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Setting Behaviour and Shrinkage of High Performance Pavement Concrete

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Abstract— The work presented in this thesis focuses on setting the behavior and shrinkage properties of high-performance pavement concrete and the effect factors, such as supplementary cementitious materials (SCMs), chemical admixtures, and temperature. The thesis consists of two papers: (1) the relation between setting behavior and the maturity of pavement concrete materials and (2) a simple statistical model to predict the shrinkage behavior of high-performance concrete containing supplementary cementitious materials. Setting behaviour and maturity of six different concrete mixtures under three different curing temperatures (18.3, 23.9, and 29.4ºC, corresponding to 65, 75 and 85ºF) were investigated. The mixtures were made with two different retarders (ASTM Types B and D) and with 0 or 20% Class C fly ash replacement for Type I cement. The initial and final set times of these mixtures were measured by the penetration resistance method according to ASTM C 403. The temperature rise of the mixtures was monitored using a thermal couple, and the concrete maturity was then computed based on the time- temperature factor (TTF). A new approach is introduced for predicting concrete set time (penetration resistance) based on the concrete maturity (time-temperature factor). The results indicate that concrete penetration resistance well correlates with maturity measurements. This relationship enables engineers to assess setting behaviour of field concrete on site autogenous shrinkage and free drying shrinkage of nine different high performance concrete mixtures used for bridge decks and bridge overlays constructions were measured, and the total shrinkage (defined as autogenous shrinkage plus free drying shrinkage) was studied. The mixtures were systemically designed for evaluating effects of class C fly ash and ground granulated blast-furance slag replacement on shrinkage properties. A simplified exponential model $\varepsilon_{auto/drying}(t)=a+b*e^{(c*t)}$ was introduced for describing and predicting shrinkage in high-performance concrete when different types and amounts of supplementary cementitious materials were used. This model fits for both autogenous and free drying shrinkage and is validated and proved by comparing measured value with predicted shrinkage value of an independent group of mixtures. The results indicate that compare to GGBF slag, fly ash performs much better to reduce the total shrinkage. Additionally, free drying shrinkage increases linearly with autogenous shrinkage between 0 and 14 days. The results of the present study indicate that the concrete maturity method successfully describes the concrete setting behavior; and the exponential model successfully predicts the shrinkage behavior of high-performance concrete with SCMs. Additionally, the results indicate Class C fly ash replacement can reduce the total shrinkage and extend the setting time of high-performance concrete. The addition of Class C fly ash should be considered if extending concrete setting time and reducing therisk of shrinkage cracking are needed.

Keywords: Shrinkage Of Concrete, Penetration Test, Free Drying Shrinkage, Curing

I. INTRODUCTION

In recent times, builders have commonly used high-performance concrete (HPC) in bridge decks and bridge overlays construction due to its high strength and rapid strength development. However, due to its properties—such as low water-to- cementitious material ratio, high doses of chemical admixtures, and high cementitious materials content—HPC always has a high potential risk of shrinkage cracking and exhibiting short setting time. At present, a study that evaluates and predicts shrinkage and setting behavior of high-performance concrete is necessary.

The purpose of this thesis is to use new approaches to describe the setting behavior and shrinkage properties of high-performance concrete. A comprehensive study was conducted to examine the effects of supplementary cementitious materials, such as fly ash, on the setting behavior and shrinkage of high-performance concrete.

For the setting behavior study (paper 1), six different HPC mixtures were designed to investigate how the 20% fly ash replacement, retarders, and curing temperatures would affect concrete initial and final setting times, as well as to investigate the relationship between the maturity index (a time–temperature factor) and penetration resistance under 18.3, 23.9, and 29.4□C. Theoretically speaking, for a specific mixture, if a concrete sample reaches an equal maturity index with another sample, its strength should also be equal. The results of this study indicate that concretematurity is related to penetration resistance because penetration resistance relates to concrete strength. The penetration resistance - elapsed time curves at three different.

Temperatures should normalize as one curve if the datum temperature is properly selected. Once the normalized curve is established, the penetration resistance at a certain temperature can be predicted by measuring only the concrete maturity.

For shrinkage model study (paper 2), nine different HPC mixtures with different replacement rates of class-C fly ash and slag were systemically designed. Two of them were designed independently to use for a model validation test. Compared to normal- strength concrete, the amount of autogenous shrinkage of HPC is always considerable and contributes to the total shrinkage. Therefore, an exponential model was developed toadd the autogenous shrinkage and free drying shrinkage together to determine the total shrinkage.

