26. Comparison of the various methods of calculating the initial setting times.

Since the maturity method produces adequate results it can be preferred to the "Penetration Resistance (PR)", the "Rod (R)", and the "2°C Temperature Increase (2 C)" methods, because of its advantage of simplicity. For the calculation of the initial setting times based on the maturity method, it is needed to know only the setting times of the mixture at two (preferably three) different temperatures in the laboratory, and the temperature development of the concrete mixture for which the initial setting time is needed. Also, another important advantage of the maturity method is that it can be applied in the field concrete element, and the initial setting times can be checked for the concrete in-place. This would be proved to be a very useful tool in continuing with the construction process regarding not only the safety aspect but also the economical aspect.

6.6 Slipforming Technique

It was mentioned earlier that the main objective of this research is to establish the "hardened front" line during slipforming operations. The hardened front line would indicate the time at which the concrete is ready to stand alone without any additional help from the formworks. The hardened front line can be obtained by knowing the initial setting times and the time of concrete's placement. So, here in this section the maturity model will be used to create a hardened front for the ice wall shown in Fig. 6.27. Then the results will be compared with the "Rod (R)", "2°C Temperature Increase (2 C)", and "Penetration Resistance (PR)" methods to validate its significance. In Table 6.32, the elevation of the top of the concrete, the layer number, the placement time of each layer, the dosage of retarder for each layer, the in-situ initial temperature of the concrete, and the hardened front elevation, are shown according to data recorded from the Hibernia project.

Layer #	Elevation of Top of Concrete (mm)	Hardened Front Elevation (mm)	Placement Time (Hrs:Mins)	Retarder Dosage (ml)	Concrete Initial Temperature (°C)
1	300	0	13:00	150	13
2	500	0	16:00	250	13.8
3	700	0	20:30	400	12
4	900	0	02:00	450	12
5	1100	330	06:00	400	13
6	1250	500	10:30	400	10
7	1350	610	15:50	350	12
8	1450	660	20:20	350	-
9	1550	830	00:44	300	9
10	1750	1040	05:40	250	10
11	1850	1250	10:00	250	16
12	1970	1390	13:30	250	14

Table 6.32. Data collected from the ice wall in Fig. 6.27 from Hibernia Project

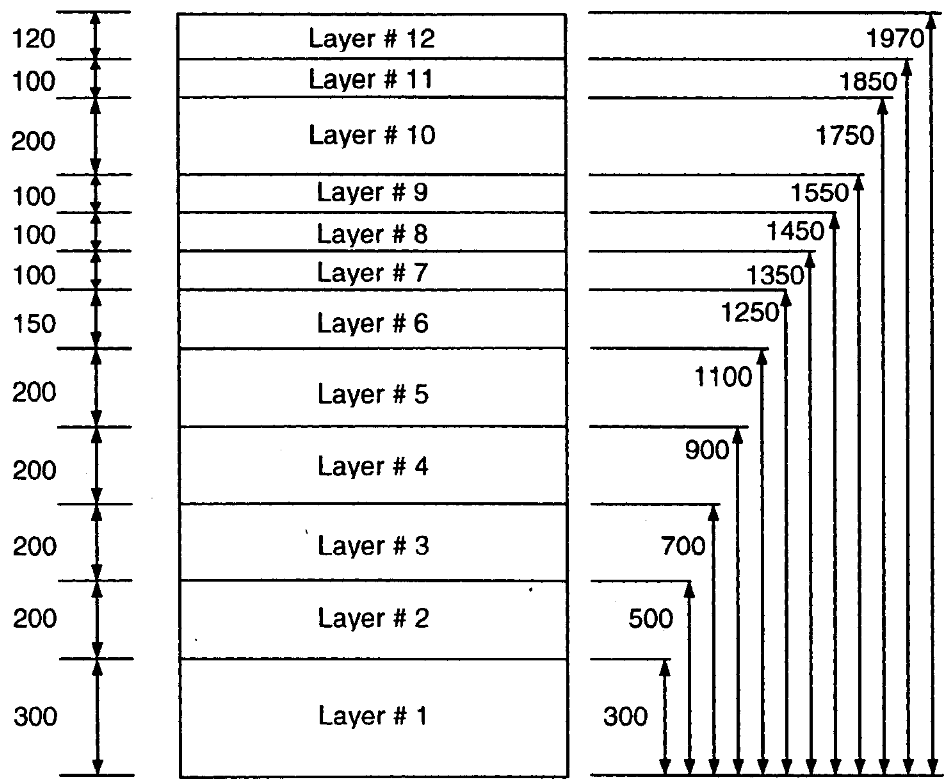

Figure 6.27. Ice wall (the distances are in mm)

Through interpolation based on Tables 6.9 to 6.11 the hardened front line for the ice wall in Fig. 6.27 is established by "2°C Temperature Increase (2 C)", "Penetration Resistance (PR)", "MI", and "MP" methods. So from Tables 6.9 to 6.11 the initial setting times for the corresponding retarder dosage and temperature, which are shown in Table 6.32, can be estimated. Then by adding the calculated initial setting times to the time of placement of the concrete, the time of mockup can be established (the time at which the slipform can be moved). The "Rod (R)" method had been used in Table 6.32 to establish the hardened front of the concrete. So by subtracting the time at which the hardened front of a layer occurs (Table 6.32) from the time at which this layer has been placed, the time of mockup can be established (Table 6.35). The results of estimating the time of mockup are presented in Tables 6.33 to 6.37 and Fig. 6.28.

Elevation (mm)	Retarder Dosage (ml)	Initial Concrete Temperature (°C)	Time of Concrete Placement (Date) (Hrs:Mins)	Initial Setting Time (Hrs)	Mockup Time (Date) (Hrs:Mins)
0	-	-	-	-	MAR 24, 03:36
300	150	13.0	MAR 23, 13:00	14:36	MAR 24, 11:00
500	250	13.8	MAR 23, 16:00	19:00	MAR 24, 22:30
700	400	12.0	MAR 23, 20:30	26:00	MAR 25, 05:06
900	450	12.0	MAR 24, 02:00	27:06	MAR 25, 07:30
1100	400	13.0	MAR 24, 06:00	25:30	MAR 25, 13:18
1250	400	10.0	MAR 24, 10:30	26:48	MAR 25, 16:26
1350	350	12.0	MAR 24, 15:50	24:36	MAR 25, 22:08
1450	350	10.0	MAR 24, 20:20	25:48	MAR 26, 01:26
1550	300	9.0	MAR 25, 00:44	24:42	MAR 26, 03:28
1750	250	10.0	MAR 25, 05:40	21:48	MAR 26, 03:42
1850	250	16.0	MAR 25, 10:00	17:42	MAR 26, 08:18
1970	250	14.0	MAR 25, 13:30	18:48	-

Table 6.33. Time of mockup by the "2°C Temperature Increase" method

Elevation (mm)	Retarder Dosage (ml)	Initial Concrete Temperature (°C)	Time of Concrete Placement (Date) (Hrs:Mins)	Initial Setting Time (Hrs)	Mockup Time (Date) (Hrs:Mins)
0	-	-	-	-	MAR 23, 23:48
300	150	13.0	MAR 23, 13:00	10:48	MAR 24, 07:24
500	250	13.8	MAR 23, 16:00	15:24	MAR 24, 18:26
700	400	12.0	MAR 23, 20:30	22:54	MAR 25, 02:00
900	450	12.0	MAR 24, 02:00	24:00	MAR 25, 04:29
1100	400	13.0	MAR 24, 06:00	22:29	MAR 25, 10:18
1250	400	10.0	MAR 24, 10:30	23:48	MAR 25, 12:26
1350	350	12.0	MAR 24, 15:50	20:36	MAR 25, 17:26
1450	350	10.0	MAR 24, 20:20	21:06	MAR 25, 19:08
1550	300	9.0	MAR 25, 00:44	18:24	MAR 25, 21:10
1750	250	10.0	MAR 25, 05:40	15:30	MAR 26, 01:30
1850	250	16.0	MAR 25, 10:00	15:30	MAR 26, 04:50
1970	250	14.0	MAR 25, 13:30	15:20	-

Table 6.34. Time of mockup by the "Penetration Resistance" method

Elevation (mm)	Hardened Front Elevation (mm)	Time of Concrete Placement (Date) (Hrs:Mins)	Mockup Time (Date) (Hrs:Mins)
0	0	-	MAR 24, 02:00
300	0	MAR 23, 13:00	MAR 24, 06:00
500	0	MAR 23, 16:00	MAR 24, 10:30
700	0	MAR 23, 20:30	MAR 24, 20:20
900	330	MAR 24, 02:00	MAR 25, 00:44
1100	500	MAR 24, 06:00	MAR 25, 05:40
1250	610	MAR 24, 10:30	-
1350	660	MAR 24, 15:50	-
1450	830	MAR 24, 20:20	-
1550	1040	MAR 25, 00:44	-
1750	1250	MAR 25, 05:40	-
1850	1390	MAR 25, 10:00	-

Table 6.35. Time of mockup by the "Rod" method

Elevation (mm)	Retarder Dosage (ml)	Initial Concrete Temperature (°C)	Time of Concrete Placement (Date) (Hrs:Mins)	Initial Setting Time (Hrs)	Mockup Time (Date) (Hrs:Mins)
0	-	-	-	-	MAR 24, 3:36
300	150	13.0	MAR 23, 13:00	14:36	MAR 24, 11:00
500	250	13.8	MAR 23, 16:00	19:00	MAR 24, 23:36
700	400	12.0	MAR 23, 20:30	27:06	MAR 25, 07:12
900	450	12.0	MAR 24, 02:00	29:12	MAR 25, 08:24
1100	400	13.0	MAR 24, 06:00	26:24	MAR 25, 15:00
1250	400	10.0	MAR 24, 10:30	28:30	MAR 25, 16:38
1350	350	12.0	MAR 24, 15:50	24:48	MAR 25, 22:20
1450	350	10.0	MAR 24, 20:20	26:00	MAR 26, 00:14
1550	300	9.0	MAR 25, 00:44	23:30	MAR 26, 02:10
1750	250	10.0	MAR 25, 05:40	20:30	MAR 26, 04:06
1850	250	16.0	MAR 25, 10:00	18:06	MAR 26, 08:24
1970	250	14.0	MAR 25, 13:30	18:54	-

Table 6.36. Time of mockup by the "MI" method

Elevation (mm)	Retarder Dosage (ml)	Initial Concrete Temperature (°C)	Time of Concrete Placement (Date) (Hrs:Mins)	Initial Setting Time (Hrs)	Mockup Time (Date) (Hrs:Mins)
0	-	-	-	-	MAR 23, 23:24
300	150	13.0	MAR 23, 13:00	10:24	MAR 24, 07:24
500	250	13.8	MAR 23, 16:00	15:24	MAR 24, 18:48
700	400	12.0	MAR 23, 20:30	22:18	MAR 25, 02:24
900	450	12.0	MAR 24, 02:00	24:24	MAR 25, 03:42
1100	400	13.0	MAR 24, 06:00	21:42	MAR 25, 10:00
1250	400	10.0	MAR 24, 10:30	23:30	MAR 25, 12:08
1350	350	12.0	MAR 24, 15:50	20:18	MAR 25, 17:38
1450	350	10.0	MAR 24, 20:20	21:18	MAR 25, 19:44
1550	300	9.0	MAR 25, 00:44	19:00	MAR 25, 22:28
1750	250	10.0	MAR 25, 05:40	16:48	MAR 26, 00:42
1850	250	16.0	MAR 25, 10:00	14:42	MAR 26, 04:54
1970	250	14.0	MAR 25, 13:30	15:24	-

Table 6.37. Time of mockup by the "MP" method

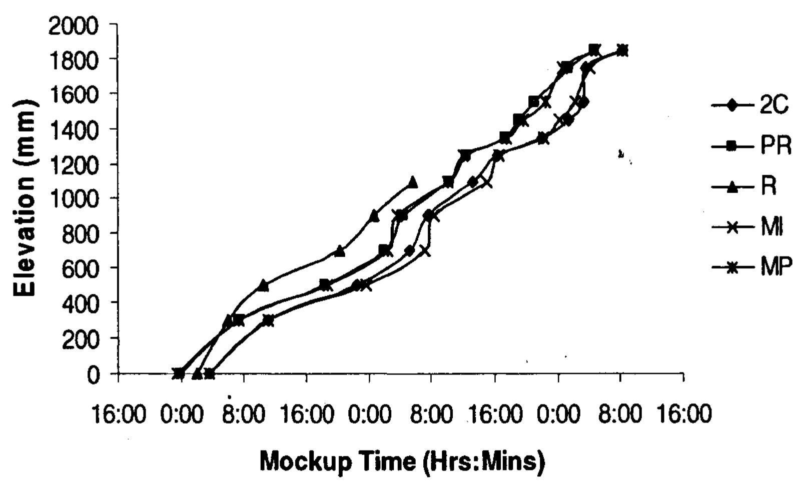

Figure 6.28. Hardened front elevation for the ice wall in Fig. 6.22

From Fig. 6.28, it can be concluded that the maturity method of predicting the initial setting times provides a good tool for calculating the hardened front line of a concrete element. It can be seen again that the results of the maturity method depend on the method upon which it is based. It can be seen that when the maturity is based on the "Penetration Resistance (PR)" method (MP), then the results are very similar to that derived by the "Penetration Resistance (PR)". Once again when the maturity is based on the "2°C Temperature Increase (2 C)" then the results of the maturity (MI) are very similar to those of the "2°C Temperature Increase (2 C)" method. The rod method is a well established method for calculating the initial setting times and it can be seen that the maturity method can produce adequate results as the "Rod (R)" method. Therefore it can be concluded that the maturity method can be used for the estimation of the initial setting times and as a consequence for obtaining the hardened front elevation of a concrete element.

6.7 Conclusion

It has been found that the maturity method is suitable for the prediction of the initial setting times of a concrete element. It is also found to be advantageous for its simplicity, since only a maturity meter and a technician (to read the meter) are enough for this practice. It is also proved to be very efficient for safety and economical aspects. The maturity method can be used in field practice to validate and to ensure that the mixture is adequate and the initial setting time that is established for the mixture is appropriate, so that the project can efficiently proceed.

However, even though the maturity is a convenient method, sometimes is disadvantageous if it is based upon a method that can not provide the adequate data. It is found that the use of the maturity method in establishing the initial setting times can only be possible if the initial setting times at two different temperatures of the same mixture are established by means of another technique. For that reason, the maturity method is depends on the other method and in order for the maturity to be efficient, this other method should be adequate to produce the true results. It is also seen that the best method to use for that purpose is the "Rod (R)" and the "Conductivity (C)" methods. The "2°C Temperature Increase (2 C)" method is also adequate but it may overestimate the initial setting times and can lead to misleading results. On the other hand, the "Penetration Resistance (PR)" method tends to underestimate the initial setting times. It is also seen that the "Penetration Resistance (PR)" method produced some discrepancies in estimating the initial setting times when high dosages of retarder (as high as 500 ml/100 kg of cement) at 10°C, 15°C, and 20°C temperatures are used. As a consequence, the maturity method based on the "Penetration Resistance (PR)" method can produce variances when calculating the initial setting times (Fig 6.12). Finally it can be concluded that the maturity method is a convenient means for determining the initial setting times and for efficient and economic slipform design.

7. Case Studies

In order to gain a more clear perspective of the use of the maturity method in the slipforming technique a typical example has been used in this section. The example consists of a wall of 5-m in height and 1-m thick (Fig. 7.1). The details of concrete mix are shown in Table 7.1. The purpose of this example is to establish the time at which the slipform should be moved and to establish the hardened front line (Section 6.6). In order to plan such an operation the type of structure, the thickness of the layers within the slipform, the initial temperature of the concrete in the site, and the initial setting time determined at the lab are needed.

This example has been divided into two different cases. The first case is separated into three different situations where the initial concrete temperature is kept constant (at 10°C, 15°C, and 20°C) and the layer thickness within the slipform is further divided into another three situations. The second case uses the most efficient layer combination within the slipform that is derived from the first case but the initial concrete temperature is varied. In each case, the initial concrete temperature is assumed to be measured locations near the slipform and the concrete mixture is assumed to be prepared at the site so as there are no delay in the setting time from the time of batching to the time of placement. Finally, the speed of the slipforming removal is checked according to the type of the structure. For ordinary silos, towers, piers, that the reinforcement is simple, the speed can go up to 8 m per day [Elimov, 2003], which is approximately 333 mm per hour. For offshore oil platforms (as is the case with Hibernia) the speed can go up to 2.5 m per day [Elimov, 2003] which is approximately 104 mm per hour. The height of the slipform assumed in this example is 1.1 m.

Material	Dosage
Cement	450 kg/m3
Water	152 kg/m3
Fine Aggregates	830 kg/m3
Coarse Aggregates	910 kg/m3
Superplasticizer EU-37	1400 ml/100 kg cement
Water Reducer TCDA-37	0 ml/100 kg cement
Air Entraining Agent AEX	15 ml/100 kg cement

Table 7.1. Mix design for the wall example

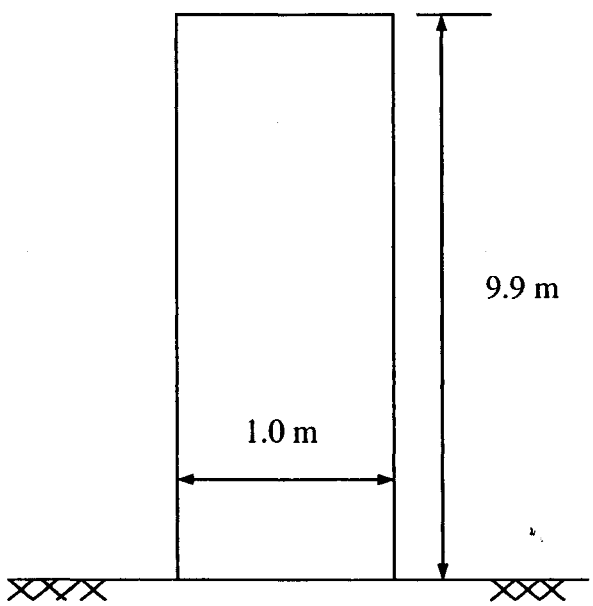

Figure 7.1. Structural wall element

7.1 Case 1

The first case is separated into three different situations where the initial temperature of the concrete is kept constant (at 10°C, 15°C, and 20°C) and the layer thickness within the slipform is further divided into another three situations. Then by knowing these initial concrete temperatures, the initial setting time can be estimated based on experiments that are established in the laboratory. It should be remembered that in order to make the slipforming technique efficient, the concrete layers within the slipform should be of 200±100 mm thickness.

7.1.1 Sub case 1.1

In this sub case the initial concrete temperature is supposed to be 10°C and the concrete within the slipform is arranged into four layers as shown in Fig. 7.2. Also, in Fig. 7.2 the suggested locations of the thermocouples or the maturity meters are shown. These locations are suggested to be at the centre of the element and near the surface that is exposed to the slipform (10 mm from the slipform). The height of the layers within the slipform is arranged so as to be uniform. In this case (Fig. 7.2) the layers have a height of 300 mm each.

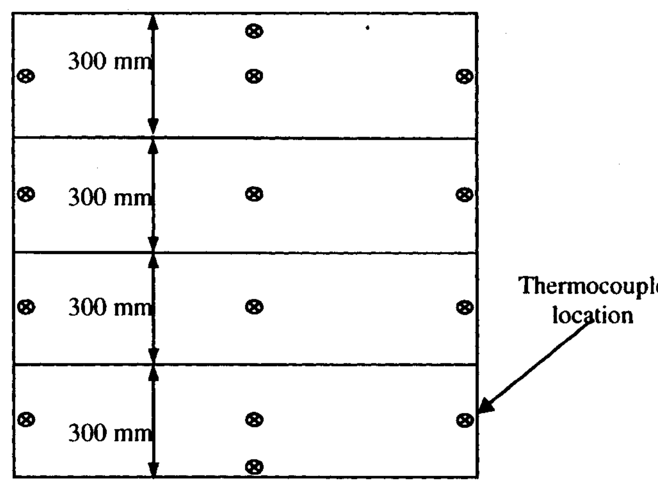

Figure 7.2. Layer and thermocouple arrangement for sub case 1.1

By using the maturity method of establishing the initial setting times, the slipforming operation can be planned. It was suggested in Chapter 4 that the maturity function suggested by Carino and Tank can be efficiently used due to its simplicity (Eq. 4.5). So, based on Fig. 6.4 the temperature sensitivity factor "B" for 0 ml of retarder dosage would be approximately 0.034 $^{o}C^{-1}$. Thus, by knowing the temperature sensitivity factor and the initial setting times of two or three different average concrete temperatures, the equivalent initial setting time can be calculated. Table 7.2 shows the initial setting times and their corresponding average concrete temperatures according to Figs. 6.5 to 6.7 based on the 0 ml retarder dosage.

Initial Setting Time (Hrs)	Average Concrete Temperature (T_{av}) (°C)	Equivalent Initial Setting Time (t_{CT}) (Hrs)
9.0	13.2	7.2
8.0	16.7	7.2
6.5	20.4	6.6
Average Equivalent Initial Setting Time (Hrs)		**7.0**

Table 7.2. Equivalent initial setting time for 0 ml retarder dosage

The equivalent initial setting time is calculated based on Eq. 4.5 and a value of the temperature sensitivity factor of 0.034 $^{o}C^{-1}$. This model is shown in Eq. 7.1.

$$t_{CT} = e^{0.034\cdot(T_{av} - 20)} \cdot \Delta t \quad (7.1)$$

Consequently, by knowing the temperature development of the concrete in the laboratory, (the data for Fig. 6.5 are represented in Table 7.3 for 0 ml retarder dosage) the actual time of the initial setting of the mix presented in Table 7.1 at a constant temperature of 10°C can be estimated (Table 7.3). As it can be seen from Table 7.3 the actual initial setting time is the one that corresponds to the equivalent age obtained from Table 7.2, which is 9.0 hours.

Actual Time (Hrs)	Concrete Temperature (°C)	Equivalent Age (t_{CT}) (Hrs)
0.0	12	0.0
0.5	12	0.4
1.0	12	0.8
1.5	12	1.2
2.0	12	1.5
2.5	12	1.9
3.0	13	2.3
3.5	13	2.7
4.0	13	3.1
4.5	13	3.5
5.0	13	3.9
5.5	13	4.3
6.0	14	4.7
6.5	14	5.1
7.0	14	5.6
7.5	14	6.0
8.0	14	6.4

8.5	15	6.8
9.0	***15***	***7.2***
9.5	16	7.7
10.0	17	8.1
10.5	17.5	8.6
11.0	18	9.0
11.5	19	9.5
12.0	20	10.0
12.5	21.3	10.5
13.0	22.5	11.0
13.5	24.5	11.6
14.0	26.5	12.2

Table 7.3. Actual initial setting time at 10°C

By knowing the actual initial setting time, the time of placement of each concrete layer and the time of the slipforming mockup (removal) can be estimated (Table 7.4).

Layer #	Layer Thickness (mm)	Elevation (mm)	Concrete Placement (Hrs)	Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Time of Mockup (Hrs)	Slipform Speed (mm/hrs)	Speed Check (104.2 mm/hr)
0	0	0	0	0	-	9.00	0	-
1	300	300	0.00	10	9	12.00	100.0	OK
2	300	600	3.00	10	9	15.00	100.0	OK
3	300	900	6.00	10	9	18.00	100.0	OK
4	300	1200	9.00	10	9	21.00	100.0	OK
5	300	1500	12.00	10	9	24.00	100.0	OK
6	300	1800	15.00	10	9	27.00	100.0	OK
7	300	2100	18.00	10	9	30.00	100.0	OK
8	300	2400	21.00	10	9	33.00	100.0	OK
9	300	2700	24.00	10	9	36.00	100.0	OK
10	300	3000	27.00	10	9	39.00	100.0	OK
11	300	3300	30.00	10	9	42.00	100.0	OK
12	300	3600	33.00	10	9	45.00	100.0	OK
13	300	3900	36.00	10	9	48.00	100.0	OK
14	300	4200	39.00	10	9	51.00	100.0	OK
15	300	4500	42.00	10	9	54.00	100.0	OK
16	300	4800	45.00	10	9	57.00	100.0	OK
17	200	5000	48.00	10	9	59.00	100.0	OK

Table 7.4. Slipforming mockup for sub case 1.1

In Table 7.4, the inputs are the in-situ concrete temperature, the initial setting time, the layer thickness, and the placement time of concrete. By knowing these factors the time of the slipform mockup (removal) can be estimated. The time of the slipform mockup is calculated by adding the initial setting time of each layer with the time of placement of the concrete's layer. In order for the mockup to be efficient, the slipform speed should be checked. The allowable limit for the offshore oil platforms is approximately 104 mm/hr as mentioned before. The calculation of the slipform speed can be adjusted by knowing the initial setting time of the layer from which the slipform should be removed, the initial setting time of the layer above, the duration of transportation of concrete, and the layer thickness [Elimov, 2003]. In this example, it is assumed that the concrete is mixed on the site so that the transportation duration would be zero. Then 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 concrete placement and the time of setting can be arranged to produce an efficient and economical construction planning. It can be seen from Table 7.4 that the duration of the erection of such wall (Fig. 7.1) under sub case 1.1 would be 59 hours.

7.1.2 Sub Case 1.2

In this sub case, the concrete initial temperature is assumed to be constant at 10°C and the slipform is arranged into five layers as shown in Fig. 7.3. The assumed locations of the thermocouples or the maturity meters are shown in Fig 7.3. These locations are at the centre of the element and near the surface that is exposed to the slipform (10 mm from the slipform). Sub case 1.2 is different from sub case 1.1 in the manner of the layer arrangement within the slipform. In sub case 1.1, the number of layers within the slipform was four (Fig. 7.2), and now in sub case 1.2 they are five (Fig. 7.3). The locations of the thermocouples or the maturity meters are same as sub case 1.1. The initial setting time is 9.0 hours and the value of the sensitivity factor is 0.034 $°C^{-1}$.

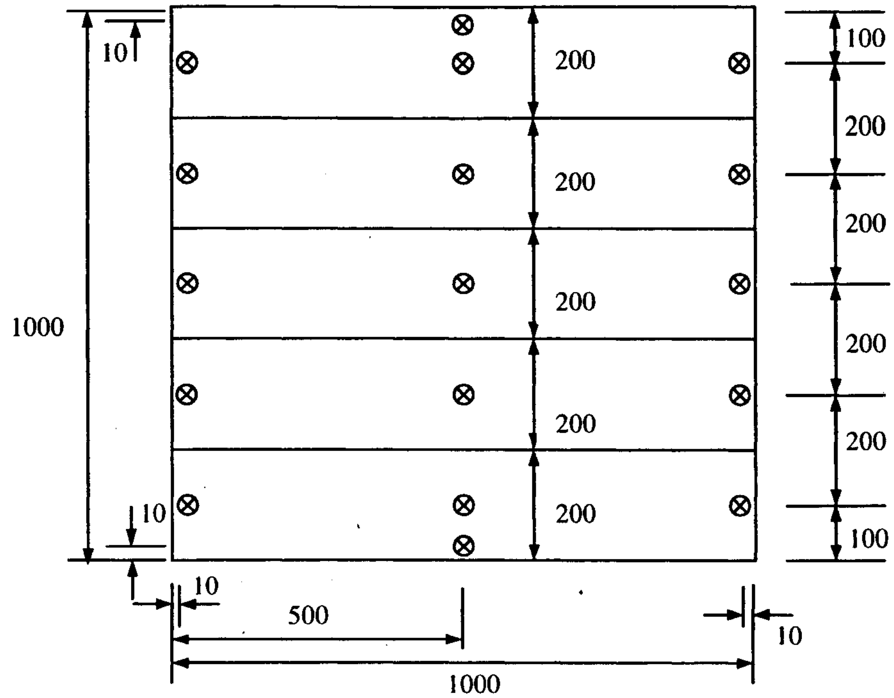

Figure 7.3. Layer and thermocouple arrangement for sub case 1.2

Layer #	Layer Thickness (mm)	Elevation (mm)	Concrete Placement (Hrs)	Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Time of Mockup (Hrs)	Slipform Speed (mm/hrs)	Speed Check (104.2 mm/hr)
0	0	0	0	0	-	9.00	0	-
1	200	200	0.00	10	9	11.00	100.0	OK
2	200	400	2.00	10	9	13.00	100.0	OK
3	200	600	4.00	10	9	15.00	100.0	OK
4	200	800	6.00	10	9	17.00	100.0	OK
5	200	1000	8.00	10	9	19.00	100.0	OK
6	200	1200	10.00	10	9	21.00	100.0	OK
7	200	1400	12.00	10	9	23.00	100.0	OK
8	200	1600	14.00	10	9	25.00	100.0	OK
9	200	1800	16.00	10	9	27.00	100.0	OK
10	200	2000	18.00	10	9	29.00	100.0	OK
11	200	2200	20.00	10	9	31.00	100.0	OK
12	200	2400	22.00	10	9	33.00	100.0	OK
13	200	2600	24.00	10	9	35.00	100.0	OK
14	200	2800	26.00	10	9	37.00	100.0	OK
15	200	3000	28.00	10	9	39.00	100.0	OK
16	200	3200	30.00	10	9	41.00	100.0	OK
17	200	3400	32.00	10	9	43.00	100.0	OK
18	200	3600	34.00	10	9	45.00	100.0	OK

19	200	3800	36.00	10	9	47.00	100.0	OK
20	200	4000	38.00	10	9	49.00	100.0	OK
21	200	4200	40.00	10	9	51.00	100.0	OK
22	200	4400	42.00	10	9	53.00	100.0	OK
23	200	4600	44.00	10	9	55.00	100.0	OK
24	200	4800	46.00	10	9	57.00	100.0	OK
25	200	5000	48.00	10	9	59.00	100.0	OK

Table 7.5. Slipforming Mockup for sub case 1.2

It can be seen from Table 7.5 that the duration of the erection of the wall (Fig. 7.1) according to sub case 1.2 would be 59 hours (4 days and 12 hours). It can be seen that the time of completion of the wall is the same as in sub case 1.1.

7.1.3 Sub Case 1.3

In this sub case, the temperature is assumed to be constant at 10°C and the slipform is arranged into eleven layers as shown in Fig. 7.4. The initial setting time is 9.0 hours and the value of the sensitivity factor is 0.034 $^{o}C^{-1}$.

