Computers and Concrete, Vol. 6, No. 4 (2009) 343-356
DOI: http://dx.doi.org/10.12989/cac.2009.6.4.343

Genetic algorithm-based yield stress equations for concrete at high temperature and prolonged mixing time

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(Received July 21, 2008, Accepted July 8, 2009)

Abstract. Experiments were designed to investigate the flow behavior of portland cement paste and concrete incorporating superplasticizers. The paste and concrete mixtures were subjected to prolonged mixing for up to 110 min at high temperature. The yield stress values of concrete and that of the corresponding cement paste were measured using a rotating rheometer and viscometer, respectively. The results reveal a weak linear correlation between the yield stress of concrete mixtures and that of the corresponding cement pastes. Results also indicate that the yield stress of concrete varies in a linear fashion with the elapsed time, while its variations with the temperature and superplasticizer dosage follow power and inverse power functions, respectively. In this study, the genetic algorithms (GA) technique was used to predict the yield stress of concrete considering various parameters, such as the mixing time, ambient temperature, and superplasticizer dosage. A sensitivity study was conducted to evaluate the ability of the GA equations thus developed to capture the effects of test parameters on the yield stress of concrete. It was found that the GA equations were sensitive to the effects of test parameters and provided yield stress predictions that compared well with corresponding experimental data.

Keywords: genetic algorithm; rheology; cement paste; concrete; high temperature; mixing time; superplasticizer; yield stress.

1. Introduction

Proper understanding and control of the rheological properties of fresh concrete can help ensuring its easy placement, consolidation and finishing, especially under severe field conditions such as prolonged hauling time and high temperature. Concrete is considered as a suspension in which aggregates are the particles and cement paste is the medium. Knowing the rheological properties of fresh cement paste may give an indication about the flow behavior of fresh concrete. It is generally accepted that the flow of cement paste conforms well to the Bingham model (Asaga and Roy 1980). The behavior of fresh concrete can also be described using the Bingham model in the following form (Tattersall 1991):

$$\tau = \tau_0 + \mu_p \dot{\gamma} \tag{1}$$

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Where, τ (Pa) is the shear stress at shear rate $\dot{\gamma}$(1/s) and τ_o (Pa) and μ_p (Pa.s) are the yield stress and plastic viscosity values, respectively. Yield stress can be defined as the force needed to overcome the friction between solid particles, while the plastic viscosity term is due to viscous dissipation resulting from the movement of water in the sheared material (Ferraris and de Larrard 1998).

The yield stress is an important rheological parameter that affects the flow behavior of cement-based materials. It plays an essential role for example when it is required to place concrete without applying vibration. Therefore, the yield stress can be used as a quality control indicator for self compacting concrete (Yahia and Khayat 2001). Using a given rheological model (e.g. Bingham model), the yield stress can be determined from flow tests through extrapolation of the shear stress-shear rate curve to find the stress corresponding to zero shear rate.

The rheological properties of fresh concrete and cement paste are complex in different ways. Hence, measuring the rheological parameters of cement paste may not allow to accurately predict that of concrete. A few researchers attempted to investigate the correlation between the flow behavior of cement paste or mortar and concrete, so that the fluidity of fresh concrete can be evaluated using simple tests on cement paste or mortar. For instance, Maruya *et al.* (2006) investigated the relationship between the yield stress of cement paste and slump flow of fresh concrete. Concrete having a water to cement ratio (w/c) of 0.35 was subjected to prolonged mixing for 60 min at 20°C, and its slump flow was measured at 5, 30, and 60 min. The cement paste was prepared with the same w/c (w/c=0.35) and the yield stress was also measured at 5, 30, and 60 min. It was found that the relationship between the slump flow of concrete and yield stress of cement paste was linear with a coefficient of correlation (R^2) of 0.62.

Struble and Chen (2005) tried to assess the correlation between the rheological properties of concrete and mortar. The concrete was continuously agitated in a mixer for up to 100 minutes at 25 °C and periodically sampled for rheological tests every 20 min. The mortar, on the other hand, was mixed only for a few minutes, rheologically tested, and then remained undisturbed until the next test; the rheological measurements were carried out every 20 min for up to 100 min. It was found that the relationship between the yield stress of mortar and that of concrete was fairly linear with a coefficient of correlation (R^2) of 0.70.

Several research efforts have been made to develop equations for predicting the yield stress of concrete. Some researchers tried to create empirical or analytical equations that relate the yield stress of concrete to its measured slump since in practice the slump test is routinely measured for quality control (Murata and Kikukawa 1992, Saak *et al.* 2004, Wallevik 2006). Other researchers tried to create relationships between the yield stress of concrete and some of its physical properties. For example, Ferraris and de Larrard (1998) developed equations to calculate the yield stress of concrete as a function of the ratio between the volumetric fraction of solid materials and the maximum packing value of these solids (Φ_i/Φ^*_i). They found that the relative concentration of concrete solid components (cement, sand, or gravel) had different relationships with yield stress. Therefore, the yield stress equations proposed by Ferraris and de Larrard (1998) followed a linear form, in which the (Φ_i/Φ^*_i) for all concrete solid gradients were summed up. They developed two yield stress equations: the first was for concrete without superplasticizers, and the second was for concrete incorporating 1% by mass of naphthalene-sulfonate (NS) superplasticizer.

