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Time dependent equations for the compressive strength of self-consolidating concrete through statistical optimization

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Abstract. Self-consolidating concrete (SCC) in the fresh state is known for its excellent deformability, high resistance to segregation, and use, without applying vibration, in congested reinforced concrete structures characterized by difficult casting conditions. Such a concrete can be obtained by incorporating either mineral or chemical admixtures. This paper presents the results of an investigation to asses the applicability of Abram's law in predicting the compressive strength of SCC to any given age. Abram's law is based on the assumption that the strength of concrete with a specific type of aggregate at given age cured at a prescribed temperature depends primarily on the water-to-cement ratio (W/C). It is doubtful that such W/C law is applicable to concrete mixes with mineral or chemical admixtures as is the case for SCC where water to binder ratio (W/B) is used instead of W/C as the basis for mix design. Strength data of various types of SCC mixtures is collected from different sources to check the performance of Abram's law. An attempt has been made to generalize Abram's law by using various optimization methodologies on collected strength data of various SCC mixtures. A set of generalized equations is developed for the prediction of SCC strength at various ages. The performance of generalized equations is found better than original Abram's equations.

Keywords: self-consolidating concrete; compressive strength equation; statistical optimization.

1. Introduction

Self-consolidating concrete (SCC) is a new generation of high performance concrete that can be placed and compacted under its self weight with little or no vibration effort. SCC was originally developed in Japan in the late 1980s and now it is becoming more popular in the rest of the world (Ozawa, *et al.* 1989, Campion and Jost 2000, Khayat, *et al.* 1997, Bouzoubaâ and Lachemi 2001).

Several different approaches have been used to develop SCC. One method to achieve self-consolidating property is to increase significantly the amount of fine materials or mineral admixtures, for example fly ash (FA), slag cement (SC), limestone (LS) filler, volcanic ash (VA) or cement kiln dust (CKD) without changing the water content compared to common concrete (Patel, *et al.* 2004, Lachemi, *et al.* 2003, Ghazel and Khayat 2002, Bui, *et al.* 2002, Hossain and Lachemi 2004). The use of such mineral admixtures can improve the slump flow and cohesiveness, reduce the segregation, lower the cost by replacing relatively costlier cement, lower the heat of hydration,

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lower the permeability and lower the shrinkage and creep of SCC. The use of mineral admixtures can not only provide low cost SCC, durable construction, and sustainability in construction industry but can also help to decrease environmental hazard and greenhouse gas emissions (Hossain and Lachemi 2004).

One alternative approach consists of incorporating a viscosity modifying admixture (VMA) to enhance stability (Rols, *et al.* 1999, Lachemi, *et al.* 2004). The use of VMA along with adequate concentration of superplasticizer (SP) can ensure high deformability and adequate workability leading to a good resistance to segregation. The use of commercial VMA such as Welan gum, a kind of natural polysaccharide as VMA has proved very effective, but these products are costly and increase the price of concrete. Investigation is also conducted to explore the potential use of new low cost VMA in the development of SCC (Lachemi, *et al.* 2004).

A comprehensive research on the development of SCC incorporating high volumes of supplementary cementing materials, natural pozzolans (volcanic ash) and new types of VMA and on their structural applications is now going on at the Ryerson University, Canada in collaboration with CANMET, Canada (Lachemi, *et al.* 2003, Patel, *et al.* 2004, Hossain and Lachemi 2004, Lachemi, *et al.* 2004). Research led to the development of high performance, environmentally friendly, and cost-effective SCC. The research on the application of such SCC for the construction and repair of structural elements will also lead to the development of innovative techniques that can be confidently used in the future.

Attempt has been made to develop statistical/rheological models to predict the fresh and hardened properties of SCC. Such models can be used as economical tools for the optimized design of SCC mixtures with desired properties (Patel, *et al.* 2004, Ghazel and Khayat 2002).