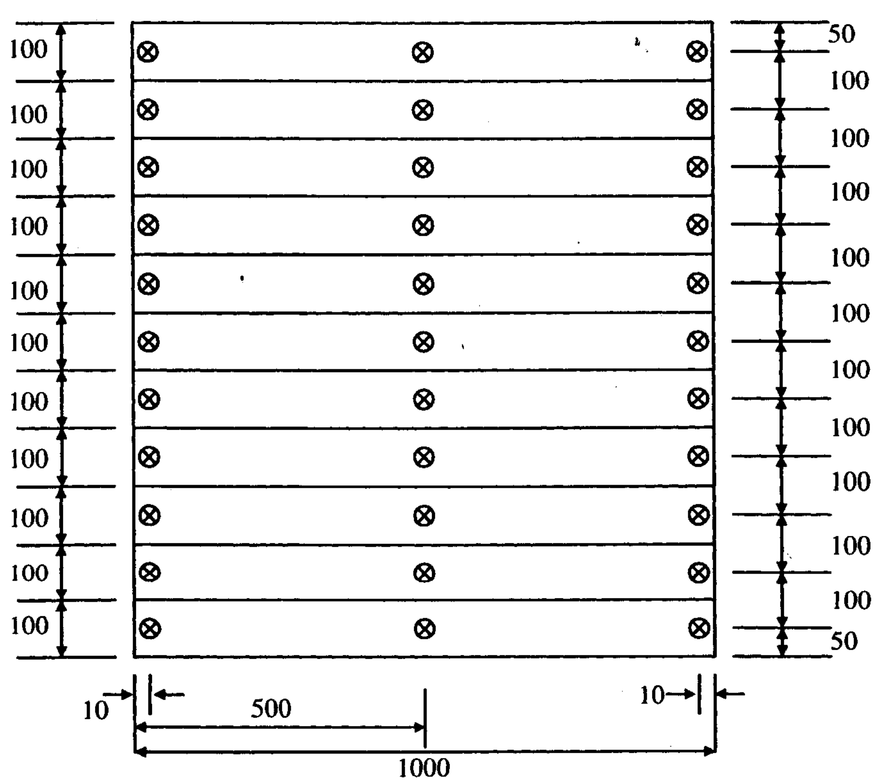

Figure 7.4. Layer and thermocouple arrangement for sub case 1.3

Layer #	Layer Thickness (mm)	Elevation (mm)	Concrete Placement (Hrs)	Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Time of Mockup (Hrs)	Slipform Speed (mm/hrs)	Speed Check
0	0	0	0	0	-	9.00	0	-
1	100	100	0.00	10	9	10.00	100.0	OK
2	100	200	1.00	10	9	11.00	100.0	OK
3	100	300	2.00	10	9	12.00	100.0	OK
4	100	400	3.00	10	9	13.00	100.0	OK
5	100	500	4.00	10	9	14.00	100.0	OK
6	100	600	5.00	10	9	15.00	100.0	OK
7	100	700	6.00	10	9	16.00	100.0	OK
8	100	800	7.00	10	9	17.00	100.0	OK
9	100	900	8.00	10	9	18.00	100.0	OK
10	100	1000	9.00	10	9	19.00	100.0	OK
11	100	1100	10.00	10	9	20.00	100.0	OK
12	100	1200	11.00	10	9	21.00	100.0	OK
13	100	1300	12.00	10	9	22.00	100.0	OK
14	100	1400	13.00	10	9	23.00	100.0	OK
15	100	1500	14.00	10	9	24.00	100.0	OK
16	100	1600	15.00	10	9	25.00	100.0	OK
17	100	1700	16.00	10	9	26.00	100.0	OK
18	100	1800	17.00	10	9	27.00	100.0	OK
19	100	1900	18.00	10	9	28.00	100.0	OK
20	100	2000	19.00	10	9	29.00	100.0	OK
21	100	2100	20.00	10	9	30.00	100.0	OK
22	100	2200	21.00	10	9	31.00	100.0	OK
23	100	2300	22.00	10	9	32.00	100.0	OK
24	100	2400	23.00	10	9	33.00	100.0	OK
25	100	2500	24.00	10	9	34.00	100.0	OK
26	100	2600	25.00	10	9	35.00	100.0	OK
27	100	2700	26.00	10	9	36.00	100.0	OK
28	100	2800	27.00	10	9	37.00	100.0	OK
29	100	2900	28.00	10	9	38.00	100.0	OK
30	100	3000	29.00	10	9	39.00	100.0	OK
31	100	3100	30.00	10	9	40.00	100.0	OK
32	100	3200	31.00	10	9	41.00	100.0	OK
33	100	3300	32.00	10	9	42.00	100.0	OK
34	100	3400	33.00	10	9	43.00	100.0	OK
35	100	3500	34.00	10	9	44.00	100.0	OK
36	100	3600	35.00	10	9	45.00	100.0	OK
37	100	3700	36.00	10	9	46.00	100.0	OK
38	100	3800	37.00	10	9	47.00	100.0	OK
39	100	3900	38.00	10	9	48.00	100.0	OK
40	100	4000	39.00	10	9	49.00	100.0	OK
41	100	4100	40.00	10	9	50.00	100.0	OK

42	100	4200	41.00	10	9	51.00	100.0	OK
43	100	4300	42.00	10	9	52.00	100.0	OK
44	100	4400	43.00	10	9	53.00	100.0	OK
45	100	4500	44.00	10	9	54.00	100.0	OK
46	100	4600	45.00	10	9	55.00	100.0	OK
47	100	4700	46.00	10	9	56.00	100.0	OK
48	100	4800	47.00	10	9	57.00	100.0	OK
49	100	4900	48.00	10	9	58.00	100.0	OK
50	100	5000	49.00	10	9	59.00	100.0	OK

Table 7.6. Slipforming mockup for sub case 1.3

It can be seen from table 7.6 that the duration of the erection of the wall according to sub case 1.3 would be 59 hours. It can be seen that the time of completion of the wall remains the same as in the previous cases. Thus, sub case 1.1 would be advantageous because the number of layers within the slipform is less than that in sub case 1.2 and 1.3.

7.1.4 Sub Case 1.4

In this sub case, the initial concrete temperature is assumed to be 15°C and the concrete within the slipform is arranged into five layers as shown in Fig. 7.3. The value of the sensitivity factor is 0.034 $°C^{-1}$. Table 7.7 represents the temperature development at 15°C. The equivalent ages are then calculated and the actual initial setting time of the mixture at 15°C is estimated (similar to section 7.1.1). So, from Table 7.7 it can be seen that actual initial setting time at 15°C is 8 hours.

Actual Time (Hrs)	Concrete Temperature (°C)	Equivalent Age (t_{CT}) (Hrs)
0.0	16	0.0
0.5	16	0.4
1.0	16	0.9
1.5	16	1.3
2.0	16	1.8
2.5	16	2.2
3.0	16	2.6
3.5	17	3.1
4.0	17	3.5
4.5	17	4.0
5.0	17	4.4

5.5	17	4.9
6.0	17	5.4
6.5	17	5.8
7.0	17	6.3
7.5	18	6.7
8.0	***18***	***7.2***
8.5	19	7.7
9.0	20	8.2
9.5	20.5	8.7
10.0	21	9.2
10.5	22.5	9.7
11.0	24	10.3
11.5	26	10.9
12.0	28	11.5
12.5	29.5	12.1
13.0	31	12.8
13.5	34	13.6
14.0	37	14.4
14.5	39.5	15.3
15.0	42	16.3
15.5	44.5	17.3

Table 7.7. Actual initial setting time at 15°C

Layer #	Layer Thickness (mm)	Elevation (mm)	Concrete Placement (Hrs)	Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Time of Mockup (Hrs)	Slipform Speed (mm/hrs)	Speed Check
0	0	0	0	0	-	8.00	0	-
1	200	200	0.00	15	8	10.00	100.0	OK
2	200	400	2.00	15	8	12.00	100.0	OK
3	200	600	4.00	15	8	14.00	100.0	OK
4	200	800	6.00	15	8	16.00	100.0	OK
5	200	1000	8.00	15	8	18.00	100.0	OK
6	200	1200	10.00	15	8	20.00	100.0	OK
7	200	1400	12.00	15	8	22.00	100.0	OK
8	200	1600	14.00	15	8	24.00	100.0	OK
9	200	1800	16.00	15	8	26.00	100.0	OK
10	200	2000	18.00	15	8	28.00	100.0	OK
11	200	2200	20.00	15	8	30.00	100.0	OK
12	200	2400	22.00	15	8	32.00	100.0	OK
13	200	2600	24.00	15	8	34.00	100.0	OK
14	200	2800	26.00	15	8	36.00	100.0	OK
15	200	3000	28.00	15	8	38.00	100.0	OK
16	200	3200	30.00	15	8	40.00	100.0	OK
17	200	3400	32.00	15	8	42.00	100.0	OK
18	200	3600	34.00	15	8	44.00	100.0	OK
19	200	3800	36.00	15	8	46.00	100.0	OK

20	200	4000	38.00	15	8	48.00	100.0	OK
21	200	4200	40.00	15	8	50.00	100.0	OK
22	200	4400	42.00	15	8	52.00	100.0	OK
23	200	4600	44.00	15	8	54.00	100.0	OK
24	200	4800	46.00	15	8	56.00	100.0	OK
25	200	5000	48.00	15	8	58.00	100.0	OK

Table 7.8. Slipforming mockup for sub case 1.4

It can be seen from Table 7.8 that the time of completion of the wall is 58 hours. This is only 1 hour less than the previous sub cases. So, it can be seen that the initial concrete temperature variation from 10°C to 15°C does not have any significant effect on the slipform mockup.

7.1.5 Sub Case 1.5

In this sub case, the initial concrete temperature is assumed to be 20°C and the slipform is arranged into five layers as shown in Fig. 7.3. The value of the sensitivity factor is 0.034 $^{\circ}C^{-1}$. Table 7.9 represents the temperature development at 20°C. The equivalent ages are then calculated and the actual initial setting time of the mixture at 20°C is estimated (similar to section 7.1.1). So, from Table 7.9 can be seen that actual initial setting time at 20°C is 7 hours.

Actual Time (Hrs)	Concrete Temperature (°C)	Equivalent Age (t_{CT}) (Hrs)
0.0	19.5	0.0
0.5	20.5	0.5
1.0	20.5	1.0
1.5	20.5	1.5
2.0	20.5	2.0
2.5	20.5	2.5
3.0	20.5	3.0
3.5	20.5	3.6
4.0	20.5	4.1
4.5	20.5	4.6
5.0	20.5	5.1
5.5	20.5	5.6
6.0	20.5	6.1
6.5	20.5	6.6
7.0	***22.5***	***7.1***

7.5	24.3	7.7
8.0	26	8.3
8.5	27.5	8.9
9.0	29	9.6
9.5	31.5	10.3
10.0	34	11.1
10.5	36.8	11.9
11.0	39.5	12.8
11.5	42	13.8
12.0	44.5	14.9
12.5	47.3	16.1
13.0	50	17.5
13.5	52	18.9
14.0	54	20.4
14.5	55.5	22.1
15.0	57	23.8
15.5	58.3	25.6
16.0	59.5	27.5
16.5	60.3	29.4
17.0	61	31.4
17.5	61	33.4
18.0	62	35.5

Table 7.9. Actual initial setting time at 20°C

Layer #	Layer Thickness (mm)	Elevation (mm)	Concrete Placement (Hrs)	Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Time of Mockup (Hrs)	Slipform Speed (mm/hrs)	Speed Check
0	0	0	0	0	-	7.00	0	-
1	200	200	0.00	20	7	9.00	100.0	OK
2	200	400	2.00	20	7	11.00	100.0	OK
3	200	600	4.00	20	7	13.00	100.0	OK
4	200	800	6.00	20	7	15.00	100.0	OK
5	200	1000	8.00	20	7	17.00	100.0	OK
6	200	1200	10.00	20	7	19.00	100.0	OK
7	200	1400	12.00	20	7	21.00	100.0	OK
8	200	1600	14.00	20	7	23.00	100.0	OK
9	200	1800	16.00	20	7	25.00	100.0	OK
10	200	2000	18.00	20	7	27.00	100.0	OK
11	200	2200	20.00	20	7	29.00	100.0	OK
12	200	2400	22.00	20	7	31.00	100.0	OK
13	200	2600	24.00	20	7	33.00	100.0	OK
14	200	2800	26.00	20	7	35.00	100.0	OK
15	200	3000	28.00	20	7	37.00	100.0	OK
16	200	3200	30.00	20	7	39.00	100.0	OK
17	200	3400	32.00	20	7	41.00	100.0	OK
18	200	3600	34.00	20	7	43.00	100.0	OK

19	200	3800	36.00	20	7	45.00	100.0	OK
20	200	4000	38.00	20	7	47.00	100.0	OK
21	200	4200	40.00	20	7	49.00	100.0	OK
22	200	4400	42.00	20	7	51.00	100.0	OK
23	200	4600	44.00	20	7	53.00	100.0	OK
24	200	4800	46.00	20	7	55.00	100.0	OK
25	200	5000	48.00	20	7	57.00	100.0	OK

Table 7.10. Slipforming mockup for sub case 1.5

It can be seen from Table 7.10 that the time of completion of the wall is 57 hours. This is only 1 hour less than sub case 1.4 and 2 hours less than sub case 1.1. So, it can be seen that the initial concrete temperature variation from 10°C to 20°C does not affect significantly, the slipform mockup.

7.2 Case 2

The second case uses the most efficient layer combination within the slipform that is derived from the first case, which is the sub case 1.1, but the initial concrete temperature is varied.

In case 2, the temperature varies through the first day between 10°C and 14°C and then increases and varies between 15°C and 18°C. In Table 7.11 the initial setting times of concrete for initial temperatures between 10°C and 20°C are estimated by linear interpolation.

Layer #	Layer Thickness (mm)	Elevation (mm)	Concrete Placement (Hrs)	Initial Concrete Temp. (°C)	Initial Setting (Hrs)	Time of Mockup (Hrs)	Slipform Speed (mm/hrs)	Speed Check
0	0	0	0	0	-	9.00	0	-
1	300	300	0.00	10	9	12.00	100.0	OK
2	300	600	3.00	10	9	15.00	100.0	OK
3	300	900	6.00	10	9	18.50	85.7	OK
4	300	1200	10.00	12	8.5	22.00	85.7	OK
5	300	1500	13.00	11	9	25.50	85.7	OK
6	300	1800	17.00	13	8.5	29.00	85.7	OK

7	300	2100	20.00	10	9	32.50	85.7	OK
8	300	2400	24.00	12	8.5	36.00	85.7	OK
9	300	2700	28.00	14	8	39.00	100.0	OK
10	300	3000	30.00	11	9	42.00	100.0	OK
11	300	3300	34.00	15	8	45.00	100.0	OK
12	300	3600	37.00	16	8	48.50	85.7	OK
13	300	3900	41.00	18	7.5	51.50	100.0	OK
14	300	4200	44.00	17	7.5	54.50	100.0	OK
15	300	4500	47.00	17	7.5	58.00	85.7	OK
16	300	4800	50.00	15	8	61.00	100.0	OK
17	200	5000	53.00	15	8	63.00	100.0	OK

Table 7.11. Slipforming mockup for case 2

It can be seen from Table 7.11 that in case 2 with variable initial concrete temperature, the completion time of the erection of the wall would be 63 hours. The time of completion of the wall in sub case 1.2 calculated to be 59 hours (constant temperature 10°C), while in sub case 1.4 58 hours (constant temperature 15°C), and in sub case 1.5 was 57 hours (constant temperature 20°C). So, there is a difference of 6 hours. Thus it could be said that even if, when the temperature is kept constant, the completion time is not affected much by the temperature (when it was kept constant in 10°C, in 15°C, and 20°C), when the temperature varies during the slipforming then the slipforming mockup is significantly affected. This is due to the fact that at different initial concrete temperatures the initial setting times differ, so the time of completion of the slipform operations may vary, as is the case here. Therefore care should be given to account for the appropriate temperature effects to the initial setting time of the concrete, and the maturity method is a very good method in experiencing such variances.

7.3 Program Development

By knowing the initial setting times at various retarder dosages and at various initial concrete temperatures, it is possible to determine the most efficient layer arrangement within the slipform and calculate the most efficient time of concrete placement as well as the time of slipform mock-up.

For a known dosage of retarder, it is possible to calculate the value of the temperature sensitivity factor (B) by using Eq. 7.1 for the concrete mixture shown in Table 7.1. Then, the actual initial setting time at various retarder dosages and concrete initial temperatures can be predicted by knowing the equivalent setting time from Table 6.8 (based on the t_{CT} function) and the temperature histories from Figs. 6.5 to 6.7 (Appendix Tables N-R).

Based on these data, a computer program has been developed, which can automatically calculate the time of mock-up during slipforming operations. This program can generate the most efficient layer arrangement, time of concrete placement, and the dosage of retarder at each layer. After generating all that data, the best time of mock-up is calculated by the program.

The program is developed using Microsoft Excel with its Visual Basic Interface (VBI) and is very easy to use. More details about the development of the program and its illustration are provided in Appendix II.

7.4 Conclusion

It was seen that the time of the completion of a wall when using the slipforming technique is not significantly affected by the thickness of the concrete layers within the slipform. Finally, the maturity method was proved to be a good tool in establishing the slipforming mockup (removal). It is practical for the slipforming planning and also it can be used to account for field verification of the initial setting times. Therefore it can be concluded that it can be efficiently used for such operations. It will not only be adequate regarding the safety aspect but also it could be sufficient in the economical issue.

8. Conclusions and Suggestions for Further Studies

8.1 Conclusions

It is known that the knowledge in advance of the time at which the concrete is ready to sustain all internal stresses without any extra support is beneficial for the construction management of a structure to ensure such aspects as safety and economy. Therefore, the time of formwork removal is of great importance. This information becomes more crucial when slipforming is used as formwork.

It was noted through this study that the slipforms should be removed from a concrete element as soon as the concrete begins to harden, to avoid a possible damage to the concrete since it could adhere to the forms during the mockup. Also, at that time the concrete should have adequate strength to support itself. This time corresponds to the time of the initial setting of the concrete mixture. Therefore, as long as the initial setting time of the concrete mixture is known, the slipforming operations can be successfully planned for a project.

Concrete is a material whose strength depends on its temperature development. Consequently, since initial setting times are estimated in the laboratory where the curing conditions are controlled, the results can be misleading. Thus, a simulation of the temperature development of the concrete in the laboratory similar to the one it will experience at the site is advantageous. However, such a simulation in the concrete temperature development can still provide variations with the one on the site. Therefore, it would be valuable to compare the initial setting times calculated in the laboratory with the actual initial setting times from the concrete on the site. Though, nondestructive tests can provide adequate results, they can not be applied in this case since the early age strength at the initial setting is required where concrete has not even hardened.

Therefore, some methods are used nowadays in projects involving slipforming operations, such as the "Rod" and the "2°C Temperature Increase". But none of these methods are standardized. The "Rod" method, even though it has been applied successfully in some projects, may be impractical in some cases. Moreover, the "2^{0}C Temperature Increase", even though it has been applied successfully in many projects, it cannot provide the adequate results at low temperatures [Elimov 2003]. Therefore, a more practical and scientific method is needed. The "Maturity" method of estimating the initial setting times has been successfully implemented in this study. This method can be successfully applied to a concrete element for the establishment of the hardened front line and eventually the mockup time and the speed of the slipforms.

8.1.1 Apparent Activation Energy and the Temperature Sensitivity Factor

In this study, Nurse-Saul "t_{NS}", Rastrup "t_R", Weaver and Sadgrove "t_{WS}", Freiesleben and Pederson "t_{FHP}", and Carino and Tank "t_{CT}" maturity functions are compared according to their ability to predict the strength development of a concrete element. For the use of "t_{FHP}" and "t_{CT}" maturity functions, it is essential to first estimate the apparent activation energy "E" and the temperature sensitivity factor "B".

In order to evaluate the credibility of the maturity meters and the use of a constant value for "E" during the whole spectrum of ages, the age conversion factors based on "t_{FHP}" are estimated based on three cases. In the first case, the age conversion factor is estimated based on a constant value of 41572 J/mol, which is the typical value of "E" used for most of the maturity meters. In the second case, a constant value of "E" of 34089 J/mol is used. This value is derived based on tests at Sherbrooke University [Kada-Benaceur and Duthoit, 1997]. Finally, in the third case, a varying value of "E" is used; a value of 25276 J/mol is used for ages up to initial setting time and then a value of 34089 J/mol is used for later ages. These three cases are applied to temperature-time data collected from Hibernia project and their values are compared between them in order to find out the correlation between them (Figs. 3.6 to 3.11). It is found that the value of "E" has to be estimated first according to ASTM C1074. Then it can be decided if the maturity meters can be used, or if the maturity meters should be calibrated to correct the value of "E". It is noted that a difference of approximately 7000 J/mol in the value "E" can give misleading result in terms of the prediction of the compressive strength of the concrete (Figs 4.7 to 4.17). However, if the temperature variation of the concrete is kept within 5°C from the reference temperature and if the variation in the value of "E" between the maturity meter and the one estimated by ASTM C1074-98 is between 7000 J/mol, then maturity meters can be safely used, without any calibration.

Furthermore, it is found that a different value of "E" should be used for ages up to initial setting of the concrete, if the temperature variation of the concrete is expected to be greater than 5°C from the reference. This value of "E" can be successfully estimated by the method suggested by Pinto and Hover (1999) as discussed in this study. Therefore, if maturity meters are used, their "E" value should be calibrated in two phases. In the first phase (for the ages up to initial setting), the "E" value has to be calibrated according to the value estimated by the maturity method suggested by Pinto and Hover (1999) (presented in Chapter 3). Then, in the second phase (for ages above the initial setting), the "E" value estimated by ASTM C1074-98 should be used.

The same issues are also true for the temperature sensitivity factor "B", since the apparent activation energy "E" and the temperature sensitivity factor "B" are closely interrelated.

8.1.2 Effect of the Retarder Dosage on the Apparent Activation Energy and the Temperature Sensitivity Factor

Study of the effect of the retarder dosage on the apparent activation energy "E" and the temperature sensitivity factor "B" is carried out, to evaluate the effects of the retarder on "E" and "B". It is found that the values of "E" and "B" increase with the increase of the dosage of the retarder. It is also found that by predicting two values of "E" or "B" for two different retarder dosages, a linear relationship between "E" or "B" and the retarder dosage, for a particular concrete mix, can be established. Therefore, for that mix, "E" or "B" can be estimated by a simple equation for any retarder dosage. However, it is suggested that the retarder dosage does not have any significant effect on the value of "E" or "B", therefore a unique value can be used.

8.1.3 Maturity Functions

After calculating "E" and "B", the maturity functions "t_{NS}", "t_R", "t_{WS}", "t_{FHP}", and "t_{CT}", are applied to the time-temperature data collected from Hibernia project and then compared in terms of predicting the compressive strength of the concrete. It is observed that "t_{NS}" is not able to represent effectively the equivalent ages over the wide range of temperature (Figs. 4.1 to 4.6). Also, "t_R" seems to overestimate the results at high temperatures. The "t_{FHP}" and "t_{CT}" functions are found to be the most convenient for the estimation of the equivalent ages. These two functions (t_{FHP} and t_{CT}) give very similar results and they are comparatively better than the others, since they can represent the strength development of the concrete for a wide range of temperatures. It is also practical to use a function, which is as simple as possible. Thus, based on the performance study, it is concluded that "t_{CT}" function is more convenient than the "t_{FHP}" function due to its simplicity.

8.1.4 Ability of the Maturity Method in Establishing the Initial Setting Times

The "t_{CT}" maturity function is applied to the data collected from the Hibernia project, to evaluate its ability to predict the initial setting times. It is found that the maturity method is suitable for the prediction of the initial setting times of a concrete element. It is also advantageous for its simplicity, since only thermocouples, digital data loggers, and a technician (to read the device) are enough for this practice. Moreover, the maturity method can also be used in the field practice to validate and to ensure that the initial setting times established in the laboratory are adequate, so that the project can efficiently proceed.

Even though, the maturity method is convenient, it can be proved to be disadvantageous if it is based upon a method that cannot provide adequate data. It is suggested that the maturity method can be used in establishing the initial setting times only if the initial setting times at two different temperatures are established for the same mixture by another method ("Penetration Resistance (PR)", "Rod (R)", "Conductivity (C)", or "2°C Temperature Increase (2C)"). Therefore, the performance of the maturity method is dependent on the other method and to make the maturity method efficient, this other method should be adequate to produce true results.

It is also confirmed that the best methods to use for that purpose are the "R" and the "C" methods. The "2 C" method is also adequate but it may overestimate the initial setting times and can lead to misleading results. On the other hand, the "PR" method tends to underestimate the initial setting times. In addition, it is found that the "PR" method can produce some discrepancies in estimating the initial setting times when high dosages of retarder (as high as 500 ml/100 kg of cement) are used. As a consequence the maturity method based on the "PR" method can produce variances in the calculation of the initial setting times (Fig 6.13). Finally, it can be concluded that the maturity method is a convenient means for determining the initial setting times.

8.1.5 Application of the Maturity Method in Slipforming Technique

The maturity method is applied to the data collected from Hibernia project regarding the slipforming mockup (removal of the slipforms). It is found that the maturity method, represented by the "t_{CT}" maturity function, is capable of estimating the times of the mockup. It is shown that it produces very good correlation with the "PR", "R", and "2C" methods (Fig. 6.29).

Also, an example of the use of the maturity method in slipforming technique is prsented. From this example, it is found advantageous and preferable to divide the concrete, within the slipform, in layers. The most efficient layer thickness that concluded from this example is 200mm. However the same results regarding the time of completion can be derived from dividing the slipform into thinner layers of 100mm, but this would not be practical.

Finally, the maturity method is found to be a good tool in establishing the slipforming mockup (removal). It is practical for the slipforming planning and also, it can be used to account for field verification of the initial setting times by applying thermocouples or maturity meters inside the concrete element.

8.1.6 Use of the Maturity Strength Models

Strength models based on the "t_{CT}" maturity functions are evaluated to establish their validity in field applications, for a more efficient construction planning. Strength models such as the "Rate Constant Model (S_k)", and the "FHP Strength Model (S_{FHP})", in the prediction of concrete strength development, are evaluated.

It is found that the "FHP Strength Model (S_{FHP})" is not good enough to account for the strength development at very early ages (prior to 2 days), but when it is used for later ages, it produces very good results. The "Rate Constant Model (S_k)" represents better concrete strength development for early ages, but at later ages it results in variations. Therefore, a strength model based on the "FHP Strength Model (S_{FHP})" is proposed in this study "S_c". This proposed strength model "S_c" is found to be adequate for the entire spectrum of ages. Once the initial setting time at the reference temperature is obtained, the proposed strength model "S_c" can be successfully used to predict the strength development of concrete in the laboratory or in field.

Nevertheless, the "S_c" strength model can provide misleading results for extreme weather conditions since the ultimate strength (S_u) of the concrete in the laboratory can be different for that in the field. This is the case when construction takes place in very hot or very cold weather conditions. In such situations, the ultimate strength of the field concrete might differ from the one calculated in the laboratory [Malhotra and Carino 1991]. Therefore, even though the strength model "S_c" provides a good approximation of the strength development of the in-place concrete (Figs. 5.9, 5.10, and 5.11), its efficiency can be questioned if significantly different temperature development occurs in laboratory as compared to the field condition.

Therefore, care should be taken when maturity strength models are used to predict the strength development of the field concrete. It is suggested that, if the field curing conditions are expected to be significantly different from the laboratory ones, then instead of using these models to predict the strength, it can be more efficient to calculate the relative strength "RS" [Carino and Lew, 2001]. The relative strength is the ratio of the strength to the ultimate strength (S/S_u). It is suggested by Carino and Lew (2001), that the 28 day strength should be used instead of the ultimate strength. The relationship between the ultimate strength and the 28 day strength "S_{28}" could be established by the use of the factor "β", which is the ratio of the ultimate strength and the 28 day strength (S_u/S_{28}).

8.1.7 Application of Computer Modeling in Slipforming Technique

It is shown (Section 7.3) that the time of the slipforming mock-up can be estimated by the use of the computer program developed in this thesis. This program can be used to accurately estimate the time at which the concrete should be placed within the slipform and then it establishes the most effective time when the slipform should be moved up. This program is simple to use and is time effective if the same amount of work had to be done manually.

8.2 Further Research

Further research should be undertaken in order to develop improved models for calculating the in-place strength by means of the maturity method as it can provide a very helpful tool for the project management of a structure.

Since the "Improved FHP Strength Model (S_c)" is able to represent the strength development of the concrete very well, further research could be aimed at idealization of the strength of a concrete mixture during its dormant period.

Further research could also be conducted to investigate the calibration of the maturity meters regarding the apparent activation energy (E). In addition, the possibility of the incorporation of the Carino and Tank maturity function (t_{CT}) into the maturity meters can be another area of further study.

Also, research is needed to establish a maturity method for estimating the initial setting times of concrete mixtures with high dosages and different types of retarders.

Furthermore, additional research on the application of the maturity method in predicting the initial setting times should be undertaken. It would be practical to calculate the initial setting times by the maturity method without any prior application of methods such as "Penetration Resistance", "2°C Temperature Increase", "Rod", or "Conductivity".

Finally, a computer model could be developed to calculate the initial setting times and then apply them to the computer model suggested in this study so as to plan the slipforming operations. Such a model would simulate the temperature development of a concrete mixture, and estimate the initial setting times using the maturity method. Also, devices can be developed for in the field to calculate the in-place initial setting times, to confirm the preplanned operations (time of placement, time of mockup, slipforming speed), and make any adjustments in the time of mockup and slipforming speed, on an as-needed basis.

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GLOSSARY

2°C Temperature Increase – An empirical method for the establishment of the initial setting times. The initial setting time according to this method corresponds to the time at which the temperature of the concrete in the measuring point increases by 2°C in a time interval of 1 hour.

A

Actual age – Refers to the age that is recorded from the analog strip chart recorders or the digital data loggers.

Affinity ratio – See age conversion factor.

Age conversion factor – A factor that is used to convert a curing time interval to the equivalent curing interval at the reference temperature.

Ambient temperature – The environment temperature.

Analog strip chart recorders – Devices that record the time and the temperature.

Apparent activation energy – The minimum energy that is needed for a reaction to occur.

Average temperature – Refers to the average temperature of a concrete element for the time interval at which the maturity is needed.

Air entraining agent – Admixture that causes air to be incorporated into the mixture in the form of minute bubbles during mixing, usually to increase the material's workability and frost resistance.

B

Blended cement – Cement containing combinations of Portland cement, pozzolans, slag, and/or other hydraulic cement.

Box method – A method that is used to simulate the temperature development of a concrete mixture in laboratory, by enclosing a concrete sample in an insulated box.

C

Coarse aggregate – natural gravel, crushed stone, or iron blast furnace slag, usually larger than 5 mm and commonly ranging in size between 10 mm and 40 mm.

Concrete – Mixture of binding materials and coarse and fine aggregates. Portland cement and water are commonly used as the binding medium for normal concrete mixtures, but may also contain pozzolans, slag, and/or chemical admixtures.

Concrete finishing – Mechanical operations like screeding, consolidating, floating, troweling, or texturing that establish the final appearance and texture of any concrete surface.

Concrete placement – Corresponds at the time at which the concrete has been poured into its place.