More recently, Petit *et al.* (2007) developed equations to calculate the yield stress of concrete using the initial yield stress value (at zero time) of the corresponding mortar. They first investigated the coupled effects of time and temperature on the rheological properties of highly flowable mortars. The ambient temperature ranged from 10 to 30°C and the changes in rheological properties of mortars were investigated over the dormant period. Thus, mortars remained in a standstill condition after being mixed and its rheological parameters were measured over time up to the end of dormant period. The time was normalized by dividing the elapsed time after the contact of cement particles with water (t) by the time, t_f, corresponding to the dormant period ($t'=t/t_f$). This non-dimensional parameter (t') that varies from 0 to 1 was used to eliminate the effect of temperature. They found that the yield stress of mortar increased linearly with the normalized time period (t'), and independently of the mixture temperature, but with different slopes for different mixtures. The same procedure was repeated on corresponding self-consolidating concrete (SCC) mixtures. It was found that the evolution of the yield stress of concrete with the normalized time (t') was exponential ($\tau_{o,c}(t') = \tau_{o,c}(0,T)e^{\alpha,t'}$), where $\tau_{o,c}$ $(0,T)$ is the initial yield stress of concrete (at zero time), which depends on the test temperature, and α is an experimental constant depending on the type of concrete. A table with different values of this constant corresponding to different concrete mixtures at 20°C was provided. Equations to predict the variation of yield stress of SCC using the measured initial yield stress of the corresponding mortar ($\tau_{o.m}$ $(0,T)$) at a given temperature were also developed.

Measuring the rheological properties of fresh concrete is a difficult task usually requiring the use of a rheometer having a large gap to accommodate coarse aggregates. Hence, the complicated methods used for this purpose are generally unsuitable for rapid quality control in field conditions. Therefore, it is important in the robotization of concreting operations to develop reliable equations for predicting the flow and deformation of concrete, in which various factors such as the mixing time, ambient temperature, and superplasticizer type and dosage are considered.

In this paper, the correlation between the yield stress of concrete mixtures and that of corresponding cement paste mixtures was investigated to explore the possibility of using the cement paste rheology to predict the rheology of concrete made with a similar paste. Furthermore, equations for calculating the yield stress of fresh concrete as a function of the mixing time, ambient temperature, and superplasticizer dosage were developed using the genetic algorithms technique (GA). These equations have been ascertained to be applicable and reasonably accurate upon exploring their sensitivity to changes in the test parameters.

2. Experimental work

2.1. Materials

The cement paste and concrete mixtures were prepared using ordinary CSA Type 10 portland cement and incorporated polycarboxylate- (PC), melamine sulfonate- (ML), or naphthalene sulfonate- (NS) based superplasticizers. All cement paste and concrete mixtures were made with a water to cement mass ratio (w/c) of 0.38. Washed natural pea gravel was used as coarse aggregate along with natural sand as fine aggregate. The concrete mixture proportions were calculated using the absolute volume method. Accordingly, all concrete mixtures were made with 475 kg/m^3 of cement, 895 kg/m^3 of fine aggregate and 800 kg/m^3 of coarse aggregate with no air entrainment.

2.2. Apparatus

The rheology of fresh concrete and cement paste was investigated using a BML rheometer and an AR-2000 viscometer, respectively. The cement paste viscometer measures the shear stress (τ) at different shear rates (γ), while the concrete rheometer measures the torque resistance (T_R) at several rotational speeds (N). For the cement paste, the relationship between shear stress and shear rate is fit to the Bingham model (Eq. 1). For concrete, the relationship between flow resistance and flow rate is typically linear and can be expressed using the following equation:

$$T_R = G + H\,N \tag{2}$$

Where, T_R (Nm) is the torque resistance, G (Nm) is the flow resistance, H (Nm.s) is the viscosity factor, and N is the rotational speed (rev/s).

Similar to the Bingham yield stress, G is the intercept of the T_R-N line with the torque axis (y), and it represents the force necessary for concrete to start flowing; H is the slope of this line and is a measure of the resistance of the concrete to an increased speed of flow (Geiker *et al*. 2002). Eqs. 3 and 4, which are based on the *Reiner-Riwlin Equation,* were used by the software that controls the viscometer to convert the measured constants (G and H) to Bingham constants (τ_o and μ) (Wallevik 2006):

$$\mu = \frac{H(1/R_i^2 - 1/R_o^2)}{8\pi^2 h} \tag{3}$$

$$\tau_o = \frac{G(1/R_i^2 - 1/R_o^2)}{4\pi h \ln(R_o/R_i)} \tag{4}$$

Where, R_i is the radius of the inner cylinder (R_i = 0.10 m), R_o is the radius of the outer cylinder (R_o = 0.145 m), and h is the height of the inner cylinder (h = 0.20 m). A detailed description of the concrete viscometer and procedure implemented can be found elsewhere (Nehdi and Al-Martini 2009).