This paper presents the results of an investigation to asses the applicability of Abram's law in predicting the compressive strength of SCC to any given age. Strength data of various types of SCC mixtures is collected from different sources to check the performance of Abram's law. An attempt has been made to generalize Abram's law by using various optimization methodologies on collected strength data of various SCC mixtures. A set of generalized equations is developed for the prediction of SCC strength at various ages. Prediction of SCC strength at specified ages with the help of these generalized time dependent equations can be helpful to design SCC mixes with desired properties with minimum cost, time and effort. SCC mixtures with wide range of mix design parameters and of different types incorporating mineral or chemical admixtures or combination of mineral and chemical admixtures are used to generalize the applicability of developed equations.

2. SCC mixtures used in this study

A wide range of SCC mixtures of different types incorporating mineral admixtures (FA, SC, VA, CKD and LS), chemical admixtures/viscosity modifying agents (VMA) such as welan gum, precipitated silica, starch, industrial by-products and combination of mineral (FA and LS) and chemical admixtures from author's researches (Patel, *et al.* 2004, Lachemi, *et al.* 2003, 2004, Hossain and Lachemi 2004) and other research studies (Ghazel and Khayat 2002, Bosiljkov 2003, Rols, *et al.* 1999, Poon and Ho 2003, Ambroise and Péra 1999, Bui, *et al.* 2002, Khurana and Saccone 1999) are used. Table 1 and Table 2 present the general details of SCCs used for comprehensive statistical analysis in this study. It was made sure that these will form a fairly

Table 1 Ranges of mix design parameters of SCC with mineral admixtures

Mix design parameters	SCC with mineral admixtures			
	SCC with SC	SCC with FA	SCC with CKD	SCC with VA
	SCSCC	FASCC	CKDSCC	VASCC
	Range of mix design parameters			
C, kg/m^3	122-205	160-427	383-428	200-320
FA, kg/m^3		90-254		
SC, kg/m^3	201-285			
VA, kg/m^3				80-200
CKD, kg/m^3			22-68	
%FA		20-60		
%SC	50-70			
%VA				20-50
%CKD			5.0-15.0	
W, kg/m^3	138-182	136-208	212-234	140-180
SP, kg/m^3	2.0-4.0	0-9.64	4.0-6.0	1.5-3.4
%SP	0.28-.51	0.0-1.12	0.44-.65	0.18-.42
Coarse Agg, kg/m^3	873-908	621-900	900	850
Fine Agg., kg/m^3	876-910	768-960	900	802-831
W/B	0.35-0.45	0.28-0.45	0.45-0.5	0.35-0.45
AEA, mL/m^3	199-302	0-483		
W/C	0.7-1.5	0.38-1.13	0.49-0.61	0.44-0.90

Table 2 Ranges of mix design parameters of VMA and combination type SCC mixtures

Mix design parameters	SCC with VMA	Combination type SCC	
		SCC with LS and VMA	SCC with FA and VMA
	VMASCC	LSVMASCC	FAVMASC
C, kg/m^3	400-520	140-400	270-350
FA, kg/m^3			115-310
LS, kg/m^3		20-360	
%FA			25-51
%LS		5-49	
W, kg/m^3	180-218	163-200	160-190
SP, kg/m^3	3.5-9.0	0-5	7.8-11.3
%SP	0.38-1.10	0-0.75	0.60-0.95
Coarse Agg, kg/m^3	855-910	700-850	660-735
Fine Agg., kg/m^3	855-937	722-1174	690-870
W/B	0.42-0.45	0.22-0.72	0.29-0.38
W/C	0.42-0.45	0.42-0.87	
VMA, kg/m^3	0.122-4.54	0.0-7.5	0.0-0.56
%VMA	0.025-0.075	0-0.3	

representative group governing all the major parameters that influence the strength behaviour of different types of SCC and present complete information required for such an evaluation. Altogether 195 SCC mixtures were evaluated in this study. Due to lack of strength data of SCC mixtures beyond 28 days, this study is concentrated on the early age strength of SCC ranging from 1 to 28 days.