Construction joint – A stopping place in the process of construction. A bond between existing concrete and new concrete, and permits no movement.

Construction loads – Any load that is due to labors and materials on the site.

Compressive strength – Maximum resistance that a concrete, mortar, or grout specimen will sustain when loaded axially in compression in a testing machine at a specified rate; expressed as force per unit of cross sectional area, such as megapascals (MPa)

Conductivity method – Refers to the use of the thermal conductivity method in the estimation of the initial setting times.

Curing – Maintenance of a satisfactory moisture content and temperature in concrete for a suitable period of time during its early stages (immediately following placing and finishing) so that the desired properties of the material can develop. Curing assures satisfactory hydration and hardening of the cementing materials.

D

Datum temperature – The temperature that is subtracted from the measured concrete temperature for calculating the temperature-time factor.

Digital data loggers – Devices that record the time and the temperature.

Dilatometer – A vessel that contains a small dilatometer tube to monitor the decrease in water level as the paste hydrates and undergoes chemical shrinkage.

Dormant period – The period from mixing until initial setting of concrete.

E

Entrained air – Spherical microscopic air bubbles – from 10 μm to 1000 μm in diameter intentionally incorporated into concrete to provide resistance to freezing and thawing when exposed to water and deicing chemicals and/or improve workability.

Equivalent age – The number of days or hours at a specified temperature required to produce a maturity equal to the maturity achieved by a curing period at temperatures different from the specified temperature.

F

FHP function – The maturity function that is suggested by Freiesleben and Pederson.

Field-cured cylinders – Cylindrical test specimens that are cast and stored in the field until the concrete hardens in accordance with the requirements of ASTM C 31, used for testing the compressive strength.

Final setting time – The time at which the concrete possess enough strength to support externally applied loads with acceptable and stable deformation.

Fine aggregate – Aggregate that passes the 10 mm sieve, almost entirely passes the 5 mm sieve, and is predominantly retained on the 80 µm sieve.

G

H

Hardened concrete – A concrete that is in a solid state and developed certain strength.

Hardened front line – A graph that shows the time at which a specific part of the concrete element has hardened.

High strength concrete – Concrete with design strength of at least 60 MPa.

Hydration – The chemical reaction between hydraulic cement and water in which new compounds with strength producing properties are formed.

Hydraulic cement – Cement that sets and hardens by chemical reaction with water and is capable of doing so under water.

I

Initial concrete temperature – The temperature of the concrete at the time of its placement.

Initial setting time – Represents the transition phase between a fluid and a rigid state (when concrete loses its plasticity and becomes an unworkable material).

In-place concrete – The concrete placed on the site.

In-place strength – The strength that corresponds to concrete in the field.

In-situ temperature – The temperature of the concrete that is placed in the field.

Insulation – Insulation materials that are used for covering concrete elements, so as to minimize the temperature gradient between the atmosphere and the concrete element.

J

K

Kinetic energy – Kinetic energy is energy of motion. The kinetic energy of an object is the energy it possesses because of its motion.

L

Linear function – The Nurse-Saul maturity function.

M

Massive concrete element – Cast in-place concrete in volume large enough to require measures to compensate for volume change caused by temperature rise from heat of hydration in order to keep cracking to a minimum.

Maturity – The extent of the development of a property of a cementitious mixture.

Maturity function – A mathematical expression that uses the measures temperature history of a cementitious mixture during the curing period to calculate an index that is indicative of the maturity at the end of that period.

Maturity index – An indicator of maturity that is calculated from the temperature history of the cementitious mixture by using a maturity function.

Maturity meter – Devices that record the time and temperature and produce a maturity index automatically.

Maturity method – A technique for estimating the concrete strength that is based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal values of the maturity index.

N

O

Offset maturity – the maturity index that corresponds to the time at which the concrete starts to develop its strength.

P

Penetration resistance – The method of the estimation of the initial and final setting times by the use of a penetrometer.

Plastic shrinkage cracks – Plastic shrinkage occurs as fresh concrete loses its moisture after placement but before any strength development has occurred. This type of shrinkage is affected by environmental effects of temperature (concrete and ambient), wind and relative humidity. It is a particular problem in hot weather concreting.

Q

R

Rate constant – The rate at which the chemical reactions, due to the hydration process, occur.

Reference temperature – A standard temperature which is used to transform the actual age to the corresponding equivalent age.

Reinforcement – Steel rods used in inside concrete elements to increase element's strength and ductility.

Relative strength – The ratio of the strength over the ultimate strength.

Retardation curve – See "Setting Time Curve".

Rod method – A method of estimating the initial setting time and the hardened front line of a concrete element, by the use of a 10 mm diameter smooth steel bar with no pointed end. The method consists of pushing the steel bar into the concrete until it reaches a hardened surface.

S

Self-load – The load that is due to the weight of the concrete.

Setting period – The period of time from initial setting until final setting.

Setting time curve – Curves that give the relation between the temperature, the initial setting time, and the retardation dosage.

Slipforming – Slipforming is a form, which moves, usually continuously, during the placing of the concrete.

Slipforming curve – See "Setting Time Curve".

Slipforming operations – Refers to the time of removal of the slipforms and the speed of the slipforming.

Slump – Measure of the consistency of freshly mixed concrete, equal to the immediate subsidence of a specimen molded with a standard slump cone.

Strength-maturity relationship – An empirical relationship between the compressive strength and maturity index that is obtained by testing specimens whose temperature history up to the time of test has been recorded.

Strength model – A function that is indicative of the strength of the concrete at any time.

Superplasticizer – admixture that increases the flowability of a fresh concrete mixture.

T

Thermal conductivity – Measures the ability of the material to conduct heat and is defined as the ratio of the flux of heat to temperature gradient.

Thermal diffusivity – The rate at which temperature change within a mass. It is thus an index of the facility with which concrete can undergo temperature change.

Temperature development – The development of the temperature within a concrete element.

Temperature history – The temperature development within the concrete element.

Temperature sensitivity factor – A factor that characterizes the relationship of the temperature and the chemical reactions.

Temperature-time factor – The maturity index computed according to Eq. 2.1.

Thermal cracking – Hydration of cement is an exothermic process (meaning it generates heat). As the concrete cools it contracts and in extreme conditions may contract in three days as much due to cooling as it could in a year due to drying conditions. A temperature differential of 2°C within 0.3 m is usually considered enough to cause cracking. However, within 24-hours of placement, concrete temperatures can reach anywhere from -7°C to 10°F hotter than ambient temperatures.

Thermal stresses – Stresses within the concrete element caused by different temperature gradients.

Thermocouple – Device that is placed within the concrete element and measures the temperature of the concrete.

Time constant – The time at which the strength reaches 37% of the ultimate strength.

U

Ultimate strength – Strength of the concrete that corresponds to its infinite strength.

V

W

Water reducer – admixture whose properties permit a reduction of water required to produce a concrete mix of a certain slump, reduce water-cement ratio, reduce cement content, or increase slump.

X

Y

Z

INDEX

APPENDIX I

Table A.

Temperature development for Channel 1 of the MNDC 69 concrete mixture and the estimated age conversion factors and equivalent ages according to the FHP maturity function (having the subscripts "a", "e", and "q") (based on three different values of the apparent activation energy (E)), according to the Rastrup maturity function with the subscript "R", Weaven and Sadgrove maturity function "WS", Nurse-Saul maturity function "NS", and Carino and Tank maturity function "CT".

$t_a = \Sigma e^{-5000[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$ $\quad\quad \gamma_a = e^{-5000[1/(273+T) - 1/(273+Tr)]}$

$t_e = \Sigma e^{-3040[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$ $\quad\quad \gamma_e = e^{-3040[1/(273+T) - 1/(273+Tr)]}$

$t_q = \Sigma e^{-4100[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$ $\quad\quad \gamma_q = e^{-4100[1/(273+T) - 1/(273+Tr)]}$

$t_R = \Sigma 2^{(T-Tr)/10} \bullet \Delta t$ $\quad\quad \gamma_R = 2^{(T-Tr)/10}$

$t_{WS} = \Sigma (T+16)^2/1296 \bullet \Delta t$ $\quad\quad \gamma_{WS} = (T+16)^2/1296$

$t_{NS} = \Sigma (T-T_o)/(T_r-T_o) \bullet \Delta t$ $\quad\quad \gamma_{NS} = (T-T_o)/(T_r-T_o)$

$t_{CT} = \Sigma e^{B(T-Tr)} \bullet \Delta t$ $\quad\quad \gamma_{CT} = e^{B(T-Tr)}$

The Initial setting time by the 2 °C Temperature Increase method is shown with bold and bigger sized letters

			Equivalent Ages (Hrs)							Age Conversion Factors						
Actual Time (Hrs)	Concrete Temp. (°C)	Average Concrete Temp. (°C)	t_a	t_e	t_q	t_R	t_{WS}	t_{NS}	t_{CT}	γ_a	γ_e	γ_q	γ_R	γ_{WS}	γ_{NS}	γ_{CT}
0	8	8	0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.6	0.6	0.4	0.4	0.6	0.6
0.5	11	9.5	0.2	0.3	0.3	0.2	0.3	0.3	0.3	0.5	0.7	0.6	0.5	0.5	0.7	0.6
1	11	11	0.5	0.7	0.6	0.5	0.5	0.7	0.6	0.6	0.7	0.6	0.5	0.6	0.7	0.7
1.5	11	11	0.8	1.1	0.9	0.8	0.8	1.0	1.0	0.6	0.7	0.6	0.5	0.6	0.7	0.7
2	11	11	1.1	1.4	1.3	1.0	1.1	1.4	1.3	0.6	0.7	0.6	0.5	0.6	0.7	0.7
2.5	11	11	1.4	1.8	1.6	1.3	1.4	1.7	1.6	0.6	0.7	0.6	0.5	0.6	0.7	0.7
3	11	11	1.7	2.1	1.9	1.6	1.7	2.1	2.0	0.6	0.7	0.6	0.5	0.6	0.7	0.7

3.5	11	11	2	2.5	2.2	1.8	1.9	2.4	2.3	0.6	0.7	0.6	0.5	0.6	0.7	0.7
4	11	11	2.3	2.9	2.5	2.1	2.2	2.8	2.6	0.6	0.7	0.6	0.5	0.6	0.7	0.7
4.5	11	11	2.5	3.2	2.9	2.4	2.5	3.1	3.0	0.6	0.7	0.6	0.5	0.6	0.7	0.7
5	11	11	2.8	3.6	3.2	2.7	2.8	3.5	3.3	0.6	0.7	0.6	0.5	0.6	0.7	0.7
5.5	12	11.5	3.1	3.9	3.5	2.9	3.1	3.8	3.6	0.6	0.7	0.7	0.6	0.6	0.7	0.7
6	12	12	3.4	4.3	3.9	3.2	3.4	4.2	4.0	0.6	0.7	0.7	0.6	0.6	0.7	0.7
6.5	13	12.5	3.8	4.7	4.2	3.5	3.7	4.6	4.3	0.6	0.8	0.7	0.6	0.6	0.8	0.7
7	13	13	4.1	5.1	4.6	3.8	4.0	5.0	4.7	0.7	0.8	0.7	0.6	0.6	0.8	0.7
7.5	13	13	4.4	5.5	4.9	4.1	4.3	5.3	5.0	0.7	0.8	0.7	0.6	0.6	0.8	0.7
8	13	13	4.8	5.9	5.3	4.4	4.7	5.7	5.4	0.7	0.8	0.7	0.6	0.6	0.8	0.7
8.5	13	13	5.1	6.3	5.6	4.7	5.0	6.1	5.8	0.7	0.8	0.7	0.6	0.6	0.8	0.7
9	13	13	5.4	6.6	6.0	5.1	5.3	6.5	6.1	0.7	0.8	0.7	0.6	0.6	0.8	0.7
9.5	14	13.5	5.8	7.0	6.3	5.4	5.6	6.9	6.5	0.7	0.8	0.7	0.6	0.7	0.8	0.7
10	14	14	6.1	7.4	6.7	5.7	6.0	7.3	6.9	0.7	0.8	0.7	0.7	0.7	0.8	0.8
10.5	14	14	6.5	7.8	7.1	6.0	6.3	7.7	7.3	0.7	0.8	0.7	0.7	0.7	0.8	0.8
11	14	14	6.8	8.2	7.5	6.4	6.7	8.1	7.6	0.7	0.8	0.7	0.7	0.7	0.8	0.8
11.5	15	14.5	7.2	8.7	7.8	6.7	7.0	8.5	8.0	0.7	0.8	0.8	0.7	0.7	0.8	0.8
12	15	15	7	9.1	8.2	7.1	7.4	8.9	8.4	0.7	0.8	0.8	0.7	0.7	0.8	0.8
12.5	15	15	7	9.5	8.6	7.4	7.8	9.3	8.8	0.7	0.8	0.8	0.7	0.7	0.8	0.8
13	15	15	8	9.9	9.0	7.8	8.2	9.7	9.2	0.7	0.8	0.8	0.7	0.7	0.8	0.8
13.5	16	15.5	8	10.3	9.4	8.1	8.5	10.2	9.6	0.8	0.9	0.8	0.7	0.8	0.9	0.8
14	16	16	9	10.8	9.8	8.5	8.9	10.6	10.0	0.8	0.9	0.8	0.8	0.8	0.9	0.8
14.5	17	16.5	9	11.2	10.3	8.9	9.3	11.0	10.5	0.8	0.9	0.8	0.8	0.8	0.9	0.9
15	17	17	9	11.7	10.7	9.3	9.8	11.5	10.9	0.8	0.9	0.9	0.8	0.8	0.9	0.9
15.5	17	17	10	12.1	11.1	9.7	10.2	11.9	11.3	0.8	0.9	0.9	0.8	0.8	0.9	0.9
16	18	17.5	10	12.6	11.6	10.1	10.6	12.4	11.8	0.9	0.9	0.9	0.8	0.9	0.9	0.9
16.5	18	18	11	13.0	12.0	10.6	11.1	12.9	12.2	0.9	0.9	0.9	0.9	0.9	0.9	0.9
17	18	18	11	13.5	12.5	11.0	11.5	13.3	12.7	0.9	0.9	0.9	0.9	0.9	0.9	0.9
17.5	19	18.5	12	14.0	12.9	11.5	12.0	13.8	13.2	0.9	0.9	0.9	0.9	0.9	1.0	0.9
18	19	19	12	14.4	13.4	11.9	12.4	14.3	13.6	0.9	1.0	1.0	0.9	0.9	1.0	1.0
18.5	20	19.5	13	14.9	13.9	12.4	12.9	14.8	14.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0

19	20	20	13	15.4	14.4	12.9	13.4	15.3	14.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0
19.5	**21**	20.5	14	15.9	14.9	13.4	13.9	15.8	15.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
20	**22**	21.5	14	16.5	15.4	14.0	14.5	16.3	15.7	1.1	1.1	1.1	1.1	1.1	1.1	1.1
20.5	**23**	22.5	15	17.0	16.0	14.6	15.1	16.9	16.2	1.2	1.1	1.1	1.2	1.1	1.1	1.1
21	24	23.5	15	17.6	16.6	15.2	15.7	17.4	16.8	1.2	1.2	1.2	1.3	1.2	1.1	1.2
21.5	26	25	16	18.2	17.2	15.9	16.3	18.0	17.5	1.3	1.3	1.3	1.4	1.3	1.2	1.3
22	27	26.5	17	18.8	17.9	16.7	17.0	18.6	18.1	1.4	1.4	1.4	1.6	1.4	1.2	1.3
22.5	29	28	18	19.5	18.6	17.6	17.8	19.2	18.9	1.6	1.5	1.5	1.7	1.5	1.3	1.4
23	31	30	18	20.2	19.4	18.6	18.6	19.9	19.6	1.8	1.6	1.6	2.0	1.6	1.3	1.6
23.5	32	31.5	19	20.9	20.3	19.7	19.4	20.6	20.5	1.9	1.7	1.7	2.2	1.7	1.4	1.7
24	33	32.5	20	21.7	21.2	20.9	20.3	21.3	21.4	2.0	1.8	1.8	2.4	1.8	1.4	1.8
24.5	34	33.5	21	22.5	22.1	22.1	21.3	22.0	22.3	2.1	1.9	1.9	2.5	1.9	1.5	1.9
25	35	34.5	23	23.3	23.1	23.5	22.3	22.8	23.3	2.2	1.9	1.9	2.7	2.0	1.5	1.9
25.5	35	35	24	24.3	24.0	24.9	23.3	23.5	24.3	2.3	2.0	2.0	2.8	2.0	1.5	2.0
26	35	35	25	25.3	25.0	26.3	24.3	24.3	25.3	2.3	2.0	2.0	2.8	2.0	1.5	2.0
26.5	35	35	26	26.2	26.0	27.8	25.3	25.0	26.3	2.3	2.0	-2.0	2.8	2.0	1.5	2.0
27	35	35	27	27.2	27.0	29.2	26.3	25.8	27.3	2.3	2.0	2.0	2.8	2.0	1.5	2.0
27.5	34	34.5	28	28.2	28.0	30.5	27.3	26.5	28.2	2.2	1.9	1.9	2.7	2.0	1.5	1.9
28	34	34	29	29.1	28.9	31.9	28.2	27.3	29.2	2.2	1.9	1.9	2.6	1.9	1.5	1.9
28.5	33	33.5	30	30.1	29.9	33.1	29.2	28.0	30.1	2.1	1.9	1.9	2.5	1.9	1.5	1.9
29	33	33	31	31.0	30.8	34.4	30.1	28.7	31.0	2.1	1.8	1.8	2.5	1.9	1.4	1.8
29.5	33	33	32	31.9	31.7	35.6	31.0	29.4	31.9	2.1	.1.8	1.8	2.5	1.9	1.4	1.8
30	33	33	33	32.8	32.6	36.8	32.0	30.1	32.9	2.1	1.8	1.8	2.5	1.9	1.4	1.8
30.5	33	33	35	33.7	33.5	38.1	32.9	30.8	33.8	2.1	1.8	1.8	2.5	1.9	1.4	1.8
31	33	33	36	34.6	34.4	39.3	33.8	31.6	34.7	2.1	1.8	1.8	2.5	1.9	1.4	1.8
31.5	33	33	37	35.5	35.3	40.5	34.7	32.3	35.6	2.1	1.8	1.8	2.5	1.9	1.4	1.8
32	32	32.5	38	36.4	36.2	41.7	35.6	33.0	36.5	2.0	1.8	1.8	2.4	1.8	1.4	1.8
32.5	32	32	39	37.3	37.0	42.9	36.5	33.7	37.3	2.0	1.7	1.7	2.3	1.8	1.4	1.7
33	32	32	40	38.1	37.9	44.0	37.4	34.4	38.2	2.0	1.7	1.7	2.3	1.8	1.4	1.7
33.5	32	32	41	39.0	38.8	45.1	38.3	35.1	39.1	2.0	1.7	1.7	2.3	1.8	1.4	1.7
34	32	32	42	39.9	39.6	46.3	39.2	35.8	39.9	2.0	1.7	1.7	2.3	1.8	1.4	1.7

34.5	32	32	43	40.7	40.5	47.4	40.1	36.5	40.8	2.0	1.7	1.7	2.3	1.8	1.4	1.7
35	32	32	44	41.6	41.4	48.6	41.0	37.2	41.7	2.0	1.7	1.7	2.3	1.8	1.4	1.7
35.5	32	32	44	42.5	42.2	49.7	41.9	37.9	42.6	2.0	1.7	1.7	2.3	1.8	1.4	1.7
36	32	32	45	43.3	43.1	50.9	42.8	38.6	43.4	2.0	1.7	1.7	2.3	1.8	1.4	1.7
36.5	32	32	46	44.2	44.0	52.0	43.6	39.3	44.3	2.0	1.7	1.7	2.3	1.8	1.4	1.7
37	32	32	47	45.1	44.8	53.2	44.5	40.0	45.2	2.0	1.7	1.7	2.3	1.8	1.4	1.7
37.5	32	32	48	45.9	45.7	54.3	45.4	40.7	46.0	2.0	1.7	1.7	2.3	1.8	1.4	1.7
38	32	32	49	46.8	46.6	55.5	46.3	41.4	46.9	2.0	1.7	1.7	2.3	1.8	1.4	1.7
38.5	32	32	50	47.7	47.4	56.6	47.2	42.1	47.8	2.0	1.7	1.7	2.3	1.8	1.4	1.7
39	32	32	51	48.5	48.3	57.8	48.1	42.8	48.6	2.0	1.7	1.7	2.3	1.8	1.4	1.7
39.5	32	32	52	49.4	49.2	58.9	49.0	43.5	49.5	2.0	1.7	1.7	2.3	1.8	1.4	1.7
40	32	32	53	50.3	50.0	60.1	49.9	44.2	50.4	2.0	1.7	1.7	2.3	1.8	1.4	1.7
40.5	31	31.5	54	51.1	50.9	61.2	50.7	44.9	51.2	1.9	1.7	1.7	2.2	1.7	1.4	1.7
41	31	31	55	51.9	51.7	62.3	51.6	45.6	52.0	1.9	1.7	1.7	2.1	1.7	1.4	1.7
41.5	31	31	56	52.8	52.6	63.3	52.4	46.2	52.9	1.9	1.7	1.7	2.1	1.7	1.4	1.7
42	31	31	57	53.6	53.4	64.4	53.3	46.9	53.7	1.9	1.7	1.7	2.1	1.7	1.4	1.7
42.5	31	31	58	54.4	54.2	65.5	54.1	47.6	54.5	1.9	1.7	1.7	2.1	1.7	1.4	1.7
43	31	31	59	55.3	55.0	66.6	55.0	48.3	55.4	1.9	1.7	1.7	2.1	1.7	1.4	1.7
43.5	30	30.5	60	56.1	55.9	67.6	55.8	49.0	56.2	1.8	1.6	1.6	2.1	1.7	1.4	1.6
44	30	30	61	56.9	56.6	68.6	56.7	49.6	57.0	1.8	1.6	1.6	2.0	1.6	1.3	1.6
44.5	30	30	62	57.7	57.4	69.6	57.5	50.3	57.8	1.8	1.6	1.6	2.0	1.6	1.3	1.6
45	30	30	62	58.5	58.2	70.6	58.3	51.0	58.6	1.8	1.6	1.6	2.0	1.6	1.3	1.6
45.5	30	30	63	59.3	59.0	71.6	59.1	51.6	59.3	1.8	1.6	1.6	2.0	1.6	1.3	1.6
46	29	29.5	64	60.0	59.8	72.6	59.9	52.3	60.1	1.7	1.6	1.6	1.9	1.6	1.3	1.5
46.5	29	29	65	60.8	60.6	73.5	60.7	52.9	60.9	1.7	1.5	1.5	1.9	1.6	1.3	1.5
47	29	29	66	61.5	61.3	74.4	61.5	53.6	61.6	1.7	1.5	1.5	1.9	1.6	1.3	1.5
47.5	29	29	67	62.3	62.1	75.4	62.2	54.2	62.4	1.7	1.5	1.5	1.9	1.6	1.3	1.5
48	29	29	67	63.1	62.8	76.3	63.0	54.9	63.1	1.7	1.5	1.5	1.9	1.6	1.3	1.5
49	29	29	69	64.6	64.4	78.2	64.6	56.2	64.7	1.7	1.5	1.5	1.9	1.6	1.3	1.5
50	29	29	71	66.1	65.9	80.0	66.2	57.5	66.2	1.7	1.5	1.5	1.9	1.6	1.3	1.5
51	29	29	72	67.6	67.4	81.9	67.7	58.8	67.7	1.7	1.5	1.5	1.9	1.6	1.3	1.5

52	28	28.5	74	69.1	68.9	83.7	69.2	60.1	69.2	1.6	1.5	1.5	1.8	1.5	1.3	1.5
53	28	28	76	70.5	70.3	85.4	70.7	61.3	70.6	1.6	1.5	1.5	1.7	1.5	1.3	1.4
54	27	27.5	77	72.0	71.7	87.1	72.2	62.6	72.0	1.5	1.4	1.4	1.7	1.5	1.3	1.4
55	27	27	79	73.4	73.1	88.7	73.6	63.8	73.4	1.5	1.4	1.4	1.6	1.4	1.2	1.4
56	27	27	80	74.7	74.5	90.4	75.0	65.1	74.8	1.5	1.4	1.4	1.6	1.4	1.2	1.4
57	29	28	82	76.2	76.0	92.1	76.5	66.3	76.2	1.6	1.5	1.5	1.7	1.5	1.3	1.4
58	29	29	83	77.7	77.5	94.0	78.1	67.6	77.7	1.7	1.5	1.5	1.9	1.6	1.3	1.5
59	29	29	85	79.2	79.0	95.8	79.7	68.9	79.2	1.7	1.5	1.5	1.9	1.6	1.3	1.5
60	29	29	87	80.7	80.5	97.7	81.2	70.2	80.8	1.7	1.5	1.5	1.9	1.6	1.3	1.5
61	29	29	88	82.3	82.0	99.6	82.8	71.5	82.3	1.7	1.5	1.5	1.9	1.6	1.3	1.5
62	29	29	90	83.8	83.6	101.4	84.4	72.8	83.8	1.7	1.5	1.5	1.9	1.6	1.3	1.5
63	29	29	92	85.3	85.1	103.3	85.9	74.1	85.3	1.7	1.5	1.5	1.9	1.6	1.3	1.5
64	29	29	93	86.8	86.6	105.2	87.5	75.4	86.8	1.7	1.5	1.5	1.9	1.6	1.3	1.5
65	29	29	95	88.3	88.1	107.0	89.0	76.7	88.3	1.7	1.5	1.5	1.9	1.6	1.3	1.5
66	29	29	97	89.8	89.6	108.9	90.6	78.0	89.8	1.7	1.5	1.5	1.9	1.6	1.3	1.5
67	29	29	98	91.4	91.1	110.8	92.2	79.3	91.3	1.7	1.5	1.5	1.9	1.6	1.3	1.5
68	29	29	100	92.9	92.7	112.6	93.7	80.6	92.9	1.7	1.5	1.5	1.9	1.6	1.3	1.5
69	30	29.5	102	94.4	94.2	114.6	95.3	81.9	94.4	1.7	1.6	1.6	1.9	1.6	1.3	1.5
70	28	29	103	95.9	95.7	116.4	96.9	83.2	95.9	1.7	1.5	1.5	1.9	1.6	1.3	1.5
71	27	27.5	105	97.4	97.1	118.1	98.3	84.5	97.3	1.5	1.4	1.4	1.7	1.5	1.3	1.4
72	26	26.5	106	98.7	98.5	119.7	99.7	85.7	98.7	1.4	1.4	1.4	1.6	1.4	1.2	1.3
73	25	25.5	108	100.0	99.8	121.1	101.1	86.9	100.0	1.4	1.3	1.3	1.5	1.3	1.2	1.3
74	25	25	109	101.3	101.1	122.6	102.4	88.1	101.2	1.3	1.3	1.3	1.4	1.3	1.2	1.3
75	24	24.5	110	102.5	102.3	123.9	103.6	89.2	102.5	1.3	1.2	1.2	1.4	1.3	1.2	1.2
76	24	24	112	103.7	103.5	125.2	104.9	90.3	103.7	1.3	1.2	1.2	1.3	1.2	1.1	1.2
77	23	23.5	113	104.9	104.7	126.5	106.1	91.5	104.8	1.2	1.2	1.2	1.3	1.2	1.1	1.2
78	24	23.5	114	106.1	105.9	127.8	107.3	92.6	106.0	1.2	1.2	1.2	1.3	1.2	1.1	1.2
79	25	24.5	115	107.3	107.1	129.2	108.5	93.7	107.2	1.3	1.2	1.2	1.4	1.3	1.2	1.2
80	25	25	117	108.6	108.4	130.6	109.8	94.9	108.5	1.3	1.3	1.3	1.4	1.3	1.2	1.3
81	25	25	118	109.8	109.6	132.0	111.1	96.1	109.8	1.3	1.3	1.3	1.4	1.3	1.2	1.3
82	26	25.5	119	111.1	110.9	133.4	112.5	97.2	111.0	1.4	1.3	1.3	1.5	1.3	1.2	1.3

83	26	26	121	112.5	112.2	135.0	113.8	98.4	112.4	1.4	1.3	1.3	1.5	1.4	1.2	1.3
84	26	26	122	113.8	113.6	136.5	115.2	99.6	113.7	1.4	1.3	1.3	1.5	1.4	1.2	1.3
85	26	26	124	115.1	114.9	138.0	116.5	100.8	115.0	1.4	1.3	1.3	1.5	1.4	1.2	1.3
86	26	26	125	116.4	116.2	139.5	117.9	102.0	116.3	1.4	1.3	1.3	1.5	1.4	1.2	1.3
87	26	26	126	117.8	117.5	141.0	119.3	103.2	117.6	1.4	1.3	1.3	1.5	1.4	1.2	1.3
88	26	26	128	119.1	118.9	142.5	120.6	104.4	119.0	1.4	1.3	1.3	1.5	1.4	1.2	1.3
89	26	26	129	120.4	120.2	144.1	122.0	105.6	120.3	1.4	1.3	1.3	1.5	1.4	1.2	1.3
90	24	25	131	121.7	121.5	145.5	123.3	106.8	121.5	1.3	1.3	1.3	1.4	1.3	1.2	1.3
91	23	23.5	132	122.9	122.6	146.7	124.5	107.9	122.7	1.2	1.2	1.2	1.3	1.2	1.1	1.2
92	23	23	133	124.0	123.8	148.0	125.7	109.0	123.9	1.2	1.2	1.2	1.2	1.2	1.1	1.1
93	23	23	134	125.2	124.9	149.2	126.8	110.1	125.0	1.2	1.2	1.2	1.2	1.2	1.1	1.1
94	23	23	135	126.3	126.1	150.4	128.0	111.2	126.1	1.2	1.2	1.2	1.2	1.2	1.1	1.1
95	22	22.5	137	127.4	127.2	151.6	129.2	112.3	127.3	1.2	1.1	1.1	1.2	1.1	1.1	1.1
96	21	21.5	138	128.5	128.3	152.7	130.2	113.4	128.3	1.1	1.1	1.1	1.1	1.1	1.1	1.1
97	21	21	139	129.6	129.3	153.8	131.3	114.4	129.4	1.1	1.0	1.0	1.1	1.1	1.0	1.0
98	20	20.5	140	130.6	130.4	154.8	132.3	115.4	130.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0
99	20	20	141	131.6	131.4	155.8	133.3	116.4	131.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0
100	19	19.5	142	132.6	132.3	156.8	134.3	117.4	132.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0
101	19	19	143	133.5	133.3	157.7	135.2	118.4	133.3	0.9	1.0	1.0	0.9	0.9	1.0	1.0
102	19	19	144	134.5	134.2	158.7	136.2	119.3	134.3	0.9	1.0	1.0	0.9	0.9	1.0	1.0
103	18	18.5	144	135.4	135.2	159.6	137.1	120.3	135.2	0.9	0.9	0.9	0.9	0.9	1.0	0.9
104	17	17.5	145	136.3	136.1	160.4	138.0	121.2	136.1	0.9	0.9	0.9	0.8	0.9	0.9	0.9
105	17	17	146	137.2	136.9	161.2	138.8	122.1	137.0	0.8	0.9	0.9	0.8	0.8	0.9	0.9
106	17	17	147	138.0	137.8	162.0	139.7	123.0	137.9	0.8	0.9	0.9	0.8	0.8	0.9	0.9
107	17	17	148	138.9	138.7	162.9	140.5	123.9	138.7	0.8	0.9	0.9	0.8	0.8	0.9	0.9
108	17	17	149	139.7	139.5	163.7	141.3	124.8	139.6	0.8	0.9	0.9	0.8	0.8	0.9	0.9
109	17	17	150	140.6	140.4	164.5	142.2	125.7	140.5	0.8	0.9	0.9	0.8	0.8	0.9	0.9
110	16	16.5	150	141.5	141.2	165.3	143.0	126.6	141.3	0.8	0.8	0.8	0.8	0.8	0.9	0.9
111	16	16	151	142.3	142.1	166.0	143.8	127.4	142.2	0.8	0.8	0.8	0.8	0.8	0.9	0.8
112	16	16	152	143.1	142.9	166.8	144.6	128.3	143.0	0.8	0.8	0.8	0.8	0.8	0.9	0.8
113	15	15.5	153	143.9	143.7	167.5	145.3	129.2	143.8	0.8	0.8	0.8	0.7	0.8	0.9	0.8

114	15	15	153	144.7	144.5	168.2	146.1	130.0	144.6	0.7	0.8	0.8	0.7	0.7	0.8	0.8
115	15	15	154	145.5	145.3	168.9	146.8	130.8	145.4	0.7	0.8	0.8	0.7	0.7	0.8	0.8
116	15	15	155	146.3	146.0	169.6	147.6	131.7	146.2	0.7	0.8	0.8	0.7	0.7	0.8	0.8
117	15	15	156	147.0	146.8	170.3	148.3	132.5	147.0	0.7	0.8	0.8	0.7	0.7	0.8	0.8
118	15	15	156	147.8	147.6	171.0	149.0	133.3	147.8	0.7	0.8	0.8	0.7	0.7	0.8	0.8
119	15	15	157	148.6	148.4	171.8	149.8	134.2	148.6	0.7	0.8	0.8	0.7	0.7	0.8	0.8
120	15	15	158	149.4	149.2	172.5	150.5	135.0	149.4	0.7	0.8	0.8	0.7	0.7	0.8	0.8
121	15	15	159	150.2	150.0	173.2	151.3	135.8	150.2	0.7	0.8	0.8	0.7	0.7	0.8	0.8

Table B.

