

# PREDICTION OF CONCRETE SETTING

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## Abstract

With knowledge of the time to initial set, contractors will be able plan measures to finish, texture, and saw cut concrete pavements on time. The point at which final set occurs is of importance, since it provides an estimate of when the concrete strength and stiffness development will start. In this study, experimental work was performed under laboratory and field conditions to determine the effect of temperature, different cements, and supplementary cementing materials on the initial and final setting times of concrete mixtures. The objectives of this paper are to present and calibrate a setting model that correlates the degree of hydration to the setting times collected under laboratory and field conditions. Initial and final set times of the concrete were determined with penetration resistance testing. Field data were collected from seven concrete pavement projects paved throughout the year, in different climatic regions. The results indicate that final setting occurs at approximately the same degree of hydration for a particular mixture irrespective of the curing history. This observation is also true for the initial set condition. Models are developed to predict the setting of concrete with the degree of hydration and the water-cementitious materials ratio as variables.

## 1. Introduction

Setting of concrete is the gradual transition from liquid to solid, and the definition of any point at which the paste is considered set, is somewhat arbitrary [1]. Final setting of concrete relates to the point where stresses and stiffness start to develop in freshly placed concrete. It has been reported that the initial thermal gradient at setting (built-in curling) has a major impact on the long-term performance of jointed concrete pavements [2]. With a model to predict concrete setting and a model to predict the development of in-place concrete temperatures, the thermal gradients at final set can be estimated and used during pavement design. Initial set is of importance, as it provides an estimate of when the concrete has reached the point where it has stiffened to such an extent that it can no longer be vibrated without damaging the concrete. Under hot weather conditions, the time to initial set will be shorter than under normal temperatures, which will affect the construction crew's ability to consolidate and finish the in-place concrete. Under cold weather conditions the time to initial set is extended and the potential of plastic shrinkage cracking occurring in the fresh concrete is extended. With knowledge of the time to initial set, contractors would be able to plan measures to finish and texture a concrete pavement on time to avoid that initial setting occurs before these activities.

Experimental work was performed for this study under laboratory and field conditions to determine the effect of temperature, different cements, and supplementary cementing materials (SCMs) on the initial and final setting times. The objectives of this paper are to present and calibrate a setting model to characterize setting times collected under laboratory and field conditions.

## 2. Background and approach

The curing temperature of the concrete is arguably the variable that has the most significant effect on the concrete's setting time. In this paper the maturity method is used to account for the effect of temperature and time on the development of hydration products. The equivalent age maturity function shown in Equation 1, as developed by Freiesleben Hansen and Pedersen [3], is widely accepted as the most accurate maturity formulation [4].

$$t_e(T_r) = \sum_0^t \exp\left(\frac{E}{R}\left(\frac{1}{273+T_r} - \frac{1}{273+T_c}\right)\right) \cdot \Delta t \quad (1)$$

where,  $t_e(T_r)$  = equivalent age at the reference curing temperature (hours),  
 $\Delta t$  = chronological time interval (hours),  
 $T_c$  = average concrete temperature during the time interval,  $\Delta t$ , (°C),  
 $T_r$  = constant reference temperature (°C),  
 $E$  = activation energy (J/mol), and  
 $R$  = universal gas constant (8.3144 J/mol/K).

ASTM C 403 [5], "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance", defines setting of the concrete in terms of initial and final set. A mortar sample is obtained from concrete by wet sieving, and the force required to penetrate needles of different sizes into the mortar is measured. At a penetration resistance of 3.4 MPa (500 psi), initial setting occurs, which was chosen to correspond with the time when the concrete can no longer be vibrated [6]. Tuthill and Cordon [6] determined that at a penetration resistance of 27.6 MPa (4000 psi) the concrete has reached a compressive strength of around 0.6 MPa (80 psi) and it could carry some measurable loads.

Pinto and Hover [7] evaluated how different temperatures affected the setting time in terms of the penetration resistance method described by ASTM C 403. Pinto and Hover [7] stated that although "... the setting process is influenced by the rheology effects of the water-cement ratio (w/c), aggregates, air voids, bleeding, and evaporation, setting is primarily influenced by hydration of the cement." Although the final set test results of Pinto and Hover [7] varied considerably when tested at different temperatures, they concluded that the computed equivalent age at setting was much more uniform for each mixture. This indicates that for any given concrete mixture, final set occurs when a specific level of microstructure development (degree of hydration) has occurred.

Test data from an adiabatic calorimeter provide a means to quantify the heat of hydration development as the hydration of the mixture progresses [8,9]. It has been shown and it is widely accepted that the ratio of the heat development as compared to the maximum heat available in the system is an accurate and practical method to quantify the degree of hydration. The degree of hydration ( $\alpha$ ) is actually defined as the ratio between the quantity of hydrated cementitious material and the original quantity of cementitious material. Figure 1 presents a physical interpretation of the degree of hydration, and it may be seen that it characterizes the

formation of hydration products for a specific concrete mixture over time. This figure illustrates why initial and final set may be correlated to the degree of hydration and this paper will investigate this hypothesis further. The exponential function shown in Equation 2 can be used to effectively characterize the S-shaped degree of hydration curve [10,11].

$$a(t_e) = a_u \cdot \exp\left(-\left[\frac{t}{t_e}\right]^b\right) \quad (2)$$

where,  $a(t_e)$  = the degree of hydration at equivalent age,  $t_e$ ,  
 $t$  = hydration time parameter (hours),  
 $b$  = hydration shape parameter, and  
 $a_u$  = ultimate degree of hydration.