Those two studies both focused on high-performance pavement concrete with similar materials (such as fine aggregate, Class C fly ash) and mix proportions and, therefore, were highly related. In some cases, concrete setting behavior also affects shrinkage measurements. For instance, to measure the autogenous shrinkage of mortar instudy 2, I first determined the corresponding final setting time according to the standard.For the 20% fly ash HPC mixture, rather that measuring its final setting, simply using the conclusion of the study 1, which meant simply multiplying the final setting time for the corresponding control mixture by a factor of 1.10.

II. OBJECTIVES

This study is aimed at developing a new approach to describe the relationship between penetration resistance and elapsed time of concrete based on the maturityconcept.

III. TEST RESULTS AND DISCUSSION

Summary of Concrete Set Time Results

Table 5 summarizes the initial set time and final set time for all six concretemixtures at three different temperatures tested in this study.

Concrete Mixtures	Temperature (ºC)	Initial Set Time (min.)	Final Set Time (min.)
Retarder 1, 20%Fly Ash	29.4	480	575
	23.9	530	630
	18.3	645	792
Retarder 1, No FlyAsh	29.4	455	548
	23.9	480	580
	18.3	555	695
Retarder 2, 20%Fly Ash	29.4	278	370
	23.9	435	490
	18.3	575	680
Retarder 2, No FlyAsh	29.4	250	335
	23.9	360	480
	18.3	530	635
No Retarder, 20%Fly Ash	29.4	195	275
	23.9	230	342
	18.3	300	428
No Retarder, NoFly Ash	29.4	165	245
	23.9	195	290
	18.3	240	375

Table 5: Concrete set times measured under different curing temperatures

A. *Effect of Curing Temperature*

To better study the effect of temperature, the obtained initial/final set time values(Columns 3 and 4 in Table 5) were averaged and plotted against temperature in Figure 4. As expected, the initial/final set time decreased linearly with the increased curing temperature. From data regression, the following relationships between the initial/final set time (IS/FS) and temperature (T) was obtained:

IS (min)= -15.4(T)+750 $(R^2 = 0.99)$ (1)
FS (min)= -18.9(T)+938 $(R^2= 0.98)$ (2)

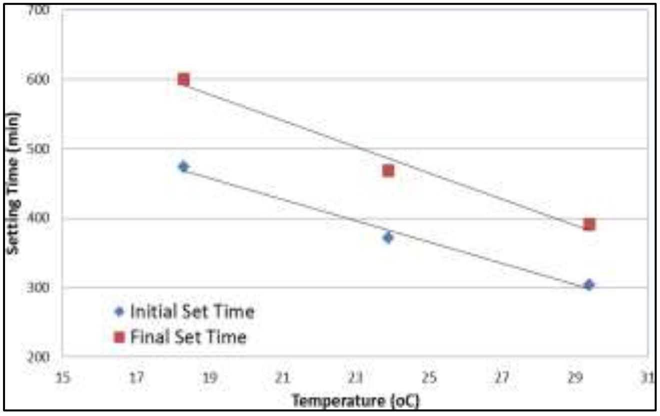
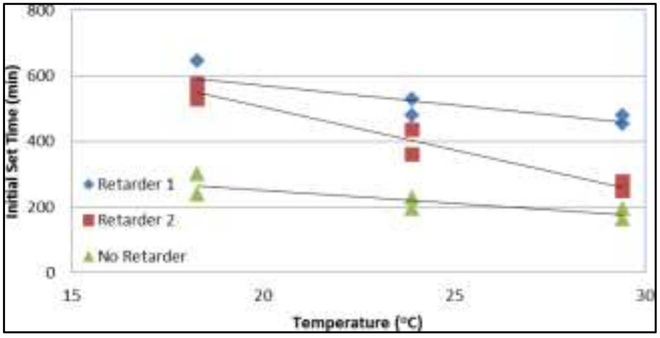


Fig. 4: Effect of temperature on concrete set time

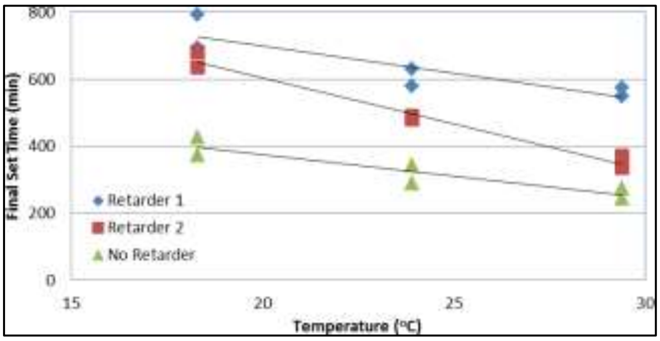
According to the linear relationship illustrated above, if curing temperature raises1ºC, the initial set time and final set time will drop about 15 min and 19 min respectively. This relationship can be used in the field to adjust the estimated concrete set time if the curing temperature has been changed.