2.3. Experimental procedure

The concrete and cement paste mixtures were continuously mixed using a drum concrete mixer with a rotational speed of 25 rpm for up to 110 min to simulate the concrete mixing in a concrete truck mixer during concrete transportation to a construction site. For high temperatures (35 and 45°C), the mixing was conducted in an environmental chamber, and for moderate temperature (22°C) mixing took place in the lab under a controlled environment at 22°C.

The rheology of fresh concrete and cement paste mixtures was measured after 20, 50, 80, and 110 minutes from the start of mixing. Figs. 1a and 1b illustrate the testing scheme used for cement paste and concrete, respectively. Further details about the mixing and rheological test procedures can be found elsewhere (Al-Martini and Nehdi 2009-a, 2009).

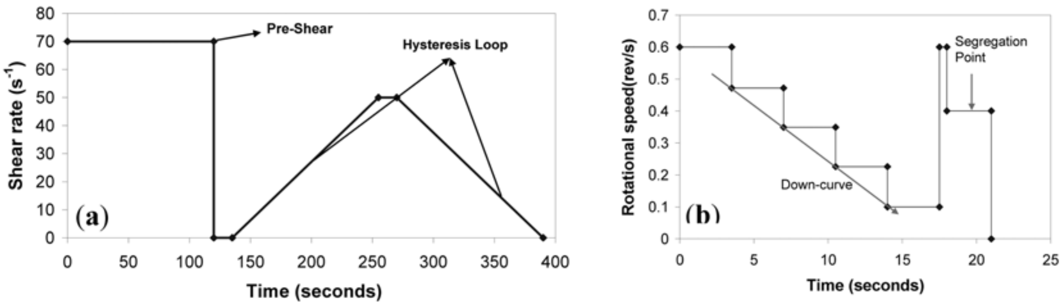

Fig. 1 Measuring procedure used: (a) for cement paste and (b) for concrete

2.4. Experimental results

Figs. 2a and 2b illustrate typical flow curves (only the down part of curves is shown) for fresh cement paste and concrete, respectively. The superplasticizer saturation dosage is traditionally defined as the dosage beyond which a higher dosage will not significantly decrease the yield stress. This definition was found to be valid for cement paste and concrete mixtures incorporating ML and NS (Al-Martini and Nehdi 2009-a, 2009). However, the saturation dosage for cement paste and concrete made with PC was identified when the yield stress stopped decreasing and started to increase with further increase of the PC dosage. An explanation of this phenomenon can be found elsewhere (Al-Martini and Nehdi 2009-a, 2009). Based on experimental results, the yield stress of cement paste made with a particular superplasticizer also reflects the behavior of this superplasticizer when it is incorporated in concrete made with a similar cement paste.

To evaluate the relationship between the rheology of fresh concrete and that of cement paste, the yield stress of concrete mixtures incorporating ML or NS was plotted versus that of corresponding cement paste mixtures (Fig. 3). It should be noted that this relationship could not be investigated for PC, because the PC saturation dosage for cement paste was much lower (0.4%) than that for the corresponding concrete (1.5%). As such, the rheology of concrete made with PC could not be investigated at a dosage below 0.4% because concrete became very stiff, which could damage the instrument. Maruya *et al.* (2006) reported that polycarboxylate superplasticizers can also be adsorbed by aggregates in concrete. Therefore, more superplasticizer is needed for concrete than that for cement paste when evaluating the fluidity of concrete and cement paste. Several functions

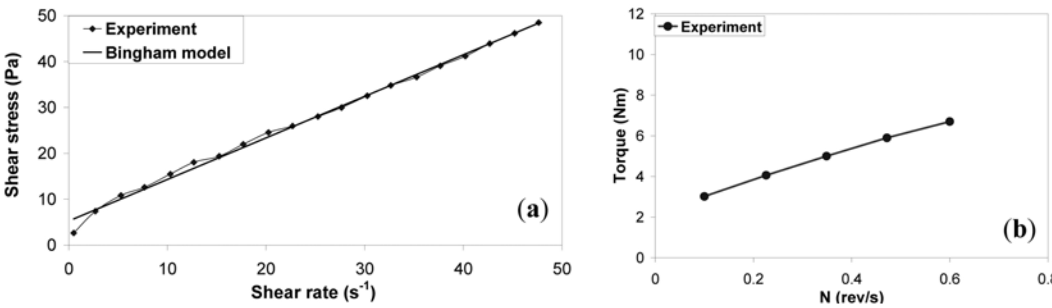

Fig. 2 Flow curves: (a) shear stress versus shear rate (down curve for cement paste), and (b) torque versus rotational speed (down curve for concrete)