Temperature development for Channel 2 of the MNDC 69 concrete mixture and the estimated age conversion factors and equivalent ages according to the FHP maturity function (having the subscripts "a", "e", and "q") (based on three different values of the apparent activation energy (E)), according to the Rastrup maturity function with the subscript "R", Weaven and Sadgrove maturity function "WS", Nurse-Saul maturity function "NS", and Carino and Tank maturity function "CT".

$$t_a = \Sigma e^{-5000[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t \qquad \gamma_a = e^{-5000[1/(273+T) - 1/(273+Tr)]}$$

$$t_e = \Sigma e^{-3040[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t \qquad \gamma_e = e^{-3040[1/(273+T) - 1/(273+Tr)]}$$

$$t_q = \Sigma e^{-4100[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t \qquad \gamma_q = e^{-4100[1/(273+T) - 1/(273+Tr)]}$$

$$t_R = \Sigma 2^{(T-Tr)/10} \bullet \Delta t \qquad \gamma_R = 2^{(T-Tr)/10}$$

$$t_{WS} = \Sigma (T+16)^2/1296 \bullet \Delta t \qquad \gamma_{WS} = (T+16)^2/1296$$

$$t_{NS} = \Sigma (T-T_o)/(T_r-T_o) \bullet \Delta t \qquad \gamma_{NS} = (T-T_o)/(T_r-T_o)$$

$$t_{CT} = \Sigma e^{B(T-Tr)} \bullet \Delta t \qquad \gamma_{CT} = e^{B(T-Tr)}$$

The Initial setting time by the 2 °C Temperature Increase method is shown with bold and bigger sized letters

			Equivalent Ages (Hrs)							Age Conversion Factors						
Actual Time (Hrs)	Concrete Temp. (°C)	Average Concrete Temp. (°C)	t_a	t_e	t_q	t_R	t_{WS}	t_{NS}	t_{CT}	γ_a	γ_e	γ_q	γ_R	γ_{WS}	γ_{NS}	γ_{CT}
0	12	12	0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.7	0.7	0.6	0.6	0.7	0.7
0.5	18	15	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.7	0.8	0.8	0.7	0.7	0.8	0.8
1	18	18	0.8	0.9	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
1.5	17	17.5	1.2	1.3	1.3	1.2	1.2	1.3	1.3	0.9	0.9	0.9	0.8	0.9	0.9	0.9
2	16	16.5	1.6	1.8	1.7	1.6	1.7	1.8	1.7	0.8	0.9	0.8	0.8	0.8	0.9	0.8
2.5	16	16	2	2.2	2.1	2.0	2.1	2.2	2.1	0.8	0.9	0.8	0.8	0.8	0.9	0.8
3	15	15.5	2.4	2.6	2.5	2.3	2.4	2.6	2.5	0.8	0.9	0.8	0.7	0.8	0.9	0.8

3.5	15	15	2.8	3.1	2.9	2.7	2.8	3.1	2.9	0.7	0.8	0.8	0.7	0.7	0.8	0.8
4	15	15	3.1	3.5	3.3	3.1	3.2	3.5	3.3	0.7	0.8	0.8	0.7	0.7	0.8	0.8
4.5	14	14.5	3.5	3.9	3.7	3.4	3.5	3.9	3.7	0.7	0.8	0.8	0.7	0.7	0.8	0.8
5	14	14	3.8	4.3	4.1	3.7	3.9	4.3	4.1	0.7	0.8	0.7	0.7	0.7	0.8	0.8
5.5	14	14	4.2	4.7	4.4	4.1	4.2	4.7	4.5	0.7	0.8	0.7	0.7	0.7	0.8	0.8
6	15	14.5	4.5	5.1	4.8	4.4	4.6	5.1	4.9	0.7	0.8	0.8	0.7	0.7	0.8	0.8
6.5	15	15	4.9	5.5	5.2	4.7	5.0	5.5	5.3	0.7	0.8	0.8	0.7	0.7	0.8	0.8
7	15	15	5.3	5.9	5.6	5.1	5.3	5.9	5.7	0.7	0.8	0.8	0.7	0.7	0.8	0.8
7.5	15	15	5.7	6.4	6.0	5.5	5.7	6.3	6.1	0.7	0.8	0.8	0.7	0.7	0.8	0.8
8	16	15.5	6	6.8	6.4	5.8	6.1	6.8	6.5	0.8	0.9	0.8	0.7	0.8	0.9	0.8
8.5	16	16	6.4	7.2	6.8	6.2	6.5	7.2	6.9	0.8	0.9	0.8	0.8	0.8	0.9	0.8
9	16	16	6.8	7.6	7.2	6.6	6.9	7.6	7.3	0.8	0.9	0.8	0.8	0.8	0.9	0.8
9.5	16	16	7.2	8.1	7.6	7.0	7.3	8.1	7.7	0.8	0.9	0.8	0.8	0.8	0.9	0.8
10	16	16	7.6	8.5	8.0	7.3	7.7	8.5	8.1	0.8	0.9	0.8	0.8	0.8	0.9	0.8
10.5	16	16	8	8.9	8.5	7.7	8.1	8.9	8.6	0.8	0.9	0.8	0.8	0.8	0.9	0.8
11	16	16	8.4	9.4	8.9	8.1	8.5	9.4	9.0	0.8	0.9	0.8	0.8	0.8	0.9	0.8
11.5	16	16	8.8	9.8	9.3	8.5	8.8	9.8	9.4	0.8	0.9	0.8	0.8	0.8	0.9	0.8
12	16	16	9	10.2	9.7	8.9	9.2	10.2	9.8	0.8	0.9	0.8	0.8	0.8	0.9	0.8
12.5	17	16.5	9	10.7	10.1	9.2	9.7	10.7	10.2	0.8	0.9	0.8	0.8	0.8	0.9	0.8
13	17	17	10	11.1	10.6	9.7	10.1	11.1	10.7	0.8	0.9	0.9	0.8	0.8	0.9	0.9
13.5	17	17	10	11.6	11.0	10.1	10.5	11.6	11.1	0.8	0.9	0.9	0.8	0.8	0.9	0.9
14	18	17.5	10	12.0	11.4	10.5	10.9	12.0	11.5	0.9	0.9	0.9	0.8	0.9	0.9	0.9
14.5	18	18	11	12.5	11.9	10.9	11.4	12.5	12.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9
15	19	18.5	11	13.0	12.3	11.4	11.8	13.0	12.5	0.9	0.9	0.9	0.9	0.9	1.0	0.9
15.5	19	19	12	13.5	12.8	11.8	12.3	13.5	12.9	0.9	1.0	1.0	0.9	0.9	1.0	1.0
16	20	19.5	12	14.0	13.3	12.3	12.8	14.0	13.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0
16.5	20	20	13	14.5	13.8	12.8	13.3	14.5	13.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
17	**20**	20	13	15.0	14.3	13.3	13.8	15.0	14.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0
17.5	**21**	20.5	14	15.5	14.8	13.8	14.3	15.5	14.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
18	**22**	21.5	14	16.0	15.4	14.4	14.8	16.0	15.5	1.1	1.1	1.1	1.1	1.1	1.1	1.1
18.5	23	22.5	15	16.5	15.9	15.0	15.4	16.5	16.0	1.2	1.1	1.1	1.2	1.1	1.1	1.1

19	25	24	16	17.1	16.5	15.6	16.0	17.1	16.6	1.3	1.2	1.2	1.3	1.2	1.1	1.2
19.5	26	25.5	16	17.7	17.2	16.4	16.7	17.7	17.3	1.4	1.3	1.3	1.5	1.3	1.2	1.3
20	28	27	17	18.4	17.9	17.2	17.4	18.3	18.0	1.5	1.4	1.4	1.6	1.4	1.2	1.4
20.5	31	29.5	18	19.0	18.6	18.2	18.2	19.0	18.8	1.7	1.6	1.6	1.9	1.6	1.3	1.6
21	34	32.5	19	19.9	19.5	19.3	19.1	19.7	19.6	2.0	1.8	1.8	2.4	1.8	1.4	1.8
21.5	37	35.5	20	20.9	20.5	20.8	20.1	20.4	20.7	2.4	2.0	2.0	2.9	2.0	1.5	2.1
22	41	39	21	22.1	21.7	22.7	21.3	21.2	21.9	2.8	2.3	2.3	3.7	2.3	1.6	2.5
22.5	45	43	23	23.5	23.1	25.1	22.7	22.1	23.3	3.5	2.8	2.8	4.9	2.7	1.8	3.0
23	48	46.5	25	25.1	24.7	28.3	24.2	23.1	25.0	4.1	3.2	3.2	6.3	3.0	1.9	3.5
23.5	49	48.5	27	26.8	26.4	31.9	25.8	24.0	26.8	4.5	3.5	3.5	7.2	3.2	2.0	3.9
24	50	49.5	30	28.6	28.2	35.7	27.4	25.0	28.8	4.8	3.6	3.6	7.7	3.3	2.0	4.1
24.5	51	50.5	32	30.5	30.1	39.9	29.1	26.0	30.8	5.0	3.7	3.7	8.3	3.4	2.0	4.3
25	51	51	35	32.4	32.0	44.2	30.9	27.1	32.9	5.1	3.8	3.8	8.6	3.5	2.0	4.4
25.5	51	51	37	34.3	33.9	48.5	32.6	28.1	35.0	5.1	3.8	3.8	8.6	3.5	2.0	4.4
26	51	51	40	36.2	35.8	52.7	34.3	29.1	37.1	5.1	3.8	3.8	8.6	3.5	2.0	4.4
26.5	51	51	43	38.1	37.7	57.0	36.1	30.1	39.1	5.1	3.8	3.8	8.6	3.5	2.0	4.4
27	51	51	45	40.0	39.6	61.3	37.8	31.1	41.2	5.1	3.8	3.8	8.6	3.5	2.0	4.4
27.5	51	51	48	41.9	41.5	65.6	39.5	32.1	43.3	5.1	3.8	3.8	8.6	3.5	2.0	4.4
28	51	51	50	43.8	43.4	69.9	41.2	33.2	45.4	5.1	3.8	3.8	8.6	3.5	2.0	4.4
28.5	51	51	53	45.7	45.3	74.2	43.0	34.2	47.5	5.1	3.8	3.8	8.6	3.5	2.0	4.4
29	51	51	55	47.7	47.3	78.5	44.7	35.2	49.6	5.1	3.8	3.8	8.6	3.5	2.0	4.4
29.5	51	51	58	49.6	49.2	82.8	46.4	36.2	51.6	5.1	3.8	3.8	8.6	3.5	2.0	4.4
30	51	51	61	51.5	51.1	87.0	48.2	37.2	53.7	5.1	3.8	3.8	8.6	3.5	2.0	4.4
30.5	51	51	63	53.4	53.0	91.3	49.9	38.2	55.8	5.1	3.8	3.8	8.6	3.5	2.0	4.4
31	50	50.5	66	55.2	54.8	95.5	51.6	39.3	57.8	5.0	3.7	3.7	8.3	3.4	2.0	4.3
31.5	50	50	68	57.1	56.7	99.5	53.3	40.3	59.8	4.9	3.7	3.7	8.0	3.4	2.0	4.2
32	50	50	70	58.9	58.5	103.5	55.0	41.3	61.8	4.9	3.7	3.7	8.0	3.4	2.0	4.2
32.5	50	50	73	60.8	60.3	107.5	56.7	42.3	63.8	4.9	3.7	3.7	8.0	3.4	2.0	4.2
33	50	50	75	62.6	62.2	111.5	58.3	43.3	65.8	4.9	3.7	3.7	8.0	3.4	2.0	4.2
33.5	50	50	78	64.4	64.0	115.5	60.0	44.3	67.8	4.9	3.7	3.7	8.0	3.4	2.0	4.2
34	49	49.5	80	66.2	65.8	119.3	61.7	45.2	69.7	4.8	3.6	3.6	7.7	3.3	2.0	4.1

34.5	49	49	82	68.0	67.6	123.1	63.3	46.2	71.6	4.7	3.5	3.5	7.5	3.3	2.0	4.0
35	49	49	85	69.7	69.3	126.8	64.9	47.2	73.5	4.7	3.5	3.5	7.5	3.3	2.0	4.0
35.5	49	49	87	71.5	71.1	130.5	66.6	48.2	75.4	4.7	3.5	3.5	7.5	3.3	2.0	4.0
36	49	49	89	73.3	72.9	134.3	68.2	49.2	77.3	4.7	3.5	3.5	7.5	3.3	2.0	4.0
36.5	49	49	92	75.0	74.6	138.0	69.8	50.2	79.2	4.7	3.5	3.5	7.5	3.3	2.0	4.0
37	48	48.5	94	76.8	76.4	141.6	71.4	51.1	81.1	4.5	3.5	3.5	7.2	3.2	2.0	3.9
37.5	48	48	96	78.5	78.1	145.1	73.0	52.1	82.9	4.4	3.4	3.4	7.0	3.2	1.9	3.8
38	48	48	98	80.2	79.7	148.6	74.6	53.1	84.7	4.4	3.4	3.4	7.0	3.2	1.9	3.8
38.5	48	48	101	81.8	81.4	152.0	76.2	54.0	86.5	4.4	3.4	3.4	7.0	3.2	1.9	3.8
39	47	47.5	103	83.5	83.1	155.4	77.7	55.0	88.3	4.3	3.3	3.3	6.7	3.1	1.9	3.7
39.5	47	47	105	85.1	84.7	158.7	79.3	55.9	90.0	4.2	3.3	3.3	6.5	3.1	1.9	3.6
40	47	47	107	86.8	86.4	161.9	80.8	56.9	91.7	4.2	3.3	3.3	6.5	3.1	1.9	3.6
40.5	46	46.5	109	88.4	88.0	165.0	82.3	57.8	93.4	4.1	3.2	3.2	6.3	3.0	1.9	3.5
41	46	46	111	89.9	89.5	168.1	83.8	58.8	95.1	4.0	3.1	3.1	6.1	3.0	1.9	3.5
41.5	46	46	113	91.5	91.1	171.1	85.3	59.7	96.7	4.0	3.1	3.1	6.1	3.0	1.9	3.5
42	45	45.5	115	93.0	92.6	174.0	86.7	60.6	98.3	3.9	3.1	3.1	5.9	2.9	1.9	3.4
42.5	45	45	117	94.5	94.1	176.9	88.2	61.5	99.9	3.8	3.0	3.0	5.7	2.9	1.8	3.3
43	45	45	119	96.0	95.6	179.7	89.6	62.5	101.5	3.8	3.0	3.0	5.7	2.9	1.8	3.3
43.5	44	44.5	121	97.5	97.1	182.4	91.0	63.4	103.0	3.7	2.9	2.9	5.5	2.8	1.8	3.2
44	44	44	123	98.9	98.5	185.1	92.4	64.3	104.5	3.6	2.9	2.9	5.3	2.8	1.8	3.1
44.5	44	44	124	100.4	100.0	187.7	93.8	65.2	106.1	3.6	2.9	2.9	5.3	2.8	1.8	3.1
45	44	44	126	101.8	101.4	190.3	95.2	66.1	107.6	3.6	2.9	2.9	5.3	2.8	1.8	3.1
45.5	44	44	128	103.3	102.9	193.0	96.6	67.0	109.1	3.6	2.9	2.9	5.3	2.8	1.8	3.1
46	43	43.5	130	104.7	104.3	195.5	97.9	67.9	110.5	3.6	2.8	2.8	5.1	2.7	1.8	3.1
46.5	43	43	132	106.1	105.7	198.0	99.3	68.7	112.0	3.5	2.8	2.8	4.9	2.7	1.8	3.0
47	43	43	133	107.4	107.0	200.5	100.6	69.6	113.4	3.5	2.8	2.8	4.9	2.7	1.8	3.0
47.5	43	43	135	108.8	108.4	202.9	102.0	70.5	114.9	3.5	2.8	2.8	4.9	2.7	1.8	3.0
48	42	42.5	137	110.2	109.8	205.3	103.3	71.4	116.3	3.4	2.7	2.7	4.8	2.6	1.8	2.9
49	42	42	140	112.8	112.4	209.9	105.9	73.1	119.0	3.3	2.7	2.7	4.6	2.6	1.7	2.9
50	42	42	143	115.5	115.1	214.5	108.5	74.9	121.8	3.3	2.7	2.7	4.6	2.6	1.7	2.9
51	41	41.5	147	118.1	117.7	218.9	111.0	76.6	124.5	3.2	2.6	2.6	4.4	2.6	1.7	2.8

52	40	40.5	150	120.6	120.2	223.1	113.5	78.3	127.0	3.1	2.5	2.5	4.1	2.5	1.7	2.7
53	40	40	153	123.0	122.6	227.1	115.9	79.9	129.5	3.0	2.4	2.4	4.0	2.4	1.7	2.6
54	40	40	156	125.5	125.1	231.1	118.3	81.6	132.1	3.0	2.4	2.4	4.0	2.4	1.7	2.6
55	39	39.5	158	127.9	127.5	234.9	120.7	83.2	134.5	2.9	2.4	2.4	3.9	2.4	1.7	2.5
56	39	39	161	130.2	129.8	238.7	123.0	84.9	136.9	2.8	2.3	2.3	3.7	2.3	1.6	2.5
57	38	38.5	164	132.5	132.1	242.3	125.3	86.5	139.2	2.8	2.3	2.3	3.6	2.3	1.6	2.4
58	38	38	167	134.8	134.4	245.7	127.6	88.1	141.5	2.7	2.2	2.2	3.5	2.3	1.6	2.4
59	37	37.5	169	137.0	136.6	249.1	129.8	89.7	143.8	2.6	2.2	2.2	3.4	2.2	1.6	2.3
60	37	37	172	139.1	138.7	252.4	131.9	91.2	146.0	2.5	2.2	2.2	3.2	2.2	1.6	2.3
61	37	37	174	141.3	140.9	255.6	134.1	92.8	148.1	2.5	2.2	2.2	3.2	2.2	1.6	2.3
62	36	36.5	177	143.4	143.0	258.7	136.2	94.4	150.3	2.5	2.1	2.1	3.1	2.1	1.6	2.2
63	36	36	179	145.5	145.1	261.8	138.3	95.9	152.4	2.4	2.1	2.1	3.0	2.1	1.5	2.1
64	36	36	182	147.5	147.1	264.8	140.4	97.4	154.5	2.4	2.1	2.1	3.0	2.1	1.5	2.1
65	36	36	184	149.6	149.2	267.8	142.5	99.0	156.5	2.4	2.1	2.1	3.0	2.1	1.5	2.1
66	35	35.5	187	151.6	151.2	270.8	144.5	100.5	158.6	2.4	2.0	2.0	2.9	2.0	1.5	2.1
67	35	35	189	153.6	153.2	273.6	146.6	102.0	160.6	2.3	2.0	2.0	2.8	2.0	1.5	2.0
68	35	35	191	155.6	155.2	276.4	148.6	103.5	162.6	2.3	2.0	2.0	2.8	2.0	1.5	2.0
69	35	35	193	157.5	157.1	279.3	150.6	105.0	164.6	2.3	2.0	2.0	2.8	2.0	1.5	2.0
70	34	34.5	196	159.5	159.1	282.0	152.5	106.5	166.5	2.2	1.9	1.9	2.7	2.0	1.5	2.0
71	34	34	198	161.4	161.0	284.6	154.5	107.9	168.4	2.2	1.9	1.9	2.6	1.9	1.5	2.0
72	34	34	200	163.3	162.9	287.3	156.4	109.4	170.3	2.2	1.9	1.9	2.6	1.9	1.5	2.0
73	34	34	202	165.1	164.7	289.9	158.3	110.9	172.2	2.2	1.9	1.9	2.6	1.9	1.5	2.0
74	33	33.5	204	167.0	166.6	292.5	160.2	112.3	174.1	2.1	1.9	1.9	2.5	1.9	1.5	1.9
75	33	33	206	168.8	168.4	294.9	162.1	113.7	175.9	2.1	1.8	1.8	2.5	1.9	1.4	1.9
76	33	33	208	170.6	170.2	297.4	163.9	115.2	177.7	2.1	1.8	1.8	2.5	1.9	1.4	1.9
77	32	32.5	210	172.4	172.0	299.8	165.7	116.6	179.5	2.0	1.8	1.8	2.4	1.8	1.4	1.8
78	32	32	212	174.1	173.7	302.1	167.5	118.0	181.2	2.0	1.7	1.7	2.3	1.8	1.4	1.8
79	31	31.5	214	175.8	175.4	304.3	169.3	119.4	182.9	1.9	1.7	1.7	2.2	1.7	1.4	1.7
80	31	31	216	177.5	177.1	306.4	171.0	120.7	184.6	1.9	1.7	1.7	2.1	1.7	1.4	1.7
81	31	31	218	179.1	178.7	308.6	172.7	122.1	186.2	1.9	1.7	1.7	2.1	1.7	1.4	1.7
82	31	31	220	180.8	180.4	310.7	174.4	123.5	187.9	1.9	1.7	1.7	2.1	1.7	1.4	1.7

83	30	30.5	222	182.4	182.0	312.8	176.0	124.8	189.5	1.8	1.6	1.6	2.1	1.7	1.4	1.7
84	30	30	223	184.0	183.6	314.8	177.7	126.2	191.1	1.8	1.6	1.6	2.0	1.6	1.3	1.6
85	30	30	225	185.6	185.2	316.8	179.3	127.5	192.7	1.8	1.6	1.6	2.0	1.6	1.3	1.6
86	30	30	227	187.2	186.8	318.8	180.9	128.8	194.3	1.8	1.6	1.6	2.0	1.6	1.3	1.6
87	30	30	229	188.8	188.4	320.8	182.6	130.2	195.9	1.8	1.6	1.6	2.0	1.6	1.3	1.6
88	30	30	230	190.4	190.0	322.8	184.2	131.5	197.4	1.8	1.6	1.6	2.0	1.6	1.3	1.6
89	29	29.5	232	191.9	191.5	324.7	185.8	132.8	199.0	1.7	1.6	1.6	1.9	1.6	1.3	1.6
90	29	29	234	193.4	193.0	326.6	187.4	134.1	200.5	1.7	1.5	1.5	1.9	1.6	1.3	1.5
91	29	29	235	195.0	194.5	328.4	188.9	135.4	202.0	1.7	1.5	1.5	1.9	1.6	1.3	1.5
92	29	29	237	196.5	196.1	330.3	190.5	136.7	203.5	1.7	1.5	1.5	1.9	1.6	1.3	1.5
93	29	29	239	198.0	197.6	332.2	192.0	138.0	205.0	1.7	1.5	1.5	1.9	1.6	1.3	1.5
94	29	29	240	199.5	199.1	334.0	193.6	139.3	206.6	1.7	1.5	1.5	1.9	1.6	1.3	1.5
95	28	28.5	242	201.0	200.6	335.8	195.1	140.6	208.0	1.6	1.5	1.5	1.8	1.5	1.3	1.5
96	28	28	244	202.4	202.0	337.6	196.6	141.9	209.5	1.6	1.5	1.5	1.7	1.5	1.3	1.5
97	28	28	245	203.9	203.5	339.3	198.1	143.1	210.9	1.6	1.5	1.5	1.7	1.5	1.3	1.5
98	28	28	247	205.3	204.9	341.1	199.6	144.4	212.4	1.6	1.5	1.5	1.7	1.5	1.3	1.5
99	27	27.5	248	206.8	206.4	342.7	201.1	145.6	213.8	1.5	1.4	1.4	1.7	1.5	1.3	1.4
100	27	27	250	208.1	207.7	344.4	202.5	146.9	215.2	1.5	1.4	1.4	1.6	1.4	1.2	1.4
101	27	27	251	209.5	209.1	346.0	203.9	148.1	216.5	1.5	1.4	1.4	1.6	1.4	1.2	1.4
102	26	26.5	253	210.9	210.5	347.6	205.3	149.3	217.9	1.4	1.4	1.4	1.6	1.4	1.2	1.4
103	26	26	254	212.2	211.8	349.1	206.7	150.5	219.2	1.4	1.3	1.3	1.5	1.4	1.2	1.3
104	26	26	256	213.5	213.1	350.6	208.0	151.7	220.5	1.4	1.3	1.3	1.5	1.4	1.2	1.3
105	25	25.5	257	214.8	214.4	352.1	209.4	152.9	221.8	1.4	1.3	1.3	1.5	1.3	1.2	1.3
106	25	25	258	216.1	215.7	353.5	210.7	154.1	223.1	1.3	1.3	1.3	1.4	1.3	1.2	1.3
107	25	25	260	217.4	217.0	354.9	212.0	155.2	224.3	1.3	1.3	1.3	1.4	1.3	1.2	1.3
108	24	24.5	261	218.6	218.2	356.3	213.2	156.4	225.6	1.3	1.2	1.2	1.4	1.3	1.2	1.2
109	24	24	262	219.8	219.4	357.6	214.5	157.5	226.8	1.3	1.2	1.2	1.3	1.2	1.1	1.2
110	24	24	263	221.0	220.6	358.9	215.7	158.7	228.0	1.3	1.2	1.2	1.3	1.2	1.1	1.2
111	24	24	265	222.2	221.8	360.2	216.9	159.8	229.2	1.3	1.2	1.2	1.3	1.2	1.1	1.2
112	23	23.5	266	223.4	223.0	361.5	218.1	160.9	230.3	1.2	1.2	1.2	1.3	1.2	1.1	1.2
113	23	23	267	224.5	224.1	362.7	219.3	162.0	231.5	1.2	1.2	1.2	1.2	1.2	1.1	1.2

114	23	23	268	225.7	225.3	363.9	220.5	163.1	232.6	1.2	1.2	1.2	1.2	1.2	1.1	1.2
115	23	23	269	226.9	226.4	365.2	221.7	164.2	233.8	1.2	1.2	1.2	1.2	1.2	1.1	1.2
116	22	22.5	271	228.0	227.6	366.4	222.8	165.3	234.9	1.2	1.1	1.1	1.2	1.1	1.1	1.1
117	22	22	272	229.1	228.7	367.5	223.9	166.4	236.0	1.1	1.1	1.1	1.1	1.1	1.1	1.1
118	22	22	273	230.2	229.8	368.7	225.0	167.4	237.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
119	22	22	274	231.3	230.9	369.8	226.1	168.5	238.2	1.1	1.1	1.1	1.1	1.1	1.1	1.1
120	22	22	275	232.4	232.0	371.0	227.3	169.6	239.3	1.1	1.1	1.1	1.1	1.1	1.1	1.1
121	21	21.5	276	233.4	233.0	372.1	228.3	170.6	240.4	1.1	1.1	1.1	1.1	1.1	1.1	1.1

Table C.

Temperature development for Channel 3 of the MNDC 69 concrete mixture and the estimated age conversion factors and equivalent ages according to the FHP maturity function (having the subscripts "a", "e", and "q") (based on three different values of the apparent activation energy (E)), according to the Rastrup maturity function with the subscript "R", Weaven and Sadgrove maturity function "WS", Nurse-Saul maturity function "NS", and Carino and Tank maturity function "CT".

