Effect of Temperature on the Setting Behavior of Concrete

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Abstract: The effects of fluctuating temperatures on the setting times of concrete mixtures made with different water-to-cement ratios, supplementary cementing materials (SCMs), and SCM dosages are evaluated in this paper. Initial and final set times of the concrete were determined with penetration resistance testing. Wet-sieved mortar samples were placed in hot and cold water baths that cycled over 24 h between temperature ranges of 32–41°C and 4–13°C, respectively. The control samples were cured at temperatures between 20 and 24°C. Results show that Class F fly ash will slightly retard setting, ground granulated blast furnace slag will slightly accelerate setting, and Class C fly ash will significantly increase setting times. It is shown that the equivalent age maturity method may be used to estimate setting times of concrete samples cured under fluctuating temperatures. Activation energy values are recommended for use with the equivalent age maturity method to predict setting.

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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 (Neville 1996). 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 (Yu et al. 1998). The ability to estimate final setting will thus be of benefit to any mechanistic-empirical model that predicts the performance of concrete pavements. Time of 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 consolidated 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, finish, and texture the in-place concrete. Under cold weather conditions, the time to initial set is extended, and the potential for plastic shrinkage cracking of the fresh concrete is increased. With knowledge of the time to initial set, contractors can more effectively plan measures to finish and texture concrete pavements and bridge decks.

For this study, experimental work was performed under laboratory conditions to determine the effect of nonisothermal (fluctuating) temperatures and various supplementary cementing materials (SCMs) on initial and final setting times. Initial and final set times of the concrete were determined with penetration resistance testing [ASTM C 403 (ASTM 1999)]. Concrete was batched at hot, cold, and control temperatures. The wet-sieved mortar samples were placed in hot and cold water baths that were programmed to cycle over 24 h between temperature ranges of 32–41°C and 4–13°C, respectively. The control samples were cured at temperatures between 20 and 24°C. This was done to simulate summer, winter, and laboratory conditions. These temperatures were chosen to maximize the effect of temperature on setting while staying within practicable temperature ranges. The effect of two Type I cements, different water-to-cement ratios, varied doses of Class F and Class C fly ashes, and varied doses of ground granulated blast furnace (GGBF) slag is examined.

Paper Objectives

The primary objectives of the research documented in this paper are as follows:

- Evaluate the effects of fluctuating temperatures on the setting times of various concrete mixes.
- Establish a setting-maturity relationship for various concrete mixtures.
- Evaluate the accuracy of the maturity method to estimate setting times.
- Evaluate the effect of various SCMs (fly ash and GGBF slag) on the setting behavior of concrete.

Research Significance

Given the knowledge of the time to initial set, contractors can effectively plan measures to finish, texture, and saw cut concrete flatwork on time. The time at which final set occurs is important because it indicates when the concrete strength and stiffness development initiates. This paper evaluates the use of the equivalent

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maturity method to account for the effect of curing temperature on the setting time of concrete. To improve the accuracy of the maturity method, guidance is provided to select appropriate activation energy values when different cement types and SCMs are used.

Background on Setting and the Maturity Method

The curing temperature of concrete is arguably the variable that has the most significant effect on the setting time of a specific concrete mixture. In this paper, the maturity method is used to account for the effect of nonisothermal temperature and time on the progress of hydration. The equivalent age maturity function shown in Eq. (1), as presented in ASTM C 1074 (ASTM 2004), is widely accepted as the most accurate maturity formulation (Carino 1991)

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

where t_e=equivalent age at the reference curing temperature (h); Δt=chronological time interval (h); T_c=average concrete temperature during the time interval, Δt (°C); T_r=constant reference temperature (°C); E=activation energy (J/mol); and R =universal gas constant (8.314 J/mol K).

ASTM C 403 (ASTM 1999), "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 (Tuthill and Cordon 1955). Tuthill and Cordon (1955) determined that at a penetration resistance of 27.6 MPa the concrete has reached a compressive strength of around 0.6 MPa and therefore could carry some measurable loads. Therefore, the 27.6 MPa level of penetration resistance was chosen to represent final setting.

Pinto and Hover (1999) evaluated how different temperatures affected the setting time in terms of the penetration resistance method described by ASTM C 403. Pinto and Hover 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 varied considerably when tested at different temperatures, they concluded that the computed equivalent age at setting was more uniform for each mixture. Thus, Pinto and Hover concluded, "initial and final set times can be estimated for any mixture by the maturity approach, given the apparent activation energy is obtained." The observations of Pinto and Hover were based on a single portland cement mortar sample (w/c=0.33). This paper will evaluate a wider range of mixtures that use different types and dosages of SCMs.

Schindler (2004) performed setting tests on several field and laboratory concrete mixtures using concrete mixtures with varying doses of SCMs. Field samples were obtained from seven concrete pavement projects paved in different seasons and in different climatic regions of Texas. Laboratory batches were made using the materials collected from the field projects. Schindler found that temperature had a significant effect on setting times of different concrete mixtures and that the equivalent age maturity method could be used to estimate the set times of laboratory and field cured concrete.