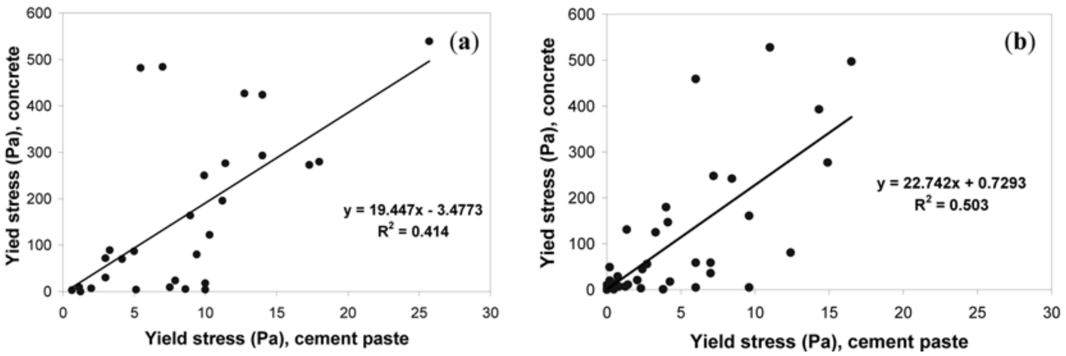

Fig. 3 Correlation between yield stress of concrete and that of cement paste made with: (a) ML and (b) NS

(such as linear, logarithmic, and polynomial) were tested to correlate the yield stress of concrete mixtures with that of corresponding cement paste mixtures; the linear function was found to give the best fit. Fig. 3a shows that the yield stress of concrete made with ML increased linearly when the yield stress of its corresponding cement paste increased, however the correlation coefficient was low (R^2 = 0.41). Similar to ML, the yield stress of concrete mixtures incorporating NS correlated linearly with the yield stress of corresponding cement pastes, but the coefficient of correlation was also weak (R^2 = 0.50) (Fig. 3b).

Thus, it can be argued that measuring the yield stress of cement paste can give some indication about the rheological behavior of concrete made with a similar paste. However, the rheology of concrete must be specifically explored to gain more accurate knowledge of its flow behavior. As such, the equations developed by the authors in previous work (Al-Martini and Nehdi 2009-b) to predict the rheological properties of cement paste mixtures subjected to prolonged mixing under various temperatures cannot be used to predict the yield stress of corresponding concrete mixtures, and therefore new equations for concrete need to be developed.

Several functions (such as linear, logarithmic, polynomial, etc.) were tested to correlate the yield torque of concrete mixtures with test parameters (i.e. time, temperature, superplasticizer dosage). It was found that the linear function gives the best fit between the yield torque and mixing time, while the relationships between the yield torque of concrete and temperature or superplasticizer dosage can be best fit to power and inverse power functions, respectively. The yield stress versus elapsed time of fresh concrete mixtures incorporating 0.8% PC, 1.8% ML, and 1.6% NS are plotted in Figs. 4a, 4b, and 4c, respectively. It can be observed that the yield stress generally increased linearly with the elapsed time at the temperatures tested. The yield stress evolution with temperature generally followed power functions for the mixing times investigated (Figs. 4d, 4e, 4f). It should be noted that the rheology of concrete made with 1.8% of ML could not be investigated at 45°C and 110 min because it became very stiff which could damage the instrument. The variation of yield stress of concrete mixtures at 45°C as a function of the superplasticizer dosage is illustrated in Figs. 4g, 4h, and 4i for mixtures incorporating 0.8% PC, 1.8% ML, and 1.6% NS, respectively. The yield stress decreased with increased superplasticizer dosage and an inverse power function governed this relationship. It should be noted that the relationships between yield stress and test variables were similar for all concrete mixtures investigated, and results for other concrete mixtures not discussed above will not be presented herein.