$t_a = \Sigma e^{-5000[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$ $\qquad \gamma_a = e^{-5000[1/(273+T) - 1/(273+Tr)]}$

$t_e = \Sigma e^{-3040[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$ $\qquad \gamma_e = e^{-3040[1/(273+T) - 1/(273+Tr)]}$

$t_q = \Sigma e^{-4100[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$ $\qquad \gamma_q = e^{-4100[1/(273+T) - 1/(273+Tr)]}$

$t_R = \Sigma 2^{(T-Tr)/10} \bullet \Delta t$ $\qquad \gamma_R = 2^{(T-Tr)/10}$

$t_{WS} = \Sigma (T+16)^2/1296 \bullet \Delta t$ $\qquad \gamma_{WS} = (T+16)^2/1296$

$t_{NS} = \Sigma (T-T_o)/(T_r-T_o) \bullet \Delta t$ $\qquad \gamma_{NS} = (T-T_o)/(T_r-T_o)$

$t_{CT} = \Sigma e^{B(T-Tr)} \bullet \Delta t$ $\qquad \gamma_{CT} = e^{B(T-Tr)}$

The Initial setting time by the 2 °C Temperature Increase method is shown with bold and bigger sized letters

			Equivalent Ages (Hrs)							Age Conversion Factors						
Actual Time (Hrs)	Concrete Temp. (°C)	Average Concrete Temp. (°C)	t_a	t_e	t_q	t_R	t_{WS}	t_{NS}	t_{CT}	γ_a	γ_e	γ_q	γ_R	γ_{WS}	γ_{NS}	γ_{CT}
0	11	9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.7	0.6	0.5	0.5	0.7	0.6
0.5	18	14.5	0.0	0.4	0.4	0.3	0.4	0.4	0.4	0.7	0.8	0.8	0.7	0.7	0.8	0.8
1	17	17.5	0.7	0.9	0.8	0.8	0.8	0.9	0.8	0.9	0.9	0.9	0.8	0.9	0.9	0.9
1.5	17	17	1.2	1.3	1.3	1.2	1.2	1.3	1.3	0.8	0.9	0.9	0.8	0.8	0.9	0.9
2	16	16.5	1.6	1.8	1.7	1.6	1.6	1.8	1.7	0.8	0.9	0.8	0.8	0.8	0.9	0.9
2.5	16	16	2.0	2.2	2.1	1.9	2.0	2.2	2.1	0.8	0.9	0.8	0.8	0.8	0.9	0.8
3	15	15.5	2.3	2.6	2.5	2.3	2.4	2.6	2.5	0.8	0.9	0.8	0.7	0.8	0.9	0.8

3.5	15	15	2.7	3.0	2.9	2.7	2.8	3.0	2.9	0.7	0.8	0.8	0.7	0.7	0.8	0.8
4	15	15	3.1	3.5	3.3	3.0	3.1	3.5	3.3	0.7	0.8	0.8	0.7	0.7	0.8	0.8
4.5	14	14.5	3.5	3.9	3.7	3.4	3.5	3.9	3.7	0.7	0.8	0.8	0.7	0.7	0.8	0.8
5	14	14	3.8	4.3	4.0	3.7	3.8	4.3	4.0	0.7	0.8	0.7	0.7	0.7	0.8	0.8
5.5	14	14	4.2	4.7	4.4	4.0	4.2	4.7	4.4	0.7	0.8	0.7	0.7	0.7	0.8	0.8
6	14	14	4.5	5.1	4.8	4.3	4.5	5.1	4.8	0.7	0.8	0.7	0.7	0.7	0.8	0.8
6.5	15	14.5	4.9	5.5	5.2	4.7	4.9	5.5	5.2	0.7	0.8	0.8	0.7	0.7	0.8	0.8
7	15	15	5.2	5.9	5.6	5.0	5.3	5.9	5.6	0.7	0.8	0.8	0.7	0.7	0.8	0.8
7.5	15	15	5.6	6.3	5.9	5.4	5.6	6.3	6.0	0.7	0.8	0.8	0.7	0.7	0.8	0.8
8	15	15	6.0	6.7	6.3	5.7	6.0	6.7	6.4	0.7	0.8	0.8	0.7	0.7	0.8	0.8
8.5	16	15.5	6.4	7.2	6.7	6.1	6.4	7.1	6.8	0.8	0.9	0.8	0.7	0.8	0.9	0.8
9	16	16	6.8	7.6	7.2	6.5	6.8	7.6	7.2	0.8	0.9	0.8	0.8	0.8	0.9	0.8
9.5	16	16	7.1	8.0	7.6	6.9	7.2	8.0	7.6	0.8	0.9	0.8	0.8	0.8	0.9	0.8
10	16	16	7.5	8.5	8.0	7.2	7.6	8.4	8.0	0.8	0.9	0.8	0.8	0.8	0.9	0.8
10.5	16	16	7.9	8.9	8.4	7.6	8.0	8.9	8.4	0.8	0.9	0.8	0.8	0.8	0.9	0.8
11	16	16	8.3	9.3	8.8	8.0	8.4	9.3	8.8	0.8	0.9	0.8	0.8	0.8	0.9	0.8
11.5	17	16.5	8.7	9.8	9.2	8.4	8.8	9.8	9.3	0.8	0.9	0.8	0.8	0.8	0.9	0.9
12	17	17	9.0	10.2	9.7	8.8	9.2	10.2	9.7	0.8	0.9	0.9	0.8	0.8	0.9	0.9
12.5	17	17	9.0	10.7	10.1	9.2	9.6	10.7	10.1	0.8	0.9	0.9	0.8	0.8	0.9	0.9
13	17	17	10.0	11.1	10.5	9.6	10.0	11.1	10.6	0.8	0.9	0.9	0.8	0.8	0.9	0.9
13.5	18	17.5	10.0	11.6	11.0	10.0	10.5	11.6	11.0	0.9	0.9	0.9	0.8	0.9	0.9	0.9
14	18	18	10.0	12.0	11.4	10.5	10.9	12.0	11.5	0.9	0.9	0.9	0.9	0.9	0.9	0.9
14.5	19	18.5	11.0	12.5	11.9	10.9	11.4	12.5	11.9	0.9	0.9	0.9	0.9	0.9	1.0	0.9
15	20	19.5	11.0	13.0	12.4	11.4	11.9	13.0	12.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15.5	20	20	12.0	13.5	12.9	11.9	12.4	13.5	12.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
16	21	20.5	12.0	14.0	13.4	12.4	12.9	14.0	13.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0
16.5	**21**	21	13.0	14.5	13.9	13.0	13.4	14.5	13.9	1.1	1.0	1.0	1.1	1.1	1.0	1.0
17	**22**	21.5	13.0	15.1	14.4	13.5	13.9	15.0	14.5	1.1	1.1	1.1	1.1	1.1	1.1	1.1
17.5	**23**	22.5	14.0	15.6	15.0	14.1	14.5	15.6	15.0	1.2	1.1	1.1	1.2	1.1	1.1	1.1
18	24	23.5	15.0	16.2	15.6	14.7	15.1	16.1	15.6	1.2	1.2	1.2	1.3	1.2	1.1	1.2
18.5	26	25	15.0	16.8	16.2	15.5	15.8	16.7	16.3	1.3	1.3	1.3	1.4	1.3	1.2	1.3

19	28	27	16.0	17.4	16.9	16.3	16.5	17.3	17.0	1.5	1.4	1.4	1.6	1.4	1.2	1.4
19.5	30	29	17.0	18.1	17.7	17.2	17.3	18.0	17.7	1.7	1.5	1.5	1.9	1.6	1.3	1.5
20	32	31	18.0	18.8	18.5	18.3	18.1	18.7	18.6	1.9	1.7	1.7	2.1	1.7	1.4	1.7
20.5	36	34	19.0	19.6	19.5	19.6	19.1	19.4	19.6	2.2	1.9	1.9	2.6	1.9	1.5	1.9
21	40	38	20.0	20.7	20.6	21.3	20.2	20.2	20.7	2.7	2.2	2.2	3.5	2.3	1.6	2.3
21.5	44	42	22.0	22.1	21.9	23.6	21.5	21.1	22.2	3.3	2.7	2.7	4.6	2.6	1.7	2.8
22	48	46	24.0	23.6	23.5	26.7	23.0	22.0	23.9	4.0	3.1	3.1	6.1	3.0	1.9	3.3
22.5	51	49.5	26.0	25.4	25.3	30.5	24.6	23.0	26.0	4.8	3.6	3.6	7.7	3.3	2.0	3.9
23	52	51.5	29.0	27.4	27.2	35.0	26.4	24.0	28.2	5.2	3.9	3.9	8.9	3.5	2.1	4.3
23.5	53	52.5	32.0	29.4	29.2	39.7	28.2	25.1	30.6	5.5	4.0	4.0	9.5	3.6	2.1	4.5
24	53	53	34.0	31.5	31.3	44.6	30.0	26.1	33.0	5.6	4.1	4.1	9.8	3.7	2.1	4.6
24.5	53	53	37.0	33.5	33.4	49.6	31.9	27.2	35.4	5.6	4.1	4.1	9.8	3.7	2.1	4.6
25	53	53	40.0	35.6	35.4	54.5	33.7	28.2	37.8	5.6	4.1	4.1	9.8	3.7	2.1	4.6
25.5	53	53	43.0	37.6	37.5	59.4	35.6	29.3	40.3	5.6	4.1	4.1	9.8	3.7	2.1	4.6
26	53	53	46.0	39.7	39.5	64.3	37.4	30.3	42.7	5.6	4.1	4.1	9.8	3.7	2.1	4.6
26.5	53	53	49.0	41.8	41.6	69.3	39.2	31.4	45.1	5.6	4.1	4.1	9.8	3.7	2.1	4.6
27	53	53	51.0	43.8	43.7	74.2	41.1	32.4	47.5	5.6	4.1	4.1	9.8	3.7	2.1	4.6
27.5	53	53	54.0	45.9	45.7	79.1	42.9	33.5	49.9	5.6	4.1	4.1	9.8	3.7	2.1	4.6
28	53	53	57.0	47.9	47.8	84.0	44.7	34.5	52.4	5.6	4.1	4.1	9.8	3.7	2.1	4.6
28.5	53	53	60.0	50.0	49.9	89.0	46.6	35.6	54.8	5.6	4.1	4.1	9.8	3.7	2.1	4.6
29	53	53	63.0	52.1	51.9	93.9	48.4	36.6	57.2	5.6	4.1	4.1	9.8	3.7	2.1	4.6
29.5	53	53	65.0	54.1	54.0	98.8	50.3	37.7	59.6	5.6	4.1	4.1	9.8	3.7	2.1	4.6
30	53	53	68.0	56.2	56.0	103.7	52.1	38.7	62.0	5.6	4.1	4.1	9.8	3.7	2.1	4.6
30.5	53	53	71.0	58.2	58.1	108.7	53.9	39.8	64.5	5.6	4.1	4.1	9.8	3.7	2.1	4.6
31	53	53	74.0	60.3	60.2	113.6	55.8	40.8	66.9	5.6	4.1	4.1	9.8	3.7	2.1	4.6
31.5	53	53	77.0	62.4	62.2	118.5	57.6	41.9	69.3	5.6	4.1	4.1	9.8	3.7	2.1	4.6
32	53	53	79.0	64.4	64.3	123.4	59.4	42.9	71.7	5.6	4.1	4.1	9.8	3.7	2.1	4.6
32.5	53	53	82.0	66.5	66.3	128.4	61.3	44.0	74.2	5.6	4.1	4.1	9.8	3.7	2.1	4.6
33	52	52.5	85.0	68.5	68.4	133.1	63.1	45.0	76.5	5.5	4.0	4.0	9.5	3.6	2.1	4.5
33.5	52	52	88.0	70.5	70.3	137.7	64.9	46.0	78.8	5.4	4.0	4.0	9.2	3.6	2.1	4.4
34	52	52	90.0	72.5	72.3	142.3	66.6	47.1	81.1	5.4	4.0	4.0	9.2	3.6	2.1	4.4

34.5	52	52	93.0	74.5	74.3	146.9	68.4	48.1	83.4	5.4	4.0	4.0	9.2	3.6	2.1	4.4
35	51	51.5	96.0	76.4	76.3	151.3	70.2	49.1	85.7	5.2	3.9	3.9	8.9	3.5	2.1	4.3
35.5	51	51	98.0	78.3	78.2	155.6	71.9	50.2	87.9	5.1	3.8	3.8	8.6	3.5	2.0	4.2
36	51	51	101.0	80.2	80.1	159.9	73.7	51.2	90.1	5.1	3.8	3.8	8.6	3.5	2.0	4.2
36.5	51	51	103.0	82.1	82.0	164.2	75.4	52.2	92.3	5.1	3.8	3.8	8.6	3.5	2.0	4.2
37	50	50.5	106.0	84.0	83.9	168.3	77.1	53.2	94.4	5.0	3.7	3.7	8.3	3.4	2.0	4.1
37.5	50	50	108.0	85.8	85.7	172.3	78.8	54.2	96.5	4.9	3.7	3.7	8.0	3.4	2.0	4.0
38	50	50	111.0	87.7	87.5	176.3	80.5	55.2	98.6	4.9	3.7	3.7	8.0	3.4	2.0	4.0
38.5	50	50	113.0	89.5	89.4	180.3	82.1	56.2	100.7	4.9	3.7	3.7	8.0	3.4	2.0	4.0
39	50	50	116.0	91.3	91.2	184.3	83.8	57.2	102.8	4.9	3.7	3.7	8.0	3.4	2.0	4.0
39.5	49	49.5	118.0	93.1	93.0	188.2	85.5	58.2	104.9	4.8	3.6	3.6	7.7	3.3	2.0	3.9
40	49	49	120.0	94.9	94.8	191.9	87.1	59.2	106.9	4.7	3.5	3.5	7.5	3.3	2.0	3.8
40.5	49	49	123.0	96.7	96.5	195.7	88.7	60.2	108.9	4.7	3.5	3.5	7.5	3.3	2.0	3.8
41	49	49	125.0	98.4	98.3	199.4	90.4	61.1	110.9	4.7	3.5	3.5	7.5	3.3	2.0	3.8
41.5	48	48.5	127.0	100.2	100.0	203.0	92.0	62.1	112.8	4.5	3.5	3.5	7.2	3.2	2.0	3.7
42	48	48	129.0	101.8	101.7	206.5	93.5	63.1	114.7	4.4	3.4	3.4	7.0	3.2	1.9	3.6
42.5	48	48	132.0	103.5	103.4	210.0	95.1	64.0	116.6	4.4	3.4	3.4	7.0	3.2	1.9	3.6
43	47	47.5	134.0	105.2	105.1	213.3	96.7	65.0	118.5	4.3	3.3	3.3	6.7	3.1	1.9	3.5
43.5	47	47	136.0	106.8	106.7	216.6	98.2	66.0	120.3	4.2	3.3	3.3	6.5	3.1	1.9	3.5
44	47	47	138.0	108.5	108.3	219.8	99.7	66.9	122.1	4.2	3.3	3.3	6.5	3.1	1.9	3.5
44.5	46	46.5	140.0	110.1	109.9	223.0	101.3	67.8	123.9	4.1	3.2	3.2	6.3	3.0	1.9	3.4
45	46	46	142.0	111.6	111.5	226.0	102.7	68.8	125.7	4.0	3.1	3.1	6.1	3.0	1.9	3.3
45.5	46	46	144.0	113.2	113.0	229.0	104.2	69.7	127.4	4.0	3.1	3.1	6.1	3.0	1.9	3.3
46	45	45.5	146.0	114.7	114.6	232.0	105.7	70.6	129.1	3.9	3.1	3.1	5.9	2.9	1.9	3.2
46.5	45	45	148.0	116.2	116.1	234.8	107.1	71.6	130.7	3.8	3.0	3.0	5.7	2.9	1.8	3.2
47	45	45	150.0	117.7	117.6	237.6	108.5	72.5	132.4	3.8	3.0	3.0	5.7	2.9	1.8	3.2
47.5	45	45	152.0	119.2	119.1	240.4	110.0	73.4	134.0	3.8	3.0	3.0	5.7	2.9	1.8	3.2
48	44	44.5	154.0	120.7	120.5	243.2	111.4	74.3	135.6	3.7	2.9	2.9	5.5	2.8	1.8	3.1
49	44	44	157.0	123.6	123.4	248.5	114.2	76.1	138.8	3.6	2.9	2.9	5.3	2.8	1.8	3.0
50	44	44	161.0	126.5	126.3	253.7	117.0	77.9	141.9	3.6	2.9	2.9	5.3	2.8	1.8	3.0
51	43	43.5	165.0	129.3	129.1	258.8	119.7	79.7	145.0	3.6	2.8	2.8	5.1	2.7	1.8	2.9

52	42	42.5	168.0	132.0	131.9	263.6	122.3	81.4	147.9	3.4	2.7	2.7	4.8	2.6	1.8	2.8
53	42	42	171.0	134.7	134.5	268.2	124.9	83.2	150.8	3.3	2.7	2.7	4.6	2.6	1.7	2.8
54	41	41.5	174.0	137.3	137.1	272.6	127.5	84.9	153.6	3.2	2.6	2.6	4.4	2.6	1.7	2.7
55	41	41	178.0	139.8	139.7	276.9	130.0	86.6	156.3	3.1	2.5	2.5	4.3	2.5	1.7	2.6
56	40	40.5	181.0	142.3	142.2	281.1	132.4	88.3	159.0	3.1	2.5	2.5	4.1	2.5	1.7	2.6
57	40	40	184.0	144.8	144.6	285.1	134.9	89.9	161.6	3.0	2.4	2.4	4.0	2.4	1.7	2.5
58	40	40	187.0	147.2	147.1	289.1	137.3	91.6	164.2	3.0	2.4	2.4	4.0	2.4	1.7	2.5
59	39	39.5	189.0	149.6	149.4	292.9	139.7	93.2	166.7	2.9	2.4	2.4	3.9	2.4	1.7	2.5
60	39	39	192.0	151.9	151.8	296.6	142.0	94.9	169.2	2.8	2.3	2.3	3.7	2.3	1.6	2.4
61	38	38.5	195.0	154.2	154.1	300.3	144.3	96.5	171.6	2.8	2.3	2.3	3.6	2.3	1.6	2.3
62	38	38	198.0	156.5	156.3	303.7	146.5	98.1	174.0	2.7	2.2	2.2	3.5	2.3	1.6	2.3
63	37	37.5	200.0	158.7	158.5	307.1	148.7	99.7	176.3	2.6	2.2	2.2	3.4	2.2	1.6	2.2
64	37	37	203.0	160.8	160.7	310.3	150.9	101.2	178.6	2.5	2.2	2.2	3.2	2.2	1.6	2.2
65	37	37	205.0	163.0	162.8	313.6	153.1	102.8	180.8	2.5	2.2	2.2	3.2	2.2	1.6	2.2
66	36	36.5	208.0	165.1	165.0	316.7	155.2	104.4	183.0	2.5	2.1	2.1	3.1	2.1	1.6	2.1
67	36	36	210.0	167.2	167.0	319.8	157.3	105.9	185.2	2.4	2.1	2.1	3.0	2.1	1.5	2.1
68	36	36	213.0	169.2	169.1	322.8	159.4	107.4	187.3	2.4	2.1	2.1	3.0	2.1	1.5	2.1
69	36	36	215.0	171.3	171.1	325.8	161.5	109.0	189.5	2.4	2.1	2.1	3.0	2.1	1.5	2.1
70	35	35.5	218.0	173.3	173.2	328.8	163.5	110.5	191.6	2.4	2.0	2.0	2.9	2.0	1.5	2.0
71	35	35	220.0	175.3	175.1	331.6	165.5	112.0	193.6	2.3	2.0	2.0	2.8	2.0	1.5	2.0
72	35	35	222.0	177.3	177.1	334.4	167.5	113.5	195.7	2.3	2.0	2.0	2.8	2.0	1.5	2.0
73	34	34.5	224.0	179.2	179.1	337.1	169.5	115.0	197.7	2.2	1.9	1.9	2.7	2.0	1.5	1.9
74	34	34	227.0	181.1	180.9	339.8	171.4	116.4	199.6	2.2	1.9	1.9	2.6	1.9	1.5	1.9
75	34	34	229.0	183.0	182.8	342.4	173.3	117.9	201.6	2.2	1.9	1.9	2.6	1.9	1.5	1.9
76	33	33.5	231.0	184.8	184.7	345.0	175.2	119.3	203.5	2.1	1.9	1.9	2.5	1.9	1.5	1.9
77	33	33	233.0	186.7	186.5	347.4	177.1	120.8	205.3	2.1	1.8	1.8	2.5	1.9	1.4	1.8
78	33	33	235.0	188.5	188.3	349.9	178.9	122.2	207.2	2.1	1.8	1.8	2.5	1.9	1.4	1.8
79	32	32.5	237.0	190.2	190.1	352.3	180.8	123.6	209.0	2.0	1.8	1.8	2.4	1.8	1.4	1.8
80	32	32	239.0	192.0	191.8	354.6	182.5	125.0	210.8	2.0	1.7	1.7	2.3	1.8	1.4	1.7
81	32	32	241.0	193.7	193.6	356.9	184.3	126.4	212.6	2.0	1.7	1.7	2.3	1.8	1.4	1.7
82	31	31.5	243.0	195.4	195.3	359.1	186.1	127.8	214.3	1.9	1.7	1.7	2.2	1.7	1.4	1.7

83	31	31	245.0	197.1	196.9	361.2	187.8	129.2	216.0	1.9	1.7	1.7	2.1	1.7	1.4	1.7
84	31	31	247.0	198.7	198.6	363.4	189.5	130.5	217.7	1.9	1.7	1.7	2.1	1.7	1.4	1.7
85	30	30.5	248.0	200.3	200.2	365.4	191.1	131.9	219.3	1.8	1.6	1.6	2.1	1.7	1.4	1.6
86	30	30	250.0	201.9	201.8	367.4	192.8	133.2	220.9	1.8	1.6	1.6	2.0	1.6	1.3	1.6
87	30	30	252.0	203.5	203.4	369.4	194.4	134.6	222.6	1.8	1.6	1.6	2.0	1.6	1.3	1.6
88	30	30	254.0	205.1	205.0	371.4	196.0	135.9	224.2	1.8	1.6	1.6	2.0	1.6	1.3	1.6
89	30	30	255.0	206.7	206.5	373.4	197.7	137.2	225.8	1.8	1.6	1.6	2.0	1.6	1.3	1.6
90	29	29.5	257.0	208.2	208.1	375.4	199.3	138.5	227.4	1.7	1.6	1.6	1.9	1.6	1.3	1.5
91	29	29	259.0	209.8	209.6	377.2	200.8	139.8	228.9	1.7	1.5	1.5	1.9	1.6	1.3	1.5
92	29	29	260.0	211.3	211.1	379.1	202.4	141.1	230.4	1.7	1.5	1.5	1.9	1.6	1.3	1.5
93	29	29	262.0	212.8	212.6	381.0	203.9	142.4	232.0	1.7	1.5	1.5	1.9	1.6	1.3	1.5
94	29	29	264.0	214.3	214.2	382.8	205.5	143.7	233.5	1.7	1.5	1.5	1.9	1.6	1.3	1.5
95	29	29	265.0	215.8	215.7	384.7	207.1	145.0	235.0	1.7	1.5	1.5	1.9	1.6	1.3	1.5
96	28	28.5	267.0	217.3	217.2	386.5	208.6	146.3	236.5	1.6	1.5	1.5	1.8	1.5	1.3	1.5
97	28	28	269.0	218.8	218.6	388.3	210.1	147.6	238.0	1.6	1.5	1.5	1.7	1.5	1.3	1.4
98	28	28	270.0	220.2	220.1	390.0	211.6	148.9	239.5	1.6	1.5	1.5	1.7	1.5	1.3	1.4
99	28	28	272.0	221.7	221.5	391.7	213.1	150.1	240.9	1.6	1.5	1.5	1.7	1.5	1.3	1.4
100	28	28	273.0	223.1	223.0	393.5	214.6	151.4	242.4	1.6	1.5	1.5	1.7	1.5	1.3	1.4
101	28	28	275.0	224.6	224.4	395.2	216.1	152.7	243.9	1.6	1.5	1.5	1.7	1.5	1.3	1.4
102	27	27.5	276.0	226.0	225.8	396.9	217.5	153.9	245.3	1.5	1.4	1.4	1.7	1.5	1.3	1.4
103	27	27	278.0	227.4	227.2	398.5	219.0	155.1	246.7	1.5	1.4	1.4	1.6	1.4	1.2	1.4
104	27	27	279.0	228.8	228.6	400.2	220.4	156.4	248.1	1.5	1.4	1.4	1.6	1.4	1.2	1.4
105	27	27	281.0	230.1	230.0	401.8	221.8	157.6	249.5	1.5	1.4	1.4	1.6	1.4	1.2	1.4
106	26	26.5	282.0	231.5	231.3	403.3	223.2	158.8	250.9	1.4	1.4	1.4	1.6	1.4	1.2	1.3
107	26	26	284.0	232.8	232.7	404.9	224.6	160.0	252.2	1.4	1.3	1.3	1.5	1.4	1.2	1.3
108	26	26	285.0	234.1	234.0	406.4	225.9	161.2	253.5	1.4	1.3	1.3	1.5	1.4	1.2	1.3
109	26	26	287.0	235.5	235.3	407.9	227.3	162.4	254.9	1.4	1.3	1.3	1.5	1.4	1.2	1.3
110	25	25.5	288.0	236.8	236.6	409.4	228.6	163.6	256.2	1.4	1.3	1.3	1.5	1.3	1.2	1.3
111	25	25	289.0	238.0	237.9	410.8	229.9	164.8	257.4	1.3	1.3	1.3	1.4	1.3	1.2	1.3
112	25	25	291.0	239.3	239.1	412.2	231.2	165.9	258.7	1.3	1.3	1.3	1.4	1.3	1.2	1.3
113	25	25	292.0	240.6	240.4	413.6	232.5	167.1	260.0	1.3	1.3	1.3	1.4	1.3	1.2	1.3

114	25	25	293.0	241.8	241.7	415.0	233.8	168.3	261.2	1.3	1.3	1.3	1.4	1.3	1.2	1.3
115	24	24.5	295.0	243.1	242.9	416.4	235.1	169.4	262.5	1.3	1.2	1.2	1.4	1.3	1.2	1.2
116	24	24	296.0	244.3	244.1	417.7	236.3	170.6	263.7	1.3	1.2	1.2	1.3	1.2	1.1	1.2
117	24	24	297.0	245.5	245.3	419.0	237.5	171.7	264.9	1.3	1.2	1.2	1.3	1.2	1.1	1.2
118	24	24	298.0	246.7	246.5	420.3	238.8	172.8	266.1	1.3	1.2	1.2	1.3	1.2	1.1	1.2
119	24	24	300.0	247.9	247.7	421.7	240.0	174.0	267.3	1.3	1.2	1.2	1.3	1.2	1.1	1.2
120	24	24	301.0	249.1	248.9	423.0	241.2	175.1	268.5	1.3	1.2	1.2	1.3	1.2	1.1	1.2
121	23	23.5	302.0	250.3	250.1	424.3	242.4	176.2	269.7	1.2	1.2	1.2	1.3	1.2	1.1	1.2

Table D

Actual initial setting times by the maturity method for the MNDC 69 concrete mixture at Channel 3 location

$$t_a = \Sigma e^{-5000[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$$

$$t_e = \Sigma e^{-3040[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$$

$$t_q = \Sigma e^{-4100[1/(273+T) - 1/(273+Tr)]} \bullet \Delta t$$

Actual Time (Hrs)	Concret e Temp. (°C)	Averag e Concre te Temp. (°C)	t_e (Hrs)	t_q (Hrs)	t_a (Hrs)
0	11	9.5	0	0	0
0.5	18	14.5	0.409985	0.38257	0.360737
1	17	17.5	0.867276	0.825843	0.792446
1.5	17	17	1.31639	1.258459	1.211531
2	16	16.5	1.757445	1.68064	1.618322
2.5	16	16	2.19056	2.092602	2.013136
3	15	15.5	2.615851	2.494558	2.396288
3.5	15	15	3.033432	2.886719	2.768084
4	15	15	3.451014	3.278879	3.139879
4.5	14	14.5	3.860999	3.661449	3.500616
5	14	14	4.263501	4.034632	3.850588
5.5	14	14	4.666003	4.407815	4.200559
6	14	14	5.068505	4.780997	4.550531
6.5	15	14.5	5.478491	5.163568	4.911268
7	15	15	5.896072	5.555728	5.283063
7.5	15	15	6.313653	5.947889	5.654859
8	15	15	6.731235	6.340049	6.026654
8.5	16	15.5	7.156525	6.742005	6.409806
9	16	16	7.58964	7.153967	6.804621
9.5	16	16	8.022756	7.565929	7.199435
10	16	16	8.455871	7.977891	7.59425
10.5	16	16	8.888986	8.389853	7.989065
11	16	16	9.322101	8.801815	8.383879
11.5	17	16.5	9.763157	9.223996	8.790669
12	17	17	10.21227	9.656612	9.209755
12.5	17	17	10.66138	10.08923	9.628841
13	17	17	11.1105	10.52184	10.04793
13.5	18	17.5	11.56779	10.96512	10.47963
14	18	18	12.03338	11.41927	10.9243
14.5	19	18.5	12.50738	11.88453	11.38227
15	20	19.5	12.99859	12.37272	11.86789
15.5	20	20	13.49859	12.87272	12.36789
16	21	20.5	14.00751	13.38478	12.88264

16.5	21	21	14.52547	13.90915	13.41252
17	22	21.5	15.0526	14.44609	13.95793
17.5	23	22.5	15.59847	15.00893	14.53558
18	24	23.5	16.16362	15.59873	15.14716
18.5	26	25	16.7587	16.23105	15.81293
19	28	27	17.39565	16.92411	16.55748
19.5	30	29	18.07682	17.68282	17.38892
20	32	31	18.80463	18.51242	18.31605
20.5	36	34	**19.60715**	**19.45888**	**19.40482**
21	40	38	20.51867	20.58272	20.74732
21.5	44	42	21.55066	21.91135	22.39387
22	48	46	22.7154	23.47554	24.40303
22.5	51	49.5	24.00705	25.27385	26.78475
23	52	51.5	25.37597	27.21873	29.40529
23.5	53	52.5	26.78486	29.2406	32.15286
24	53	53	28.21407	31.30191	34.96593
24.5	53	53	29.64329	33.36321	37.77899
25	53	53	31.0725	35.42452	40.59206
25.5	53	53	32.50172	37.48582	43.40513
26	53	53	33.93094	39.54713	46.2182
26.5	53	53	35.36015	41.60844	49.03127
27	53	53	36.78937	43.66974	51.84434
27.5	53	53	38.21859	45.73105	54.65741

Table E

Strength development of the MNDC 69 concrete mixture under various hypothetical constant concrete temperatures according to various maturity functions