Experimental Work

Batching and Curing Conditions

In an effort to simulate concrete made at a batch plant and placed on a construction site, the concrete used in this study was batched at both hot and cold temperatures. This was done to study the effects of concrete setting under summer and winter concreting conditions. For comparison purposes, a control mixture was batched under normal laboratory conditions. To produce concrete

Table 1. Concrete Mixture Proportions Used for Experimental Work

	Type I cement			Class C fly ash		Class F fly ash		GGBF slag	
Constituent	Type I-0.41	Type I-0.44	Type I-0.48	20%	30%	20%	30%	30%	50%
Water (kg/m^3)	158	162	177	158	158	158	158	158	158
Type I cement-Batch A (kg/m^3)	390	—	—	312	274	312	274	274	195
Type I cement-Batch B (kg/m^3)	—	368	368	—	—	—	—	—	—
Class F fly ash (kg/m^3)	—	—	—	—	—	78	117	—	—
Class C fly ash (kg/m^3)	—	—	—	78	117	—	—	—	—
GGBF slag (kg/m^3)	—	—	—	—	—	—	—	117	195
Coarse aggregate (kg/m^3)	1,082	1,165	1,140	1,082	1,082	1,082	1,082	1,082	1,082
Coarse aggregate size (crushed stone)	Number 67	Number 67	Number 67	Number 67	Number 67	Number 67	Number 67	Number 67	Number 67
Fine aggregate (kg/m^3)	718	675	662	705	698	693	680	710	704
Target slump (mm)	76	76	76	76	76	76	76	76	76
Target air (%)	5.0	4.0	4.0	5.0	5.0	5.0	5.0	5.0	5.0
Air-entraining admixture (mL/m^3)	116.0	77.4	58.0	116.0	116.0	116.0	116.0	116.0	116.0
ASTM C 494-Type D admixture (mL/m^3)	762.0	359.7	—	762.0	762.0	762.0	762.0	762.0	762.0
w/c	0.41	0.44	0.48	0.51	0.58	0.51	0.58	0.58	0.81
w/cm	0.41	0.44	0.48	0.41	0.41	0.41	0.41	0.41	0.41

Table 2. Chemical and Physical Characteristics of the Cementitious Materials

	Type I portland cement		Fly ash		
Parameter	Batch A	Batch B	Class C	Class F	GGBF slag
Silicon dioxide (SiO_2) (%)	20.32	20.85	39.94	53.09	32.68
Aluminum oxide ($A1_2O_3$) (%)	4.75	4.47	18.51	29.10	9.67
Iron oxide (Fe_2O_3) (%)	3.03	2.96	5.71	7.54	1.12
Calcium oxide (CaO) (%)	65.12	64.11	23.01	1.56	45.92
Free CaO (%)	0.21	0.24	—	—	—
Magnesium oxide (MgO) (%)	2.46	2.77	5.26	0.94	7.40
Alkalies ($Na_2O+0.658K_2O$) (%)	0.25	0.28	2.25	2.04	—
Sulfur trioxide (SO_3) (%)	2.56	2.90	1.56	0.10	1.66
Loss on ignition (LOI) (%)	1.10	1.19	0.23	2.19	0.84
Tricalcium silicate (C_3S) (%)	67.08	60.01	—	—	—
Dicalcium silicate (C_2S) (%)	7.66	14.51	—	—	—
Tricalcium aluminate (C_3A) (%)	7.48	6.83	—	—	—
Tetracalcium aluminoferrite (C_4AF) (%)	9.21	9.00	—	—	—
Specific surface area (m^2/kg)	380	—	—	—	520
Specific gravity	3.15	3.15	2.63	2.29	2.91

with different fresh temperatures, the raw materials for the hot and cold mixtures were placed in an environmental chamber set at 46°C and 4°C, respectively, for at least 2 days prior to batching. This yielded fresh concrete temperatures of approximately 40 and 14°C for hot and cold batches, respectively. The fresh concrete temperature of the control batch was between 20 and 24°C. All the concrete was mixed and batched in an air-conditioned enclosed concrete laboratory.

To control the variable temperature of the fresh mortar used for penetration resistance testing, two tanks with copper radiating pipes were constructed. The two 2.4 m by 0.76 m by 0.6 m tanks were surrounded by 100-mm-thick polystyrene insulation. A 28-L programmable heating/cooling circulator controlled the temperature in the tanks through a closed system of 13-mm diameter copper tubing within the tanks. The circulators were programmed to run on 24-h cycles to simulate night and day temperatures. Initially, calibration runs were required to achieve the desired temperature cycles in the tanks. In this study, 530 L of water had to be controlled by the circulating system. Prior to the start of testing, the circulator program was adjusted until the desired temperature ranges of 32–41°C and 4–13°C for the tank water were reliably produced over multiple 24-h cycles. A tank exposed to normal room temperatures between 20 and 24°C was used for the control temperature. Examples of typical mortar and water bath temperatures measured in this study are presented in Fig. 1.