B. *Effect of Retarders*

Figure 5 illustrates the effects of the two retarders used in the study on concrete initial and final set times. As anticipated, both the retarders extended concrete set time. However, the degree of extension was higher for the concrete mixtures with 325 ml/100 kg of Retarder 1 than the mixtures with 260 ml/100 kg of Retarder 2. It is also noted thatthe mixtures with Retarder 2 were more sensitive to the change of curing temperature, and their set times decreased more rapidly than those of the mixtures with Retarder 1 as the curing temperature increased.



(a) Initial Set



(b) Final Set

Fig. 5: Effect of retarder type on concrete set time

C. *Effect of Fly Ash Replacement*

As expected, the 20% fly ash replacement for cement extended concrete initial/final set time due to its slow hydration process and water reducing effect. To effectively evaluate the influence of the fly ash, the initial/final set times for concrete mixtures with fly ash replacement are normalized (or divided) by the set times of the corresponding concrete mixtures without fly ash replacement, and the results are listed inTable 6.

As seen in Table 6, the normalized initial set times for mixtures with different retarders under three different temperature conditions are very close, 1.15, while the normalized final set times for these mixtures are approximately equal to 1.10. Based on these results, when a new retarder is used in a concrete mixture, one can estimate the initial/final set times of the mixture with 20% fly ash replacement by testing initial/finalset time for the mixture without fly ash replacement and multiplying the results with thefactor of 1.15 or 1.10, respectively, thus, significantly reducing the number of set time tests required for construction operations.

Temperature(°C)		Normalized Set Time			
		Retarder 1	Retarder 2	No Retarder	Average
Initial	29.4	1.05	1.11	1.18	1.12
	23.9	1.10	1.21	1.18	1.16
	18.3	1.16	1.08	1.25	1.17
Final	29.4	1.05	1.10	1.12	1.09
	23.9	1.09	1.02	1.18	1.10
	18.3	1.14	1.07	1.14	1.12

Table 6: Normalized set times of concrete mixtures

D. *Concrete Setting Behavior and Maturity*

The maturity concept has been widely used to account for the effect of different curing temperatures on the strength development of concrete (4, 5). Since penetration resistance is also related to concrete strength, a correlation between the penetrationresistance and concrete maturity is expected.

According to ASTM C 1074, concrete maturity can be expressed as the time-temperature factor (TTF) based on the Nurse-Saul equation as shown below:

$$M \text{ or } TTF = \Sigma\,[(T_a - T_0)\,\Delta t] \qquad (3)$$

In this equation, M is the maturity; T_0, the datum temperature of concrete, belowwhich the concrete has no strength gain; Δt, a time interval in terms of hours; and T_a, the average concrete temperature during Δt.

State DOTs	Specification	Datum Temp. (°C)	State DOTs	Specification	Datum Temp. (°C)
Alabama	ALDOT-425	0	Missouri	Section 507	-10
Indiana	ITM 402-04T	-10	Ohio	Supplement 1098	0
Iowa	IM 383	-10	Tennessee	Developing	-10
Kansas	KT-44	-10	Texas	Tex-426-A	-10
Kentucky	64-322-08	-10	Wisconsin	CMM 8.70	0

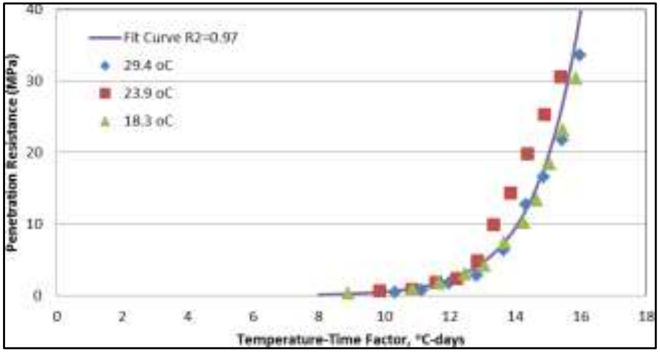
Table 7: Datum temperature used by State DOTs in United States
*Information updated in March 2012

The datum temperature (T_0) depends on the property of cement, fly ash and chemical admixture used, and it varies widely (6, 7). Table 7 presents the datum temperatures that are used by several state highway agencies, and it indicates that the value of -10°C is most commonly used (8). Iowa Department of Transportation currently uses -10°C as the datum temperature for evaluating maturity of concrete pavement.