			Temperature = 15°C													
Actual Time (Hrs)	Strength (MPa)	Temp. (°C)	t_a	t	t_e	t	t_q	t	t_{ws}	t	t_{NS}	t	t_R	t	t_{CT}	t
24	16.5	23.3	30.9	**41.5**	29.5	**37.5**	29.5	**37.5**	32.6	**44.0**	30.2	**36.3**	27.5	**39.0**	29.4	**37.0**
29	37.5	40	45.8	**61.5**	41.7	**53.0**	41.7	**53.0**	52.6	**71.0**	42.3	**51.0**	35.9	**50.8**	41.9	**52.8**
40	43	24	59.6	**80.0**	55.0	**70.0**	55.0	**70.0**	67.1	**90.5**	55.9	**67.0**	48.3	**68.4**	55.2	**69.5**
48.5	46	19.4	67.8	**91.0**	63.3	**80.5**	63.3	**81.0**	75.2	**101.5**	64.1	**77.0**	56.7	**80.0**	63.4	**80.0**
72	51	18.9	89.9	**121.0**	85.6	**109.0**	85.6	**109.0**	97.0	**N/A**	86.2	**103.5**	79.3	**112.0**	85.8	**108.0**
168	63	20.9	191.0	**N/A**	185.8	**N/A**	185.8	**N/A**	199.2	**N/A**	187.1	**N/A**	178.2	**N/A**	185.8	**N/A**
			Temperature = 18°C													
Time	Strength	Temp	t_a	t	t_e	t	t_q	t	t_{ws}	t	t_{NS}	t	t_R	t	t_{CT}	t
24	16.5	23.3	30.9	**34.7**	29.5	**32.5**	29.5	**32.5**	32.6	**36.5**	30.2	**32.5**	27.5	**31.5**	29.4	**32.3**
29	37.5	40	45.8	**51.5**	41.7	**45.8**	41.7	**46.0**	52.6	**59.0**	42.3	**45.4**	35.9	**41.3**	41.9	**46.0**
40	43	24	59.6	**67.0**	55.0	**60.5**	55.0	**60.5**	67.1	**75.2**	55.9	**59.8**	48.3	**55.5**	55.2	**60.5**
48.5	46	19.4	67.8	**76.0**	63.3	**69.5**	63.3	**69.8**	75.2	**84.2**	64.1	**68.8**	56.7	**65.0**	63.4	**69.5**
72	51	18.9	89.9	**101.0**	85.6	**94.0**	85.6	**94.0**	97.0	**109.0**	86.2	**92.5**	79.3	**91.0**	85.8	**94.0**
168	63	20.9	191.0	**N/A**	185.8	**N/A**	185.8	**N/A**	199.2	**N/A**	187.1	**N/A**	178.2	**N/A**	185.8	**N/A**
			Temperature = 20°C													
Time	Strength	Temp	t_a	t	t_e	t	t_q	t	t_{ws}	t	t_{NS}	t	t_R	t	t_{CT}	t
24	16.5	23.3	30.9	**31.0**	29.5	**29.5**	29.5	**29.5**	32.6	**32.6**	30.2	**30.2**	27.5	**27.5**	29.4	**29.4**
29	37.5	40	45.8	**45.8**	41.7	**41.7**	41.7	**41.7**	52.6	**52.6**	42.3	**42.3**	35.9	**35.9**	41.9	**41.9**
40	43	24	59.6	**59.6**	55.0	**55.0**	55.0	**55.0**	67.1	**67.1**	55.9	**55.9**	48.3	**48.3**	55.2	**55.2**
48.5	46	19.4	67.8	**67.8**	63.3	**63.3**	63.3	**63.3**	75.2	**75.2**	64.1	**64.1**	56.7	**56.7**	63.4	**63.4**
72	51	18.9	89.9	**89.9**	85.6	**85.6**	85.6	**85.6**	97.0	**97.0**	86.2	**86.2**	79.3	**79.3**	85.8	**85.8**

168	63	20.9	191.0	**191.0**	185.8	**185.8**	185.8	**185.8**	199.2	**199.2**	187.1	**187.1**	178.2	**178.2**	185.8	**185.8**

Temperature = 22°C

Time	Strength	Temp	t_a	t	t_e	t	t_q	t	t_{ws}	t	t_{NS}	t	t_R	t	t_{CT}	t
24	16.5	23.3	30.9	**27.5**	29.5	**27.0**	29.5	**26.9**	32.6	**29.3**	30.2	**28.5**	27.5	**24.0**	29.4	**26.7**
29	37.5	40	45.8	**40.8**	41.7	**38.0**	41.7	**38.0**	52.6	**47.2**	42.3	**39.6**	35.9	**31.3**	41.9	**38.3**
40	43	24	59.6	**53.0**	55.0	**50.0**	55.0	**50.0**	67.1	**60.1**	55.9	**52.5**	48.3	**42.0**	55.2	**50.5**
48.5	46	19.4	67.8	**60.2**	63.3	**57.7**	63.3	**57.5**	75.2	**67.5**	64.1	**60.0**	56.7	**49.5**	63.4	**58.0**
72	51	18.9	89.9	**80.0**	85.6	**78.0**	85.6	**78.0**	97.0	**87.0**	86.2	**81.0**	79.3	**69.0**	85.8	**78.2**
168	63	20.9	191.0	**N/A**	185.8	**N/A**	185.8	**N/A**	199.2	**N/A**	187.1	**N/A**	178.2	**N/A**	185.8	**N/A**

Temperature = 25°C

Time	Strength	Temp	t_a	t	t_e	t	t_q	t	t_{ws}	t	t_{NS}	t	t_R	t	t_{CT}	t
24	16.5	23.3	30.9	**23.3**	29.5	**23.5**	29.5	**23.4**	32.6	**25.0**	30.2	**26.0**	27.5	**19.5**	29.4	**23.5**
29	37.5	40	45.8	**34.5**	41.7	**33.2**	41.7	**33.0**	52.6	**40.5**	42.3	**36.3**	35.9	**25.3**	41.9	**33.4**
40	43	24	59.6	**44.3**	55.0	**43.8**	55.0	**43.5**	67.1	**51.8**	55.9	**48.0**	48.3	**34.2**	55.2	**43.9**
48.5	46	19.4	67.8	**51.0**	63.3	**50.5**	63.3	**50.0**	75.2	**58.0**	64.1	**55.0**	56.7	**40.0**	63.4	**50.5**
72	51	18.9	89.9	**67.5**	85.6	**68.0**	85.6	**67.8**	97.0	**75.0**	86.2	**74.0**	79.3	**56.0**	85.8	**68.2**
168	63	20.9	191.0	**N/A**	185.8	**N/A**	185.8	**N/A**	199.2	**N/A**	187.1	**N/A**	178.2	**N/A**	185.8	**N/A**

Temperature = 30°C

Time	Strength	Temp	t_a	t	t_e	t	t_q	t	t_{ws}	t	t_{NS}	t	t_R	t	t_{CT}	t
24	16.5	23.3	30.9	**17.5**	29.5	**19.0**	29.5	**18.5**	32.6	**20.0**	30.2	**22.7**	27.5	**13.8**	29.4	**18.5**
29	37.5	40	45.8	**26.0**	41.7	**26.8**	41.7	**26.3**	52.6	**32.3**	42.3	**31.8**	35.9	**18.0**	41.9	**26.5**
40	43	24	59.6	**34.0**	55.0	**35.0**	55.0	**34.6**	67.1	**41.2**	55.9	**42.0**	48.3	**24.1**	55.2	**34.9**
48.5	46	19.4	67.8	**38.5**	63.3	**40.3**	63.3	**40.0**	75.2	**46.0**	64.1	**48.0**	56.7	**28.3**	63.4	**40.0**
72	51	18.9	89.9	**51.3**	85.6	**54.3**	85.6	**54.0**	97.0	**59.5**	86.2	**64.5**	79.3	**39.6**	85.8	**54.5**
168	63	20.9	191.0	**108.5**	185.8	**117.5**	185.8	**117.0**	199.2	**N/A**	187.1	**N/A**	178.2	**89.1**	185.8	**117.2**

Temperature = 40°C

Time	Strength	Temp	t_a	t	t_e	t	t_q	t	t_{ws}	t	t_{NS}	t	t_R	t	t_{CT}	t
24	16.5	23.3	30.9	**10.5**	29.5	**13.0**	29.5	**12.0**	32.6	**13.5**	30.2	**18.2**	27.5	**6.9**	29.4	**11.8**
29	37.5	40	45.8	**15.3**	41.7	**17.9**	41.7	**17.0**	52.6	**21.8**	42.3	**25.5**	35.9	**9.0**	41.9	**16.8**
40	43	24	59.6	**20.0**	55.0	**23.3**	55.0	**22.5**	67.1	**27.8**	55.9	**33.5**	48.3	**12.0**	55.2	**22.0**

48.5	46	19.4	67.8	**22.8**	63.3	**26.8**	63.3	**26.0**	75.2	**31.1**	64.1	**38.5**	56.7	**14.3**	63.4	**25.4**
72	51	18.9	89.9	**30.3**	85.6	**35.8**	85.6	**35.0**	97.0	**40.0**	86.2	**51.2**	79.3	**19.8**	85.8	**34.2**
168	63	20.9	191.0	**64.2**	185.8	**76.8**	185.8	**76.0**	199.2	**82.5**	187.1	**112.3**	178.2	**44.6**	185.8	**74.0**

TABLE F
Strength Data for Channel 1
(Bold and bigger sized are the data that are used in table 5.11 to plot figure 5.9)

$t_{CT} = e^{[0.046\cdot(T_{av}-20)]} \cdot \Delta t$
$S_k = S_u \{k_r (t_e - t_{or}) / [1 + k_r (t_e - t_{or})]\}$
$S_{FHP} = S_u \cdot e^{-(\tau/t)^{\alpha}}$
$S_c = S_u \cdot e^{-[\tau/(t_{CT}-t_{ir})]^{\alpha}}$

Actual Time (Hrs)	Concrete Temp. (°C)	Average Concrete Temp. (°C)	t_{CT} (Hrs)	S_{FHP} (MPa)	S_k (MPa)	S_C (MPa)	S_L (MPa)
0	**8**	**8**	**0.0**	**#DIV/0!**	**-122.4**	-	-
0.5	11	9.5	0.3	0.0	-116.6	-	-
1	11	11	0.7	0.0	-110.9	-	-
1.5	11	11	1.1	0.0	-105.5	-	-
2	11	11	1.5	0.0	-100.4	-	-
2.5	11	11	1.8	0.0	-95.6	-	-
3	11	11	2.2	0.0	-91.0	-	-
3.5	11	11	2.6	0.0	-86.7	-	-
4	11	11	2.9	0.1	-82.6	-	-
4.5	11	11	3.3	0.1	-78.6	-	-
5	11	11	3.7	0.2	-74.9	-	-
5.5	12	11.5	4.0	0.3	-71.3	-	-
6	12	12	4.4	0.5	-67.8	-	-
6.5	13	12.5	4.8	0.7	-64.4	-	-
7	13	13	5.2	1.0	-61.1	-	-
7.5	13	13	5.6	1.3	-57.9	-	-
8	13	13	6.0	1.6	-54.9	-	-
8.5	13	13	6.4	2.0	-52.0	-	-
9	13	13	6.8	2.3	-49.3	-	-
9.5	14	13.5	7.2	2.8	-46.6	-	-
10	**14**	**14**	**7.6**	**3.2**	**-44.0**	-	-
10.5	14	14	8.0	3.7	-41.5	-	-
11	14	14	8.4	4.2	-39.0	-	-
11.5	15	14.5	8.8	4.7	-36.7	-	-
12	15	15	9.2	5.2	-34.4	-	-
12.5	15	15	9.7	5.8	-32.2	-	-
13	15	15	10.1	6.4	-30.0	-	-
13.5	16	15.5	10.5	6.9	-28.0	-	-
14	16	16	10.9	7.5	-25.9	-	-
14.5	17	16.5	11.4	8.1	-23.9	-	-
15	17	17	11.8	8.7	-22.0	-	-
15.5	17	17	12.3	9.3	-20.1	-	-
16	18	17.5	12.8	10.0	-18.3	-	-

16.5	18	18	13.2	10.6	-16.5	-	-
17	18	18	13.7	11.2	-14.7	-	-
17.5	19	18.5	14.2	11.9	-13.0	-	-
18	19	19	14.6	12.5	-11.4	-	-
18.5	20	19.5	15.1	13.1	-9.7	-	-
19	20	20	15.6	13.8	-8.1	-	-
19.5	21	20.5	16.1	14.4	-6.6	-	-
20	**22**	**21.5**	**16.7**	**15.1**	**-5.0**	**-**	**-**
20.5	23	22.5	17.2	15.8	-3.5	-	-
21	24	23.5	17.8	16.5	-1.9	-	-
21.5	26	25	18.4	17.2	-0.3	-	-
22	27	26.5	19.0	17.9	1.3	0.0	-
22.5	29	28	19.7	18.7	2.9	0.1	-
23	31	30	20.4	19.5	4.5	0.7	-
23.5	32	31.5	21.1	20.3	6.2	1.9	-
24	33	32.5	21.9	21.1	7.8	3.6	-
24.5	34	33.5	22.6	21.9	9.4	5.5	-
25	35	34.5	23.5	22.8	11.0	7.6	-
25.5	35	35	24.5	23.7	12.8	10.0	6.1
26	35	35	25.5	24.7	14.6	12.3	8.2
26.5	35	35	26.5	25.6	16.2	14.5	10.3
27	35	35	27.5	26.5	17.8	16.5	12.4
27.5	34	34.5	28.4	27.4	19.3	18.3	14.5
28	34	34	29.4	28.1	20.6	20.0	16.5
28.5	33	33.5	30.3	28.9	21.9	21.5	18.5
29	33	33	31.2	29.6	23.1	22.9	20.4
29.5	33	33	32.1	30.3	24.2	24.2	22.3
30	**33**	**33**	**33.0**	**31.0**	**25.3**	**25.5**	**24.2**
30.5	33	33	33.9	31.6	26.4	26.7	26.1
31	33	33	34.9	32.3	27.4	27.8	28.0
31.5	33	33	35.8	32.9	28.3	28.8	29.9
32	32	32.5	36.7	33.5	29.3	29.8	31.8
32.5	32	32	37.5	34.0	30.1	30.7	33.6
33	32	32	38.4	34.6	31.0	31.5	35.5
33.5	32	32	39.3	35.1	31.8	32.4	37.3
34	32	32	40.1	35.6	32.5	33.1	37.8
34.5	32	32	41.0	36.1	33.3	33.9	38.1
35	32	32	41.9	36.6	34.0	34.6	38.4
35.5	32	32	42.7	37.1	34.7	35.3	38.8
36	32	32	43.6	37.6	35.4	36.0	39.1
36.5	32	32	44.5	38.0	36.0	36.6	39.4
37	32	32	45.3	38.5	36.7	37.2	39.7
37.5	32	32	46.2	38.9	37.3	37.8	40.0
38	32	32	47.1	39.3	37.9	38.4	40.4
38.5	32	32	47.9	39.7	38.5	38.9	40.7
39	32	32	48.8	40.1	39.1	39.4	41.0

39.5	32	32	49.7	40.5	39.6	39.9	41.3
40	**32**	**32**	**50.6**	**40.9**	**40.1**	**40.4**	**41.6**
40.5	31	31.5	51.4	41.3	40.7	40.9	42.0
41	31	31	52.2	41.6	41.1	41.3	42.3
41.5	31	31	53.1	42.0	41.6	41.8	42.6
42	31	31	53.9	42.3	42.1	42.2	42.9
42.5	31	31	54.7	42.7	42.5	42.6	43.2
43	31	31	55.5	43.0	43.0	43.0	43.5
43.5	30	30.5	56.4	43.3	43.4	43.4	43.8
44	30	30	57.1	43.6	43.8	43.7	44.1
44.5	30	30	57.9	43.9	44.2	44.0	44.4
45	30	30	58.7	44.2	44.5	44.4	44.7
45.5	30	30	59.5	44.5	44.9	44.7	45.0
46	29	29.5	60.3	44.7	45.3	45.0	45.2
46.5	29	29	61.1	45.0	45.6	45.3	45.5
47	29	29	61.8	45.2	46.0	45.6	45.8
47.5	29	29	62.6	45.5	46.3	45.9	46.9
48	29	29	63.3	45.7	46.6	46.2	47.0
49	29	29	64.8	46.2	47.2	46.7	47.2
50	**29**	**29**	**66.3**	**46.7**	**47.8**	**47.2**	**47.4**
51	29	29	67.9	47.1	48.4	47.7	47.6
52	28	28.5	69.3	47.6	48.9	48.2	47.8
53	28	28	70.8	48.0	49.4	48.6	48.0
54	27	27.5	72.2	48.4	49.9	49.0	48.2
55	27	27	73.6	48.7	50.4	49.4	48.3
56	27	27	75.0	49.1	50.8	49.8	48.5
57	29	28	76.4	49.5	51.3	50.2	48.7
58	29	29	77.9	49.8	51.7	50.5	48.9
59	29	29	79.4	50.2	52.2	50.9	49.1
60	**29**	**29**	**80.9**	**50.5**	**52.6**	**51.3**	**49.3**
61	29	29	82.5	50.9	53.0	51.6	49.5
62	29	29	84.0	51.2	53.4	51.9	49.7
63	29	29	85.5	51.5	53.8	52.3	49.9
64	29	29	87.0	51.9	54.1	52.6	50.1
65	29	29	88.5	52.2	54.5	52.9	50.4
66	29	29	90.0	52.5	54.9	53.2	50.6
67	29	29	91.5	52.7	55.2	53.4	50.8
68	29	29	93.0	53.0	55.5	53.7	51.0
69	30	29.5	94.6	53.3	55.9	54.0	51.2
70	**28**	**29**	**96.1**	**53.6**	**56.2**	**54.3**	**51.4**
71	27	27.5	97.5	53.8	56.5	54.5	51.6
72	26	26.5	98.9	54.1	56.7	54.7	51.7
73	25	25.5	100.2	54.3	57.0	54.9	51.9
74	25	25	101.4	54.5	57.2	55.1	52.1
75	24	24.5	102.6	54.7	57.4	55.3	52.3
76	24	24	103.8	54.9	57.6	55.5	52.4

77	23	23.5	105.0	55.1	57.8	55.7	52.6
78	24	23.5	106.2	55.2	58.0	55.8	52.7
79	25	24.5	107.4	55.4	58.2	56.0	52.9
80	**25**	**25**	**108.7**	**55.6**	**58.5**	**56.2**	**53.1**
81	25	25	109.9	55.8	58.7	56.3	53.2
82	26	25.5	111.2	56.0	58.9	56.5	53.4
83	26	26	112.5	56.2	59.1	56.7	53.6
84	26	26	113.9	56.3	59.3	56.9	53.8
85	26	26	115.2	56.5	59.5	57.0	53.9
86	26	26	116.5	56.7	59.7	57.2	54.1
87	26	26	117.8	56.9	59.8	57.3	54.3
88	26	26	119.1	57.0	60.0	57.5	54.5
89	26	26	120.5	57.2	60.2	57.7	54.7
90	**24**	**25**	**121.7**	**57.3**	**60.4**	**57.8**	**54.8**
91	23	23.5	122.9	57.5	60.5	57.9	55.0
92	23	23	124.0	57.6	60.7	58.1	55.1
93	23	23	125.2	57.8	60.8	58.2	55.3
94	23	23	126.3	57.9	61.0	58.3	55.4
95	22	22.5	127.5	58.0	61.1	58.4	55.6
96	21	21.5	128.5	58.1	61.2	58.5	55.7
97	21	21	129.6	58.3	61.4	58.6	55.9
98	20	20.5	130.6	58.4	61.5	58.7	56.0
99	20	20	131.6	58.5	61.6	58.8	56.2
100	**19**	**19.5**	**132.6**	**58.6**	**61.7**	**58.9**	**56.3**
101	19	19	133.5	58.7	61.8	59.0	56.4
102	19	19	134.5	58.8	61.9	59.1	56.5
103	18	18.5	135.4	58.9	62.0	59.2	56.7
104	17	17.5	136.3	59.0	62.1	59.3	56.8
105	17	17	137.2	59.1	62.2	59.4	56.9
106	17	17	138.0	59.2	62.3	59.4	57.0
107	17	17	138.9	59.2	62.4	59.5	57.1
108	17	17	139.8	59.3	62.5	59.6	57.3
109	17	17	140.7	59.4	62.6	59.7	57.4
110	**16**	**16.5**	**141.5**	**59.5**	**62.7**	**59.8**	**57.5**
111	16	16	142.3	59.6	62.7	59.8	57.6
112	16	16	143.2	59.7	62.8	59.9	57.7
113	15	15.5	144.0	59.7	62.9	60.0	57.8
114	15	15	144.8	59.8	63.0	60.0	57.9
115	15	15	145.6	59.9	63.1	60.1	58.0
116	15	15	146.4	60.0	63.1	60.2	58.1
117	15	15	147.2	60.0	63.2	60.2	58.3
118	15	15	148.0	60.1	63.3	60.3	58.4
119	15	15	148.8	60.2	63.4	60.4	58.5
120	**15**	**15**	**149.6**	**60.2**	**63.4**	**60.4**	**58.6**
121	15	15	150.3	60.3	63.5	60.5	58.7

TABLE G

Strength Data for Channel 2

(Bold and bigger sized are the data that are used in table 5.12 to plot figure 5.10)

$$t_{CT} = e^{[0.046\cdot(T_{av}-20)]}\cdot\Delta t$$

$$S_k = S_u\,\{k_r\,(t_e - t_{or})\,/\,[1 + k_r\,(t_e - t_{or})]\}$$

$$S_{FHP} = S_u \cdot e^{-(\tau/t)^{\alpha}}$$

$$S_c = S_u \cdot e^{-[\tau/(t_{CT}-t_{ir})]^{\alpha}}$$

Actual Time (Hrs)	Concrete Temp. (°C)	Average Concrete Temp. (°C)	t_{CT} (Hrs)	S_{FHP} (MPa)	S_k (MPa)	S_C (MPa)	S_L (MPa)
0	**12**	**12**	**0.0**	**-**	**-122.4**	**-**	**-**
0.5	18	15	0.4	0.0	-115.5	-	-
1	18	18	0.9	0.0	-108.4	-	-
1.5	17	17.5	1.3	0.0	-101.9	-	-
2	16	16.5	1.8	0.0	-96.0	-	-
2.5	16	16	2.2	0.0	-90.6	-	-
3	15	15.5	2.7	0.0	-85.6	-	-
3.5	15	15	3.1	0.1	-80.9	-	-
4	15	15	3.5	0.2	-76.5	-	-
4.5	14	14.5	3.9	0.3	-72.5	-	-
5	14	14	4.3	0.5	-68.7	-	-
5.5	14	14	4.7	0.7	-65.0	-	-
6	15	14.5	5.1	0.9	-61.5	-	-
6.5	15	15	5.6	1.3	-58.1	-	-
7	15	15	6.0	1.6	-54.9	-	-
7.5	15	15	6.4	2.0	-51.8	-	-
8	16	15.5	6.8	2.4	-48.8	-	-
8.5	16	16	7.3	2.9	-45.9	-	-
9	16	16	7.7	3.4	-43.2	-	-
9.5	16	16	8.2	3.9	-40.5	-	-
10	**16**	**16**	**8.6**	**4.4**	**-38.0**	**-**	**-**
10.5	16	16	9.0	5.0	-35.5	-	-
11	16	16	9.5	5.5	-33.2	-	-
11.5	16	16	9.9	6.1	-31.0	-	-
12	16	16	10.3	6.7	-28.8	-	-
12.5	17	16.5	10.8	7.3	-26.7	-	-
13	17	17	11.2	7.9	-24.7	-	-
13.5	17	17	11.7	8.5	-22.7	-	-
14	18	17.5	12.1	9.1	-20.8	-	-
14.5	18	18	12.6	9.8	-18.9	-	-
15	19	18.5	13.1	10.4	-17.0	-	-
15.5	19	19	13.6	11.1	-15.2	-	-
16	20	19.5	14.1	11.7	-13.4	-	-

16.5	20	20	14.6	12.4	-11.7	-	-
17	20	20	15.1	13.0	-10.0	-	-
17.5	21	20.5	15.6	13.7	-8.4	-	-
18	22	21.5	16.1	14.4	-6.7	-	-
18.5	23	22.5	16.6	15.0	-5.1	-	-
19	25	24	17.2	15.8	-3.5	-	-
19.5	26	25.5	17.8	16.5	-1.8	-	-
20	**28**	**27**	**18.4**	**17.3**	**-0.1**	**-**	**-**
20.5	31	29.5	19.1	18.1	1.6	0.0	-
21	34	32.5	19.9	18.9	3.4	0.2	-
21.5	37	35.5	20.7	19.9	5.4	1.3	-
22	41	39	21.7	20.9	7.5	3.3	-
22.5	45	43	22.8	22.1	9.7	5.9	-
23	48	46.5	24.0	23.3	12.0	8.9	-
23.5	49	48.5	25.3	24.6	14.4	12.0	8.0
24	50	49.5	26.7	25.8	16.6	15.0	10.9
24.5	51	50.5	28.1	27.1	18.8	17.7	13.8
25	51	51	29.6	28.3	20.9	20.3	16.9
25.5	51	51	31.6	29.9	23.6	23.5	21.2
26	51	51	33.7	31.5	26.1	26.4	25.6
26.5	51	51	35.8	32.9	28.4	28.8	30.0
27	51	51	37.9	34.3	30.5	31.0	34.4
27.5	51	51	40.0	35.5	32.4	33.0	37.7
28	51	51	42.0	36.7	34.1	34.8	38.5
28.5	51	51	44.1	37.8	35.8	36.3	39.3
29	51	51	46.2	38.9	37.3	37.8	40.0
29.5	51	51	48.3	39.9	38.7	39.1	40.8
30	**51**	**51**	**50.4**	**40.8**	**40.0**	**40.3**	**41.6**
30.5	51	51	52.4	41.7	41.3	41.5	42.3
31	50	50.5	54.5	42.6	42.4	42.5	43.1
31.5	50	50	56.5	43.3	43.4	43.4	43.8
32	50	50	58.5	44.1	44.4	44.3	44.6
32.5	50	50	60.4	44.8	45.3	45.1	45.3
33	50	50	62.4	45.4	46.2	45.8	46.0
33.5	50	50	64.4	46.1	47.0	46.6	47.1
34	49	49.5	66.4	46.7	47.8	47.2	47.4
34.5	49	49	68.3	47.3	48.5	47.8	47.6
35	49	49	70.2	47.8	49.2	48.4	47.9
35.5	49	49	72.0	48.3	49.9	49.0	48.1
36	49	49	73.9	48.8	50.5	49.5	48.4
36.5	49	49	75.8	49.3	51.1	50.0	48.6
37	48	48.5	77.7	49.8	51.7	50.5	48.9
37.5	48	48	79.5	50.2	52.2	50.9	49.1
38	48	48	81.3	50.6	52.7	51.3	49.4
38.5	48	48	83.1	51.0	53.2	51.8	49.6
39	47	47.5	84.9	51.4	53.6	52.1	49.9

39.5	47	47	86.6	51.8	54.1	52.5	50.1
40	**47**	**47**	**88.4**	**52.1**	**54.5**	**52.8**	**50.3**
40.5	46	46.5	90.1	52.5	54.9	53.2	50.6
41	46	46	91.7	52.8	55.2	53.5	50.8
41.5	46	46	93.4	53.1	55.6	53.8	51.0
42	45	45.5	95.0	53.4	55.9	54.1	51.2
42.5	45	45	96.6	53.7	56.3	54.3	51.4
43	45	45	98.1	53.9	56.6	54.6	51.7
43.5	44	44.5	99.7	54.2	56.9	54.8	51.9
44	44	44	101.2	54.5	57.2	55.1	52.1
44.5	44	44	102.7	54.7	57.4	55.3	52.3
45	44	44	104.2	54.9	57.7	55.5	52.5
45.5	44	44	105.7	55.2	58.0	55.8	52.7
46	43	43.5	107.2	55.4	58.2	56.0	52.9
46.5	43	43	108.6	55.6	58.4	56.2	53.1
47	43	43	110.1	55.8	58.7	56.4	53.3
47.5	43	43	111.5	56.0	58.9	56.6	53.5
48	42	42.5	112.9	56.2	59.1	56.7	53.6
49	42	42	115.7	56.6	59.5	57.1	54.0
50	**42**	**42**	**118.4**	**56.9**	**59.9**	**57.4**	**54.4**
51	41	41.5	121.1	57.3	60.3	57.7	54.7
52	40	40.5	123.7	57.6	60.6	58.0	55.1
53	40	40	126.2	57.9	60.9	58.3	55.4
54	40	40	128.7	58.2	61.3	58.5	55.8
55	39	39.5	131.2	58.4	61.5	58.8	56.1
56	39	39	133.5	58.7	61.8	59.0	56.4
57	38	38.5	135.9	58.9	62.1	59.2	56.7
58	38	38	138.2	59.2	62.3	59.5	57.0
59	37	37.5	140.4	59.4	62.6	59.7	57.3
60	**37**	**37**	**142.6**	**59.6**	**62.8**	**59.8**	**57.6**
61	37	37	144.8	59.8	63.0	60.0	57.9
62	36	36.5	146.9	60.0	63.2	60.2	58.2
63	36	36	149.0	60.2	63.4	60.4	58.5
64	36	36	151.1	60.4	63.6	60.5	58.8
65	36	36	153.2	60.6	63.8	60.7	59.1
66	35	35.5	155.2	60.7	63.9	60.9	59.3
67	35	35	157.2	60.9	64.1	61.0	59.6
68	35	35	159.2	61.0	64.3	61.1	59.9
69	35	35	161.2	61.2	64.4	61.3	60.1
70	**34**	**34.5**	**163.2**	**61.4**	**64.6**	**61.4**	**60.4**
71	34	34	165.1	61.5	64.7	61.5	60.7
72	34	34	167.0	61.6	64.9	61.7	60.9
73	34	34	168.9	61.8	65.0	61.8	61.2
74	33	33.5	170.7	61.9	65.1	61.9	61.4
75	33	33	172.5	62.0	65.3	62.0	61.7
76	33	33	174.4	62.2	65.4	62.1	61.9

77	32	32.5	176.1	62.3	65.5	62.2	62.2
78	32	32	177.9	62.4	65.6	62.3	62.4
79	31	31.5	179.6	62.5	65.7	62.4	62.6
80	**31**	**31**	**181.2**	**62.6**	**65.8**	**62.5**	**62.8**
81	31	31	182.9	62.7	65.9	62.6	63.1
82	31	31	184.6	62.8	66.0	62.7	-
83	30	30.5	186.2	62.9	66.1	62.8	-
84	30	30	187.8	63.0	66.2	62.9	-
85	30	30	189.3	63.1	66.3	63.0	-
86	30	30	190.9	63.2	66.4	63.1	-
87	30	30	192.5	63.3	66.5	63.2	-
88	30	30	194.1	63.4	66.6	63.2	-
89	29	29.5	195.6	63.5	66.7	63.3	-
90	**29**	**29**	**197.2**	**63.6**	**66.8**	**63.4**	**-**
91	29	29	198.7	63.7	66.9	63.5	-
92	29	29	200.2	63.7	66.9	63.5	-
93	29	29	201.7	63.8	67.0	63.6	-
94	29	29	203.2	63.9	67.1	63.7	-
95	28	28.5	204.7	64.0	67.2	63.7	-
96	28	28	206.1	64.1	67.2	63.8	-
97	28	28	207.6	64.1	67.3	63.9	-
98	28	28	209.0	64.2	67.4	63.9	-
99	27	27.5	210.4	64.3	67.5	64.0	-
100	**27**	**27**	**211.8**	**64.3**	**67.5**	**64.1**	**-**
101	27	27	213.2	64.4	67.6	64.1	-
102	26	26.5	214.5	64.5	67.6	64.2	-
103	26	26	215.9	64.5	67.7	64.2	-
104	26	26	217.2	64.6	67.8	64.3	-
105	25	25.5	218.5	64.7	67.8	64.4	-
106	25	25	219.7	64.7	67.9	64.4	-
107	25	25	221.0	64.8	67.9	64.5	-
108	24	24.5	222.2	64.8	68.0	64.5	-
109	24	24	223.4	64.9	68.0	64.6	-
110	**24**	**24**	**224.6**	**64.9**	**68.1**	**64.6**	**-**
111	24	24	225.8	65.0	68.1	64.6	-
112	23	23.5	227.0	65.0	68.2	64.7	-
113	23	23	228.1	65.1	68.2	64.7	-
114	23	23	229.3	65.1	68.3	64.8	-
115	23	23	230.4	65.2	68.3	64.8	-
116	22	22.5	231.6	65.2	68.4	64.9	-
117	22	22	232.7	65.3	68.4	64.9	-
118	22	22	233.8	65.3	68.5	65.0	-
119	22	22	234.8	65.4	68.5	65.0	-
120	**22**	**22**	**235.9**	**65.4**	**68.5**	**65.0**	**-**
121	21	21.5	237.0	65.5	68.6	65.1	-