3. Abram's law for prediction of compreesive strength of concrete

Abram's law states that the strength at a specific age of a fully compacted concrete incorporating a specific type of aggregate and cured at specific temperature depends primarily on the water-to-cement ratio (w/c) (Neville 1995, Oluokun 1994). Abram's law relating concrete strength and w/c can be expressed as:

$$f_c = \beta\lambda^{-r} \tag{1}$$

where f_c is the compressive strength of the concrete; r is the water (w) -to- cement (c) ratio (w/c); β is known as the "magnitude" parameter which controls the maximum strength of concrete regardless of r; and λ is known as the "curvature" parameter as it controls the curvature of the strength vs. r curve. β and λ depend on materials, age and curing conditions of concrete.

Proposed relationships between f_c and r for Portland cement concrete under normal temperature and moisture conditions as per Abram are as follows:

For 7-day strength (MPa): $$f_{c,7} = 63.45 \times 14^{-r} \tag{2}$$

For 28-day strength (MPa): $$f_{c,28} = 96.55 \times 8.2^{-r} \tag{3}$$

It is doubtful that Abram's water-to-cement ratio law is applicable to concrete mixes with supplementary cementitious materials (cm) or mineral admixtures such as FA, VA, SC, LS etc.. It would be more realistic to use water-to-cementitious material ratio (w/cm) or water-to-binder ratio (W/B) instead of w/c as the basis for mix design and strength prediction of concretes incorporating mineral admixtures.

3.1. Performance of Abram's law in predicting the strength of SCC

Abrams's Eq. (2) and Eq. (3) based on w/c (= r) are used to predict 7-day ($f_{c,7}$) and 28-day ($f_{c,28}$) compressive strengths of SCC mixtures. The ratio of predicted to experimental strength is plotted in Fig. 1 and 2. The ratio of predicted to experimental 7-day strength ranges between 0.05 and 1.56 with a mean value and st. dev. of 0.54 and 0.40, respectively. The ratio of predicted to experimental 28-day strength ranges between 0.14 and 2.01 with a mean value and st. dev. of 0.63 and 0.24, respectively. This indicates that Abram's equations based on w/c (= r) are suitable for predicting the compressive strength of SCC mixtures especially with mineral admixtures. Abram's equations are generally found to under-predict the strength of SCC mixtures.

Previous research studies have also shown that when the water-to-cementitious material/binder ratio (w/cm or w/b = r) is used instead of w/c as the basis for mix design, strength prediction for concretes with mineral admixtures becomes more accurate (Babu and Rao 1996). Comprehensive study on FA concretes suggested that the effect on w/c of a weight of w_{FA} of FA would be

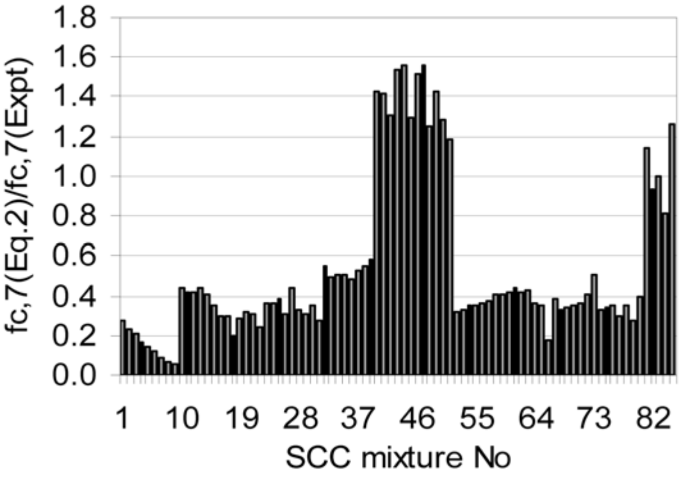

Fig. 1 Prediction of 7-day SCC strength by Eq. (2)