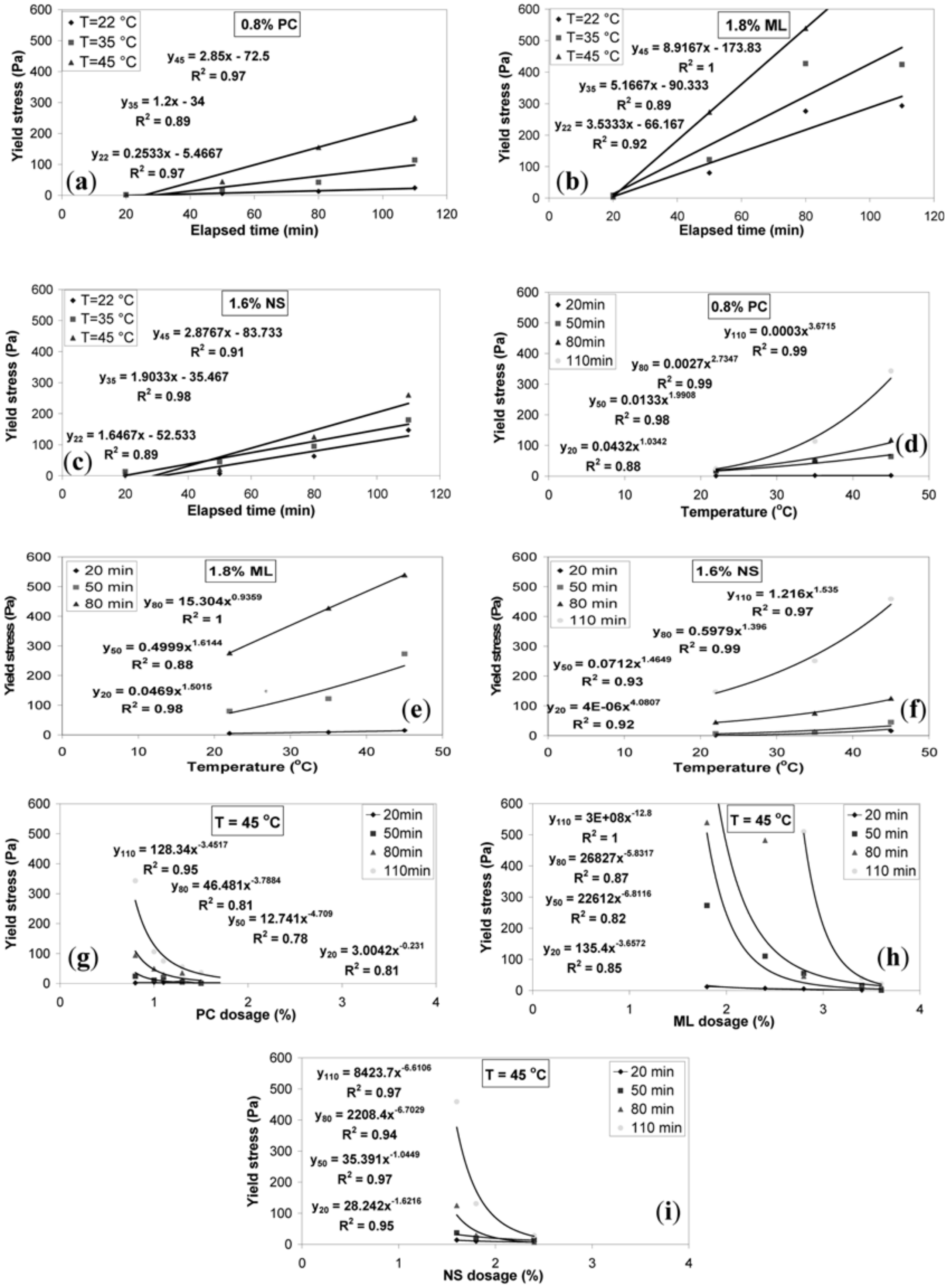

Fig. 4 Typical variation in yield stress of concrete as a function of mixing time, ambient temperature, and superplasticizer dosage for different superplasticizers

3. Database

In order to develop genetic algorithm (GA) models able of capturing the relationships between input and output parameters, such models must be trained on a relatively large number of representative data sets. Data used in the training and testing of the GA models developed in the present study were obtained from the experimental program conducted by the present authors (Nehdi and Al-Martini 2009). In total, 120 concrete mixtures were tested (40 for each of the 3 superplasticizers). For each superplasticizer, 30 mixtures were used during the model training process, and the remaining 10 mixtures were used for testing the model. The GA-based equations were optimized to predict the Bingham yield stress for each concrete mixture. It should be noted that each flow curve consists of 5 data points (Fig. 2b). Hence, 150 data points (30 mixtures multiplied by 5 points each) for each superplasticizer were used for the training process, while 50 data points (10 mixtures multiplied by five points each) were used for testing.

4. Modeling methodology

The genetic algorithms (GA) approach (see for example Michalewicz 1996) was used in this investigation to develop yield stress equations for fresh concrete mixtures incorporating various superplasticizers and subjected to prolonged mixing at various temperatures. For this goal, an original equation defining the overall flow behavior of concrete must be used in the GA-based optimization process. Eq. 2 was used in this study to create GA-based yield stress equations for fresh concrete.

The experimental results showed that the yield stress had a linear relationship with the mixing time, and therefore the relationship between the yield torque (yield torque is proportional to yield stress) and time can be expressed as follows:

$$G = a\,t - b \tag{5}$$

Based on the experimental results, the relationship between the yield torque of concrete and temperature can be generally fit to a power function as follows:

$$G = cT^{d} \tag{6}$$

The yield stress has an inverse power function with the superplasticizer dosage below the saturation dosage, and therefore the relationship between the yield torque and superplasticizer dosage can be written as follows:

$$G = eD^{-f} \tag{7}$$

Accordingly, the yield torque can be expressed as a function of the mixing time, ambient temperature, and superplasticizer dosage using the method of separation of variables:

$$G = \frac{(at - b)(cT^{d})}{(eD^{f})} \tag{8}$$

Where *a, b, c, d, e,* and *f* are model constants. Table 1 shows the ranges of the abovementioned experimental coefficients.