Batching and Test Methods

Nine different mixture proportions were developed and mixed at three different temperatures, giving 27 total batches for this study. All batches were 0.16 m^3 and mixed in a 0.34-m^3 drum mixer. Before each batch, the mixer was "buttered" to coat the sides and blades of the mixer with mortar. Coarse and fine aggregates were first added and mixed with 80% of the mixing water and air-entraining chemical admixture. After 2 min of mixing, all the cement and SCMs, the remaining 20% water, and any ASTM C 494-Type D (water-reducing and retarding) chemical admixtures were added. All the materials were then mixed for 3 min, followed by a 3-min rest, followed by 2 min of final mixing.

After completion of mixing, the slump, air content, unit weight, and temperature of the fresh concrete were measured and recorded according to the appropriate ASTM standards. After all the fresh concrete quality control tests were performed, 19 150-mm diameter by 300-mm high cylinders were made for a related strength study. At the same time, concrete was wet sieved through a 4.75-mm (No. 4) sieve into a nonabsorptive pan. A vibrating table was used to wet sieve the concrete. The sieved mortar was rodded into a closable mold that was 216 mm in diameter and 178 mm in height. Prior to penetration resistance testing, one side of the specimen was raised to allow for the collection and removal of bleed water.

A temperature sensor was placed in the center of the fresh mortar specimen at approximately midheight to record the temperature history of the mortar. Thermochron iButtons made by Dallas Semiconductor (Dallas, Tex.) were used to measure and record the temperature development of each mortar sample. iButtons record the temperature in programmable intervals and reportedly have an accuracy of ±1.0°C. Wires were attached to each iButton to download the recorded data to a personal computer. After the wires were attached, each iButton was sealed with two layers of a liquid urethane coating. A time interval of 2 min was used to record the temperature of the mortar samples. Finally,

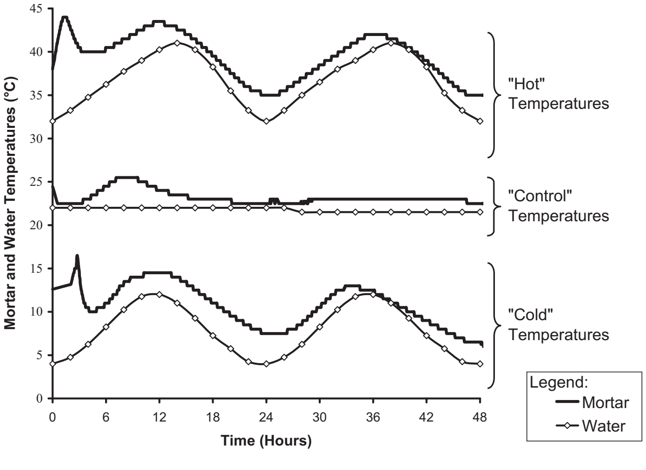

Fig. 1. Typical mortar and water bath temperatures measured in this study

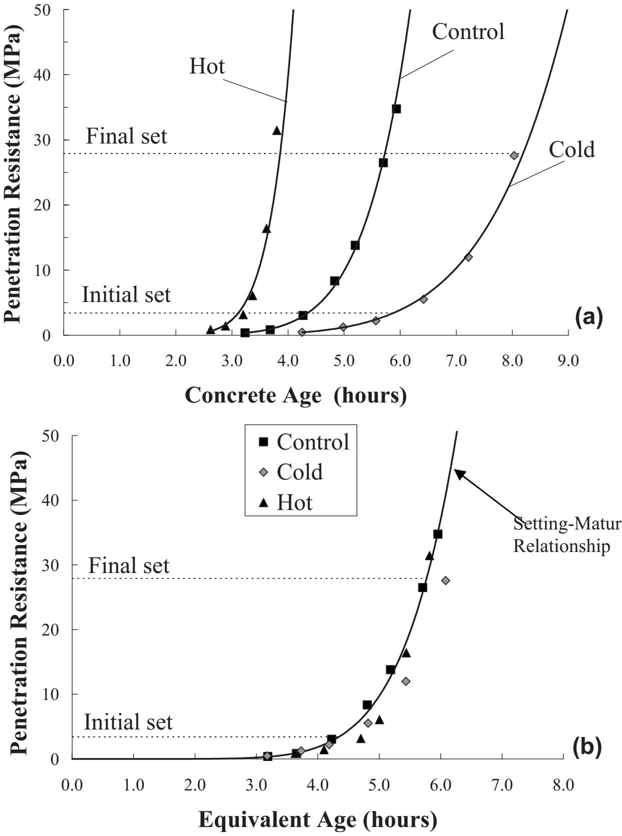

Fig. 2. Results for the 30% slag mixture: (a) effect of temperature on setting times; (b) setting-maturity relationship

each mortar specimen was placed in the required water bath, where it was submerged to about four-fifths of the mold height. This curing method was sufficient to control the temperature of the mortar to simulate the desired summer, winter, and laboratory conditions.