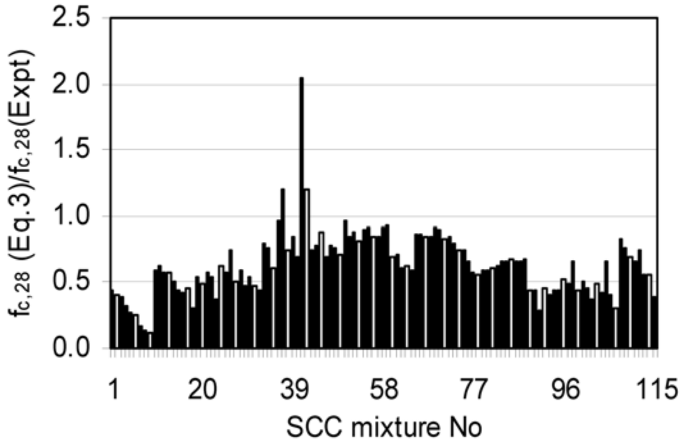

Fig. 2 Prediction of 28-day SCC strength by Eq. (3)

equivalent to a weight $m.w_{FA}$ of cement where m is an efficiency factor (Babu and Rao 1996). A set of values for ‘m’ (that ranges widely between 0.13 and 1.40) was suggested for various ages up to 90 days and percentages of cement replacement up to 75%. For concrete with mineral admixture used as cement replacement, the w/cm or w/b can be written as:

$$r = w/(C + mw_{FA} + w_{SC} + w_{VA} + \ldots..) \quad (4)$$

where w = water content, C = cement content, w_{FA} = weight of FA, w_{sc} = weight of slag cement, w_{VA} weight of VA. Much work has been done on the generalization of Abram’s formula to the composition of materials and little research has been done to generalize the law to the age of concrete (Popovics 1990, Nagaraj and Banu 1996).

An attempt has been made in this study to generalize Abram’s formula to predict the strength of SCC at a given age based on w/b. In this study, efficiency factors (m) for mineral admixtures are considered as unity.

4. Generalization of Abram's law for compressive strength and model development for SCC

Strength data of different types of SCC mixtures incorporating mineral, chemical and their combinations as presented in Table 1 and Table 2 are used to develop models based on statistical analysis. In the preliminary stages of the study, it is intended to enhance the applicability of developed models (which are based on the philosophy of Abram's law) for practical applications by covering an age that ranges between 3 days and 28 days.

Three models for the prediction of compressive strength of various types of SCC mixtures are developed based on Abram's original law.

4.1. Model 1: specific age formula

The development of this model includes the following steps: (a) collection of strength data of SCC mixtures at the specified age and (b) development of a specific formula for strength prediction at the specified age by generating a set of specific magnitude parameter (β) and curvature parameter (λ).

Using Abram's formula stated in Eq. (1) (here, r is considered as water-to-binder ratio, w/b)

$$\text{Ln}\ (f_c) = \text{Ln}\ (\beta) - r\ \text{Ln}\ (\lambda)$$

which can be written as: $Y = p + qX$ where

$$Y = \text{Ln}\ (f_c),\ p = \text{Ln}\ (\beta),\ q = -\text{Ln}\ (\lambda),\ X = r$$

Solving the regression coefficients p and q in the regression equation $Y = p + qX$, we get

$$\beta = e^{p} \quad \text{and} \quad \lambda = e^{-q}$$

Typical regression equation ($Y = p + qX$) for 28 day strength of SCC mixtures is shown in Fig. 3.

Regression analysis of 1 and 28-day compressive strength of various SCC mixtures provided the following results:

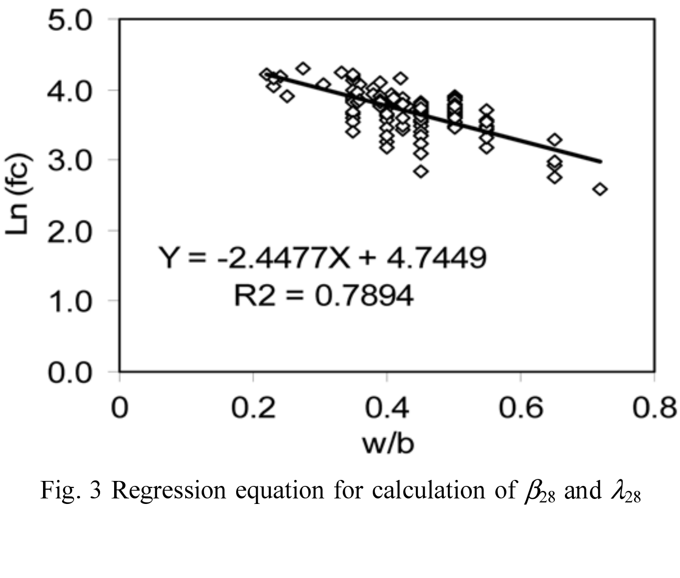

Fig. 3 Regression equation for calculation of β_{28} and λ_{28}

28-day strength:

$Y = 4.744 - 2.4477$ X ($R^2 = 0.7894$) (Fig. 3)

$\beta_{28} = 114.9963$

$\lambda_{28} = 11.554$

The specific age formula for 28-day strength can be written as:

$$f_{c,28} = \beta_{28}\lambda_{28}^{-r} = 114.9963 \times 11.554^{-r} \tag{5}$$

7-day strength:

$Y = 3.8758 - 1.598$ X ($R^2 = 0.6814$)

$\beta_7 = 48.221$

$\lambda_7 = 4.943$

The specific age formula for 7-day strength can be written as:

$$f_{c,7} = \beta_7\lambda_7^{-r} = 48.221 \times 4.943^{-r} \tag{6}$$

1-day strength:

$Y = 2.3993 + 0.0013$ X ($R^2 = 0.6312$)

$\beta_1 = 11.0154$

$\lambda_1 = 0.9987$

The specific age formula for 1-day strength can be written as:

$$f_{c,1} = \beta_1\lambda_1^{-r} = 11.0154 \text{ x } 0.9987^{-r} \tag{7}$$

4.1.1. Performance of specific age formulas (Eqs. 5, 6 and 7)

The performance of specific age formulas (Eqs. 5, 6 and 7) are checked by predicting the strength of SCC mixtures at 1, 7 and 28 days. Fig. 4 shows the plot of experimental and predicted (Eq. 5) 28-day strengths of SCC mixtures. Eq. (5) seems to predict the 28-day compressive strength of SCC mixtures reasonably well with a mean ratio of predicted to experimental values of 1.023 (ratio

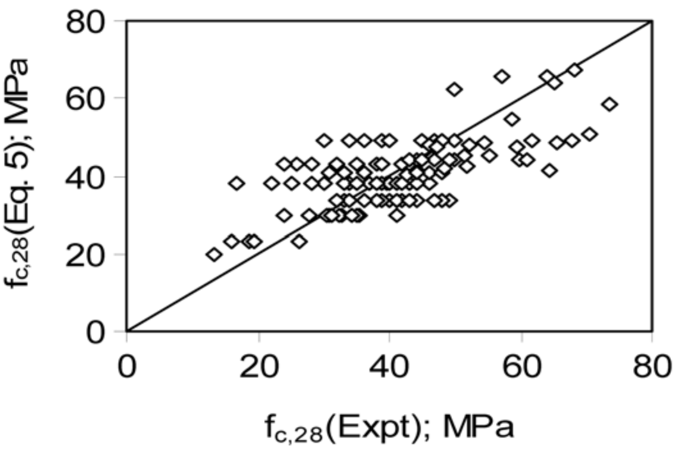

Fig. 4 Predictive ability of specific age formula

ranges between 0.73 and 1.24 with st. dev. of 0.23). Eq. (6) also shows reasonably good prediction of 7-day strength of SCC mixtures with a mean ratio of predicted to experimental values of 1.16 (ratio ranges between 0.68 and 1.53 with st. dev. of 0.33). Eq. (7) also shows reasonably good prediction of 1-day strength of SCC mixtures with a mean ratio of predicted to experimental values of 1.08 (ratio ranges between 0.58 and 1.43 with st. dev. of 0.26).