Table 1 Range for model coefficients

Coefficient	PC	ML	NS
a	0.1-4.0	0.1-10.0	0.3-5.0
b	0.1-150.0	1.5-200.0	10-200.0
c	0.0000007-1	0.0001-15	0.0001-2
d	0.5-5.0	0.8-4.0	0.1-2.0
e	0.4-500	10000-90000	20000-50000
f	1-5	1-15	0.9-10.0

Substituting Eq. 8 in the first term of Eq. 2, the flow curve can be obtained as follows:

$$T_R = \frac{(at-b)(cT^d)}{(eD^f)} + HN \tag{9}$$

Where, t is time (min), T is temperature (°C), and D is the superplasticizer dosage (% by cement mass). The second term in Eq. 9 (the viscosity factor, H) was considered as a constant for each flow curve and its value was taken from the measured slope of the flow curve considered.

Using the genetic algorithms approach, Eq. 9 was optimized and the optimum coefficients in this equation were determined so that the yield torque in Eq. 9 can be predicted with an acceptable accuracy within the ranges of the tested mixing time, ambient temperature, and superplasticizer dosage. A new equation was developed for each superplasticizer type, because previous work by the authors (Nehdi and Al Martini 2009) showed that each superplasticizer behaved differently.

An objective function was constructed to measure how well the predicted yield torque data agree with the corresponding measured experimental values. The GA search process was terminated when a set of coefficients that minimizes the objective function was found. Table 2 shows the model parameters. The optimized equations were converted to the Bingham yield stress through multiplying each by the conversion factor introduced in Eq. 4. The optimized equations are shown below:

For concrete incorporating a polycarboxylate superplasticizer:

$$\tau_{oPC} = \left[\frac{(0.371t-5.62)\times(10^{-7}T^{1.563})}{500D^{2.93}} \times \frac{(1/R_i^2 - 1/R_o^2)}{4\pi h \ln(R_o/R_i)}\right] \tag{10}$$

Table 2 Parameters used in genetic algorithm setting

Number of Individuals	70
Variable Format	Real values
Maximum Generations	10000
Selection Method	Roulette wheel selection
Selection Pressure	1.7
Recombination Name	Extended line
Recombination Rate	0.74
Mutation Rate	0.01

For concrete incorporating a melamine-sulfonate superplasticizer:

$$\tau_{oML} = \left[\frac{(1.5t - 29.3) \times (0.00079 T^{1.5})}{50000 D^{2.5}} \times \frac{(1/R_i^2 - 1/R_o^2)}{4\pi h \ln(R_o/R_i)} \right] \tag{11}$$

For concrete incorporating a naphthalene-sulfonate superplasticizer:

$$\tau_{oNS} = \left[\frac{(0.43t - 8.5) \times (0.00007 T^{0.1})}{20000 D^{4}} \times \frac{(1/R_i^2 - 1/R_o^2)}{4\pi h \ln(R_o/R_i)} \right] \tag{12}$$

5. Results and discussion

5.1. Validation of yield stress equations

The predicted yield stress data of fresh concrete mixtures is plotted versus the corresponding experimentally measured values in Fig. 5. The figure includes both training data (data used during the construction of the equations) as well as testing data (data not used during the construction of the equations and thus unknown to the model). The data points predicted by the GA model for PC, ML, and NS are shown in Figs. 5a, 5b, and 5c, respectively; they are located on or within small ranges around the equity lines.

The testing data, which are unknown to the GA model in the training process, were used to validate the yield stress equations (10-12). The ability of each of the yield stress equations to