Materials and Mixtures Used

The setting behavior of nine mixtures is investigated in this paper. Each mixture was tested under hot, cold, and control temperatures. Chemical admixtures were added to achieve the target air and slump for the control batch temperature (between 20°C and 24°C). Hot and cold batches were identical to the room temperature mixture proportions, regardless of effect of temperature on the concrete's consistency. As previously published, it was observed that the higher the fresh concrete temperature, the lower the slump. Table 1 summarizes the nine mixture proportions including water-to-cement ratio, chemical admixtures used, and target air and slump. A standard ASTM type I cement (Batch A) was used for the control mixture (Type I-0.41) and this mixture had a w/c=0.41. The type and dosage level of the SCMs used with this cement were varied. Class C fly ash and Class F fly ash at replacement dosages of 20 and 30% were tested. A Grade 120 GGBF slag was used at replacement dosages of 30 and 50%. The cement replacement dosages of the SCMs were determined on a mass basis.

Type I Cement A is the basis for all comparisons as this cement was used with the SCMs. The Type I-0.44 and Type I-0.48 mixtures have water-to-cement ratios of 0.44 and 0.48, respectively. These mixtures were developed to determine the effect of an increase in water-to-cement ratio on setting. Due to an increase in the water-to-cement ratio between Mixtures type I-0.41, I-0.44, and I-0.48 the mixture proportions and chemical admixtures had to be adjusted to obtain similar consistencies. Due to a shortage of cement, a different batch of cement (Batch B) was used for Mixtures type I-0.44 and I-0.48. These two Type I cements were produced at the same plant, but were sampled a few months apart. A chemical analysis was performed by an independent commercial laboratory on both Type I cements and all SCMs used. The chemical composition and physical properties of the cementitious materials are presented in Table 2. It may be seen that the different batches of cement were similar.

Testing and Data Analysis

The times of initial and final set were determined by means of penetration resistance testing in accordance with ASTM C 403 (ASTM 1999). In this test, the maximum force required to penetrate needles of different sizes to a depth of 25 mm over a 10-s period is measured. As the concrete stiffens, the size of needle is progressively decreased, which increases the pressure that can be applied to the mortar surface. ASTM C 403 recommends a minimum of six penetration tests be carried out and testing should continue until the final setting penetration resistance is exceeded. During the data analysis, the best-fit power function, as recommended by ASTM C 403, was fitted through the data points. The initial and final set times are calculated by interpolating the initial and final set pressures from the best-fit power curve.

Since the temperature history of each mortar sample was collected, the equivalent age of the sample can be determined. The best-fit curve obtained for curing the samples at the isothermal reference temperature was used to estimate the setting times at the two fluctuating temperature conditions. Initially the temperature sensitivity of each mixture was not known, the writers assumed an initial activation energy value of 40,000 J/mol as recommended by ASTM C 1074 (ASTM 2004). To determine activation energy for each mixture, batched at three different temperature histories, the sum of the square of the errors (SSEs) between the actual test age (y_i) and the estimated age ($\hat{y}_i$) at each penetration resistance measurement computed with maturity principles was minimized. This can mathematically be expressed as shown in Eq. (2)

$$\mathrm{SSE} = \sum (\hat{y}_i - y_i)^2 \tag{2}$$

where SSE=sum of the square of the errors; $\hat{y}_i = i$th estimated age (h); and $y_i = i$th actual test age (h).

The age computed by maturity principles was determined by using the penetration resistance readings and times collected at the control condition. This procedure produced approximately the same activation energy values as those obtained by plotting the Arrhenius plot as presented by Pinto and Hover (1999). When the Arrhenius plot is produced, the activation energy is equal to the product of the universal gas constant (8.314 J/mol K) and the negative of the slope of the best-fit line on the Arrhenius plot (ASTM 2004; Carino 1991).

Results and Discussion

Effect of Fluctuating Temperatures on Setting Times

First, the effect of fluctuating and variable temperatures on setting times is examined. Fig. 2(a) shows the penetration resistance

Table 3. Setting Times and Activation Energies

Mix	Batch	Concrete age (h)		Equivalent age (h)		Activation energy (J/mol)
		Initial set	Final set	Initial set	Final set	
Type I-0.41	Hot	3.40	4.12	4.92	6.05	27,100
	Control	4.63	6.09	4.55	6.06	
	Cold	6.64	8.83	4.64	6.32	
Type I-0.44	Hot	2.87	3.63	4.49	5.81	31,600
	Control	4.25	5.54	4.36	5.69	
	Cold	6.01	8.22	4.36	5.96	
Type I-0.48	Hot	2.82	3.59	4.77	6.29	33,400
	Control	4.52	6.14	4.39	6.06	
	Cold	6.75	9.42	4.72	6.65	
20% C	Hot	4.86	5.72	7.25	8.76	27,000
	Control	7.63	9.17	7.06	8.53	
	Cold	10.53	13.23	7.15	9.07	
30% C	Hot	5.45	6.51	8.63	10.37	29,300
	Control	9.26	11.33	8.47	10.43	
	Cold	12.07	15.12	8.44	10.57	
20% F	Hot	4.01	4.91	5.52	6.91	25,700
	Control	6.10	7.70	5.42	6.90	
	Cold	7.68	9.92	5.38	7.10	
30% F	Hot	3.96	4.69	5.98	7.21	23,300
	Control	6.38	8.00	5.67	7.17	
	Cold	8.09	10.59	5.85	7.69	
30% slag	Hot	3.12	3.85	4.52	5.95	26,700
	Control	4.36	5.72	4.33	5.74	
	Cold	5.89	8.18	4.41	6.18	
50% slag	Hot	2.65	3.30	4.47	5.89	35,200
	Control	4.96	6.29	4.51	5.77	
	Cold	7.31	9.85	4.44	5.97	