4.2. Model 2: time factor model

In this model, the strength ($f_{c,t}$) at a given age (t) is obtained by multiplying the strength at a specified age usually 28-day strength ($f_{c,28}$) by a time factor which is a function of age (α_t). The general equation is:

$$f_{c,t} = (\alpha_t)\, f_{c,28}$$

The model implies that the time effect is independent of the composition of material which seems unreasonable. The model includes the following steps:

(a) Determination of best values of β and λ in strength prediction formula at the specified age (28-day) from regression analysis,

(b) Prediction of 28-day strength ($f_{c,28p}$) for all SCC mixtures using 28-day strength prediction formula (Eq. 5),

(c) Calculation of time factor (α_t): $\alpha_t = f_{c,t}/f_{c,28p}$
where $f_{c,t}$ is the actual strength at age t and $f_{c,28p}$ is the predicted 28-day strength,

(d) Calculation of the average time factor at specific age (1, 3, 7, 14, 28……days) and

(e) Derivation of a best fit regression equation for time factor.

The analysis from step a to d using experimental SCC mixtures produced time factor model for strength at any age, t as follows:

$$f_{c,t} = \alpha_t\, \beta_{28} \lambda_{28}^{-r} = \alpha_t \times 114.9963 \times 11.5536^{-r} \tag{9}$$

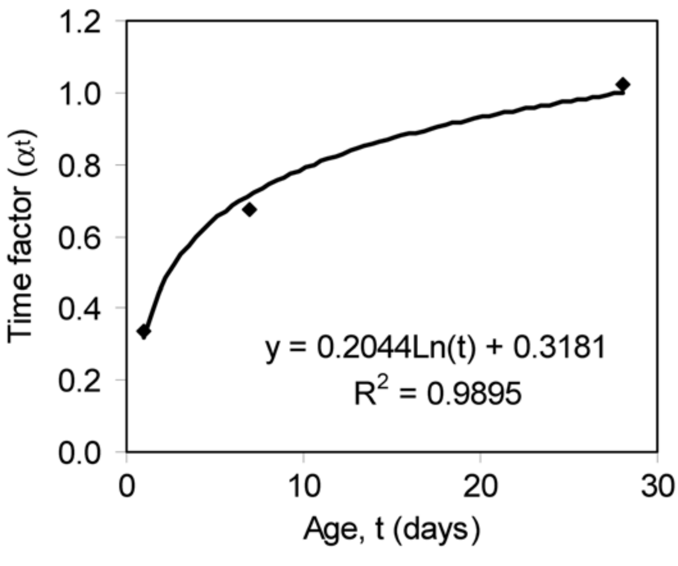

Fig. 5 Regression equation for time factor (α_t)

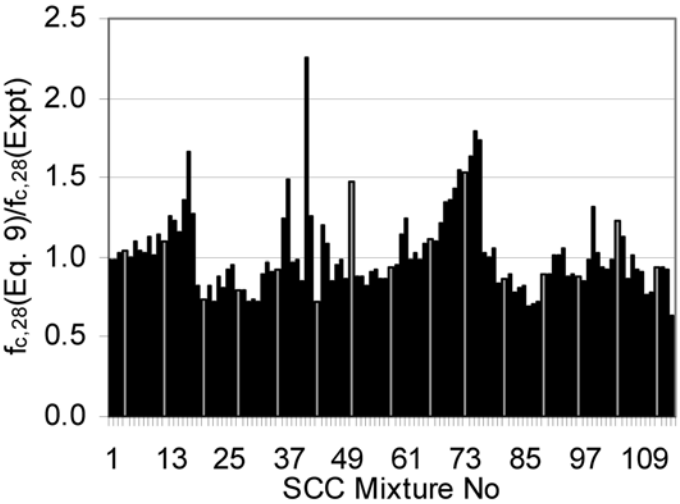

Fig. 6 Predictive ability of time factor model (Eq. 9)

where α_t = 0.2044 Ln (t) + 0.3181 (Fig. 5 which is derived following steps a to d)