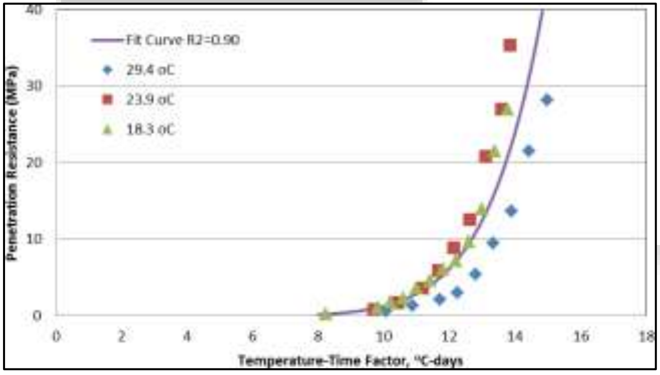
Using the temperature measurements shown in Figure 1 and the datum temperature of -10°C, the TTF values of the concrete mixes studied were computed according to Equation (3). These values were then plotted against the penetration resistance of the corresponding concrete measured from the standard set time test (ASTM C 403). Figures 6 and 7 show the penetration resistance versus TTF curves for the concrete mixes with Retarder 1 and without retarder, respectively. Different from Figure 3 (penetration resistance vs. elapsed time), Figures 6 and 7 suggest that the penetration behavior of a concrete under different curing temperatures can be described by a single curve if the maturity concept was used. The significance of the maturity application here is to predict the penetration resistance for concrete cured under differenttemperatures.

When the above maturity method was also applied to the concrete mixtures containing Retarder 2, Figure 8 is obtained for the datum temperature of -10°C. The three curves in Figure 8 suggest that the use of -10°C datum temperature is not appropriate here. The datum temperature, related to cement hydration, is affected by the chemistry of cement system, and therefore, may change when different chemical admixtures are used. Figure 9 illustrates that a single penetration resistance-maturity relationship can be obtained when the datum temperature of 4ºC is used. This result indicates that a proper selection of the datum temperature is very important for the maturity application.

It shall be noted that although many state DOTs use the datum temperature of -10 ºC, ASTM C 1074 (3) recommends a datum temperature of 0ºC for concrete used Type Icement and without chemical admixtures. Brooks (9) reported datum temperatures of to 3.4ºC for concrete made with various SCMs. Johnson (10) suggested a datum temperature of 3.8 ºC for Maryland DOT. Dong (11) recommended a datum temperatureranging from -2.0 ºC to 4.5ºC for AKDOT. A datum temperature of 4ºC used in Figure 9is within the range reported in literatures.

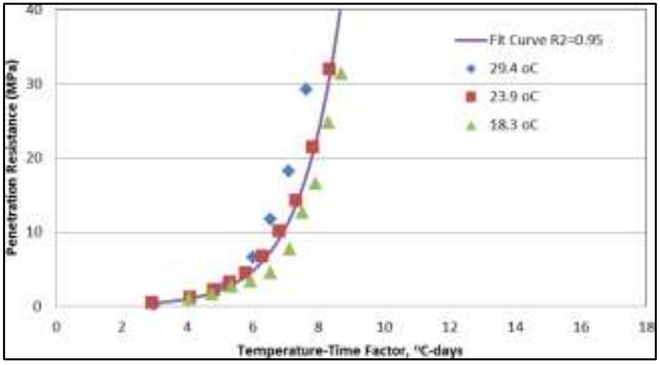


(a) With fly ash

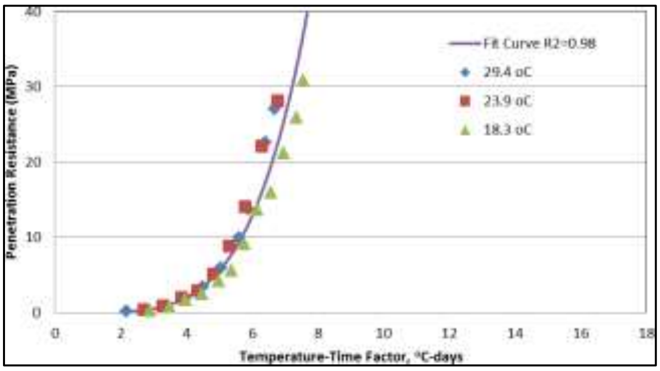


(b) Without fly ash

Fig. 6: Penetration resistance-maturity relationship of mixtures with retarder 1(T_0 = -10ºC)