points collected for three batches (hot, cold, and control) for the 30% slag mixture. The best-fit power curve for each batch is also shown as a solid line on Fig. 2(a). The significant effect that temperature has on setting, as shown by this figure, is typical for all the mixtures. The initial and final setting times for all the mixtures are summarized in Table 3. In Fig. 2(a) and Table 3, it may be seen that the concrete batched and cured at the hot temperature set much faster than the corresponding concrete batched and cured at the two lower temperatures. This agrees with previous studies performed by Pinto and Hover (1999) using isothermal conditions and by Schindler (2004) using isothermal and field conditions. Since these results indicate that setting occurs earlier at higher temperatures and later at lower temperatures, the use of the maturity method should be explored to determine if this method can be used to estimate the setting of a variety of mixtures.

Activation Energy Values

By using the method described previously, best-fit activation energy values were determined for all nine mixtures. A reference temperature (T_r) of 22.8°C was used for all maturity calculations. The activation energy (E) value that was obtained for each mixture is listed in the last column of Table 3. The activation energy defines the temperature sensitivity of a concrete mixture. A large activation energy value means that the mixture has large temperature sensitivity. In other words, the higher the activation energy the larger the difference in setting times when samples of a given concrete mixture are cured at different temperatures. The importance of the activation energy value increases as the curing temperatures become further removed from the reference temperature.

For a straight Type I cement mortar with no chemical admixtures, Pinto and Hover (1999) reported activation energy values that ranged between 37,600 and 40,900 J/mol. ASTM C 1074 (ASTM 2004) recommends an activation energy value in the range of 40,000–45,000 J/mol for strength estimation applications when a Type I cement with no admixtures is used. Based on setting tests performed at different temperatures, Schindler (2004) reported activation energy values that range from 35,300 to 50,600 J/mol for Type I cement mixtures with various types and dosages of SCMs. The activation energy values determined in this study ranged between 23,300 and 35,200 J/mol as seen in Table 3. The average activation energy obtained for Type I cement is 30,700 J/mol. The activation energies found in this study are generally lower than previous values given by Pinto and Hover (1999) and Schindler (2004).

Some trends can be observed from the activation energies in Table 3 when the Type I-0.41 mixture is compared to the various SCM mixtures as well as to the mixtures with different water-to-cement ratios (i.e., Types I-0.44 and I-0.48). The Type I-0.41 mixture has an activation energy of 27,100 J/mol. It can be seen that increased replacement of Class F fly ash generally decreases the activation energy. Mixtures with low dosages of Class C fly ash (dosage ≤20%) and GGBF slag (dosage ≤30%) appear to

Table 4. Comparison of Measured versus Estimated Setting Time

Mix	Batch	Initial set Measured time (h)	Initial set Estimated time (h)	Initial set Difference (min)	Final set Measured time (h)	Final set Estimated time (h)	Final set Difference (min)
Type I-0.41	Hot	3.40	3.17	14	4.12	4.12	0
	Cold	6.64	6.52	7	8.83	8.52	19
Type I-0.44	Hot	2.87	2.80	4	3.63	3.55	5
	Cold	6.01	6.01	0	8.22	7.88	20
Type I-0.48	Hot	2.82	2.63	11	3.59	3.47	7
	Cold	6.75	6.31	26	9.42	8.62	48
20% C	Hot	4.86	4.73	8	5.72	5.58	8
	Cold	10.53	10.42	7	13.23	12.48	45
30% C	Hot	5.45	5.36	5	6.51	6.53	−1
	Cold	12.07	12.10	−2	15.12	14.93	11
20% F	Hot	4.01	3.94	4	4.91	4.90	1
	Cold	7.68	7.74	−4	9.92	9.70	13
30% F	Hot	3.96	3.77	11	4.69	4.66	2
	Cold	8.09	7.87	13	10.59	9.90	41
30% slag	Hot	3.12	2.99	8	3.85	3.75	6
	Cold	5.89	5.81	5	8.18	7.62	34
50% slag	Hot	2.65	2.67	−1	3.30	3.24	4
	Cold	7.31	7.29	1	9.85	9.53	19