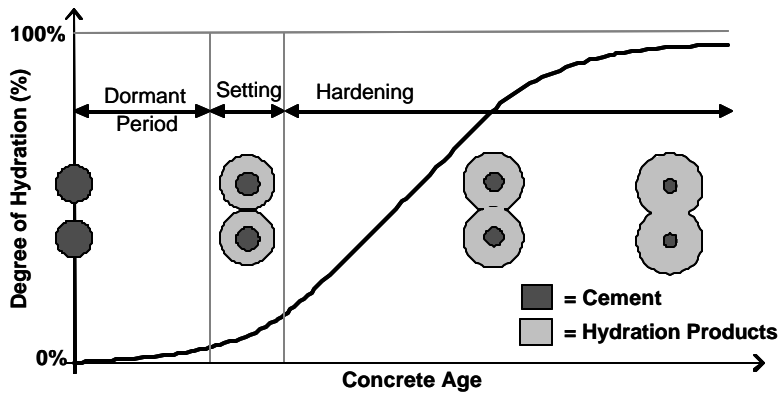


Figure 1: Physical interpretation of the degree of hydration development

The activation energy ( $E$ ) defines the temperature sensitivity of the concrete mixture in the equivalent age maturity function (Equation 1). In this paper a model to characterize the activation energy in terms of the cement composition and SCMs in the concrete mixture was used. The activation energy model can be summarized as follows [12]:

$$E = 22,100 \cdot f_E \cdot p_{C_3A}^{0.30} \cdot p_{C_4AF}^{0.25} \cdot Blaine^{0.35} \quad (3)$$

where,  $p_{C_3A}$  = weight ratio of  $C_3A$  in terms of the total cement content,  
 $p_{C_4AF}$  = weight ratio of  $C_4AF$  in terms of the total cement content,  
 $Blaine$  = Blaine value, specific surface area of cement ( $m^2/kg$ ), and  
 $f_E$  = activation energy modification factor, defined as:

$$f_E = 1 - 1.05 \cdot p_{FA} \cdot \left(1 - \frac{p_{FACaO}}{0.40}\right) + 0.40 \cdot p_{SLAG} \quad (4)$$

where,  $p_{FA}$  = mass ratio replacement of the fly ash,  
 $p_{FACaO}$  = mass ratio of the CaO content in the fly ash, and  
 $p_{SLAG}$  = mass ratio replacement of the GGBF Slag.

Byfors [13] defined the term “critical degree of hydration” ( $\alpha_{cr}$ ) as the degree of hydration that has to be reached before any strength gain will occur. Byfors concluded that the critical degree of hydration is dependent on the water-cement ratio and presented the following expression:

$$a_{cr} = k_s \times (w/c) \quad (5)$$

where,  $k_s$  = constant that varies between 0.4 and 0.46, and  
 $w/c$  = water-cement ratio.

Byfors's definition of the critical degree of hydration is very similar to the point at which final setting occurs; however, the value was obtained by extrapolating the degree of hydration versus strength development data until the time of zero strength is reached. In this paper it is proposed that the initial and final set times of concrete be evaluated in terms of the degree of hydration development. The effect of the water-cement ratio will be incorporated, since it has been shown to influence the degree of hydration at setting [13,14]. This is necessary since a higher water-cement ratio will result in a greater distance between cement particles, which will in turn require a higher degree of hydration before setting of the mixture can occur.

### 3. Experimental work

In order to develop a setting model, setting test data were collected under laboratory and field conditions. Field data were collected from seven concrete pavement projects paved in different seasons and in different climatic regions of Texas. At each field site, quantities of raw materials were gathered to enable the reproduction of the field mixtures in the laboratory. ASTM C 403 [5] tests were performed on-site by sampling fresh concrete placed in front of the concrete paver. Table 1 provides a brief summary of the mixture proportions of the continuously reinforced concrete pavement (CRCP) sites visited.

Table 1: Summary of the CRCP concrete mixtures tested

Mix No.	Site Description	Cementitious Materials	Total Cementitious Content (kg/m <sup>3</sup> )	w/cm
1	Dallas - May	Type I/II + 20% Class F fly ash	293	0.39
2	Houston - May	Type I/II + 25% Class C fly ash	318	0.44
3	Dallas - Aug	Type I	346	0.46
4	Houston - Aug	Type I/II + 35% Class C fly ash	320	0.41
5	El Paso - Aug	Type I/II + 50% GGBF Slag	279	0.54
6	Dallas - Sept	Type I/II + 20% Class F fly ash	272	0.50
7	Houston - Oct	Type I/II + 25% Class C fly ash	347	0.41

Semi-adiabatic tests were performed on 150 x 300mm cylindrical concrete specimens, to define the degree of hydration for each mixture. The semi-adiabatic testing equipment used during this project was supplied by Digital Site Systems, Inc., Pennsylvania. The within-test repeatability with this equipment is reported to be within 1% to 3%. Based on standard American testing temperatures, a reference temperature of 21.1°C (70°F) was used for the back-calculation of the degree of hydration of the mixtures. The best-fit hydration parameters for the degree of hydration formulation, shown in Equation 2, are summarized in Table 2.