TABLE H

Strength Data for Channel 3

(Bold and bigger sized are the data that are used in table 5.13 to plot figure 5.11)

$t_{CT} = e^{[0.046 \cdot (T_{av} - 20)]} \cdot \Delta t$

$S_k = S_u \{k_r (t_e - t_{or}) / [1 + k_r (t_e - t_{or})]\}$

$S_{FHP} = S_u \cdot e^{-(\tau/t)^{\alpha}}$

$S_c = S_u \cdot e^{-[\tau/(t_{CT} - t_{ir})]^{\alpha}}$

Actual Time (Hrs)	Concrete Temp. (°C)	Average Concrete Temp. (°C)	t_{CT} (Hrs)	S_{FHP} (MPa)	S_k (MPa)	S_C (MPa)	S_L (MPa)
0	**11**	**9.5**	**0.0**	**-**	**-122.4**	**-**	**-**
0.5	18	14.5	0.4	0.0	-115.6	-	-
1	17	17.5	0.9	0.0	-108.6	-	-
1.5	17	17	1.3	0.0	-102.2	-	-
2	16	16.5	1.8	0.0	-96.3	-	-
2.5	16	16	2.2	0.0	-90.8	-	-
3	15	15.5	2.6	0.0	-85.8	-	-
3.5	15	15	3.1	0.1	-81.2	-	-
4	15	15	3.5	0.2	-76.8	-	-
4.5	14	14.5	3.9	0.3	-72.7	-	-
5	14	14	4.3	0.5	-68.9	-	-
5.5	14	14	4.7	0.7	-65.2	-	-
6	14	14	5.1	0.9	-61.8	-	-
6.5	15	14.5	5.5	1.2	-58.4	-	-
7	15	15	6.0	1.6	-55.2	-	-
7.5	15	15	6.4	2.0	-52.1	-	-
8	15	15	6.8	2.4	-49.1	-	-
8.5	16	15.5	7.2	2.8	-46.3	-	-
9	16	16	7.7	3.3	-43.5	-	-
9.5	16	16	8.1	3.8	-40.8	-	-
10	**16**	**16**	**8.5**	**4.4**	**-38.3**	**-**	**-**
10.5	16	16	9.0	4.9	-35.8	-	-
11	16	16	9.4	5.5	-33.5	-	-
11.5	17	16.5	9.9	6.0	-31.2	-	-
12	17	17	10.3	6.6	-29.0	-	-
12.5	17	17	10.8	7.3	-26.8	-	-
13	17	17	11.2	7.9	-24.8	-	-
13.5	18	17.5	11.7	8.5	-22.7	-	-
14	18	18	12.1	9.1	-20.8	-	-
14.5	19	18.5	12.6	9.8	-18.9	-	-
15	20	19.5	13.1	10.4	-16.9	-	-
15.5	20	20	13.6	11.1	-15.1	-	-
16	21	20.5	14.1	11.8	-13.2	-	-

16.5	21	21	14.6	12.5	-11.5	-	-
17	22	21.5	15.2	13.2	-9.7	-	-
17.5	23	22.5	15.7	13.9	-8.0	-	-
18	24	23.5	16.3	14.6	-6.2	-	-
18.5	26	25	16.9	15.3	-4.5	-	-
19	28	27	17.5	16.1	-2.7	-	-
19.5	30	29	18.2	16.9	-0.9	-	-
20	**32**	**31**	**18.9**	**17.8**	**1.0**	**0.0**	**-**
20.5	36	34	19.7	18.7	3.0	0.1	-
21	40	38	20.6	19.8	5.1	1.1	-
21.5	44	42	21.7	20.9	7.4	3.2	-
22	48	46	22.9	22.2	9.9	6.1	-
22.5	51	49.5	24.2	23.5	12.5	9.5	-
23	52	51.5	25.7	24.9	15.0	12.8	8.8
23.5	53	52.5	27.2	26.3	17.4	16.0	11.9
24	53	53	28.8	27.6	19.7	18.9	15.2
24.5	53	53	30.3	28.9	21.9	21.5	18.4
25	53	53	31.8	30.1	23.9	23.8	21.6
25.5	53	53	34.1	31.7	26.5	26.8	26.4
26	53	53	36.4	33.3	29.0	29.5	31.3
26.5	53	53	38.7	34.7	31.2	31.8	36.1
27	53	53	40.9	36.1	33.2	33.9	38.1
27.5	53	53	43.2	37.4	35.1	35.7	38.9
28	53	53	45.5	38.5	36.8	37.3	39.8
28.5	53	53	47.8	39.7	38.4	38.8	40.6
29	53	53	50.1	40.7	39.9	40.2	41.5
29.5	53	53	52.4	41.7	41.2	41.4	42.3
30	**53**	**53**	**54.6**	**42.6**	**42.5**	**42.6**	**43.2**
30.5	53	53	56.9	43.5	43.7	43.6	44.0
31	53	53	59.2	44.3	44.8	44.6	44.8
31.5	53	53	61.5	45.1	45.8	45.5	45.7
32	53	53	63.8	45.9	46.8	46.3	47.0
32.5	53	53	66.0	46.6	47.7	47.1	47.3
33	52	52.5	68.3	47.3	48.5	47.8	47.6
33.5	52	52	70.5	47.9	49.3	48.5	47.9
34	52	52	72.6	48.5	50.1	49.1	48.2
34.5	52	52	74.8	49.1	50.8	49.7	48.5
35	51	51.5	76.9	49.6	51.4	50.3	48.8
35.5	51	51	79.0	50.1	52.0	50.8	49.1
36	51	51	81.1	50.6	52.6	51.3	49.4
36.5	51	51	83.2	51.0	53.2	51.8	49.6
37	50	50.5	85.2	51.5	53.7	52.2	49.9
37.5	50	50	87.2	51.9	54.2	52.6	50.2
38	50	50	89.2	52.3	54.7	53.0	50.4
38.5	50	50	91.2	52.7	55.1	53.4	50.7
39	50	50	93.2	53.1	55.6	53.7	51.0

39.5	49	49.5	95.1	53.4	56.0	54.1	51.2
40	**49**	**49**	**97.0**	**53.7**	**56.4**	**54.4**	**51.5**
40.5	49	49	98.9	54.1	56.7	54.7	51.8
41	49	49	100.8	54.4	57.1	55.0	52.0
41.5	48	48.5	102.7	54.7	57.4	55.3	52.3
42	48	48	104.5	55.0	57.7	55.6	52.5
42.5	48	48	106.3	55.3	58.1	55.8	52.7
43	47	47.5	108.1	55.5	58.4	56.1	53.0
43.5	47	47	109.8	55.8	58.6	56.3	53.2
44	47	47	111.5	56.0	58.9	56.6	53.5
44.5	46	46.5	113.2	56.2	59.2	56.8	53.7
45	46	46	114.9	56.5	59.4	57.0	53.9
45.5	46	46	116.5	56.7	59.7	57.2	54.1
46	45	45.5	118.1	56.9	59.9	57.4	54.3
46.5	45	45	119.7	57.1	60.1	57.6	54.6
47	45	45	121.3	57.3	60.3	57.7	54.8
47.5	45	45	122.9	57.5	60.5	57.9	55.0
48	44	44.5	124.4	57.7	60.7	58.1	55.2
49	44	44	127.4	58.0	61.1	58.4	55.6
50	**44**	**44**	**130.4**	**58.4**	**61.5**	**58.7**	**56.0**
51	43	43.5	133.4	58.7	61.8	59.0	56.4
52	42	42.5	136.2	59.0	62.1	59.3	56.8
53	42	42	139.0	59.2	62.4	59.5	57.2
54	41	41.5	141.7	59.5	62.7	59.8	57.5
55	41	41	144.3	59.8	62.9	60.0	57.9
56	40	40.5	146.8	60.0	63.2	60.2	58.2
57	40	40	149.4	60.2	63.4	60.4	58.6
58	40	40	151.9	60.4	63.6	60.6	58.9
59	39	39.5	154.3	60.6	63.9	60.8	59.2
60	**39**	**39**	**156.7**	**60.8**	**64.1**	**61.0**	**59.5**
61	38	38.5	159.1	61.0	64.2	61.1	59.9
62	38	38	161.3	61.2	64.4	61.3	60.2
63	37	37.5	163.6	61.4	64.6	61.4	60.5
64	37	37	165.8	61.5	64.8	61.6	60.8
65	37	37	168.0	61.7	64.9	61.7	61.1
66	36	36.5	170.1	61.9	65.1	61.9	61.3
67	36	36	172.2	62.0	65.2	62.0	61.6
68	36	36	174.3	62.2	65.4	62.1	61.9
69	36	36	176.4	62.3	65.5	62.3	62.2
70	**35**	**35.5**	**178.4**	**62.4**	**65.7**	**62.4**	**62.5**
71	35	35	180.4	62.6	65.8	62.5	62.7
72	35	35	182.4	62.7	65.9	62.6	63.0
73	34	34.5	184.3	62.8	66.0	62.7	-
74	34	34	186.2	62.9	66.1	62.8	-
75	34	34	188.1	63.0	66.3	62.9	-
76	33	33.5	190.0	63.2	66.4	63.0	-

77	33	33	191.8	63.3	66.5	63.1	-
78	33	33	193.6	63.4	66.6	63.2	-
79	32	32.5	195.4	63.5	66.7	63.3	-
80	**32**	**32**	**197.1**	**63.6**	**66.8**	**63.4**	**-**
81	32	32	198.9	63.7	66.9	63.5	-
82	31	31.5	200.6	63.8	67.0	63.6	-
83	31	31	202.2	63.8	67.0	63.6	-
84	31	31	203.9	63.9	67.1	63.7	-
85	30	30.5	205.5	64.0	67.2	63.8	-
86	30	30	207.1	64.1	67.3	63.9	-
87	30	30	208.7	64.2	67.4	63.9	-
88	30	30	210.3	64.3	67.4	64.0	-
89	30	30	211.9	64.3	67.5	64.1	-
90	**29**	**29.5**	**213.4**	**64.4**	**67.6**	**64.1**	**-**
91	29	29	214.9	64.5	67.7	64.2	-
92	29	29	216.4	64.6	67.7	64.3	-
93	29	29	217.9	64.6	67.8	64.3	-
94	29	29	219.5	64.7	67.9	64.4	-
95	29	29	221.0	64.8	67.9	64.5	-
96	28	28.5	222.4	64.8	68.0	64.5	-
97	28	28	223.9	64.9	68.1	64.6	-
98	28	28	225.3	65.0	68.1	64.6	-
99	28	28	226.8	65.0	68.2	64.7	-
100	**28**	**28**	**228.2**	**65.1**	**68.2**	**64.7**	**-**
101	28	28	229.7	65.2	68.3	64.8	-
102	27	27.5	231.1	65.2	68.4	64.9	-
103	27	27	232.5	65.3	68.4	64.9	-
104	27	27	233.8	65.3	68.5	65.0	-
105	27	27	235.2	65.4	68.5	65.0	-
106	26	26.5	236.6	65.5	68.6	65.1	-
107	26	26	237.9	65.5	68.6	65.1	-
108	26	26	239.2	65.6	68.7	65.1	-
109	26	26	240.5	65.6	68.7	65.2	-
110	**25**	**25.5**	**241.8**	**65.7**	**68.8**	**65.2**	**-**
111	25	25	243.1	65.7	68.8	65.3	-
112	25	25	244.3	65.8	68.9	65.3	-
113	25	25	245.6	65.8	68.9	65.4	-
114	25	25	246.8	65.9	68.9	65.4	-
115	24	24.5	248.1	65.9	69.0	65.5	-
116	24	24	249.3	66.0	69.0	65.5	-
117	24	24	250.5	66.0	69.1	65.5	-
118	24	24	251.7	66.0	69.1	65.6	-
119	24	24	252.9	66.1	69.2	65.6	-
120	**24**	**24**	**254.1**	**66.1**	**69.2**	**65.7**	**-**
121	23	23.5	255.3	66.2	69.2	65.7	-

Table I

Temperature development at initial concrete temperature of 10°C and the corresponding equivalent ages based on the "t_{CT}" maturity function (Eq. 6.2) for the calculation of the actual initial setting times for the mixture presented in table 6.1.

-Initial setting times by the "2°C Temperature Increase" (MI) are shown by bold and bigger sized letters.
-Initial setting times by the "Penetration Resistance" (MP) are shown with bold, italic and bigger sized letters.

	Retarder Dosage (ml/100 kg of cement)						Equivalent Age "t_{CT}" for the corresponding Retarder Dosages (Hrs)					
	0	100	200	300	400	500						
Actual Time (Hrs)	**Temperature (°C)**						**0**	**100**	**200**	**300**	**400**	**500**
0.0	12	11.0	11.0	11.0	10.0	10.0	0	0	0	0	0	0
0.5	12	11.0	11.0	11.0	10.0	10.0	0.4	0.4	0.4	0.4	0.3	0.4
1.0	12	11.0	11.0	11.0	11.0	11.0	0.8	0.7	0.7	0.7	0.7	0.7
1.5	12	11.0	11.0	11.0	11.0	11.0	1.1	1.1	1.1	1.1	1.1	1.1
2.0	12	12.0	11.0	11.0	11.0	11.0	1.5	1.5	1.5	1.4	1.4	1.5
2.5	12	12.0	12.0	11.0	11.0	11.0	1.9	1.9	1.8	1.8	1.8	1.8
3.0	13	12.0	12.0	12.0	11.0	11.0	2.3	2.2	2.2	2.2	2.2	2.2
3.5	13	12.0	12.0	12.0	12.0	11.0	2.7	2.6	2.6	2.6	2.5	2.6
4.0	13	12.0	12.0	12.0	12.0	11.0	3.1	3.0	3.0	2.9	2.9	2.9
4.5	13	13.0	13.0	12.0	12.0	11.0	3.5	3.4	3.3	3.3	3.3	3.3
5.0	13	13.0	13.0	12.0	12.0	11.0	3.9	3.8	3.7	3.7	3.6	3.7
5.5	13	13.0	13.0	12.0	12.0	11.0	4.3	4.2	4.1	4.1	4.0	4.0
6.0	14	13.0	13.0	12.0	12.0	11.0	***4.7***	4.6	4.5	4.4	4.4	4.4
6.5	14	13.0	13.0	13.0	13.0	11.0	5.1	5.0	4.9	4.8	4.8	4.8
7.0	14	13.0	13.0	13.0	13.0	11.0	5.5	5.4	5.3	5.2	5.2	5.1
7.5	14	13.0	13.0	13.0	13.0	11.0	5.9	5.8	5.7	5.6	5.6	5.5
8.0	14	13.0	13.0	13.0	13.0	11.0	6.3	6.1	6.1	6.0	5.9	5.9
8.5	15	13.0	13.0	13.0	13.0	12.0	**6.7**	6.5	6.5	6.4	6.3	6.2
9.0	15	13.0	13.0	13.0	13.0	12.0	7.1	6.9	6.9	6.8	6.7	6.6
9.5	16	14.0	13.0	13.0	13.0	12.0	7.6	7.3	7.3	7.1	7.1	7.0
10.0	17	14.0	13.0	13.0	13.0	12.0	8.0	7.7	7.7	7.5	7.5	7.4
10.5	17.5	15.0	14.0	14.0	13.0	12.0	8.5	***8.2***	8.1	7.9	7.9	7.8
11.0	18	15.0	14.0	14.0	13.0	12.0	8.9	8.6	8.5	8.3	8.3	8.2
11.5	19	15.0	14.0	14.0	14.0	12.0	9.4	9.0	8.9	8.7	8.7	8.5
12.0	20	16.0	14.0	14.0	14.0	12.0	9.9	9.4	9.3	9.1	9.1	8.9
12.5	21.3	16.0	15.0	14.0	14.0	12.0	10.4	9.9	9.7	9.5	9.5	9.3
13.0	22.5	17.0	15.0	14.0	14.0	13.0	10.9	10.3	10.1	9.9	9.9	9.7
13.5	24.5	17.0	15.0	14.0	14.0	13.0	11.5	**10.8**	10.5	10.3	10.3	10.1
14.0	26.5	18.0	15.0	14.0	14.0	13.0	12.1	11.2	10.9	10.7	10.7	10.5
14.5	29	19.0	15.0	15.0	14.0	13.0	12.8	11.7	***11.4***	11.2	11.1	10.9
15.0	31.5	20.0	15.0	15.0	14.0	13.0	13.5	12.2	11.8	11.6	11.5	11.3
15.5	33	21.0	16.0	15.0	14.0	13.0	14.2	12.7	12.2	12.0	11.9	11.7

16.0	34.5	22.0	16.0	15.0	14.0	13.0	15.0	13.2	12.6	12.4	12.3	12.0
16.5	37.8	23.5	16.0	15.0	14.0	13.0	15.9	13.8	13.1	12.8	12.7	12.4
17.0	41	25.0	16.0	15.0	15.0	14.0	16.8	14.4	13.5	13.2	13.1	12.8
17.5	44	28.3	17.0	15.0	15.0	14.0	17.9	15.0	**14.0**	13.7	13.5	13.2
18.0		31.5	17.0	15.0	15.0	14.0		15.7	14.4	14.1	13.9	13.7
18.5		34.8	18.0	15.0	15.0	14.0		16.5	14.9	14.5	14.4	14.1
19.0		38.0	18.0	15.0	15.0	14.0		17.3	15.3	***14.9***	14.8	14.5
19.5		41.0	19.0	16.0	15.0	15.0		18.3	15.8	15.3	15.2	14.9
20.0		44.0	20.5	16.0	15.0	15.0		19.4	16.3	15.8	15.6	15.3
20.5		44.5	21.0	16.0	15.0	15.0		20.5	16.8	16.2	16.0	15.7
21.0			22.0	16.0	15.0	15.0			17.3	16.6	16.4	16.2
21.5			24.0	16.0	15.0	15.0			17.9	17.1	16.9	16.6
22.0			25.5	16.0	16.0	15.0			18.5	17.5	17.3	17.0
22.5			28.0	17.0	16.0	16.0			19.1	17.9	17.7	17.4
23.0			31.0	17.0	16.0	16.0			19.8	18.4	18.2	17.9
23.5				17.0	17.0	16.0				**18.8**	***18.6***	18.3
24.0				17.0	17.0	16.0				19.3	19.0	18.7
24.5				17.0	17.0	16.0				19.7	19.5	19.2
25.0				18.5	18.0	16.0				20.2	20.0	19.6
25.5				19.5	19.0	17.0				20.7	20.4	20.1
26.0				20.5	19.0	17.0				21.2	20.9	20.5
26.5				21.3	20.0	17.0				21.7	21.4	21.0
27.0				22.0	21.0	17.0				22.2	21.9	21.4
27.5				24.0	22.5	18.0				22.8	22.4	21.9
28.0				26.0	24.0	18.0				23.4	23.0	***22.3***
28.5				29.0	25.0	18.0				24.0	**23.6**	22.8
29.0				32.0	26.0	18.0				24.8	24.2	23.3
29.5					29	19.0					24.9	23.7
30.0					32	19.0					25.6	24.2
30.5					34.5	20.0					26.4	24.7
31.0					37	21.0					27.3	25.2
31.5					39	22.0					28.2	25.8
32.0					41	23.0					29.3	26.3
32.5					45	23.0					30.4	26.8
33.0					46	25.5					31.7	**27.4**

Table J

Temperature development at initial concrete temperature of 15°C and the corresponding equivalent ages based on the "t_{CT}" maturity function (Eq. 6.2) for the calculation of the actual initial setting times for the mixture presented in table 6.1.

-Initial setting times by the "2°C Temperature Increase" (MI) are shown by bold and bigger sized letters.
-Initial setting times by the "Penetration Resistance" (MP) are shown with bold, italic and bigger sized letters.

Actual Time (Hrs)	Retarder Dosage (ml/100 kg of cement)						Equivalent Age "t_{CT}" for the corresponding Retarder Dosages (Hrs)					
	0	100	200	300	400	500	0	100	200	300	400	500
0.0	16	15.0	15.0	15.0	15.0	16.0	0	0	0	0	0	0
0.5	16	15.0	15.0	15.0	15.0	16.0	0.4	0.4	0.4	0.4	0.4	0.4
1.0	16	16.0	16.0	15.0	15.0	16.0	0.9	0.9	0.8	0.8	0.8	0.9
1.5	16	16.0	16.0	16.0	16.0	16.0	1.3	1.3	1.3	1.3	1.3	1.3
2.0	16	16.0	16.0	16.0	16.0	16.0	1.7	1.7	1.7	1.7	1.7	1.7
2.5	16	16.0	16.0	16.0	16.0	16.0	2.2	2.2	2.2	2.1	2.1	2.2
3.0	16	16.0	16.0	16.0	16.0	17.0	2.6	2.6	2.6	2.6	2.6	2.6
3.5	17	16.0	16.0	16.0	16.0	17.0	3.1	3.0	3.0	3.0	3.0	3.0
4.0	17	16.0	16.0	16.0	16.0	17.0	3.5	3.5	3.5	3.4	3.4	3.5
4.5	17	16.0	16.0	16.0	16.0	17.0	4.0	3.9	3.9	3.9	3.9	3.9
5.0	17	16.0	16.0	16.0	16.0	17.0	***4.4***	4.3	4.3	4.3	4.3	4.4
5.5	17	17.0	16.0	16.0	16.0	17.0	4.9	4.8	4.8	4.7	4.7	4.8
6.0	17	17.0	16.0	16.0	16.0	17.0	5.3	5.2	5.2	5.2	5.2	5.3
6.5	17	17.0	17.0	17.0	17.0	17.0	5.8	5.7	5.6	5.6	5.6	5.7
7.0	17	17.0	17.0	17.0	17.0	17.0	6.2	6.1	6.1	6.0	6.0	6.2
7.5	18	17.0	17.0	17.0	17.0	17.0	**6.7**	6.6	6.5	6.5	6.5	6.6
8.0	18	17.0	17.0	17.0	17.0	18.0	7.1	7.0	7.0	6.9	6.9	7.1
8.5	19	17.0	17.0	17.0	17.0	18.0	7.6	7.5	7.4	7.4	7.4	7.5
9.0	20	17.0	17.0	17.0	17.0	18.0	8.1	***7.9***	7.9	7.8	7.8	8.0
9.5	20.5	18.0	17.0	17.0	17.0	18.0	8.6	8.4	8.3	8.3	8.3	8.5
10.0	21	20.0	17.0	17.0	17.0	18.0	9.1	8.9	8.8	8.7	8.7	8.9
10.5	22.5	20.0	17.0	17.0	17.0	18.0	9.7	9.4	9.2	9.2	9.2	9.4
11.0	24	20.5	18.0	17.0	17.0	18.0	10.2	9.9	9.7	9.6	9.6	9.9
11.5	26	21.5	18.0	17.0	17.0	18.0	10.8	10.4	10.2	10.1	10.1	10.3
12.0	28	22.5	18.0	17.0	17.0	18.0	11.4	**10.9**	10.6	10.5	10.5	10.8
12.5	29.5	25.0	18.0	17.0	17.0	18.0	12.1	11.5	11.1	11.0	11.0	11.3
13.0	31	27.5	19.0	17.0	17.0	18.0	12.8	12.1	***11.6***	11.4	11.4	11.7
13.5	34	30.0	19.0	18.0	18.0	18.0	13.6	12.8	12.1	11.9	11.9	12.2
14.0	37	32.5	19.0	18.0	18.0	18.0	14.4	13.5	12.5	12.4	12.4	12.7
14.5	39.5	34.8	19.0	18.0	18.0	18.0	15.4	14.3	13.0	12.8	12.8	13.1
15.0	42	37.0	20.0	18.0	18.0	18.0	16.4	15.2	13.5	13.3	13.3	13.6
15.5	44.5	40.5	20.0	18.0	18.0	18.0	17.5	16.1	14.0	13.8	13.8	14.0
16.0	47	44.0	21.0	18.0	18.0	18.0	18.7	17.2	**14.5**	14.2	14.2	14.5
16.5	48.5	46.0	22.0	18.0	18.0	18.5	20.0	18.4	15.0	14.7	14.7	15.0

17.0	50	48.0	22.5	18.0	18.0	19.0	21.3	19.6	15.6	***15.1***	15.1	15.5
17.5	51.3	49.0	24.3	19.0	18.0	19.0	22.7	20.9	16.1	15.6	15.6	15.9
18.0	52.5	50.0	26.0	19.0	18.0	19.0	24.2	22.3	16.7	16.1	16.1	16.4
18.5		51.5	27.8	19.0	19.0	19.0		23.7	17.4	16.6	16.6	16.9
19.0		52.5	29.5	19.0	19.0	19.0		25.2	18.1	17.1	17.0	17.4
19.5		53.0	33.5	19.0	19.0	19.0		26.7	18.8	17.5	17.5	17.9
20.0		53.5	37.5	20.0	19.0	19.0		28.3	19.7	18.0	18.0	18.3
20.5		54.5		21.0	19.0	19.0		29.9		18.5	***18.5***	18.8
21.0		56.0		22.0	19.0	19.0		31.5		**19.1**	19.0	19.3
21.5				23.5	19.0	19.0				19.6	19.4	19.8
22.0				25.0	20.0	19.0				20.2	19.9	20.3
22.5				27.5	20.0	19.5				20.8	20.4	20.8
23.0				30.0	20.0	19.5				21.5	20.9	21.2
23.5				34.5	20.0	20.0				22.3	21.4	21.7
24.0				39.0	20.0	20.5				23.2	21.9	***22.2***
24.5				43.0	20.5	21.0				24.3	22.4	22.8
25.0				47.0	21.0	21.0				25.5	**23.0**	23.3
25.5				48.0	22.5	21.0				26.9	23.5	23.8
26.0				49.0	24.0	23.0				28.2	24.0	24.3
26.5				49.0	25.5	23.5				29.7	24.6	24.9
27.0				50.0	27.0	24.0				31.1	25.3	25.5
27.5				51.0	29.0	25.0				32.6	25.9	26.1
28.0				51.0	31.0	27.0				34.1	26.7	26.7
28.5				52.0	36.0	28.0				35.7	27.5	**27.4**
29.0				53.0	41.0					37.3	28.4	
29.5				53.5	44.0					39.0	29.6	
30.0				54.0	47.0					40.6	30.8	
30.5				54.5	48.0					42.4	32.2	
31.0				55.0	48.0					44.1	33.5	
31.5				55.0						45.9		
32.0				55.0						47.6		
32.5				55.0						49.4		
33.0				55.0						51.2		

Table K

Temperature development at initial concrete temperature of 20°C and the corresponding equivalent ages based on the "t_{CT}" maturity function (Eq. 6.2) for the calculation of the actual initial setting times for the mixture presented in table 6.1.

-Initial setting times by the "2°C Temperature Increase" (MI) are shown by bold and bigger sized letters.
-Initial setting times by the "Penetration Resistance" (MP) are shown with bold, italic and bigger sized letters.