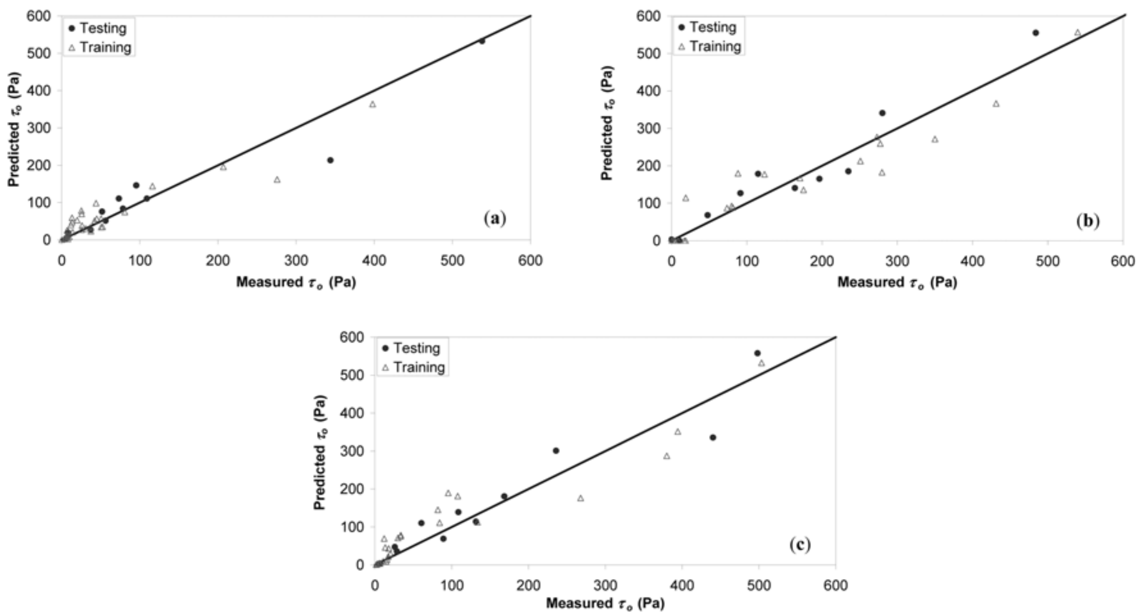

Fig. 5 Measured versus predicted yield stress for concrete mixtures at different temperatures and mixing times and incorporating: (a) PC, (b) ML, and (c) NS

Table 3 Performance of calculation equations for the yield stress of fresh concrete mixtures incorporating different superplasticizers

Superplasticizer	AAE (%)	γ_o (measured)/γ_o(calculated) (All test points)		
		Average	SD	COV(%)
PC	0.36	0.94	0.35	0.37
ML	0.28	0.92	0.25	0.27
NS	0.33	0.97	0.35	0.36

accurately estimate the yield stress of fresh concrete mixture with variation of the mixing time, temperature, and superplasticizer type and dosage was evaluated using the average absolute error (*AAE*) (Eq. 13) along with the ratio of the measured to predicted yield stress ($\tau_{o,m}/\tau_{o,p}$).

$$AAE = \frac{\left|\tau_{o,m} - \tau_{o,p}\right|}{\tau_{o,m}} \times 100 \tag{13}$$

The average, standard deviation (*SD*), and coefficient of variation (*COV*) of the measured-to-predicted yield stress ratio and average absolute error (*AAE*) for testing data are presented in Table 3. It can be observed that the *AAE* values were 0.36, 0.28, and 0.33 for PC, ML, and NS, respectively. The results indicate that the GA model was able to learn the relationships between yield stress and the different testing parameters.

5.2. Sensitivity analysis

There is need to explore whether the GA-based equations thus developed have captured the effects of the various test variables on yield stress. Hence, the influence of the mixing time, ambient temperature, and superplasticizer dosage on the yield stress of fresh concrete was tested. Concrete mixtures made with 0.8% PC, 1.8% ML, and 1.6% NS were selected from the experimental database to conduct the sensitivity analysis; these mixtures were not used in the training process of the models.

Fig. 6a illustrates the sensitivity of the GA-based equations to change in the mixing time. It should be noted that the yield stress values at 60 and 100 min were not experimentally tested, but were predicted by the model (Fig. 6a). It can be observed from Fig. 6a that the GA equations were able to capture the effect of the mixing time on the yield stress of concrete; the predicted yield stress increased with the elapsed time. The experimental results used for comparison are reasonably located close to the corresponding predicted values (Fig. 6a).

To examine the sensitivity of the GA-based equations to the ambient temperature, the yield stress of the selected concrete mixtures was predicted at various temperatures and at 50 min (Fig. 6b). The yield stress of concrete at temperatures not tested experimentally was also predicted as shown in Fig. 6b. It can be observed that the yield stress increased with the increase of temperature, indicating that the GA model has captured the effect of temperature on the yield stress of concrete. It can also be observed in Fig. 6b that yield stress predictions were reasonably close to the corresponding experimentally measured values.

To evaluate whether the developed equations captured the effect of the superplasticizer dosage on yield stress, the yield stress of concrete at 50 min and 45 °C was calculated at varying