4.2.1. Performance of time factor model (Eq. 9)

The performance of time factor model (Eq. 9) is checked by predicting the strength of SCC mixtures at 1, 7 and 28 days. Fig. 6 shows the ratio of predicted (Eq. 9) to experimental 28-day strength of SCC mixtures. Eq. (9) seems to predict the 28-day compressive strength of SCC mixtures reasonably well with a mean ratio of predicted to experimental values of 1.02 (ratio ranges between 0.74 and 2.28 with st. dev. of 0.25). Eq. (9) also shows reasonably good prediction of 7-day strength of SCC mixtures with a mean ratio of predicted to experimental values of 1.18 (ratio ranges between 0.71 and 1.34 with st. dev. of 0.23). Eq. (9) also shows reasonably good prediction of 1-day strength of SCC mixtures with a mean ratio of predicted to experimental values of 1.18 (ratio ranges between 0.68 and 1.29 with st. dev. of 0.21).

4.3. Model 3: time dependent parameter model

The model is based on the development of time dependent regression equations for parameters β and λ so that Abram's formula for strength at an age can be generalized to the following form:

$$f_{c,t} = \beta_t \lambda_t^{-r} \tag{10}$$

where β_t and λ_t are generalized parameters as a function of age. The generalized model takes into account the effect of time on the concrete material and thereby, eliminating the shortcomings of model 2 (Eq. 9). The model includes following steps:

(a) Generation of β and λ for specific age (t = 1, 3, 7, 14, 28 …..days) using strength data of experimental SCC mixtures and

(b) Building of regression equations for β and λ as a function of age to be used in Eq. (10).

Figs. 7 and 8 show the time dependent regression equations for β and λ derived from the data of SCC mixtures following steps a and b. Analysis of SCC mixtures produces the following time

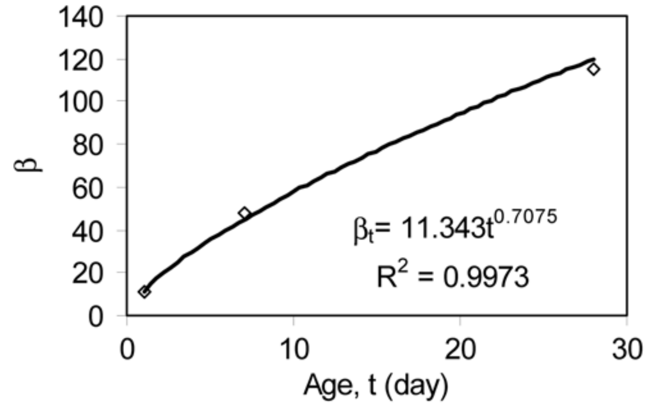

Fig. 7 Time dependent regression equation for β

dependent parameter model for compressive strength at any age:

$$f_{c,t} = \beta_t \lambda_t^{-r} \tag{11}$$

where $\beta_t = 11.343\, t^{0.7075}$ and $\lambda_t = 1.0463\, t^{0.7404}$

4.3.1. Performance of time dependent parameter model (Eq. 11)

The performance of time dependent parameter model (Eq. 11) is checked by predicting the strength of SCC mixtures at 1, 7 and 28 days. Fig. 8 shows the ratio of predicted (Eq. 11) to experimental 28-day strength of SCC mixtures. Eq. (11) seems to predict the 28-day compressive strength of SCC mixtures reasonably well with a mean ratio of predicted to experimental values of 1.03 (ratio ranges between 0.75 and 1.83 with st. dev. of 0.21). Eq. (11) also shows reasonably good prediction of 7-day strength of SCC mixtures with a mean ratio of predicted to experimental values of 1.12 (ratio ranges between 0.75 and 1.24 with st. dev. of 0.19). Eq. (9) also shows reasonably good prediction of 1-day strength of SCC mixtures with a mean ratio of predicted to experimental values of 1.08 (ratio ranges between 0.88 and 1.15 with st. dev. of 0.16).