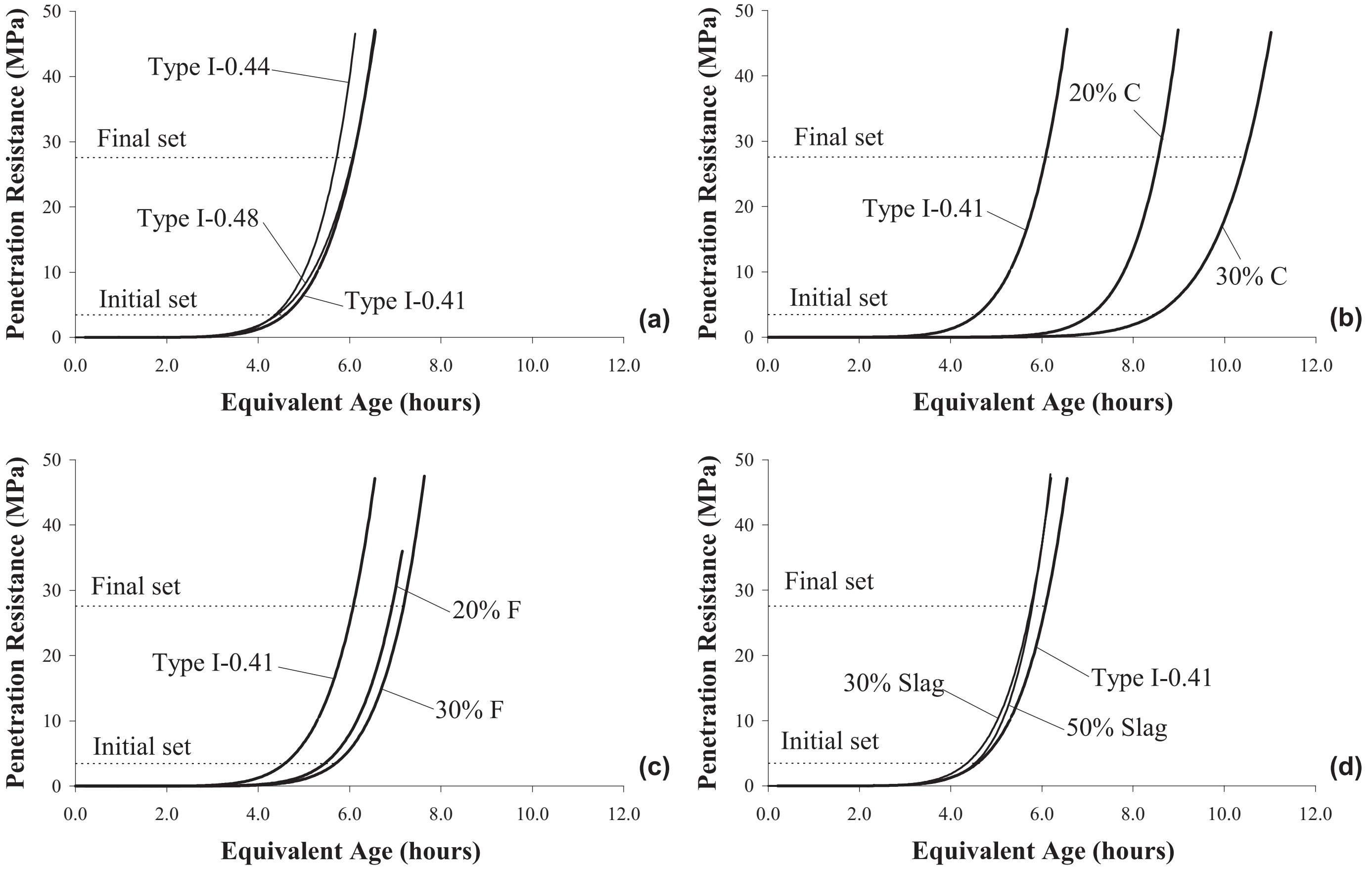

Fig. 3. Setting-maturity relationships for all mixtures: (a) effect of w/c; (b) effect of Class C fly ash; (c) effect of Class F fly ash; and (d) effect of GGBF slag