Actual Time (Hrs)	Retarder Dosage (ml/100 kg of cement)						Equivalent Age "t_{CT}" for the corresponding Retarder Dosages (Hrs)					
	0	100	200	300	400	500	0	100	200	300	400	500
0.0	19.5	19.5	19.5	19.5	18.5	18.5	0	0	0	0	0	0
0.5	20.5	19.5	19.5	19.5	18.5	18.5	0.5	0.5	0.5	0.5	0.5	0.5
1.0	20.5	19.5	19.5	19.5	19.5	18.5	1.0	1.0	1.0	1.0	1.0	0.9
1.5	20.5	19.5	19.5	19.5	19.5	18.5	1.5	1.5	1.5	1.5	1.4	1.4
2.0	20.5	19.5	19.5	19.5	19.5	18.5	2.0	2.0	2.0	2.0	1.9	1.9
2.5	20.5	20.5	20.5	19.5	19.5	18.5	2.5	2.5	2.5	2.5	2.4	2.4
3.0	20.5	20.5	20.5	19.5	19.5	18.5	3.0	3.0	3.0	2.9	2.9	2.8
3.5	20.5	20.5	20.5	19.5	19.5	18.5	3.6	3.5	3.5	3.4	3.4	3.3
4.0	20.5	20.5	20.5	19.5	19.5	18.5	4.1	4.0	4.0	3.9	3.9	3.8
4.5	20.5	20.5	20.5	19.5	19.5	19.5	***4.6***	4.5	4.5	4.4	4.4	4.3
5.0	20.5	20.5	20.5	19.5	19.5	19.5	5.1	5.0	5.0	4.9	4.9	4.8
5.5	20.5	20.5	20.5	19.5	19.5	19.5	5.6	5.5	5.5	5.4	5.4	5.2
6.0	20.5	20.5	20.5	19.5	19.5	19.5	6.1	6.0	6.0	5.9	5.9	5.7
6.5	20.5	22	21.5	19.5	19.5	19.5	6.6	6.5	6.5	6.4	6.4	6.2
7.0	22.5	22	21.5	20.5	20.5	19.5	7.1	7.1	7.1	6.9	6.9	6.7
7.5	24.3	22	21.5	20.5	20.5	20.5	7.7	7.6	7.6	7.4	7.4	7.2
8.0	26	22	21.5	20.5	20.5	20.5	8.3	***8.2***	8.1	7.9	7.9	7.7
8.5	27.5	22	21.5	20.5	20.5	20.5	8.9	8.7	8.7	8.4	8.4	8.2
9.0	29	22	21.5	20.5	20.5	20.5	9.6	9.2	9.2	8.9	8.9	8.7
9.5	31.5	22	21.5	20.5	20.5	20.5	10.3	9.8	9.7	9.4	9.4	9.3
10.0	34	22	21.5	21.5	20.5	20.5	11.1	10.3	10.2	9.9	9.9	9.8
10.5	36.8	22.5	21.5	21.5	20.5	20.5	11.9	**10.8**	10.8	10.5	10.4	10.3
11.0	39.5	23.5	21.5	21.5	20.5	20.5	12.8	11.4	11.3	11.0	10.9	10.8
11.5	42	25	21.5	21.5	21.5	20.5	13.8	12.0	***11.8***	11.5	11.4	11.3
12.0	44.5	26.5	21.5	21.5	21.5	20.5	14.9	12.6	12.3	12.1	12.0	11.8
12.5	47.3	28.5	21.5	21.5	21.5	20.5	16.1	13.2	12.9	12.6	12.5	12.3
13.0	50	31	21.5	21.5	21.5	20.5	17.5	13.9	13.4	13.1	13.0	12.8
13.5	52	33.5	21.5	22.5	21.5	20.5	18.9	14.7	13.9	13.7	13.6	13.3
14.0	54	35.5	23	22.5	21.5	20.5	20.4	15.5	14.5	14.2	14.1	13.8
14.5	55.5	38.5	24	22.5	21.5	20.5	22.1	16.4	**15.0**	14.7	14.6	14.4
15.0	57	42	25	22.5	21.5	20.5	23.8	17.4	15.6	***15.3***	15.1	14.9
15.5	58.3	46	25.8	22.5	21.5	20.5	25.6	18.5	16.2	15.8	15.7	15.4
16.0	59.5	50	26.5	22.5	21.5	20.5	27.5	19.8	16.8	16.4	16.2	15.9
16.5	60.3	55	29	22.5	21.5	21.5	29.4	21.3	17.5	16.9	16.7	16.4

17.0	61	57	31.5	22.5	22.5	22.5	31.4	23.0	18.2	17.5	17.3	16.9
17.5	61	58	34.3	22.5	22.5	22.5	33.4	24.8	19.0	18.0	17.8	17.5
18.0	62	58.5	37	22.5	22.5	22.5	35.5	26.6	19.9	18.6	18.4	18.0
18.5		59	40.8	22.5	22.5	22.5		28.5	20.8	**19.1**	***18.9***	18.6
19.0			44.5	22.5	22.5	22.5			21.9	19.7	19.5	19.1
19.5			47.8	23.5	22.5	22.5			23.2	20.2	20.0	19.7
20.0			51	24.5	22.5	22.5			24.6	20.8	20.5	20.2
20.5				25.5	22.5	22.5				21.4	21.1	20.8
21.0				26.5	22.5	22.5				22.0	21.6	21.3
21.5				28.5	22.5	22.5				22.7	22.2	21.9
22.0				30.5	22.5	22.5				23.4	22.7	***22.4***
22.5				32.5	23.3	22.5				24.1	**23.3**	23.0
23.0				35.5	24	22.5				25.0	23.9	23.5
23.5				40	24.7	23.5				25.9	24.4	24.1
24.0				44.5	25.5	23.5				27.0	25.0	24.6
24.5				47.8	26.5	23.5				28.3	25.7	25.2
25.0				51	27.5	23.5				29.7	26.3	25.8
25.5				53.3	29.8	24				31.3	27.0	26.4
26.0				55.5	32	24.5				33.1	27.7	**26.9**
26.5				57	35	24.5				34.9	28.5	27.5
27.0				58.5	38	25.5				36.9	29.5	28.1
27.5				59.5	42.8	26.5				38.9	30.5	28.8
28.0				60.5	47.5	27.5				41.0	31.7	29.4
28.5				61.3	50.3	29.3				43.2	33.1	30.1
29.0				62	53					45.4	34.7	
29.5				62	54.5					47.7	36.4	
30.0				62	56					50.0	38.2	
30.5				62	57.5					52.2	40.0	
31.0				63	59					54.5	42.0	
31.5				63						56.9		
32.0				63						59.2		
32.5				63						61.6		
33.0				63						63.9		

Table L

Temperature development at initial concrete temperatures of 13°C, 16°C, and 14°C, and the corresponding equivalent ages based on the "t_{CT}" maturity function (Eq. 6.2) for the calculation of the actual initial setting times for the mixture presented in table 6.12.

Initial setting times by the "MI" method are shown with bold and bigger sized letters.

Initial Concrete Temperature (°C)	**13**	**16**	**16**	**16**	**14**	**13**	**16**	**16**	**16**	**14**
Retarder Dosage (ml/100kg cement)	**150**	**150**	**250**	**400**	**450**	**150**	**150**	**250**	**400**	**450**
Actual Time (Hrs)	**Temperature development (°C)**					**Equivalent Ages "t_{CT}" (Hrs)**				
0.0	13.4	15.9	15.9	15.7	14	0	0	0	0	0
0.5	13.4	15.9	15.9	15.7	14	0.4	0.4	0.4	0.4	0.4
1.0	14	16.7	16.3	15.9	14.2	0.8	0.9	0.9	0.9	0.8
1.5	14	16.7	16.7	16.7	14.2	1.2	1.3	1.3	1.3	1.2
2.0	14.2	16.7	16.7	16.7	14.2	1.6	1.8	1.8	1.7	1.6
2.5	14.4	16.9	16.8	16.7	14.2	2.0	2.2	2.2	2.2	2.0
3.0	14.4	16.9	16.8	16.7	14.2	2.4	2.7	2.7	2.6	2.4
3.5	14.4	16.9	16.8	16.7	14.3	2.9	3.1	3.1	3.1	2.8
4.0	14.4	16.9	16.8	16.7	14.3	3.3	3.6	3.5	3.5	3.2
4.5	14.8	16.9	16.8	16.7	14.3	3.7	4.0	4.0	4.0	3.6
5.0	14.8	16.9	16.8	16.7	14.3	4.1	4.5	4.4	4.4	4.0
5.5	15.1	17.3	16.8	16.7	14.3	4.5	4.9	4.9	4.8	4.4
6.0	15.1	17.3	16.8	16.7	14.3	5.0	5.4	5.3	5.3	4.8
6.5	15.4	17.95	17.7	17.5	14.4	5.4	5.8	5.8	5.7	5.3
7.0	15.4	17.95	17.8	17.7	14.4	5.8	6.3	6.2	6.2	5.7
7.5	15.4	17.95	17.8	17.7	14.4	6.2	6.8	6.7	6.7	6.1
8.0	15.4	17.95	17.8	17.7	14.4	6.7	7.2	7.2	7.1	6.5
8.5	15.4	17.95	17.8	17.7	14.5	7.1	7.7	7.6	7.6	6.9
9.0	15.4	17.95	17.8	17.7	15.3	7.5	8.2	8.1	8.0	7.3
9.5	15.9	18.35	17.8	17.7	15.3	7.9	8.6	8.6	8.5	7.7
10.0	16.5	19.15	17.9	17.7	15.3	8.4	9.1	9.0	9.0	8.1
10.5	16.9	19.2	17.9	17.7	15.3	8.8	9.6	9.5	9.4	8.6
11.0	17.35	19.9	18.3	17.7	15.3	9.3	10.1	10.0	9.9	9.0
11.5	17.65	20.45	18.3	17.9	15.4	9.7	10.6	10.4	10.3	9.4
12.0	18.15	21	18.3	17.9	15.4	10.2	11.1	10.9	10.8	9.8
12.5	19.1	22.2	18.3	17.9	16.2	10.7	11.6	11.4	11.3	10.2
13.0	20.35	23.85	18.7	17.9	16.3	11.2	12.2	11.8	11.7	10.7
13.5	21.1	25.1	19.2	18.7	16.3	11.7	**12.8**	12.3	12.2	11.1
14.0	22.05	26.45	19.35	18.7	16.3	12.2	13.4	12.8	12.7	11.5
14.5	22.94	27.77	19.45	18.7	16.3	**12.8**	14.0	13.3	13.2	12.0
15.0	24.1	29.5	19.95	18.7	16.3	13.3	14.7	13.8	13.6	12.4

15.5	25.55	31.38	20.03	18.7	16.3	13.9	15.4	14.3	14.1	12.9
16.0	27.1	33.65	20.5	18.7	16.3	14.5	16.2	14.8	14.6	13.3
16.5	28.3	35.6	21.15	18.7	17.1	15.2	17.0	15.3	15.1	13.7
17.0	29.35	37.05	21.6	18.9	17.3	15.9	17.9	15.8	15.5	14.2
17.5	31.05	38.55	23	18.9	17.3	16.6	18.8	16.4	16.0	14.6
18.0	32.5	39.95	23.95	18.9	17.3	17.3	19.7	**17.0**	16.5	15.1
18.5	34.35	41.7	25.05	19.7	17.3	18.1	20.8	17.5	17.0	15.5
19.0	35.8		26.1	19.7	17.3	18.9		18.1	17.5	16.0
19.5	37.95		28.13	19.7	17.4	19.8		18.8	18.0	16.5
20.0	40.2		30.55	19.7	17.4	20.8		19.5	18.5	16.9
20.5				19.7	17.4				19.0	17.4
21.0				19.7	17.4				19.5	17.8
21.5				19.7	18.2				20.0	18.3
22.0				20.5	18.3				20.5	18.7
22.5				20.66	19.2				21.0	19.2
23.0				20.8	19.2				21.5	19.7
23.5				20.94	19.3				22.0	20.2
24.0				21.1	19.3				22.5	20.7
24.5				21.7	20.1				**23.1**	21.2
25.0				22.3	20.2				23.6	21.7
25.5				23.96	21.2				24.1	22.2
26.0				25.6	22				24.7	22.7
26.5				27.4	23.7				25.4	23.3
27.0				29.2	25.4				26.0	23.9
27.5				31.76	28.05				26.8	24.5
28.0				34.3	31				27.6	**25.2**
28.5				38.86	34.14				28.5	26.0
29.0				43.4	37.2				29.6	26.9
29.5				46.1	40.4				30.8	27.9
30.0				48.8	43.5				32.1	29.0
30.5				49.9	44.65				33.6	30.3
31.0				50.2	45.8				35.0	31.5

Table M

Initial setting times by maturity based upon "Penetration Resistance", "Conductivity", "Rod", and "2°C Temperature Increase"

MP: maturity method based upon the "Penetration Resistance" method
MC: maturity method based upon the "Conductivity" method
MR: maturity method based upon the "Rod" method
MI: maturity method based upon the "2°C Temperature Increase" method

( ) Initial Setting Times by MP
[ ] Initial Setting Times by MC
< > Initial Setting Times by MR
" " Initial Setting Times by MI

Actual Time (Hrs)	Temperature (°C)				MP Equivalent Age (Hrs)				MC Equivalent Age (Hrs)				MR Equivalent Age (Hrs)				MI Equivalent Age (Hrs)			
	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25	10	15	20	25
0	17.5	17.5	20.5	22.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	16	16.5	19.5	25.5	0.4	0.4	0.5	0.6	0.4	0.4	0.5	0.6	0.4	0.4	0.5	0.6	0.4	0.4	0.5	0.7
1	16.5	16.5	19.5	27.5	0.8	0.8	1.0	1.4	0.8	0.8	1.0	1.4	0.8	0.8	1.0	1.4	0.8	0.8	1.0	1.5
1.5	16	16.25	20	28	1.2	1.2	1.5	2.2	1.2	1.2	1.5	2.2	1.2	1.2	1.5	2.1	1.2	1.2	1.5	2.3
2	16	16	20.5	28	1.6	1.6	2.0	3.0	1.6	1.6	2.0	3.0	1.6	1.6	2.0	2.9	1.5	1.6	2.0	3.2
2.5	16	16.25	20.7	28	2.0	2.0	2.5	3.8	2.0	2.0	2.5	3.8	2.0	2.0	2.5	3.7	1.9	1.9	2.5	4.1
3	16.5	16.5	21	28	2.4	2.4	3.0	4.6	2.4	2.4	3.0	4.6	2.4	2.4	3.0	4.5	2.3	2.3	3.0	4.9
3.5	16.5	16.65	21	28	2.8	2.8	3.6	5.4	2.8	2.8	3.6	5.4	2.8	2.8	3.6	5.3	2.7	2.7	3.6	5.8
4	16	16.8	21	28	3.2	3.2	4.1	6.2	3.2	3.2	4.1	6.2	3.2	3.3	4.1	6.1	3.1	3.1	4.1	6.7
4.5	16	16.9	21	28	3.6	3.7	4.6	7.0	3.6	3.7	4.6	7.0	3.6	3.7	4.6	6.9	3.5	3.5	4.6	7.6
5	16	17	21	28	4.0	4.1	5.2	7.8	4.0	4.1	5.2	7.8	4.0	4.1	5.1	7.7	3.8	3.9	5.2	8.4
5.5	15.8	17.1	21	28.5	4.4	4.5	5.7	8.7	4.4	4.5	5.7	8.7	4.4	4.5	5.7	8.5	4.2	4.3	5.7	9.3
6	15.6	17.2	21.1	29	4.8	4.9	6.2	**(9.5)**	4.8	4.9	6.2	**[9.5]**	4.8	4.9	6.2	**<9.4>**	4.6	4.7	6.3	10.3
6.5	15.4	17.35	21.25	30.5	5.1	5.3	6.8	10.4	5.1	5.3	6.8	10.4	5.2	5.4	6.7	10.2	4.9	5.2	6.8	**"11.2"**
7	15.2	17.5	21.4	31.9	5.5	5.8	7.3	11.4	5.5	5.8	7.3	11.4	5.6	5.8	7.3	11.2	5.3	5.6	7.3	12.3

7.5	15	17.65	21.8	33.6	5.9	6.2	7.8	12.4	5.9	6.2	7.8	12.4	5.9	6.2	7.8	12.2	5.7	6.0	7.9	13.6
8	14.8	17.8	22.2	35.3	6.3	6.6	8.4	13.6	6.3	6.6	8.4	13.6	6.3	6.7	8.4	13.4	6.0	6.4	8.5	14.9
8.5	14.6	17.92	22.9	37.7	6.6	7.1	9.0	15.0	6.6	7.1	9.0	15.0	6.7	7.1	9.0	14.7	6.4	6.9	9.1	16.5
9	14.4	18.1	23.6	40	7.0	7.5	**(9.6)**	16.5	7.0	7.5	**[9.6]**	16.5	7.0	7.6	**<9.6>**	16.2	6.7	7.3	9.7	18.4
9.5	14.2	18.35	24.7	42.2	7.3	8.0	10.2	18.3	7.3	8.0	10.2	18.3	7.4	8.0	10.2	17.9	7.0	7.7	**"10.4"**	20.6
10	14	18.6	25.8	44.4	7.7	8.4	10.9	20.3	7.7	8.4	10.9	20.3	7.8	8.5	10.9	19.8	7.4	8.2	11.1	23.1
10.5	14.1	19	27.2	46.1	8.0	8.9	11.7	22.6	8.0	8.9	11.7	22.6	8.1	8.9	11.6	22.0	7.7	8.6	11.9	26.1
11	14.2	19.3	28.6	47.8	8.4	9.4	12.5	25.1	8.4	**[9.4]**	12.5	25.1	8.5	**<9.4>**	12.4	24.4	8.0	9.1	12.8	29.4
11.5	14	20	30.7	48.5	8.7	**(9.8)**	13.4	27.8	8.7	9.8	13.4	27.8	8.8	9.9	13.3	26.9	8.4	9.6	13.7	33.0
12	13.6	20.6	32.8	49.2	9.1	10.4	14.4	30.7	9.1	10.4	14.4	30.7	**<9.2>**	10.4	14.3	29.6	8.7	10.1	14.9	36.7
12.5	13.6	21.5	34.6	49.6	9.4	10.9	15.5	33.6	**[9.4]**	10.9	15.5	33.6	9.5	10.9	15.4	32.3	9.0	**"10.7"**	16.2	40.6
13	13.6	22.2	36.4	50	**(9.8)**	11.4	16.8	36.6	9.8	11.4	16.8	36.6	9.9	11.5	16.6	35.2	9.3	11.2	17.7	44.7
13.5	14	23.5	38	49.7	10.1	12.0	18.2	39.6	10.1	12.0	18.2	39.6	10.2	12.1	18.0	38.0	9.6	11.8	19.3	48.7
14	14.2	24.7	40.3	49.4	10.5	12.7	19.8	42.5	10.5	12.7	19.8	42.5	10.6	12.7	19.5	40.8	10.0	12.5	21.2	52.7
14.5	14.6	26	41.4	49	10.8	13.4	21.5	45.4	10.8	13.4	21.5	45.4	10.9	13.4	21.2	43.5	10.3	13.2	23.4	56.5
15	15	27.5	42.5	48.6	11.2	14.1	23.4	48.2	11.2	14.1	23.4	48.2	11.3	14.1	22.9	46.1	**"10.7"**	14.0	25.7	60.3
15.5	15.4	28.7	43.5		11.6	14.9	25.4		11.6	14.9	25.4		11.7	14.9	24.8		11.0	14.9	28.2	
16	15.8	30	44.4		11.9	15.8	27.5		11.9	15.8	27.5		12.1	15.8	26.9		11.4	15.9	30.9	
16.5	16.8	31.5			12.4	16.8			12.4	16.8			12.5	16.7			11.8	16.9		
17	17.8	33.1			12.8	17.8			12.8	17.8			12.9	17.8			12.2	18.1		
17.5	18.6	34.3			13.2	18.9			13.2	18.9			13.3	18.9			12.6	19.4		
18	19.2	35.6			13.7	20.2			13.7	20.2			13.8	20.1			13.1	20.8		
18.5	20.5	36.2			14.2	21.5			14.2	21.5			14.3	21.3			13.6	22.4		
19	21.4	36.9			14.7	22.8			14.7	22.8			14.8	22.6			14.1	24.0		
19.5	22	37.2			15.3	24.2			15.3	24.2			15.4	24.0			14.7	25.6		
20	22.8	37.5			15.8	25.6			15.8	25.6			16.0	25.3			15.3	27.3		
20.5	23.5	37.5			16.5	27.1			16.5	27.1			16.6	26.7			15.9	29.0		
21	24.4	37.5			17.1	28.5			17.1	28.5			17.2	28.1			16.6	30.7		
21.5	25.1	37.5			17.8	29.9			17.8	29.9			17.9	29.5			17.3	32.4		
22	25.8	37			18.4	31.3			18.4	31.3			18.5	30.8			18.0	34.1		
22.5	26.3	37			19.2	32.7			19.2	32.7			19.3	32.2			18.7	35.7		
23	26.7	37			19.9	34.1			19.9	34.1			20.0	33.5			19.5	37.4		
23.5	27.5	36.2			20.7	35.4			20.7	35.4			20.7	34.8			20.4	39.0		

24	28.6	35.6	21.5	36.7	21.5	36.7	21.5	36.1	21.2	40.5
24.5	29		22.3		22.3		22.4		22.2	
25	29.4		23.2		23.2		23.2		23.1	
25.5	30.5		24.1		24.1		24.1		24.1	
26	31		25.1		25.1		25.0		25.2	
26.5	31		26.0		26.0		26.0		26.3	
27	31		27.0		27.0		26.9		27.3	
27.5	31		28.0		28.0		27.9		28.4	
28	31		28.9		28.9		28.8		29.5	
28.5	31		29.9		29.9		29.8		30.6	
29	31		30.9		30.9		30.7		31.7	
29.5	31		31.8		31.8		31.7		32.7	
30	31		32.8		32.8		32.6		33.8	
30.5	30.7		33.8		33.8		33.5		34.9	
31	30.5		34.7		34.7		34.5		35.9	
31.5	30.2		35.6		35.6		35.4		37.0	
32	30		36.5		36.5		36.3		38.0	
32.5	29.5		37.4		37.4		37.2		39.0	
33	29		38.3		38.3		38.0		39.9	

APPENDIX II
(Computer Program)

Generation of Data

In the laboratory, the initial setting times of concrete mixtures at various retarder dosages (0, 100, 200, 300, and 400 ml/100 kg of cement) and temperatures (10, 15, and 20°C) are determined. Based on these data and using the maturity approach as presented in Section 6.3, the actual initial setting times at any retarder dosage are ranging between 0 and 400 ml/100 kg of cement, and at any initial concrete temperature ranging between 10 and 20°C. The application of the maturity method needs initial setting times at various retarder dosages and at least at three different initial concrete temperatures. Then the apparent activation energy (E) or the temperature sensitivity factor (B) as well as the equivalent initial setting times are established.

From known time-temperature history at the three different initial temperatures (10, 15, and 20°C) (Tables 6.5 to 6.7), the temperature development of the concrete mixture at any arbitrary temperature between 10 and 20°C is simulated (Appendix tables N-R).

The actual initial setting times of the concrete mixture are obtained by using the equivalent ages (t_{CT}) to the simulated temperature development history and the equivalent initial setting times (Table 6.8). The data generated in this process is then tabulated in Microsoft Excel in the manner as shown in Table N.

Retarder Dosage (ml/100 kg of cement)	Initial Concrete Temperature (°C)	Actual Initial Setting Time (Hrs)

Table N. Classification of the Initial Setting Times at the Different Retarder Dosages and Temperatures.

The program covers retarder dosages of 0, 50, 100, 150, 200, 250, 300, 350, and 400 ml/100 kg of cement. It also covers initial concrete temperatures of 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, and 20°C. The initial setting times, initial concrete temperature, and retarder dosage on the program is developed is shown in Table O.

Retarder Dosage (ml/100 kg of cement)	Initial Concrete Temperature (°C)	Actual Initial Setting Time (Hrs)
0	10	9
0	11	9
0	12	8.5
0	13	8.5
0	14	8
0	15	8
0	16	8
0	17	7.5
0	18	7.5
0	19	7
0	20	7
50	10	11.25
50	11	11
50	12	10.5
50	13	10.5
50	14	10
50	15	9.75
50	16	9.75
50	17	9.25
50	18	9.25
50	19	8.75
50	20	8.75
100	10	13.5
100	11	13
100	12	12.5
100	13	12.5
100	14	12
100	15	11.5
100	16	11.5
100	17	11
100	18	11
100	19	10.5
100	20	10.5
150	10	15.5
150	11	15.25
150	12	14.75
150	13	14.5
150	14	14
150	15	13.5
150	16	13.5

150	17	13
150	18	12.75
150	19	12.25
150	20	12
200	10	17.5
200	11	17.5
200	12	17
200	13	16.5
200	14	16
200	15	15.5
200	16	15.5
200	17	15
200	18	14.5
200	19	14
200	20	13.5
250	10	20.5
250	11	20.25
250	12	19.75
250	13	19.25
250	14	18.75
250	15	18.25
250	16	18
250	17	17.5
250	18	17
250	19	16.5
250	20	16
300	10	23.5
300	11	23
300	12	22.5
300	13	22
300	14	21.5
300	15	21
300	16	20.5
300	17	20
300	18	19.5
300	19	19
300	20	18.5
350	10	26
350	11	25.5
350	12	25
350	13	24.5
350	14	23.75
350	15	23.25
350	16	22.75
350	17	22.25
350	18	21.75

350	19	21.25
350	20	20.75
400	10	28.5
400	11	28
400	12	27.5
400	13	27
400	14	26
400	15	25.5
400	16	25
400	17	24.5
400	18	24
400	19	23.5
400	20	23

Table O. Initial Setting Times at various Retarder Dosages and at various Initial Concrete Temperatures.

Program Development and Illustration

The program is described in five steps. So, after the establishment of data generation and establishment of the table as illustrated in Table N, the used should move to step 1. The text within the parenthesis represents the data to be provided by the user, and the text without the parenthesis represents the data that will be automatically generated by the program.

- **Step 1**

In Table P, Enter the desirable height of the slipform, which must be between 1 m and 1.3 m (e.g. 1100 mm) and also the height of the wall that is desired to be built (e.g. 10000 mm) as illustrated in Table P.

Enter Slipform Height (1000 - 1300 mm)	(1100)
Enter Wall Elevation (mm)	(10000)
Number of Layers within the Slipform	5

Table P. Program table for Step 1.

- **Step 2**

After Step 1, the User should fill Table Q. Table Q represents a typical arrangement of the layers within the slipform, where the thickness of each layer should be provided in mm. Each time the thickness of a layer is provided, the Program will automatically generate the elevation of the concrete within the slipform and the number of the layers and complete Table Q. When the elevation reaches the desired height of the slipform (e.g. 1100mm) then the user must stop the procedure.

Layer Number	Thickness of Layer (mm)	Elevation of Concrete within the Slipform (mm)
0	0	0
1	(300)	300
2	(200)	500
3	(200)	700
4	(200)	900
5	(200)	1100

Table Q. Enter Thickness of each Layer within the Slipform.

- **Step 3**

After completing the Table Q, the user should run the program in order to produce the corresponding "concrete elevation" and "number of layers" (as shown in Table R). The program is designed to "run" for 5 to 13 layers. This depends on the indicative number shown in Table P (e.g. 5). Each time this number changes, the program must be "run" accordingly. The user shall then push the button with the corresponding number shown in "Number of Layers within the Slipform" in Table P. For each number of layers there is a corresponding text that should be selected so that the program would "run". For example if the total number of layers within one slipform is 5, then the user must press the button that has the word "FIVE" written on it.

Layer Number	Layer Thickness (mm)	Concrete Elevation (mm)
0	0	0
1	300	300
2	200	500
3	200	700
4	200	900
5	200	1100
6	300	1400
7	200	1600
8	200	1800
9	200	2000
10	200	2200
11	300	2500
12	200	2700
13	200	2900
14	200	3100
15	200	3300
16	300	3600
17	200	3800
18	200	4000
19	200	4200
20	200	4400
21	300	4700
22	200	4900
23	100	5000

Table R. Number of Layers, Layer Thickness, and Concrete Elevation, calculated by the program.

- **Step 4**

After running the program for the "concrete elevation", the user shall enter manually the desired dosage of retarder and initial concrete temperature in the respective columns of Table S. Table S illustrates an example of the table that will appear in Excel after running the program for "concrete elevation".

Layer Number	Layer Thickness (mm)	Concrete Elevation (mm)	Concrete Placement (Hrs)	Retarder Dosage (ml/100kg cement)	Initial Concrete Temp. On Site (°C)	Initial Setting (Hrs)	Time of Mock-up (Hrs)	Slipform Speed (mm/hrs)	Speed Check
0	0	0	0	0	0	-	#VALUE!	-	-
1	300	300		(0)	(15)				

2	200	500		(0)	(15)				
3	200	700		(0)	(15)				
4	200	900		(0)	(15)				
5	200	1100		(0)	(15)				
6	300	1400		(0)	(15)				
7	200	1600		(0)	(15)				
8	200	1800		(0)	(15)				
9	200	2000		(0)	(15)				
10	200	2200		(0)	(15)				
11	300	2500		(0)	(15)				
12	200	2700		(0)	(15)				
13	200	2900		(0)	(15)				
14	200	3100		(0)	(15)				
15	200	3300		(0)	(15)				
16	300	3600		(0)	(15)				
17	200	3800		(0)	(15)				
18	200	4000		(0)	(15)				
19	200	4200		(0)	(15)				
20	200	4400		(0)	(15)				
21	300	4700		(0)	(15)				
22	200	4900		(0)	(15)				
23	100	5000		(0)	(15)				

Table S. Program Table after the Program is set to "RUN" for "Concrete Elevation" and after entering manually the "Retarder Dosages" and "Concrete Temperatures".

Then the user shall "run" the program again for "concrete placement". This means that the program now will automatically calculate the most effective time at which each concrete layer should be poured into the slipform, and also it will calculate the best time of the slipform mock-up (Table T). Finally, the program will also calculate the speed of the slipform at the time of mock-up, with a speed check to ensure that everything works properly. Table T illustrates the completed program Table. In order to "run" for "concrete placement", the user shall press the button with the name "PLACEMENT" written on it. If the program stops to "run", then the user should push the button with the name "PLACEMENT1" written on it, and if it stops again, then the user should push the button with the name "PLACEMENT2" written on it. Also, each time the user wishes to "run" the program for "concrete placement", the user shall first delete the contents of this column and then "run" it again. Finally, this program is designed for walls with a height of up to 15 m with 5 layers arrangement within one slipform.

Layer Number	Layer Thickness (mm)	Concrete Elevation (mm)	Concrete Placement (Hrs)	Retarder Dosage (ml/100kg cement)	In-situ Concrete Temp. (°C)	Initial Setting (Hrs)	Time of Mock-up (Hrs)	Slipform Speed (mm/hrs)	Speed Check
0	0	0	0	0	0	-	8.00	-	-
1	300	300	0.00	(0)	(15)	8	11.00	100.0	OK
2	200	500	3.00	(0)	(15)	8	13.00	100.0	OK
3	200	700	5.00	(0)	(15)	8	15.00	100.0	OK
4	200	900	7.00	(0)	(15)	8	17.00	100.0	OK
5	200	1100	9.00	(0)	(15)	8	19.00	100.0	OK
6	300	1400	11.00	(0)	(15)	8	22.00	100.0	OK
7	200	1600	14.00	(0)	(15)	8	24.00	100.0	OK
8	200	1800	16.00	(0)	(15)	8	26.00	100.0	OK
9	200	2000	18.00	(0)	(15)	8	28.00	100.0	OK
10	200	2200	20.00	(0)	(15)	8	30.00	100.0	OK
11	300	2500	22.00	(0)	(15)	8	33.00	100.0	OK
12	200	2700	25.00	(0)	(15)	8	35.00	100.0	OK
13	200	2900	27.00	(0)	(15)	8	37.00	100.0	OK
14	200	3100	29.00	(0)	(15)	8	39.00	100.0	OK
15	200	3300	31.00	(0)	(15)	8	41.00	100.0	OK
16	300	3600	33.00	(0)	(15)	8	44.00	100.0	OK
17	200	3800	36.00	(0)	(15)	8	46.00	100.0	OK
18	200	4000	38.00	(0)	(15)	8	48.00	100.0	OK
19	200	4200	40.00	(0)	(15)	8	50.00	100.0	OK
20	200	4400	42.00	(0)	(15)	8	52.00	100.0	OK
21	300	4700	44.00	(0)	(15)	8	55.00	100.0	OK
22	200	4900	47.00	(0)	(15)	8	57.00	100.0	OK
23	100	5000	49.00	(0)	(15)	8	58.00	100.0	OK

Table T. Completed Program Table.

- **Step 5**

After finishing Step 4, the user can examine the situation and if he/she considers that it needs some modifications, then he/she can change the layer arrangement within the slipform, or the dosage of the retarder, or the initial concrete temperature, so as to optimize the slipforming operation and make it more effective. Then the user should run the program again as many times as he/she finds it necessary in order to have the desirable results.

Summarizing the Steps

To summarize the steps, the user once completes Table O, should:

1. Enter the "Slipform Height" and the "Wall Height" in Table P,
2. Enter the "Layer Thicknesses" in Table Q,
3. "RUN" the program for "Concrete Elevation",
4. Enter the "Retarder Dosage" and the "Initial Concrete Temperature On Site", and
5. "RUN" the program for "Concrete Placement".

The whole procedure of the Program is shown in the flow chart in Fig. A.

Appendix Figure A
(Flow Chart of the Program Procedure)