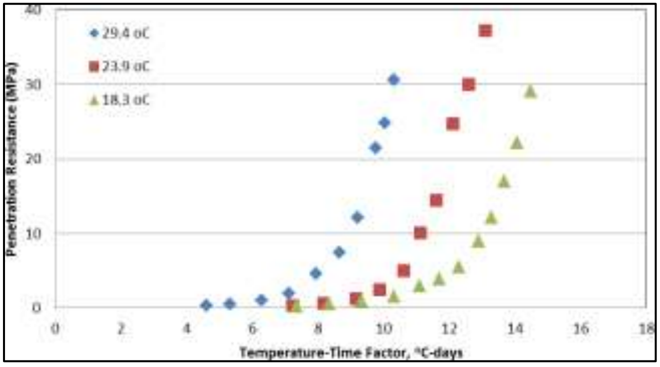


(a) With fly ash

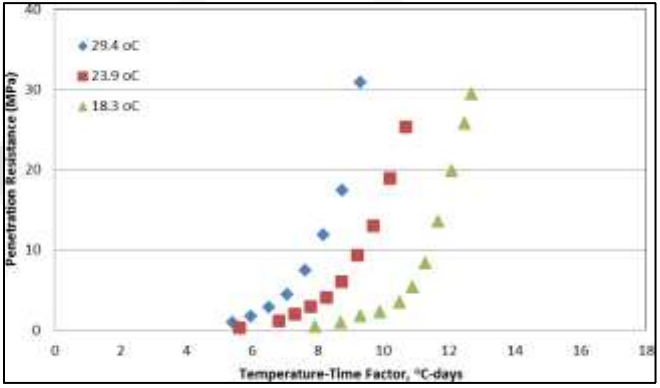


(b) Without fly ash

Fig. 7: Penetration resistance-maturity relationship of mixtures without retarder(T_0 = -10ºC)

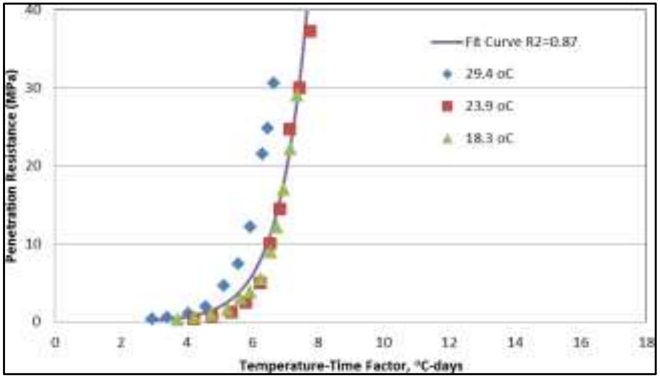


(a) With fly ash

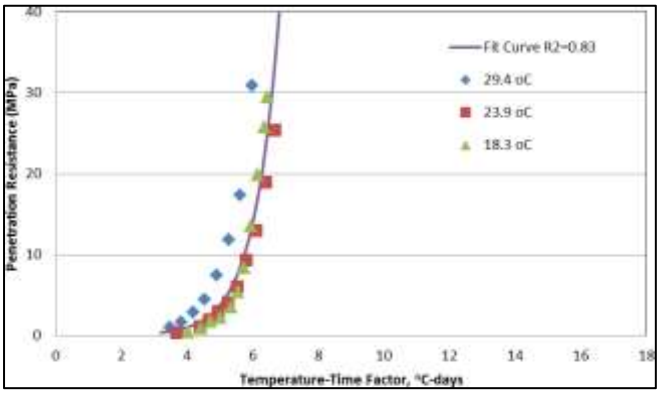


(b) Without fly ash

Fig. 8: Penetration resistance-maturity relationship of mixtures with retarder 2(T_0 = -10ºC)



(a) With Fly Ash



(b) without Fly Ash

Fig. 9: Penetration resistance-maturity relationship of mixtures with retarder 2(T_0 = 4ºC)

IV. CONCLUSION AND FUTURE SCOPE

The maturity concept is used to describe the setting behavior or penetration resistance of concrete under different curing temperatures. It is found that concrete penetration resistance correlated well with its maturity, i. e. time-temperature factor (TTF), when the datum temperature of the concrete was properly selected. Once the relationship is established, one can predict the concrete penetration resistance by simply measuring the concrete maturity. Further study is needed to investigate the effect of chemical admixtures on datum temperature of concrete.

In addition, the study indicates that:

1) If curing temperature raises 1ºC, the initial set time and final set time will drop about 15 min and 19 min, respectively.
2) Mixtures with Retarder 2 (sodium salt) are more sensitive with temperaturechanges.
3) The 20% fly ash replacement increases the concrete initial and final set times bya factor of approximate 1.15 and 1.10, respectively.

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