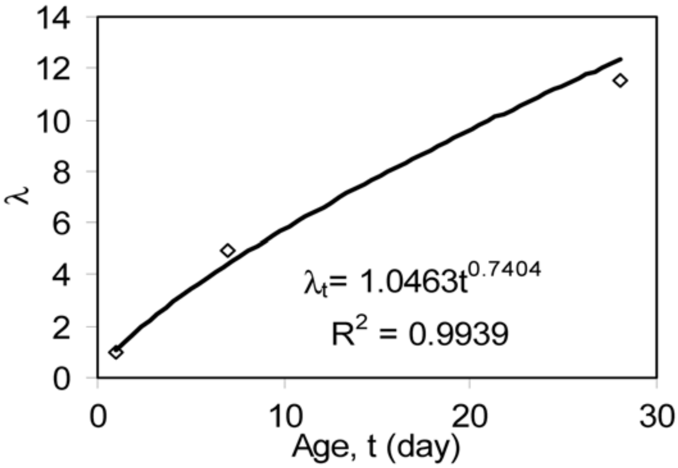

Fig. 8 Time dependent regression equation for λ

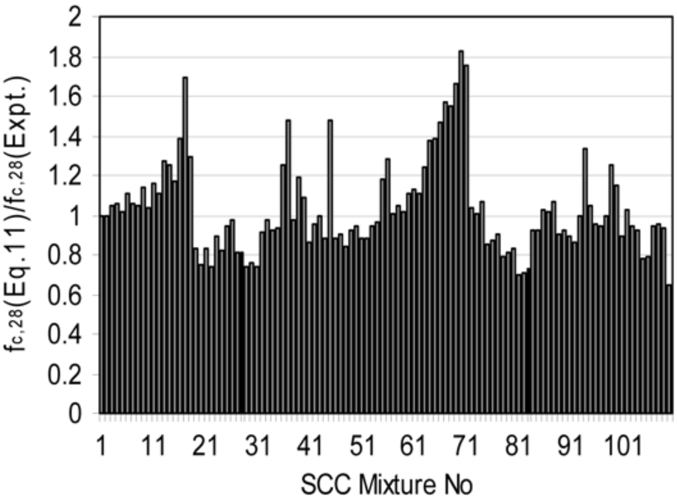

Fig. 9 Predicting ability of time dependent parameter model (Eq. 11)

5. Conclusions

This paper presents the applicability of Abram's law in predicting the compressive strength of self-consolidating concrete (SCC) to any given age. An attempt has been made to generalize Abram's law by using various optimization methodologies on collected strength data of various types of SCC mixtures. A set of generalized equations is developed from three different models for the prediction of SCC strength at various ages. The following conclusions are drawn from the study:

- Abram's original formulas based on water-to-cement ratio (w/c) are not suitable for the prediction of compressive strength SCC incorporating both mineral, chemical and combination of mineral and chemical admixtures. Abram's formula generally under predicts the strength of such SCCs.
- Three time dependent models are proposed in this study namely specific age model, time factor model and time dependent parameter model. These models are developed based on water-to-binder ratio (w/b) instead of w/c. Equations based on these models are found better than original Abram's equations and able to predict the compressive strength of SCCs reasonably well up to an age of 28-day.
- The performance of time dependent parameter model is found to be the best followed by time factor model. The better performance of time dependent parameter model can be attributed to consideration of the effect of time in deriving regression equations for magnitude (β) and curvature (λ) parameter in the model.
- Time dependent models proposed in this study provide guidelines for the prediction of strength at any age for a SCC mixture. However, limited strength data of SCC mixtures limits the applicability of the proposed models beyond 28 days. The proposed models can be modified in future to cover SCC strength beyond 28 days when experimental strength data will be available.
- The development of models for each type of SCC based on large number of data will definitely further improve the predictive ability and performance of the models.

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