The times of initial and final set were determined by means of penetration resistance testing in accordance with ASTM C 403 [5]. Setting results were obtained from the mixtures under field conditions (fluctuating temperatures) and controlled laboratory conditions (constant temperatures). The concrete mixtures were sieved through a 4.75mm sieve to obtain a representative mortar sample of the fresh concrete. In this test, the maximum force required to penetrate needles of different sizes to a depth of 25 mm over a 10 second period is measured.

As the concrete stiffens, the size of needle is progressively decreased. Thermocouples were used to monitor ambient and mortar temperatures. During the data analysis, the best-fit power function, as recommended by ASTM C 403, was fitted through the data points. The penetration resistance test results for the concretes sampled in the morning and the afternoon on a CRCP project in Houston are shown in Figure 2. The setting results under laboratory conditions for the mixture is also plotted on Figure 2. The effect of different curing temperatures on the setting times can clearly be seen in this figure. Air temperatures during construction of this pavement were above the 25°C; hence, setting occurred earlier on-site than under laboratory conditions. Similarly, setting for the section placed in the afternoon occurred faster, since the afternoon placement's concrete temperatures were higher than the morning placement's concrete temperatures. Table 3 provides a summary of the chronological initial and final setting times determined in the field and under laboratory conditions.

Table 2: Best-fit hydration parameters obtained from semi-adiabatic testing ( $T_r = 21.1^\circ\text{C}$ )

Mix No.	Activation Energy (J/mol)	Hydration Parameters		
		$b$	$t$ (hours)	$a_u$
1	36,848	1.010	15.50	0.725
2	36,636	0.818	31.05	0.841
3	45,712	0.935	13.39	0.729
4	35,341	0.720	28.35	0.857
5	50,600	0.562	40.58	0.800
6	39,031	0.681	17.89	0.788
7	38,375	0.573	35.95	0.850

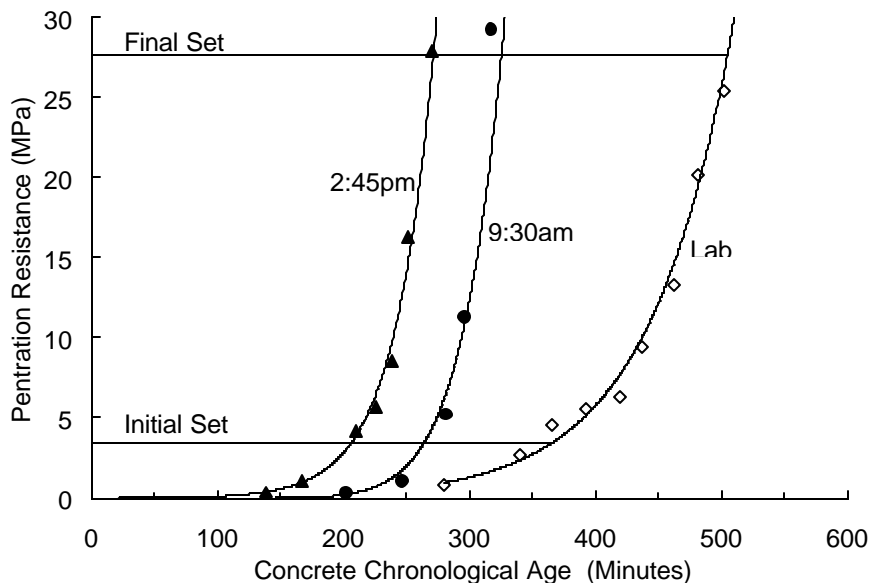


Figure 2: Chronological times of setting by penetration resistance of Mix No. 4

Table 3: Summary of initial and final set times as obtained by penetration resistance

Mix No.	Site Description	Laboratory (hours)		Field Conditions (hours)			
		Initial Set	Final Set	Section No. 1		Section No. 2	
				Initial Set	Final Set	Initial Set	Final Set
1	Dallas – May	4.9	6.5	-	-	-	-
2	Houston - May	7.9	10.1	-	-	-	-
3	Dallas – Aug	4.1	5.4	2.6	3.3	-	-
4	Houston - Aug	5.8	8.7	4.4	5.4	3.3	4.7
5	El Paso - Aug	7.0	10.3	2.9	4.1	3.5	5.4
6	Dallas – Sept	7.2	9.1	3.3	4.2	-	-
7	Houston - Oct	5.1	6.8	5.3	6.7	-	-