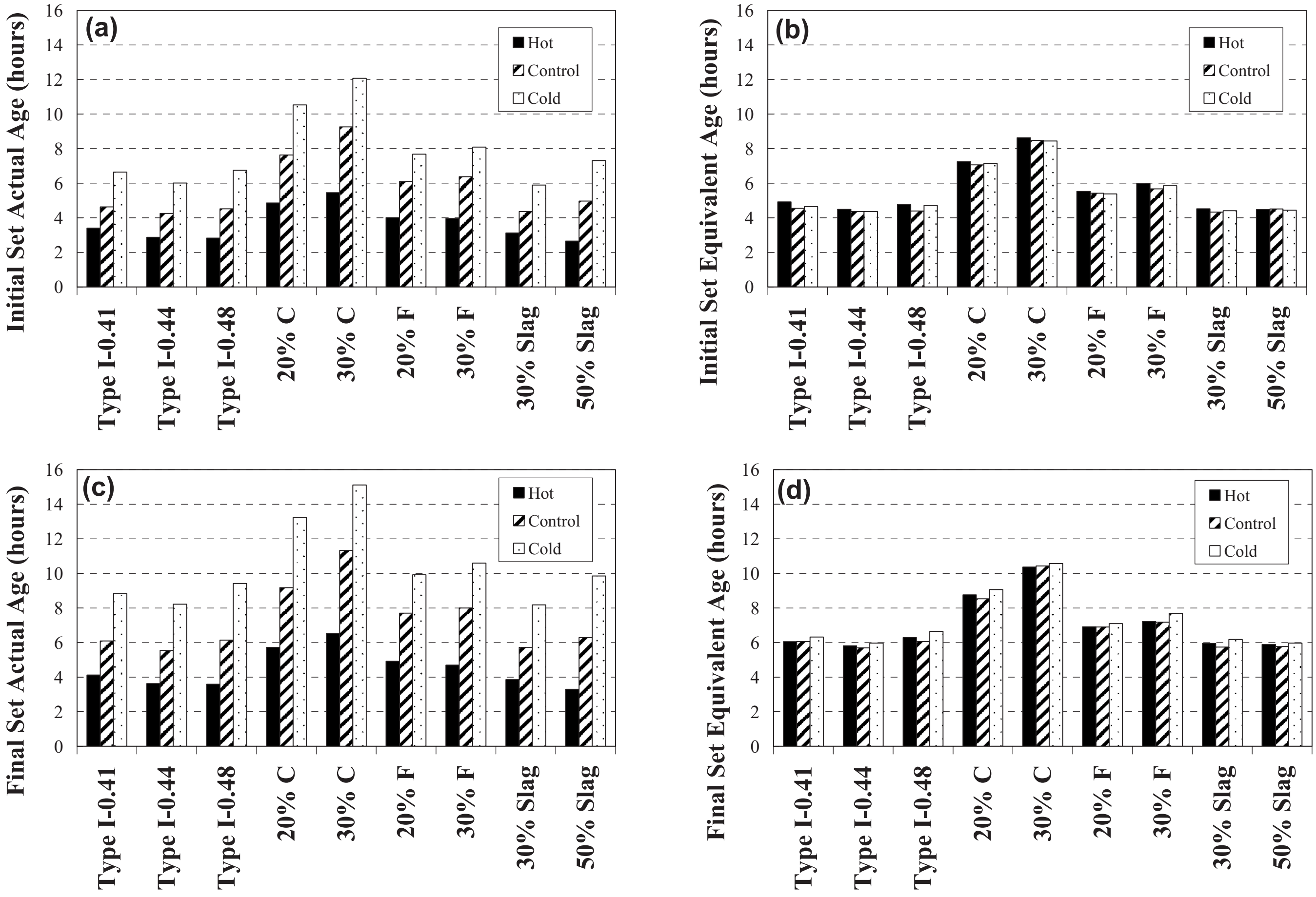

Fig. 4. Set times for all mixtures: (a) initial set in actual concrete age; (b) initial set in equivalent age; (c) final set in actual concrete age; and (d) final set in equivalent age

have activation energy values similar to the straight Type I cement mixture. In addition, the 50% mixture replacement dosage of GGBF slag seems to have a 30% larger activation energy than the straight Type I cement mixture. When the three Type I mixtures are compared, it is evident that an increase in w/c yields an increase in activation energy.

Application of the Maturity Method to Estimate Setting Times

Fig. 2(b) shows all the penetration resistance results collected for the 30% slag mixture with the equivalent age of each test plotted on the horizontal axis. It may be seen in Fig. 2(b) that the use of an activation energy value of 26,700 J/mol and the equivalent age maturity method causes all the data points to approximately converge onto a unique penetration resistance curve. The curve developed is a mixture-specific relationship that can be used to estimate setting times at any temperature, both isothermal and fluctuating. Analogous to the strength-maturity relationship concept defined in ASTM C 1074 (ASTM 2004), the writers of this paper propose to introduce the setting-maturity relationship concept to estimate setting at different temperatures. The setting-maturity relationship for 30% slag mixture is the solid curve indicated on Fig. 2(b), and this curve characterizes the setting of the mixture should it be tested at an isothermal temperature equal to the reference temperature (the setting-maturity relationships for all the mixtures can be seen in Fig. 3, and these will be discussed in more detail in the following section).

Table 3 shows the initial and final setting times, in actual hours and equivalent age hours, for all mixtures. To allow visual comparison of the data, the various setting times are also plotted on Fig. 4. It can be seen from Table 3 and Figs. 4(a and c) that the time to initial and final set decreases as the temperature increases for all mixtures. However, when equivalent age maturity values are examined, Figs. 4(b and d), it may be seen that for each mixture unique equivalent ages are reached at initial and final set, respectively. These observations are similar to those reached by Pinto and Hover (1999). Therefore, the equivalent age maturity method may be used to estimate the setting of concrete samples cured under fluctuating temperature histories even if they are made with different water-to-cement ratios, SCMs, and SCM dosages.