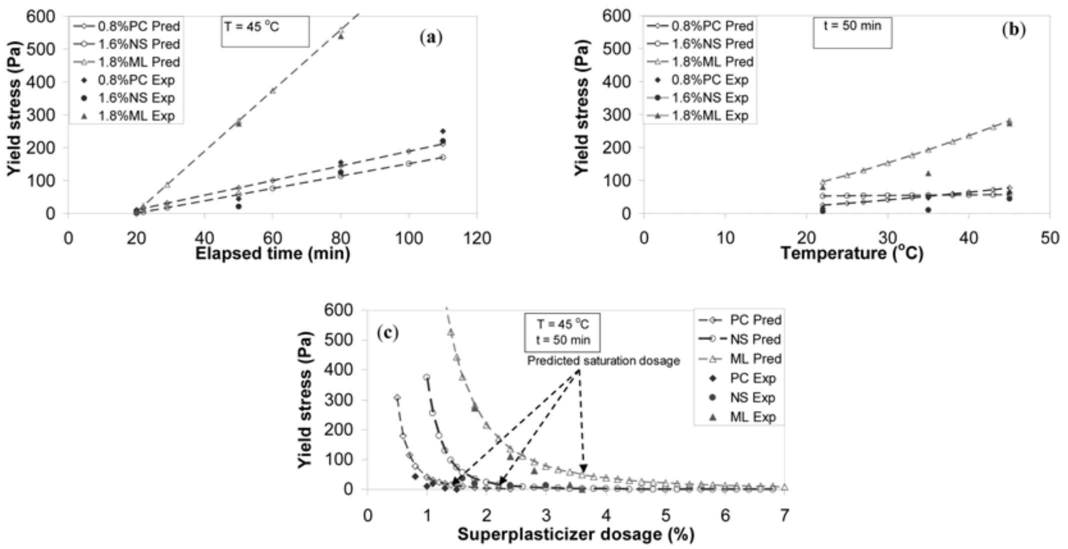

Fig. 6 Variation in yield stress of superplasticized concrete mixtures versus: (a) elapsed time at 45 °C, (b) ambient temperature at 50 min, and (c) superplasticizer dosage at 45 °C and 50 min

superplasticizer dosages. Fig. 6c illustrates the ability of the GA-based equations to capture the influence of the superplasticizer dosage on the yield stress values of fresh concrete mixtures; the yield stress decreased in a curvilinear trend with the increase of the superplasticizer dosage and the predicted values of yield stress are reasonably close to the corresponding experimental data (Fig. 6c). At a certain dosage, the decrease of yield stress became quasi linear and marginal for all superplasticizers tested (Fig. 6c). This critical dosage was depicted for each superplasticizer and compared to the corresponding saturation dosage measured experimentally. The predicted critical dosages were 1.4%, 3.6%, and 2.2%, for PC, ML, and NS, respectively, and the corresponding experimentally measured saturation dosages were 1.5%, 3.4%, and 2.0% for PC, ML, and NS, respectively (Nehdi and Al-Martini 2009). The saturation dosage for each superplasticizer was estimated reasonably well by the GA-based equations.

6. Conclusions

The correlation between the rheology of fresh concrete and that of cement paste mixtures was evaluated by measuring the yield stress of concrete and that of its corresponding cement paste. The concrete and cement paste mixtures incorporated various dosages of different superplasticizers, namely PC, ML, or NS, and were subjected to prolonged mixing at high temperature. The results showed weak linear correlations between the yield stress of concrete and that of its corresponding cement paste, indicating that cement paste rheology cannot be used alone to accurately predict the rheology of concrete made with a similar paste.

The genetic algorithms technique was used to develop equations for predicting the yield stress of concrete. Three equations (a separate equation for each superplasticizer) were developed to calculate the yield stress of concrete at various mixing times, ambient temperatures, and superplasticizer dosages. The calculated yield stress results using the proposed equations agreed well with corresponding experimental values. A sensitivity analysis for each equation to various test parameters was carried out. Based on this work, the following conclusions can be made:

- The GA-based equations captured the effect of the mixing time on the yield stress of concrete; the calculated yield stress increased with the elapsed time.
- The GA-based equations captured the effect of the ambient temperature on the yield stress of concrete, and the calculated yield stress increased with the increase of the ambient temperature.
- The GA-based equations were also sensitive to the effect of the superplasticizer dosage on the yield stress of concrete, and the calculated yield stress decreased in a curvilinear mode when the superplasticizer dosage increased.
- The saturation dosage for each superplasticizer was depicted from the calculated yield stress versus dosage curves; the depicted saturation dosages agreed well with corresponding experimental values.
- It should be empathized that the proposed yield stress equations for concrete are valid for the type of materials tested and within the range of parameters investigated. Therefore, the validity of these equations must be further verified by conducting additional experimental research in which different materials and test parameter ranges are used.

Notations

$\dot{\gamma}$	Shear rate (1/s)
μ_p	Plastic viscosity (Pa.s)
a, b, c, d, e, f	Model constants
D	Superplasticizer dosage (% by cement mass)
G	Flow resistance (Nm)
h	Height of the inner cylinder (m)
H	Viscosity factor (Nm.s)
N	Rotational speed (rev/s)
R_i	Radius of the inner cylinder (m)
R_o	Radius of the outer cylinder (m)
T	Ambient temperature (°C)
t	Mixing time (min)
t'	Normalized time
t_f	Time corresponding to dormant period (min)
T_R	Torque resistance (Nm)
α	Experimental constant
τ	Shear stress (Pa)
τ_o	Yield stress (Pa)
$\tau_{o,c}(0, T)$	Initial yield stress of concrete (at zero time)
Φ^*_I	Maximum packing density of a dry mixture
Φ_i	Solid volume fraction of a constituent

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