#### 4. Calibration of the initial and final setting model

The convention introduced by Pinto and Hover [7] was adopted and the degree of hydration values that correspond to initial ( $\alpha_i$ ) and final ( $\alpha_f$ ) set were determined for all the mixtures. The chronological setting times shown in Table 3 indicate that a wide range of initial and final set times may occur for the different mixtures. During testing, the temperature of the setting paste was monitored under both laboratory and field conditions. The measured concrete temperatures were used to determine the equivalent ages at initial and final set. The hydration parameters and activation energy as listed in Table 2 were used to determine the critical degree of hydration that corresponds to the respective initial and final setting times. The results for initial and final set are summarized in Tables 4 and 5. In general, it was found that setting occurred at around the same equivalent age in the field and laboratory mixtures, which is in agreement with the findings reported by Pinto and Hover [7]. As the degree of hydration is a function of the equivalent age, this is in agreement with the formulation of Byfors [13], who stated that setting occurs at a specific “critical” degree of hydration. Figure 3 provides an example comparison between the equivalent age and degree of hydration at set. In this figure, it may be seen that irrespective of the curing history, final set occurs at around the same degree of hydration for a particular mixture. This observation is also true for the initial set condition.

Table 4: Summary of initial set parameters

Mix No.	Laboratory Conditions				Field Conditions			
	Actual Time (hrs)	$t_e$ (hrs)	$a_i$	$k_{si}$	Actual Time (hrs)	$t_e$ (hrs)	$a_f$	$k_{si}$
1	4.9	5.9	0.052	0.14	-	-	-	-
2	7.9	9.9	0.066	0.15	-	-	-	-
3	4.1	5.7	0.080	0.19	2.6	5.0	0.060	0.14
4	5.8	7.0	0.055	0.14	4.4	7.8	0.069	0.18
					3.3	7.3	0.061	0.16
5	7.0	6.9	0.054	0.10	2.9	6.6	0.050	0.09
					3.5	7.5	0.060	0.11
6	7.2	5.9	0.094	0.19	3.3	5.4	0.082	0.16
7	5.1	6.4	0.059	0.14	5.3	7.1	0.067	0.16

Table 5: Summary of final set parameters

Mix No.	Laboratory Conditions				Field Conditions			
	Actual Time (hrs)	$t_c$ (hrs)	$a_f$	$k_{sf}$	Actual Time (hrs)	$t_c$ (hrs)	$a_f$	$k_{sf}$
1	6.5	8.1	0.105	0.29	-	-	-	-
2	10.1	12.7	0.105	0.24	-	-	-	-
3	5.4	7.8	0.138	0.33	3.3	7.8	0.137	0.33
4	8.7	10.4	0.109	0.28	5.4 4.7	10.3 10.8	0.108 0.116	0.28 0.30
5	10.3	12.2	0.112	0.21	4.1 5.4	10.6 11.7	0.096 0.107	0.18 0.20
6	9.1	7.7	0.133	0.27	4.2	7.9	0.136	0.27
7	6.8	9.0	0.093	0.23	6.7	9.3	0.097	0.24

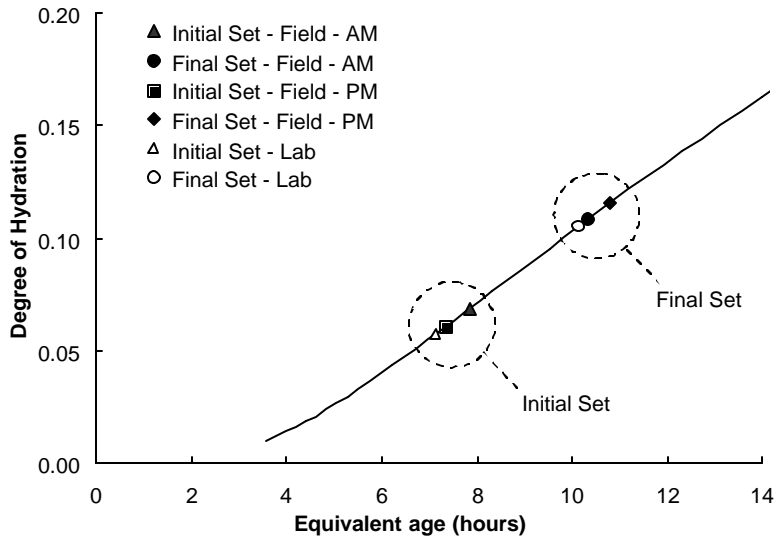


Figure 3: Degree of hydration at initial and final set for Mix No. 4

The formulation shown in Equation 5 was used to account for the effect of the water-cementitious materials ratio on the initial and final set behavior. The ratio between the critical degree of hydration at setting and the water-cementitious materials ratio (see Equation 5) for initial set ( $k_{si}$ ) and final set ( $k_{sf}$ ) is shown in Tables 4 and 5 for each mixture. It may be seen that for most of the mixtures the ratio appears constant; however, when GGBF slag is used, setting occurs at an earlier degree of hydration. This effect is present in all three cases where the setting of GGBF slag was tested (Mix No. 5). The reason for this effect is not clear at this stage, and based on the limited data available on the behavior of GGBF slag, no attempt will be made to modify the setting model when GGBF slag is used. However, it is recommended that the interaction between the setting and hydration of GGBF slag be further investigated. Based on the values of  $k_s$  listed in Tables 4 and 5, the average  $k_s$  values were determined and the following formulation is recommended for use:

$$\text{ASTM C 403 Initial set: } a_i = 0.15 \times (w/cm) \quad (6)$$

$$\text{ASTM C 403 Final set: } a_f = 0.26 \times (w/cm) \quad (7)$$

where,  $a_i$  = degree of hydration at initial set,  
 $a_f$  = degree of hydration at final set, and  
 $w/cm$  = water-cementitious materials ratio.