Accuracy of Setting-Maturity Relationship

As can be seen in Fig. 2(b), there are some differences between actual setting times and those estimated by the mixture-specific setting-maturity curve. The difference between the measured and estimated initial and final setting times were determined and these are summarized in Table 4. Since the setting-maturity relationship was determined from the results obtained at the control temperature, differences are only shown for the variable hot and cold temperature batches. The estimated initial set times for all mixtures tested are within 30 min of the measured values (94% of the values are within 15 min). This is well within a practicable time range for jobsite decisions. The estimated final set values show some larger differences. All hot batched/cured final set times are within 10 min of the estimated final set times. On the other hand, all of the cold batched/cured final set times are within 50 min of the estimated values. All cold batches achieved final set after the estimated time. This indicates that the time translation provided by the equivalent age maturity method should probably be larger from the reference to the cold temperature than from the reference to the hot temperature. Even though the estimates for cold temperatures are not as accurate, setting at these temperatures occurs at later times, and the relative accuracy is still acceptable. For example when final setting of the 20% C mixture is considered, a 45-min error over 13.23 h (6% error) is only slightly less accurate than an 8-min error over 5.7 h (2% error). These results show that initial and final setting times can be estimated within practicable ranges provided that mixture-specific setting-maturity relationship and activation energy are used.

Effect of Supplementary Cementing Materials and Water-to-Cement Ratio on Setting Behavior

The setting-maturity relationships determined for all the mixtures are summarized in Fig. 3. The shape of the setting-maturity curves in Fig. 3 provides valuable information on the setting behavior of the different mixtures. Each graph in Fig. 3 shows the Type I-0.41 mixture compared to a specific group of SCMs or to the change in water-to-cement ratio.

First, the effect of SCMs on setting behavior will be discussed. It can be concluded from Fig. 3(b) that the use of this Class C fly ash significantly increases setting times, which is as reported by Eren et al. (1995). The increase in setting time (retardation) increases as the replacement dosage of Class C fly ash is increased from 0 to 30%. From Fig. 3(c) it can be concluded that the use of this Class F fly ash generally increases set times, but Class F fly ash does not retard setting as much as Class C fly ash. An increase in the replacement dosage of Class F fly ash slightly increases the setting times. Fig. 3(d) shows that the use of Grade 120 GGBF slag has little effect on setting times. The Grade 120 GGBF slag appears to slightly accelerate the setting process. It should be clarified that the 50% slag mixture will set faster at higher temperatures than the Type I-0.41 mixture since it was shown to have a higher activation energy value.

Next, the effect of increased water-to-cement ratio on the setting-maturity relationship is examined on Fig. 3(a). From this figure it would appear that the use of different water-to-cement ratios has little effect on the setting times. However, due to the different water-to-cement ratios and the desire to produce concrete with equal consistency, it should be noted that different dosages of an ASTM C 494-Type D (water-reducing and retarding) chemical admixture were used in these three mixtures. It is possible that the effect of adding the Type D chemical admixture to the Type I-0.41 mixture is similar to having no Type D chemical admixture and a higher w/c ratio, in terms of setting times. However, due to the limited data available, this issue should be investigated further to support and further explain these findings.

Conclusions

In this study, the setting behavior of nine concrete mixtures was examined under fluctuating curing temperatures. The effect of two Type I cements, different water-to-cement ratios, varied doses of Class F and Class C fly ashes, and varied doses of GGBF slag was examined. Penetration resistance tests were performed according to ASTM C 403 (ASTM 1999). The results of the experimental study documented in this paper support the following conclusions:

1. Under fluctuating curing temperatures, setting occurs earlier at higher temperatures and later at lower temperatures.
2. The equivalent age maturity method may be used to estimate setting times of concrete samples cured under fluctuating temperatures even if they are made with different water-to-cement ratios, SCMs, and SCM dosages.
3. Initial and final setting times can be estimated within practicable ranges provided that mixture-specific setting-maturity relationship and activation energy are used.
4. The use of Class C fly ash significantly increases setting times. The retardation increases with an increase in the Class C fly ash replacement dosage.
5. The use of Class F fly ash generally increases set times, but Class F fly ash does not retard as much as Class C fly ash. An increase in the replacement dosage of Class F fly ash slightly increases the setting times.
6. The use of Grade 120 GGBF slag seems to have little effect on setting times. If any, the Grade 120 GGBF slag appears to slightly accelerate the setting process.

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Notation

The following symbols are used in this paper:

E = activation energy (J/mole);
R = universal gas constant, 8.3144 J/mol/K;
SSE = sum of the square of the errors;
T_c = average concrete temperature during time interval (°C);
T_r = reference temperature (°C);
t = chronological age (h);
t_e = maturity in terms of equivalent age (h);
y_i = ith actual test age (h);
$\hat{y}_i$ = ith estimated age (h); and
Δt = chronological time interval between temperature measurements (h).

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