In Table 6 the degree of hydration at setting computed with the formulations shown in Equations 6 and 7 are evaluated for different water-cementitious materials ratios. With a  $w/cm$  of 0.50, it may be seen that initial and final set are predicted to occur after, respectively, 7.5% and 13% of hydration products have been developed. Table 6 indicates that for setting to occur, more hydration products have to develop at higher  $w/cm$  ratios, and visa versa, which is in accordance with findings in past literature [13,14].

Table 6: The effect of different  $w/cm$  ratios on the degree of hydration at setting

ASTM C 403	Degree of Hydration		
	$w/cm = 0.40$	$w/cm = 0.50$	$w/cm = 0.60$
Initial Set	0.060	0.075	0.090
Final Set	0.104	0.130	0.156

Figures 4 and 5 provide a comparison of the predicted equivalent age versus the measured equivalent age at setting using the proposed model shown in Equations 6 and 7. These figures indicate that an accurate estimate of the equivalent age at setting can be obtained with the proposed model. The  $r^2$  values were 0.735 and 0.766, respectively, for the predicted versus measured initial and final setting. It may be seen that the initial and final setting times for the GGBF slag mixtures are over predicted, and this effect is present in all three cases where the setting of GGBF slag was tested. This may be due to the fact that setting occurs at an earlier degree of hydration. It is recommended that the interaction between setting and hydration of GGBF slag be further investigated.

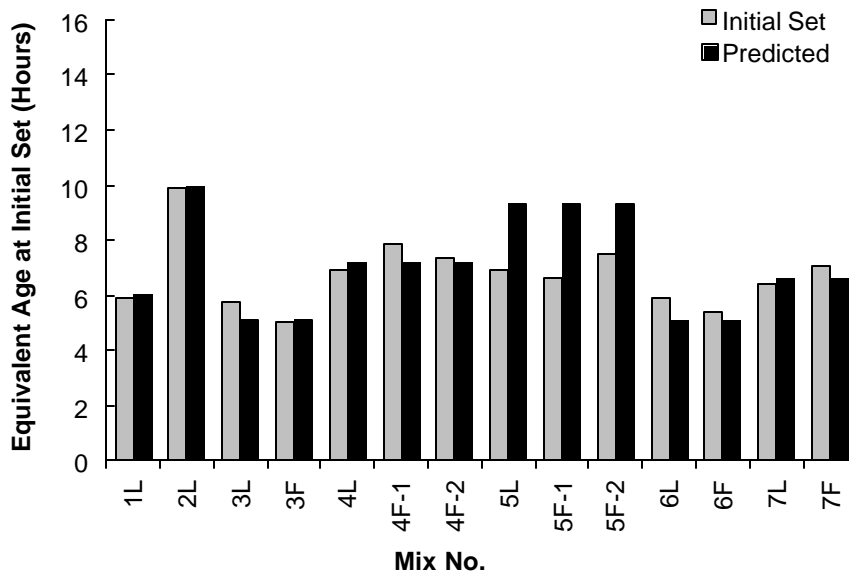


Figure 4: Comparison of measured and predicted equivalent ages to reach initial set (Note: L = Laboratory conditions, F=Field conditions, 1=Section No.1, 2=Section No. 2)

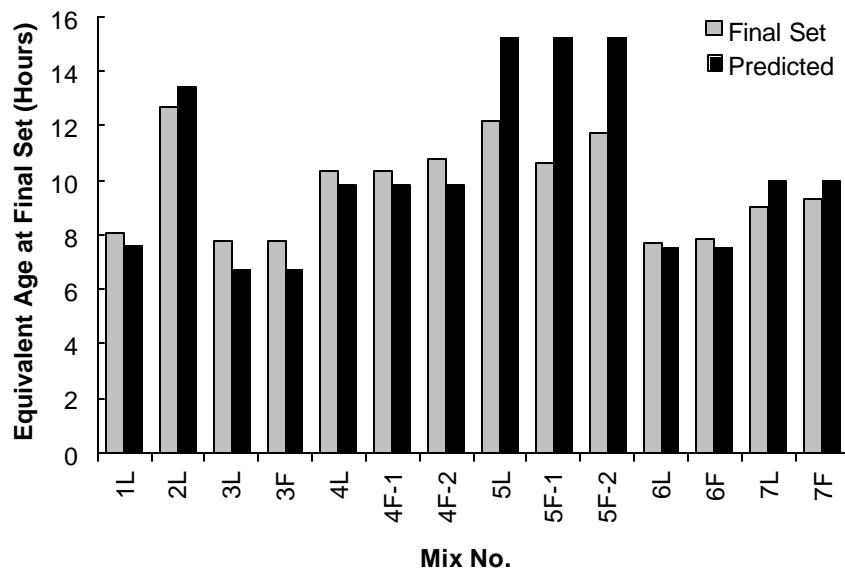


Figure 5: Comparison of measured and predicted equivalent ages to reach final set (Note: L = Laboratory conditions, F=Field conditions, 1=Section No.1, 2=Section No. 2)

## 5. Additional remarks regarding the concrete setting model

In Section 2, it was discussed that Byfors [13] recommended a  $k_s$  value between 0.4 and 0.46 to multiply with the water-cement ratio to obtain the critical degree of hydration when the strength development starts. However, based on the calibration of the ASTM C 403 setting data, a  $k_s$  value of 0.26 was found to best represent the measured the final set times. These values appear to contradict one another.

The “arbitrary” definition of set used by ASTM C 403 and that used by Byfors originate from different requirements. The difference between the ASTM C 403 approach and that taken by Byfors is schematically shown in Figure 6. Byfors determined the start of strength development by extrapolating a linear line from degree of hydration versus strength graphs. By extrapolating a linear line from the later age strength, the slow initial gain in strength is not considered. Concerning this issue, Byfors [13] remarks that, “...the relation between strength and the degree of hydration is, however, exponential at a very early stage, from the setting phase and a few hours after.” This exponential gain in initial strength is captured by the ASTM C 403 procedure and this behavior may be seen in typical ASTM C 403 test results as shown in Figure 2.

Based on the discussion above, it may be concluded that a difference between the degree of hydration at final set as proposed by the author and Byfors [13] is not unexpected. The difference arises from the use of different definitions of the time of final set. The use of either of the two approaches may be adopted; however, compatibility concerning strength and stiffness gain should be maintained. It is recommended to determine the degree of hydration at initial and final set in terms of the formulation shown in Equations 6 and 7.

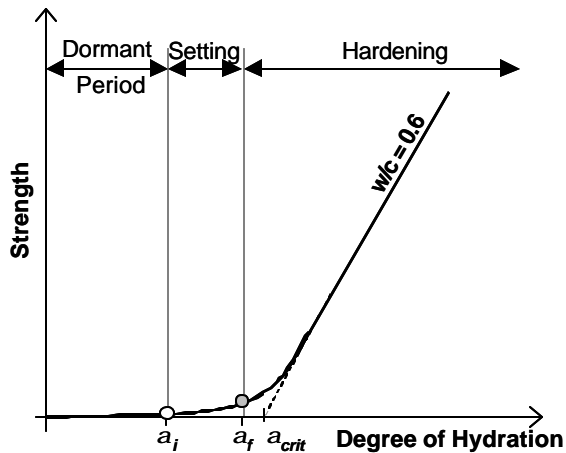


Figure 6: Hypothesis on differences in setting degree of hydration

## 6. Closed-form mathematical formulation of concrete setting times

The use of the exponential formulation to characterize the degree of hydration development was defined in Section 2. With the model recommended in Equations 6 and 7, the equivalent age at setting can directly be determined from the hydration parameters. The proposed closed-form formulation is shown in Equations 8 and 9. These formulations can be very useful, since the setting times at the reference temperature can now be obtained after adiabatic calorimeter test results are available for a mixture.

$$\text{ASTM C 403 Initial set: } t_{ei} = t \cdot \left( -\ln \left[ \frac{0.14 \cdot w/cm}{a_u} \right] \right)^{\frac{-1}{b}} \quad (8)$$

$$\text{ASTM C 403 Final set: } t_{ef} = t \cdot \left( -\ln \left[ \frac{0.26 \cdot w/cm}{a_u} \right] \right)^{\frac{-1}{b}} \quad (9)$$

where,  $t_{ei}$  = equivalent age at initial set (hours),  
 $t_{ef}$  = equivalent age at final set (hours), and  
 $w/cm$  = water-cementitious materials ratio.

### 6.1 Modification of hydration parameters to include the effect of chemical admixtures

It is customary to express the effect of chemical admixtures such as retarders and accelerators in terms of their effect on initial set at different temperatures. With the formulation presented in Equation 8, the initial set time for the cement without any chemical admixtures can be estimated. Next, the effect recommend by the supplier of the chemical admixture can be added to the calculated initial set time. In the case of retarders, the initial set time will be increased, and when accelerators are used, the initial set time will be reduced. With this approach, the assumption is made that only the hydration time parameter is affected by the use of chemical admixtures. The following is an example of the guidelines contained in manufacture's data sheets for different chemical admixtures:

- **Retarder:** ASTM 494 Type B and Type D: Brand A retarder retards the initial and final set of concrete. At the usual addition rate of 195 mL/ 100 kg (3 fl oz/100 lb) cement it

will extend the initial setting time of portland cement concrete by 2 to 3 hours at 21°C (70°F).

- **Accelerator:** ASTM 494 Type E: Brand A accelerator is used at an addition rate of 520 to 2600 mL/100 kg (8 to 40 fl oz/100 lb) of cement. The amount used will depend upon the setting time of the non-admixtured concrete and the temperature at placement. In most instances, the addition of 780 to 1040 mL of Brand A accelerator/100 kg (12 to 16 fl oz/100 lb) of cement will reduce the setting time of a typical Type I cement concrete at 10°C (50°F) by 2 to 3 hours and increase the 3 day compressive strength by 25 to 50%.

With the above information, the new hydration time parameter, which includes the effect of retarders or accelerators can be determined. The new hydration time parameter can be determined as follows:

$$\text{ASTM C 403 Initial set: } \quad t_{chem} = (t_{ei} + \Delta_{chem}) \cdot \left( -\ln \left[ \frac{0.14 \cdot w/cm}{a_u} \right] \right)^{\frac{1}{b}} \quad (10)$$

where,  $\tau_{chem}$  = adjusted hydration time parameter to include the effect of a retarder or accelerator (hours),  
 $t_{ei}$  = equivalent age at initial set of the cement without chemical admixtures determined from Equation 8 (hours), and  
 $D_{chem}$  = effect of chemical admixture on the time at initial set at the reference temperature (21.1°C), where positive retards and negative accelerates.

## 6.2 Example problem to include the effect of chemical admixtures

The implementation of the approach outlined above is best explained by an example. The hydration parameters used for this exercise are those listed in Table 2, for Mix No. 3, where  $b = 0.720$ ,  $t = 13.39$  hours,  $a_u = 0.729$ ,  $E = 45712$  J/mol, and  $w/cm = 0.46$ . When this mixture is considered without the presence of any chemical admixtures, it may be found from Equation 8 that initial setting at 21°C (70°F) is expected to occur at the following equivalent age:

$$t_{ei} = 13.39 \cdot \left( -\ln \left[ \frac{0.14 \cdot 0.46}{0.729} \right] \right)^{\frac{-1}{0.720}} = 3.91 \text{ hours} \quad (11)$$

When Brand A retarder is added to this mixture, the effect of the retarder is as provided by the manufacturer above, and it will extend the initial setting time of portland cement concrete by 2 hours at 21°C (70°F). In order to implement the formulation shown in Equation 10, the following parameter can now be determined:  $D_{chem} = +2.0$  hours. From Equation 10, the adjusted hydration time parameter to include the effect of the Brand A retarder can be determined to be 20.24 hours as shown in Equation 12. It may be seen that the addition of the retarder causes the hydration time parameter ( $t$ ) to increase from 13.39 hours to 20.24 hours. With this adjustment of the hydration parameter, the effect of the retarder on the degree of hydration development is as shown on Figure 7. The effect of the retarder on the rate of heat liberation is shown on Figure 8.

$$t_{chem} = (3.91 + 2.0) \cdot \left( -\ln \left[ \frac{0.14 \cdot 0.46}{0.729} \right] \right)^{\frac{1}{0.720}} = 20.24 \text{ hours} \quad (12)$$

When Brand A accelerator is added to this mixture, the effect of the accelerator is as provided by the manufacturer above, and it will reduce the initial setting time of portland cement concrete by 3 hours at 10°C (50°F). In order to implement the formulation shown in Equation 10, the following parameter can now be determined:  $D_{chem} = -3.0 \text{ hours} \times \text{the age conversion factor} = -3.0 \text{ hours} \times 0.483 = -1.450 \text{ hours}$ . Note that the age conversion factor is used to account for the fact that the 3.0 hours increase is measured at a temperature of 10°C and not 21°C. From Equation 10, the adjusted hydration time parameter to include the effect of Brand A accelerator can be determined to be 8.42 hours. It can be seen that the addition of the accelerator causes hydration time parameter ( $\tau$ ) to decrease from 13.39 hours to 8.42 hours. With this adjustment to the hydration parameter, the effect of the accelerator on the degree of hydration development is shown on Figure 7. The effect of the accelerator on the rate of heat liberation is shown on Figure 8. In both instances the adjustment to the hydration time parameter effectively accounts for the effect of the chemical admixture.

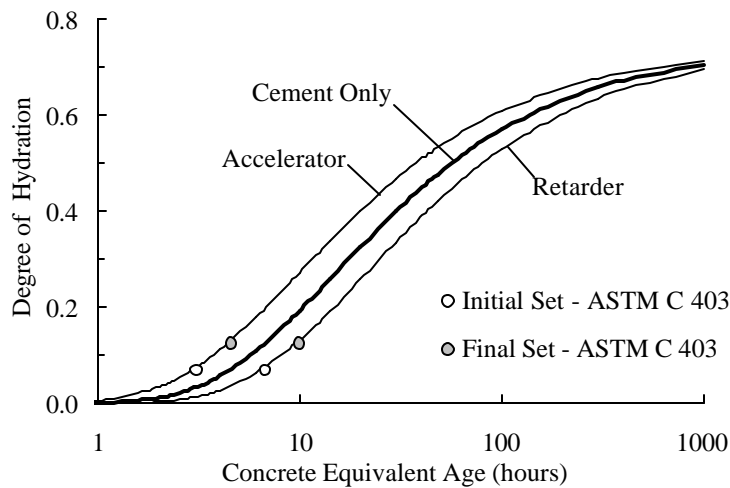


Figure 7: The effect of a retarder and accelerator and on the degree of hydration development

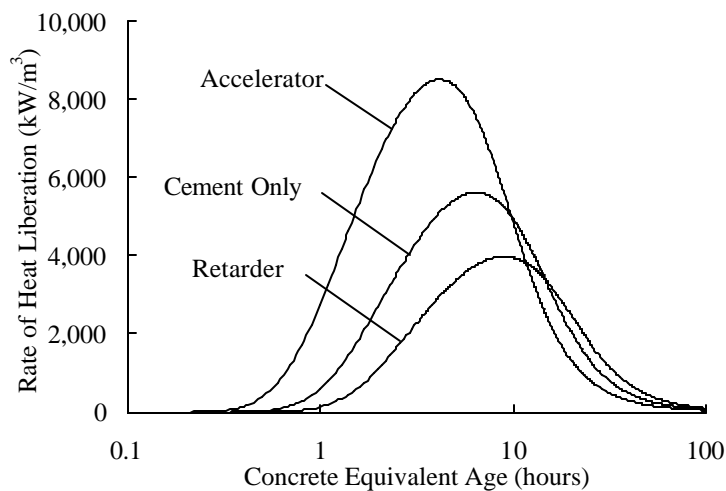


Figure 8: The effect of a retarder and accelerator on the rate of heat liberation

## 7. Summary and conclusions

With knowledge of the time to initial set, contractors will be able to plan measures to finish, texture, and saw cut concrete pavements on time to prevent setting of occurring before these activities. With the setting model proposed in this paper, the effect of temperature, different cements, and supplementary cementing materials on the initial and final setting times may be evaluated. Penetration resistance (ASTM C 403) setting data were collected under field and laboratory conditions for concrete mixtures containing different cements, fly ash types, and GGBF slag. The water-cementitious materials ratio of the mixtures varied between 0.39 and 0.54, and the cementitious materials content varied between 272 and 347 kg/m<sup>3</sup>. It was shown that setting of concrete in general occurs when a specific amount of hydration products have formed. These findings are in agreement with those reported by other researchers [7,13]. The proposed setting model is presented in Equations 6 and 7. With this model, accurate estimates of the equivalent age at initial and final setting can be obtained. However, when GGBF slag is used, setting occurs at an earlier degree of hydration. It is for this reason recommended that the interaction between setting and the hydration of GGBF slag be further investigated.

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## 9. References

1. Neville, A.M., 'Properties of concrete', 4th Edn, (John Wiley and Sons, Incorporated, New York, 1996).
2. Yu, H.T., Khazanovich, L., Darter, M.I., and Ardani, A., 'Analysis of concrete pavement responses to temperature and wheel loads measured from instrumented slabs', *Transportation Research Record* **1639** (1998), 94-101.
3. Freiesleben Hansen, P., and Pedersen, E.J., 'Maturity computer for controlling curing and hardening of concrete', *Nordisk Betong* **1**(19) (1977) 21-25.
4. Carino, N.J., 'The maturity method', in 'CRC Handbook on nondestructive testing of concrete', Chapter 5, V.M. Malhotra, and N.J. Carino, eds., (CRC Press, Florida, 1991).
5. ASTM C 403, 'Standard test method for time of setting of concrete mixtures by penetration resistance', *American Society for Testing and Materials*, Pennsylvania, (1999).
6. Tuthill, L.H., and Cordon, W.A., 'Properties and uses of initially retarded concrete', *Proceedings of the American Concrete Institute* **52**(2) (1955) 273-286.
7. Pinto, R.C.A., and Hover, K.C., 'Application of maturity approach to setting times', *ACI Materials Journal* **96** (6) (1999) 686-691.
8. Van Breugel, K., 'Simulation of hydration and formation of structure in hardening cement based materials', Ph.D. Thesis, 2nd Edn, (Delft University Press, Netherlands, 1997).
9. RILEM Technical Committee 119-TCE, 'Adiabatic and semi-adiabatic calorimetry to determine the temperature increase in concrete due to hydration heat of cement', in RILEM Report 15, 'Prevention of thermal cracking in concrete at early ages', R. Springenschmid, ed., (E & FN Spon, London, 1998) 315-330.
10. Freiesleben Hansen, P., and Pedersen, E.J., 'Curing of concrete structures', in 'Draft DEB-Guide to durable concrete structures', Appendix 1, (Comité Euro-International du

- Béton, Switzerland, 1985).
11. Pane, I., and Hansen, W., 'Concrete hydration and mechanical properties under nonisothermal conditions', *ACI Materials Journal* **9**(6) (2002) 534-422.
  12. Schindler, A.K., 'Concrete hydration, temperature development, and setting at early-ages', Ph.D. Dissertation, (The University of Texas at Austin, Texas, 2002).
  13. Byfors, J., 'Plain concrete at early ages', Research 3:80, (Swedish Cement and Concrete Research Institute, Stockholm, 1980).
  14. Chen, Y., and Odler, I., 'On the origin of portland cement setting', *Cement and Concrete Research* **22**(6) (1992) 1130-1140.